CONTRACT NO. A932-185
FINAL REPORT
NOVEMBER 1993

Characterization of Driving Patterns and Emissions from Light-Duty Vehicles in California

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

CHARACTERIZATION OF DRIVING PATTERNS AND EMISSIONS FROM LIGHT-DUTY VEHICLES IN CALIFORNIA

Final Report
Contract No. A932-185

Prepared for:

California Air Resources Board
Research Division
2020 L Street
Sacramento, CA 95814

Prepared by:

Thomas C. Austin
Francis J. DiGenova
Thomas R. Carlson
Richard W. Joy
Kathryn A. Gianolini
John M. Lee

Sierra Research, Inc.
1801 J Street
Sacramento, California 95814

November 1993

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CHARACTERIZATION OF DRIVING PATTERNS AND EMISSIONS FROM LIGHT-DUTY VEHICLES IN CALIFORNIA

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CHARACTERIZATION OF DRIVING PATTERNS AND EMISSIONS FROM LIGHT-DUTY VEHICLES IN CALIFORNIA

1. SUMMARY

Under Agreement No. A932-185, Sierra Research, Inc. (Sierra) has performed several tasks for the Air Resources Board (ARB) related to the characterization of driving patterns and emissions from passenger cars and light trucks operating in California. The major tasks included:

- Developing of a personal computer version of a vehicle emissions simulation model (named VEHSIME) that uses engine maps and other specified vehicle characteristics to estimate exhaust emissions over any user-specified driving cycle;
- Using a transportation system planning model to select representative driving routes in the South Coast Air Basin;
- Using an instrumented "chase car" to record the speed-time profiles of randomly selected vehicles driving over representative driving routes;
- Constructing a new driving cycle using data collected by the chase car; and
- Using the emissions simulation model to estimate the difference between emissions on the new cycle and emissions on the "LA4" cycle currently used during the testing of light-duty vehicles under the Federal Test Procedure (FTP).

During the course of the contract, the chase car, equipped with a forward-looking laser range finder system mounted in the front grill, was used to record the speed-time profiles of hundreds of different vehicles driving along a randomly selected sample of road routes in the Greater Metropolitan Los Angeles area. Supplemental information regarding the operation of vehicles at the beginning and end of trips was developed through field surveys.

Analysis of the data indicates that the speed-time profile used in the Federal Test Procedure for light-duty vehicles does not represent the full range of vehicle operation occurring in Los Angeles. Compared to

the FTP, the data collected under the contract contain higher acceleration rates and higher speeds.

A methodology was developed for constructing a representative driving cycle by selecting a subset of the available speed-time profiles that closely matches the distribution of velocity and acceleration in the full data set. Using this cycle development methodology, a speed-time profile of approximately the same length as the LA4 was constructed to represent all of the data collected during 1992 using the chase car. As shown in Figure 1, the new "LA92" cycle contains periods of significantly higher vehicle speed than occur on the LA4. The top speed of the new cycle is 108.1 km/hr (67 mph), about 16 km/hr (10 mph) faster than the 91.5 km/hr (56.7 mph) top speed on the LA4. The peak acceleration rate on the new cycle is 3.02 m/s^2, over twice as high as the peak acceleration rate of 1.48 m/s^2 on the LA4.

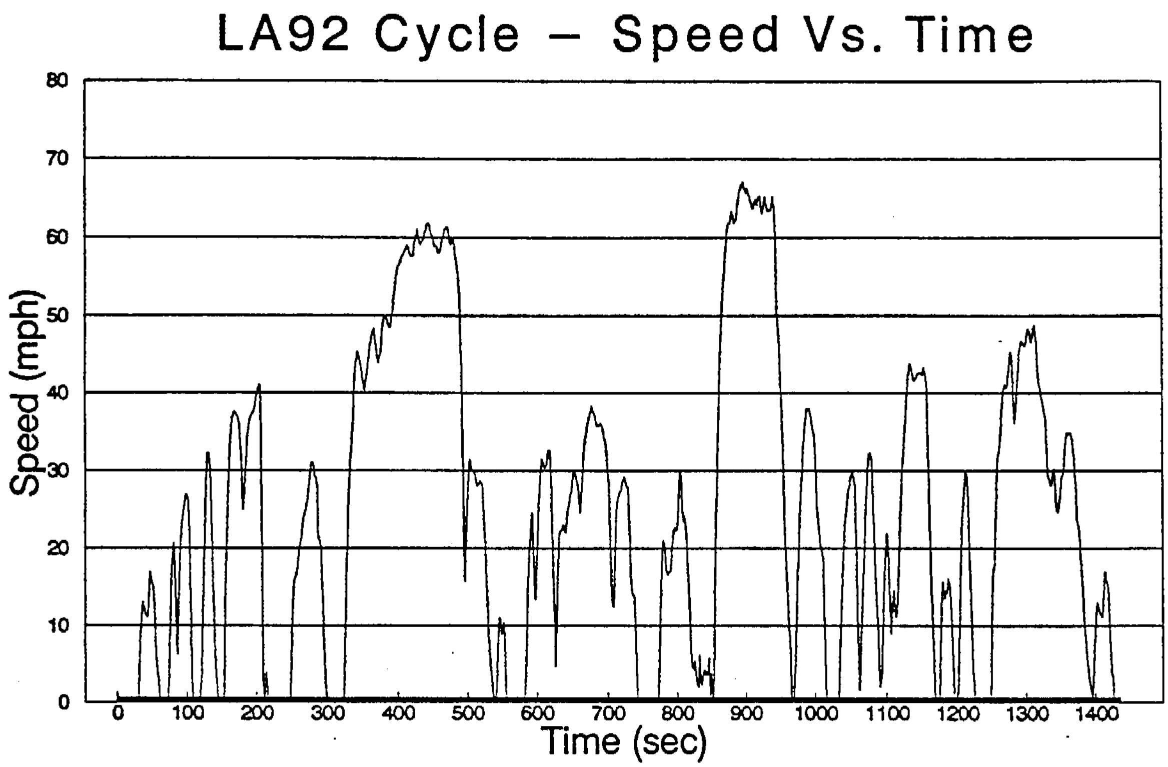
Using the VEHSIME computer model to compare exhaust emissions from a typical vehicle driven over the new cycle to one driven over the LA4, CO and NOx emissions are projected to be over twice as high on the new cycle than on the FTP, while HC emissions are nearly the same on both cycles.

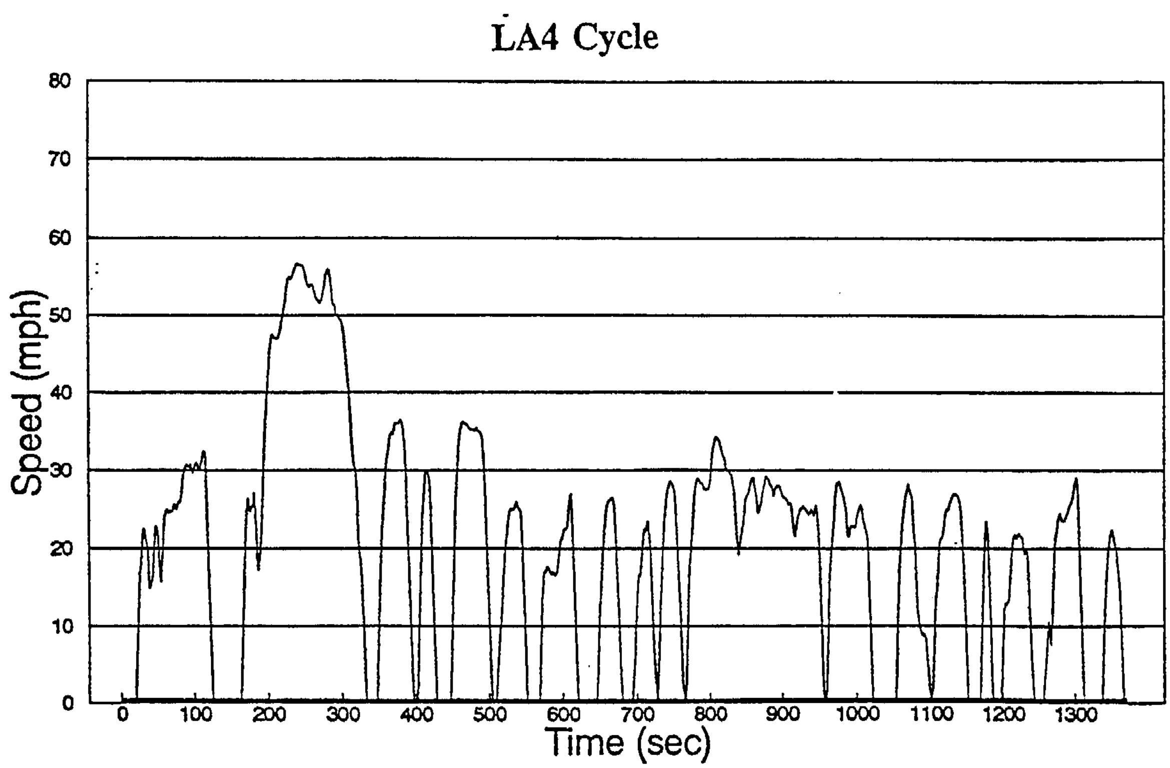
Based on the results of the project, the use of a new cycle that better represents current day driving patterns during testing of vehicles recruited from customer service would improve the quality of emissions inventories. In addition, the use of a more representative cycle during certification testing, either as a replacement for or as a supplement to the LA4, would provide an incentive for vehicle manufacturers to design emissions control systems to remain effective during modes of operation that are not currently represented in the official test procedures used during the certification process. However, standards used with a more representative test procedure would have to be different from those used with the LA4 if equivalent stringency is to be maintained. Even uncontrolled vehicles would be expected to emit more CO and NOx emissions on a cycle that includes higher acceleration rates and higher speeds.

One means of adjusting LA4-based standards would be to use the VEHSIME model to estimate emissions on both the LA4 cycle and a new cycle using engine maps that represent uncontrolled engines. Another approach would be to test a representative sample of vehicles without emissions control

Figure 1

Speed-Time Profile for "LA92" Cycle
vs. LA4 Cycle





systems using both cycles.* Either of these approaches could be used to develop adjustment factors that would be applied to LA4-based standards. Alternatively, new standards could be developed based on the results of testing vehicles designed to effectively control emissions during a broader range of operating conditions than are encountered on the LA4 cycle.

The "LA92" cycle developed during the course of the project is clearly superior to the LA4 cycle for representing current day travel in the South Coast Air Basin. Whether ARB should use the LA92 cycle to replace or supplement the LA4 depends on the extent to which consistency with the federal test procedures is to be maintained. Sierra is currently involved in a cycle development effort for EPA which will utilize data collected from instrumented vehicles operating in Baltimore, Maryland. The Baltimore data set is very similar to the LA92 data set in terms of the distribution of vehicle operation by speed and acceleration overall. If a similar cycle is developed for EPA, ARB may want to use it for consistency. Alternatively, ARB may want to consider a more comprehensive data collection effort in California.

Before a new cycle is used on a routine basis, further consideration should be given to the treatment of "starts". Under the current test procedure, the LA4 is split into two segments. The first 505 seconds of the cycle are run once using a cold start and once after the vehicle is thoroughly warmed up. One "cold" start and one "hot" start may not be sufficient to adequately represent vehicle emissions during the broad range of conditions that exist at the beginning of trips. In addition, the weighting factors used in the current test procedure may need to be modified to represent the proper proportion of cold and hot start trips. This issue is being addressed under the EPA cycle development effort and the product of that work should be available to ARB in the immediate future.

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*Exhaust emission standards based on the LA4 driving cycle are intended to represent a certain degree of control over vehicles with little or no emissions control. For example, the 3.4 g/mi CO standard represents a 90% reduction from the emissions of 1970 model-year federal vehicles, which had relatively little control. The 0.4 g/mi NOx standard represent a 90% reduction from the emissions of 1971 model federal vehicles, which had no NOx control. To the extent emissions only under speeds and loads that occur on the LA4 cycle, an emissions control system design that achieves 90% control over a cycle that is more representative of vehicle operation in customer service. The difference between the emissions of a vehicle on the LA4 cycle and a more representative cycle may not reflect the relative severity of the two cycles unless the vehicle being tested is "uncontrolled".

2. INTRODUCTION

Since model year 1972, passenger cars and light trucks have been tested for compliance with California and federal exhaust emissions standards using a dynamometer driving cycle commonly referred to as the "LA4". The name of the cycle results from the fact that it was generated by recording the speed-time profile of a vehicle driven over a route in downtown Los Angeles that had been designated as "L.A. road route number four" by the predecessor agency of the Air Resources Board. The LA4 is a "stop-and-go" driving cycle with a length of 7.46 miles and 22.9 minutes, an average speed of 19.6 mph, a top speed of 56.7 mph, and about four minutes of idle.

The characteristics of the LA4 cycle are important due to the enormous variations in vehicle emission rates across the range of operating conditions experienced in customer service. Even ignoring the effects of cold start and warm up, carbon monoxide (CO) emissions expressed in grams per mile may be over 1,000 times higher during acceleration than during steady speeds. Variations in other pollutants are less dramatic; however, 100:1 variations in hydrocarbon (HC) and 10:1 variations in NOx emission rates can be observed when vehicles are tested over a wide range of speeds and loads.[1*] Because of the strong relationship between operating conditions and emissions, it is important that the driving cycles and test procedures used to measure emissions represent the broad range of operating conditions that occur in customer service.

In response to the concerns outlined above, ARB issued a Request for Proposals to accomplish two basic objectives:

1. The development of a computer model capable of characterizing light-duty vehicle emissions over virtually any possible driving cycle; and

2. The development of new driving cycles to represent light-duty vehicle travel during peak morning, peak afternoon, and off-peak commutes.

The computer model was to be a menu-driven, microcomputer model capable of predicting emissions for almost any second-by-second speed-time profile that the user might want to evaluate.

The development of new driving cycles was to be accomplished through a two-step process. The first step was to define "typical" driving patterns over California roadways. The second step was to obtain

* Superscripts denote references provided in Section 9.

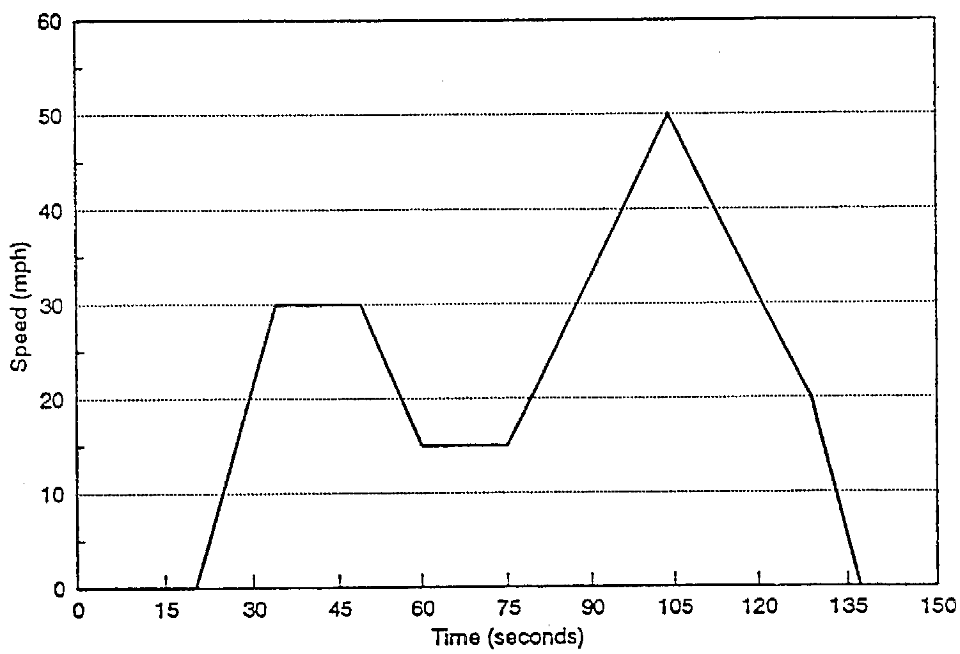
detailed information on the operation of specific vehicles engaged in typical driving.

2.1 Background

The 7-Mode Cycle - The first driving cycle for light-duty vehicle exhaust emissions measurement was based on a 1956 survey[2] of Los Angeles area traffic by the Automobile Manufacturers Association (the predecessor of the Motor Vehicle Manufacturers Association, recently renamed the American Automobile Manufacturers Association). As shown in Figure 2, the "7-mode" cycle consisted of a series of idle, constant rate accelerations and decelerations, and steady-state cruise modes. With weighting factors applied to each mode, the cycle was intended to represent average driving conditions throughout Los Angeles County. The 7-mode cycle was adopted by the California Motor Vehicle Pollution Control Board in 1961 and subsequently modified in 1964. It was used as the standard test cycle for 1966 through 1971 model year vehicles.

Figure 2

The 7-Mode Driving Cycle



Even before the 7-mode cycle was used to certify 1966 model vehicles, serious deficiencies with the cycle were recognized. Because so few operating modes were included, the cycle encouraged vehicle manufacturers to design control systems that would function on the 7-mode cycle but not under other common driving conditions. In addition, it was recognized that the cycle did not represent driving under the morning rush hour traffic conditions that were thought to be the most important source of vehicle emissions. Since the 7-mode cycle was designed to be used in conjunction with the measurement of tailpipe emission concentrations, it was also recognized that it unfairly penalized small, fuel-efficient engines.

Although not initially recognized as a serious deficiency, another problem with the 7-mode cycle is that the series of straight lines that make up the speed-time trace for the 7-mode cycle are not representative, for two reasons. First, neither the performance characteristics of automobiles nor the habits of motorists are consistent with constant rate accelerations. In real driving, the acceleration rate gradually diminishes as the desired cruising speed is approached. Second, a straight-line speed-time trace does not reflect the almost constant variations in throttle position that occur in real driving. Throttle position variations cause variations in air-fuel ratio (even with fuel metering systems that do not use "accelerator pumps"), which, in turn, affect emissions.

The XC-15 Cycle - In 1965, work began on the development of a new driving cycle.[3] The criteria for the new cycle were that it be "self-weighting" (i.e., representative of the proper mix of driving without the use of weighting factors), use the minimum number of modes possible, and match morning peak-hour driving conditions in central Los Angeles in terms of:

- pollutant concentrations,
- exhaust volume, and
- average speed.

The development of the new cycle was based on the following methodology:

1. Determine the average engine operating mode distribution (based on manifold vacuum and rpm ranges) in central Los Angeles using a variety of drivers and routes with a single test vehicle;
2. Find a specific road route that produces the same average mode distribution with a variety of drivers using the same test vehicle;
3. Using the same vehicle, develop a dynamometer test cycle that produces the same mode distribution as the specific road route; and
4. Validate the dynamometer cycle by comparing emissions of other vehicles and drivers.

The operating mode distribution of vehicles driven in central Los Angeles was recorded using an instrumentation package originally developed by DuPont.[4] The instrumentation consisted of a set of timers that recorded the time spent in various manifold vacuum-rpm ranges. (The chronology of engine operation was not recorded, just the total time in each operating range.) Using an instrumented 1964 Chevrolet, recordings were made of actual home-to-work commute trips by employees of the California emissions laboratory, then located on South San Pedro Street in Los Angeles. By trial and error, a specific street route in the vicinity of the Lab was found that matched the average speed/load distribution of the commute trips. That road route was called the LA4. Starting at the laboratory, the route was a 12-mile long, figure-eight loop that went from San Pedro to Third Street, to the Harbor Freeway, to Exposition Boulevard, to Western Avenue, to Olympic Boulevard, to Santee Street, to Ninth Street, to San Pedro Street, and back to the lab.

The methodology outlined above led to the development of the ill-fated XC-15 cycle. The XC-15 cycle consisted of 18 separate idles, accelerations, cruises, and decelerations. Like the 7-mode, all of the speed changes were done at a constant rate and all of the cruises were done at steady state. Although the cycle matched the on-road vehicle operation in terms of percent of time in specific load-speed ranges, the dynamometer cycle did not correlate with emissions from several different vehicles operating on the road route (measured with onboard "proportional samplers"). Although the XC-15 cycle was never adopted as a standard, the effort put into the development of the cycle was not wasted. A significant aspect of the XC-15 cycle development effort was the establishment of the specific road route found to represent typical driving in central Los Angeles during morning peak-hour traffic.

The Urban Dynamometer Driving Schedule - At the time that the XC-15 cycle was being developed, federal air pollution control officials were also becoming interested in the development of an improved light-duty vehicle driving cycle. Federal officials started adding more sophisticated instrumentation packages to vehicles to record the time sequence of engine load-speed profiles in addition to total time in each operating range.[4] Using this equipment, Department of Health, Education, and Welfare (HEW) officials developed a road route near their facility in Cincinnati, Ohio that approximated the LA4 road route.

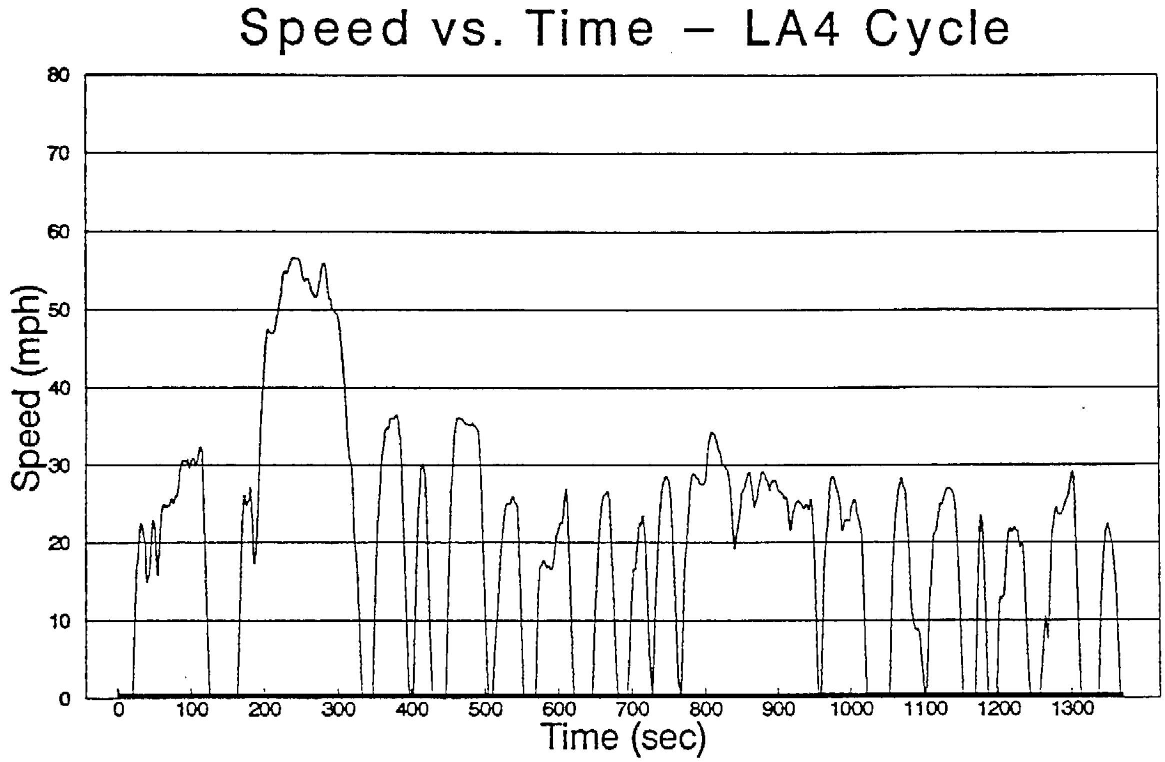
When the federal program was moved to Ypsilanti, Michigan, a similarly instrumented vehicle was used to find a new road route near the Michigan facility that would match the characteristics of the Cincinnati road route. This vehicle was also equipped with a "5th wheel" and a strip chart recorder to record the actual speed-time history of the vehicle. During efforts to match the Cincinnati engine load-rpm profiles in the Ypsilanti area, it was discovered that it was much easier to work with the vehicle speed-time strip chart. It also became apparent that the vehicle's speed-time history with all drivers contained a substantial amount of high-frequency, low-amplitude speed fluctuations that were not being recorded by the engine load-speed instrumentation package. For the first time, it became apparent that the effect on emissions of these minor speed deviations might be significant. Immediately, an attempt was made to follow an actual speed-time history during a chassis dynamometer test and it was learned that drivers could easily duplicate the minor speed deviations almost perfectly[4]. At that point, all of the previous efforts to record engine load-speed data were abandoned, and federal air pollution control personnel (soon to become part of the new Environmental Protection Agency) set out to develop a new driving cycle using actual speed-time traces generated along a road route.

An engineer and an electronics technician were sent to Los Angeles to record a speed-time profile over the LA4 road route. Six different drivers from EPA's West Coast Laboratory drove a 1969 Chevrolet over the route. Back in Ypsilanti, 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 and the other five were surprisingly consistent. Of those five, the trace with the actual time closest to the average was selected as the most representative speed-time trace. This trip 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[5], 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 the time. Mass emission tests comparing the shortened cycle to the full cycle showed very high correlation. The final version of the cycle, shown in Figure 3, was designated the LA4-S4 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 light-duty vehicles since the 1972 model year. Since the 1975 model year, the initial 505 seconds of the cycle are repeated following a 10-minute hot soak. After weighting factors are applied to the first 505 seconds of the cold start and the 505 second hot start portion, the test provides a more accurate reflection of typical customer service than running just one 7.46 mile cycle from a cold start.[6]

The Highway Cycle - In 1973, the disruption of U.S. oil imports caused by an embargo heightened interest in vehicle fuel economy. EPA had recently begun publishing vehicle fuel economy estimates based on a "carbon balance" calculation of carbon-containing emissions measured during the certification testing of vehicles on the LA4 driving cycle. Since the LA4 represents vehicle operation in congested urban areas, vehicle manufacturers complained that fuel economy under non-urban operation should be included in any computation of fuel economy published by the federal government. Some manufacturers began advertising "highway" fuel economy figures based on their own tests. The Federal Trade Commission immediately became concerned about the potentially misleading nature of such fuel economy claims. In response to this situation, EPA undertook a crash program to develop a new driving cycle to represent non-urban operation.

Figure 3
The LA4 Driving Cycle



Based on the EPA project team's knowledge of factors affecting emissions and fuel economy from light-duty vehicles, the design criteria for the new highway cycle included the use of a representative trip length, preservation of the non-steady-state nature of real-world driving, and the use of a representative average speed <u>and number of stops per mile</u>.[7] Although the EPA highway cycle has been criticized for exaggerating the level of fuel economy achieved by typical vehicles in non-urban driving, this is almost exclusively due to a policy decision made by EPA to have the cycle represent operation in areas where the new 55 mph speed limit was being strictly enforced. Subsequent testing using instrumented vehicles demonstrated that the cycle is very well correlated with actual highway driving under such conditions.[8]

Like the LA4, the EPA Highway cycle is based on the speed-time history of a specific vehicle travelling over a specific road course. However, while the LA4 is a minimally shortened version of one particular trip over the LA4 road route, the Highway cycle is comprised of four different segments of operation selected from different trips made by different drivers of a vehicle that was following other cars over 1,050 miles of non-urban roads in southern Michigan and northern Ohio and Indiana.

In the Highway cycle development program, the target mix of operation involved achieving a specific mix of travel over four specific types of non-urban roads (principal arterial, minor arterial, collector, and local). Unlike the LA4, the routes over which EPA travelled did not contain the target mix of operation. When the shortened version of the cycle was constructed, the length of the speed-time trace from each type of road was selected to achieve the target mix. In addition, each segment of the speed-time trace was selected to match the average characteristics of all operation on the same type of road in terms of average speed, major speed deviation frequency, minor speed deviation frequency, and stops per mile. It was also necessary to identify segments of operation that had end points that could be matched with adjacent portions of the cycle (to eliminate discontinuities between segments).

The technique used by EPA in the development of the highway driving cycle was not a purely "chase car" approach. The chase car drivers were instructed to "flow along with traffic, that is, to pass as many cars as passed them."[7] As long as it had been previously determined that the chase car driver generated representative minor speed deviations, this technique eliminated the potential bias associated with pure chase car techniques that results from motorists sensing that they are being followed.

Although EPA developed the Highway cycle, it was ARB that first used the cycle to control emissions from motor vehicles. In the late 1970s, ARB determined that certain vehicle manufacturers were developing control systems that would fail to control NOx emissions during extended higher speed operation. The ARB staff made the case that such operation does occur in the South Coast Air Basin and contributes to violations of the ambient air quality standards. Manufacturers were therefore required to demonstrate that NOx emissions from candidate vehicle models would not be substantially higher on the EPA Highway cycle than on the LA4.

<u>Other Driving Cycles</u> - Since their development, the UDDS or "LA4" and the EPA Highway cycle have been the standard test cycles for emission testing in the United States. However, it has been recognized that these cycles fail to represent typical driving conditions in certain areas. Because of the relatively high speed "freeway" segments of the LA4, the cycle does not represent typical driving patterns in extremely congested areas, like New York City. In addition, based on observations about the storage and release of sulfate in catalysts, it was clear that the LA4 would not represent the worst-case cycle for sulfate emissions from catalyst-equipped cars and trucks. To deal with these concerns, the New York City Cycle (7.1 mph average speed) and special "sulfate" driving cycles were developed by the state of New York and EPA. In addition, EPA has used portions of the LA4 to construct "speed correction cycles" to evaluate the effect of speed changes on vehicle emissions. These other cycles have been developed in an attempt to represent driving conditions other than those thought to be typical of Los Angeles.

Outside of the U.S., cycles of the 7-mode type have been developed for use in Japan and many European countries. The "ECE" cycle used in Europe and the Japanese "10-mode" are less realistic because they ignore minor speed deviations and have been shown to have acceleration rates that are much too gentle to adequately represent typical urban driving.[9] Much more realistic cycles have been proposed by H.C. Watson and his associates from the University of Melbourne, Australia.[10] Unlike the Japanese and ECE cycles, Watson's cycles reflect the transient nature of real-world driving, as does the LA4. Unlike the LA4, Watson's cycles contain higher acceleration rates.

<u>Potential Problems With the Current Cycles</u> – Both the LA4 and the EPA Highway cycle have become institutionalized as the standard cycles to represent urban and non-urban driving. As can be seen from the preceding discussion, however, the basis for the LA4 and the Highway cycles is substantially out of date. Travel along the LA4 road route was determined to be representative of central LA driving 27 years ago, but there have been enormous changes in the Basin since that time. It would be purely fortuitous if the LA4 route currently provided the best representation of light-duty vehicle operation in the South Coast Air Basin. Since the speed correction cycles are a patchwork that includes pieces of the 27-year-old speed-time profile for the LA4 road route, they are also of questionable relevance to present conditions in the South Coast Air Basin.

The EPA Highway/Cycle is also of questionable validity for the South Coast Air Basin. Most people are not aware that it was developed to represent <u>non-urban</u> driving only <u>in areas where the 55 mph speed limit was being strictly enforced</u>. Most South Coast freeways would not be considered "non-urban" and most people who have driven on California freeways recognize that many vehicles often travel at significantly higher speeds than those represented on the Highway cycle.

Other indications of potential problems with the current cycles have been pointed out in several different technical papers presented by Watson and his associates. Watson has shown that the acceleration rates contained in the LA4 are significantly lower than those observed in typical urban traffic.[10] Based on Watson's analysis, data from the General Motors chase car program[11] also show that LA4 acceleration rates are generally too low.

Based on a 1988 vehicle emissions testing program conducted by Sierra and Southwest Research Institute,[1] it is clear that late-model automobiles are extremely sensitive to acceleration rate. A less well-researched concern with the representativeness of the current driving cycles is the extent to which they adequately simulate cold start emissions. With properly maintained late-model cars and light trucks, the emissions that occur prior to catalyst light-off represent a substantial portion of the total emissions for the LA4 cycle. The operation of the vehicle during warm-up affects how fast the catalyst reaches operating temperature as well as the level of emissions through the bed of the cold catalyst. The LA4 cycle subjects the vehicle to relatively high speed freeway operating conditions within three minutes of the cold start. If this little time between cold start and high load operation is not typical, it might affect the length of the catalyst warm-up period and affect average emissions over the entire cycle.

<u>Modeling Emissions Under Alternative Driving Conditions</u> – Since vehicle emissions are extremely sensitive to vehicle operating conditions, it is important for standardized driving cycles to appropriately reflect actual driving in customer service. However, due in part to substantial

geographic and temporal variations in driving patterns, one driving cycle cannot be expected to represent light-duty vehicle operation at all times and places. Historically, EPA and ARB have attempted to estimate area-specific vehicle emissions through the application of speed and temperature correction factors to data generated with the standard test procedures. Such factors are incorporated within the MOBILE4 and EMFAC computer models. However, the correction factors built into these models were developed by interpolating and extrapolating stabilized (not including cranking) "hot start" test results for the LA4 compared to other speed-time traces, such as the New York City cycle and the Highway cycle. By their very nature, the correction factors cannot be expected to provide accurate predictions of operations that involve significantly different acceleration rates in addition to differences in average speed.

Temperature correction factors currently in use are based exclusively on the results of LA4 cycle operation at different ambient temperatures. Such adjustments cannot be expected to produce accurate estimates of temperature effects under a fundamentally different speed-time sequence.

A model with inherently better capability to predict the effect of driving pattern changes would appear to be desirable.

2.2 Considerations Affecting the Development of the Work Program

During the development of the work plan, two approaches for characterizing the operation of vehicles in customer service were considered: 1) collect data from instrumented vehicles driven by a variety of motorists; and 2) collect data using an instrumented "chase car" that follows randomly selected motorists. As described above, the LA4 cycle was developed based on the use of data from an instrumented vehicle operating in customer service and the Highway cycle was developed based on the use of hybrid ("go with the flow") chase car data. As discussed below, however, neither of the techniques previously used for cycle development provide assurance that the resultant cycle adequately represents light-duty vehicle operation in customer service.

Cold Start and Warm-Up Effects - Given the vehicle-to-vehicle variability in cold start and warm-up performance, no single trip length can possibly represent the average emissions for every make and model of vehicle. A related factor is that, given the continuous distribution of soak times between trips, no single soak time can possibly be expected to represent the initial conditions of the engine and emissions control system during all starts. The test procedure used in conjunction with the LA4 cycle attempts to represent the range of initial conditions by weighting together emissions measured from a "cold" start (minimum 12 hour soak time) and a "hot" start (10 minute soak time). Using an estimate of 4.7 total trips per day, two of the trips are assumed to be from a cold start and 2.7 of the trips are assumed to be from a hot start. Implicit in the test procedure is that all trips are 7.5 miles in length, regardless of whether they are hot start or cold start. Implicit in the test procedure used with the Highway cycle is that all non-urban trips are assumed to start with a warm engine.

In order to ensure that the effect of hot and cold starts could be properly accounted for in the final cycle, the cycle development needs to be structured to ensure that vehicle operation during the beginning of the cycle will reflect vehicle operation during the beginning of a trip. If this is accomplished, replication of the initial portion of the cycle with differing degrees of warmup can be used in conjunction with weighting factors to properly represent the effect of variations in the condition of the vehicle at start up.

Speed-Time Profile Effects - Vehicle emissions are known to be strongly affected by variations in acceleration rate and speed. Because traffic congestion, speed limits, traffic signals, and other roadway characteristics affect the speed-time profile of vehicles travelling a particular route, the development of a representative driving cycle must involve the characterization of vehicle operation over a wide range of roadway and driving conditions that collectively represent travel occurring in the area of interest. Given the vehicle-to-vehicle variation in performance and driver-to-driver variation in "aggressiveness", no single vehicle-driver combination can be expected to represent the distribution of acceleration rates that occurs in customer service even if travel over a wide range of traffic conditions is monitored. The need to represent the range of speed-time profiles is important when emissions that occur infrequently are much higher than emissions that occur under "typical" conditions. For example, consider the hypothetical case of a particular mode of vehicle operation that occurs only 0.1% of the time. If emission rates during this infrequently occurring mode are 1,000 times higher than during other modes of operation, then the exclusion of this mode would cause average emissions to be understated by 50%. The overall average emissions of the vehicle would be twice as high as the emissions that occur 99.9% of the time:

$$(1 \times .999) + (1{,}000 \times 0.001) = 2.0$$

As mentioned earlier, the "hypothetical" example shown above is a concern because previous testing programs have shown that CO emissions can be 1,000 times higher under hard accelerations than under the more moderate accelerations contained in the LA4 cycle. Given the potential significance of infrequent events, it would be desirable to know the contribution to emissions in customer service of as many instantaneous operating conditions as possible. With such information, a cycle could be constructed that not only produces emissions equal to the true average, but also reflects the specific operational characteristics that determine the average. If the length of the cycle needed to achieve the proper average is excessive, weighting factors of less than 1.0 could be considered for those elements of vehicle operation that cause extraordinarily high emissions.

The LA4 driving cycle contains a speed-time profile that represents the manner in which one particular car was driven by one particular driver during one particular trip. As such, the speed-time profile cannot reasonably be expected to represent the wide range of speed-time profiles occurring in customer service. The Highway driving cycle incorporates data from several different trips by a vehicle that followed the flow of traffic; however, the segments of the speed-time trace used in the development of the cycle were selected based on how well they represented the average speed for the full data set. In addition, the Highway cycle was specifically developed to represent non-urban vehicle operation in areas where the 55 mph speed limit was strictly enforced. Its applicability to the current situation must be seriously questioned. The freeway speed limit has been raised to 65 mph in most non-urban areas and frequent violations of the 55 mph limit in urban areas are known to occur. As with the LA4, the Highway cycle cannot reasonably be expected to represent the wide range of speed-time profiles occurring in customer service.

Roadway Grade - Previous efforts to characterize the operation of vehicles in customer service have concentrated on the measurement of speed-time profiles. Implicit in the analysis of speed-time data and its subsequent translation into a dynamometer driving cycle was that the effects of roadway grade could be ignored. In areas with rolling terrain, this assumption may lead to significant differences between the emissions emitted during dynamometer testing and the emissions actually occurring over the road. Because of the non-linear relationship between vehicle emissions and vehicle load, there could be significant emissions effects of travel over road routes with periodic grade changes even though the net grade change is zero. The most obvious effect would be reflected in carbon monoxide emissions during stop-and-go operation in hilly terrain. During uphill accelerations, vehicles would be more likely to go into power enrichment which, in the case of vehicles that do not use air injection after warmup, causes emissions to increase by more than an order of magnitude. Lighter average loads during downhill operation would not produce correspondingly large emission reductions.

Data Collection Alternatives - The considerations outlined above have several implications. It is apparent that soak time prior to the beginning of a trip is important and must be known to determine how emissions during the initial phase of a trip are being affected by the initial conditions of the engine. Because of the cold start/warm-up effects, average emissions per mile will also be affected by the length of the trip. In order to ensure representative speed-time profiles, it will be necessary to ensure that the data being collected from trips are representative in terms of level of traffic congestion, roadway type, and driver behavior. As set forth below, alternative data collection methods have different strengths and weaknesses.

Diary Data - Asking motorists to keep track of their travel behavior in a written log could conceivably generate a substantial amount of data on soak times, trip lengths, and average speeds at relatively low cost. Representativeness of the sample, however, would be an obvious concern. Motorists willing to participate in a diary data collection effort may not represent the full range of motorists. Accuracy and consistency of information obtained in such a manner would be questionable, and detailed speed-time profiles could not be obtained.

Questionnaires/Surveys - Asking motorists to provide information on their driving through the use of questionnaires or surveys would be expected to suffer from many of the same deficiencies as diary data collection efforts. Representativeness of the sample would remain a potential problem. Expecting motorists to remember times and mileages accurately could be a serious problem. As with the case of diary data, detailed speed-time information would not be available. The technique has some promise, however, for obtaining short-term data on trip locations and soak times with reasonable accuracy and low cost, provided a high response rate can be achieved through the use of sufficient incentives for participation.

Instrumented Vehicles - The use of instrumented vehicles provides the opportunity to obtain excellent resolution on speed-time profiles, as well as accurate information on soak times between trips; however, representativeness of the sample remains a concern for several reasons. The only feasible means of obtaining data from instrumented vehicles without the knowledge of the motorist would probably involve the use of rental cars or loaner vehicles. There would be obvious concerns with the representativeness of the manner and circumstances under which such vehicles might be driven. By restricting the sample to motorist-owned vehicles, two other factors might be expected to influence the results. First, motorists who would volunteer to have their vehicle instrumented may not be representative. Second, motorists who are knowingly driving an instrumented vehicle might alter their driving behavior (e.g., reduce their tendency to speed).

Chase Cars - Surreptitiously following vehicles in traffic with an instrumented "chase car" eliminates some of the concerns with instrumented vehicles while introducing other concerns. The main advantage of the chase car approach is that the speed-time profile of other drivers and vehicles can be sampled without the need for volunteers who know they are involved in an experiment. The accuracy of the speed-time data collected depends on the sophistication of the instrumentation package on the chase car and/or the ability of the chase car driver to generate the same speed-time trace as the vehicle being followed. The representativeness of the data collected by the chase car also depends on whether the vehicles followed are selected on a random basis and whether the time and location of chase car operation adequately represents travel in the area. If representative routes have been identified, however, chase cars provide the ability to sample a relatively large number of vehicle miles travelled per day (compared to instrumented motorist-owned vehicles).

Provided that an acceptable method is used to randomly select vehicles to follow, one limitation of the chase car approach is that certain vehicles are difficult to follow, especially those that are being driven in an aggressive or erratic manner. Another limitation of the chase car approach is that it is not amenable to determining soak times between trips or to capturing "trip ends". A concern, but not necessarily a significant limitation, is that, depending on the technique being used, following other vehicles could influence the drivers' behavior.

2.3 Work Program Summary

Vehicle Simulation Modeling - To satisfy the requirements of the scope for a computer model to estimate emissions over any specified driving cycle, Sierra developed personal computer versions of two related models, VEHSIM and VEHSIME. VEHSIM is a vehicle simulation model, originally developed by General Motors in the early 1970's, that determines the second-by-second engine speed and torque required to drive a vehicle over any specified speed-time profile. The second-by-second engine operating conditions are used in conjunction with a "map" of fuel consumption for a particular engine to determine the second-by-second fuel consumption for the vehicle. By accumulating the second-by-second results, the model predicts fuel consumption over the specified driving cycle. The VEHSIM model was modified by the U.S. Department of Transportation and an EPA contractor to perform simultaneous computations of fuel economy and emissions of HC, CO and NOx. This was accomplished by writing a new program, VSIME, which utilizes the VEHSIM program output for engine speed and torque time histories in conjunction with engine emission maps to calculate instantaneous and cumulative emission rates over a driving cycle. The program output includes emission quantities computed by VSIME and fuel consumption quantities computed by VEHSIM.

During 1987, the emissions-prediction version of the model was recreated by Sierra from a written description of the earlier EPA effort. Sierra's version of the model currently has over 4,000 lines of source code and comments. It is called VEHSIME to distinguish it from the original version of the model, VSIME. Numerous enhancements to the original version have been implemented during the past five years.

Vehicle configuration data characterize shift logic, fan losses, power steering losses, and air conditioning losses. The shift logic is expressed for gear changes based on vehicle speed and manifold vacuum. Using these data in conjunction with other vehicle characteristics (e.g., weight, frontal area, aerodynamic drag), VEHSIM computes the engine speed, load and fuel consumed by a vehicle to maintain the acceleration and speed requirements set for a particular segment of driving cycle being used. The driving cycle files used by VEHSIM specify the vehicle acceleration/deceleration requirements and associated vehicle speed levels for each segment of the cycle. Segments are defined to be one second in length. Acceleration/deceleration requirements are determined from the driving cycle, and the program uses them to determine the engine speed and load required to achieve the desired velocity set for the segment. The program employs many contingencies to accommodate conditions where the vehicle is unable to achieve the desired velocity or the specifications of the engine map are exceeded. Once the desired engine speed and load conditions needed to satisfy a particular segment have been identified, the instantaneous fuel consumption rate (i.e., the rate across the segment) is determined by a double interpolation with respect to speed and load within the engine map.

The first interpolation is with respect to load within each of the relevant rpm settings. The second interpolation is between the load values for each of the rpm settings. Instantaneous (i.e., per segment) engine speed, load point and fuel consumption values are then recorded for each segment of the cycle. The outputs of VEHSIM include:

- cumulative distance (miles) and time (seconds);

- second-by-second and cumulative fuel consumption (pounds);

- second-by-second engine horsepower (hp) and torque (lb-ft);

- second-by-second engine speed (rpm);

- second-by-second manifold vacuum (inches of mercury); and

- second-by-second percent of wide open throttle.

Inputs to VEHSIME consist of the above outputs from VEHSIM plus engine emission maps for HC, CO and NOx. Each engine emission map gives the emission rate as a function of engine rotational speed (rpm) and engine torque (lb-ft). The HC and NOx emission rates are input in units of grams per hour. The CO emission rate is entered in units of 10 grams per hour.

For each segment of the driving cycle, the time duration is defined to be one second. VEHSIME reads the load and engine speed values computed by VEHSIM and uses that information to compute the instantaneous emission rate. Emission rates are then determined by double interpolation with respect to load and rpm within each engine map. The first two interpolations are with respect to load, for the constant rpm lines that bracket the rpm value, and the final interpolation is with respect to rpm. The VEHSIME program predicts HC, CO, and NOx emissions for each second of the driving cycle. There were seven different engine maps in the format required by the model when it was originally obtained by Sierra. Those engine maps spanned a size range from 91 to 350 cubic inches. There were also seven different chassis ranging from 2500 to 5000 pounds; however, it is possible to add weight to these chassis through the user-selectable inputs. The program also contains several different transmissions from which to choose.

Prior to the beginning of the project, the most current engine map data contained in the model were for mid-1970s vintage engines equipped with oxidation catalysts. In addition, no data were available that allowed the effects of cold start and warmup to be taken into account. During the course of the contract, Sierra added a cold start algorithm and developed a 3-way catalyst engine map using data supplied by EPA.

<u>Collection of Data on Vehicle Operation</u> - Based on the considerations outlined in Section 2.2, Sierra developed a multifaceted data collection effort to characterize light-duty vehicle operation in routine customer service. To characterize speed-time profiles on public roadways, the selected approach involved the use of a chase car, instrumented to measure the speed-time profile of other vehicles without having to follow them in a close or consistent manner. To ensure representative traffic conditions, road routes for the chase car to follow were selected randomly from a validated transportation model after the routes had been "trip-weighted". To overcome the problem with recording trip end behavior, supplemental data were obtained from a trip end survey involving visual observation of trip origins and destinations. To overcome the problem of not knowing soak times between trips, survey information was to be collected from a random sample of motorists

stopped at Highway Patrol roadblocks or interviewed during refueling operations at service stations.

Although the RFP was silent as to whether the contractor was expected to focus on the South Coast Air Basin, Sierra concluded that the level of available resources made it impractical to consider differences in driving patterns that may exist throughout the state's urban and non-urban areas. Data collection efforts were therefore focussed on the South Coast Air Basin.

Cycle Construction - Under Sierra's original proposal, analysis of the data from the chase car survey would have been based on the same approach used by EPA during the development of the Highway driving cycle. Cycle(s) developed from the data were to have been defined in terms of average speed, stops per mile, and major speed deviations per mile; and augmented by criteria suggested by Watson, which include:

- average speed while moving;
- average acceleration;
- average deceleration;
- percent idle; and
- positive acceleration, kinetic energy change ("PKE").

The concept for using these supplemental criteria was to make it possible to distinguish between radically different driving patterns that superficially appear to be the same using the criteria that have been employed in the development of driving cycles in the past. For example, "PKE" is a measure of the acceleration work required in a driving cycle and it can be substantially different for two cycles with the same average speed.

The original concept was for segments of actual driving traces to be selected that closely match the overall statistics and fit together in a logical and representative manner and provide a representative trip length. During the course of the contract, the concept of constructing a cycle from segments of actual driving traces was maintained; however, Sierra developed a variation on the concept of designing a cycle to match a list of individual criteria. That concept involved developing a cycle to match a 3-dimensional surface called a "Velocity Acceleration Probability Density Function," a technique for characterizing vehicle operation developed by Watson. By matching the 3-dimensional surface, most of the individually identified criteria are also matched.

2.4 Organization of the Report

Following this introductory section, Section 3 describes the development of the chase car used to collect data from randomly selected vehicles followed along preselected driving routes.

Section 4 describes a test program under which a variety of Sierra employees drove the chase car over the same road route during similar traffic conditions in order to determine the extent to which the operation of the vehicle was affected by different drivers.

Section 5 describes the methodology used to select the road routes over which the chase car would be used to collect data and the operational procedures used while collecting data.

Section 6 describes the survey of trip-end activity used to collect data charactering vehicle operation that was not feasible to collect using the chase car.

Section 7 describes the analysis of chase car data.

Section 8 describes the cycle development process used to generate a driving cycle from the chase car and trip-end data. This section also describes the results of the computer modeling of estimated emissions on the new driving cycle compared to the LA4.

Section 9 contains a list of references cited in the body of the report.

Appendix A contains a detailed description of a supplemental speed measurement system developed for the chase car.

Appendix B contains more detailed summaries of data collected during the field survey of "trip end" activity.

Appendix C contains a Users Manual for the PC version of the VEHSIM/VEHSIME computer model.

Appendix D contains a second-by-second tabulation of the LA92 driving cycle.

Data collected by the chase car while driving the selected road routes have been provided to ARB on magnetic tape. In addition, a set of video tapes has been provided that document the roadway conditions under which the data were collected.

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3. CHASE CAR DEVELOPMENT

Under Sierra's original scope of work for ARB, the concept for the chase car involved using a vehicle with a relatively high power/weight ratio that would be instrumented to record its own road speed once per second while closely following other vehicles in traffic, especially during major speed deviations. Accurate characterization of the speed-time profile of vehicles being followed would have been a function of the ability of the chase car driver to match the vehicles' driving patterns. However, in support of its efforts to review the light-duty driving cycle as mandated by the recent Clean Air Act amendments, the Certification Division of EPA augmented the resources available to Sierra to collect data in Los Angeles. This made possible the adaptation of a laser range finder system for use in the chase car so that the speed time profiles of vehicles in front of the chase car could be accurately determined without following the vehicle closely or at a consistent distance.

3.1 Vehicle Selection

Once the decision was made to pursue the development of a system to measure the relative speed of vehicles being followed without maintaining of a fixed separation distance, the power/weight ratio of the chase car became somewhat less important. Higher priority was assigned to identifying vehicles with sufficient room for the instrumentation needed to monitor the speed of the vehicle being followed. An inconspicuous appearance remained a high priority.

When the size constraints for the instrumentation package were identified, it was clear that vehicles with the largest possible space between the radiator/condenser and the grill were going to be desirable. The Chevrolet Caprice and the Lincoln Town Car were identified as two vehicles with a large space behind the grill. Of these, the Caprice provided easier access to this space and nearly the same power/weight ratio, at substantially lower cost. The Caprice was also considered to be a somewhat less conspicuous car, especially from the front. Because the Caprice is a popular model for police vehicles, it was ordered with aluminum wheels and white sidewall tires and the rear glass was tinted to help ensure that it would not be mistaken for a police vehicle. White was selected as the exterior color for two reasons: it is the most common color for a light-duty vehicle (and therefore somewhat less conspicuous); and it is the most practical color for minimizing heat build up in the trunk and passenger compartment. To improve handling and performance, the vehicle was ordered with the trailer-towing package consisting of higher rate springs and a numerically higher rear-end ratio (3.08:1).

3.2 Laser Range Finder Development

The initial efforts related to alternative instrumentation packages involved investigating a forward-looking, "same lane" radar system to record the relative speed of a vehicle being followed. Police-type radars proved to be inadequate because of accuracy limitations at speed differentials below about 10 mph. This limitation is fundamental to doppler-based radar systems, which operate on the principal that a radar signal's frequency shifts as a result of reflection from a target having a non-zero relative speed. As the relative speed of the target approaches zero, so does the frequency shift, rendering the task of estimating speed more difficult. This problem is compounded, in the application of interest here, because most commercial doppler radar designs for law enforcement application are not concerned with small (e.g., <10 mph) relative speed differences.

A representative of the California Highway Patrol advised Sierra that he was aware of at least one laser-based speed measurement system currently being developed. Various other communications led to the identification of Laser Atlanta as a company that already had working models of a hand-held laser range finder-based speed measurement system designed to compete with hand-held police radar units. By measuring time of flight of an eye-safe, invisible (infrared) laser pulse reflected off a target, the Laser Atlanta system could measure the range to a target. By sending out approximately 400 laser light pulses per second and timing the return reflections, distance to a static target is measured to within about one foot, on average. Through laser firmware, relative target speeds could be inferred to within about one mph.

During an on-site visit to Laser Atlanta, Sierra was given the opportunity to use the hand-held system to record the speeds of moving vehicles. The system locked on to vehicles quickly and returned relative speed readings that appeared to be accurate. Unfortunately, the system would not function at ranges of less than about 70 feet. In addition, the system was not designed to compute speed at very low relative velocities (as would occur if the system were installed in a moving vehicle following another vehicle).

Although the system designed for police use was not suitable, Laser Atlanta expressed an interest in developing a modified version of the system for use in the chase car. By isolating the laser gun from the receiver, Laser Atlanta believed they could accurately measure shorter time of flight and make the system function down to a range of two feet. By increasing the diameter of the laser beam, it would also be easier to keep the laser on the back end of a vehicle being followed over hills and around curves. Sierra signed an agreement with Laser Atlanta for the development of a vehicle-mountable system that would measure distance to within one foot over a range of 2-200 feet.

In its original configuration, the laser functioned as both rangefinder and velocimeter. If the return signals indicated a variable range, the instrument automatically switched to speed-measuring mode and attempted to determine relative speed in mph. Discontinuities in range measurements were an indication that the laser beam had moved off of the target and no speed was computed. When there were no discontinuities, the laser, after about 1-3 seconds (depending on the relative speed), indicated "lock on" to a target. This delay in locking onto targets and the change in mode of laser operation from static to moving targets was found to introduce uncertainty into the record of continuous speed measurements. Accordingly, the laser was modified by Laser Atlanta to function only as a rangefinder, providing discrete range measurements at a rate of two per second. This output signal was sampled once per second and differentiated to provide relative target speed.

Figure 4 shows the custom laser range finder developed by Laser Atlanta as installed in the Caprice. The rectangular box above the two lenses encloses a miniature CCD (charge coupled display) television camera, which provides a high resolution video signal. The slanted glass cover of the video camera lens provides for an on-screen digital display of target relative speed in the video picture, along with an illuminated reticle which shows where the laser and camera are aimed. Figure 5 is another view of the laser system mounted in the chase car with the hood closed.

Figure 4
Custom Laser System Mounted in Chase Car
(shown with hood open)

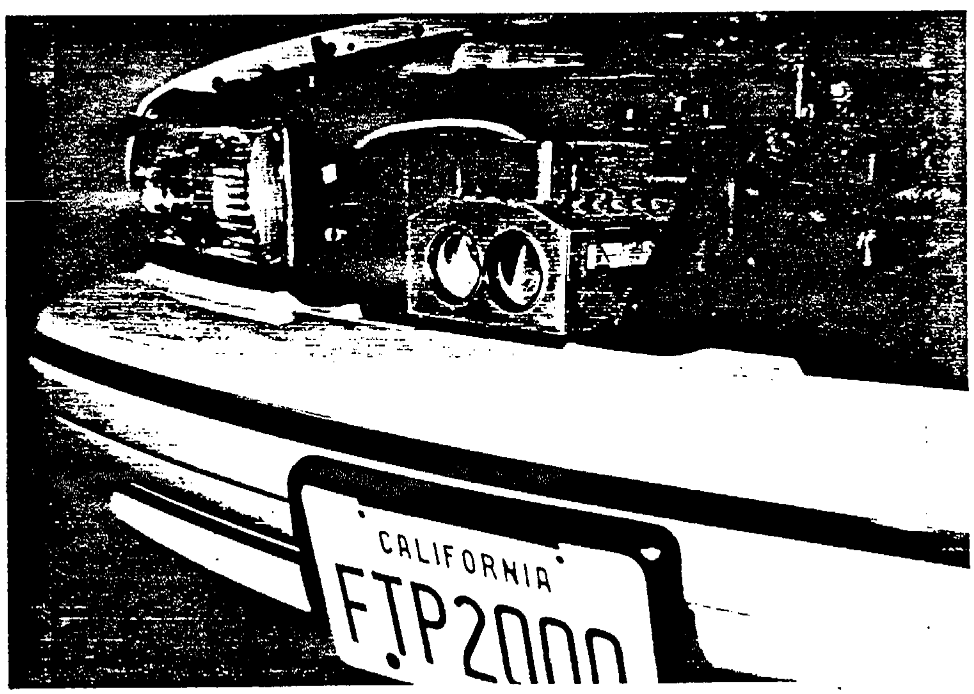
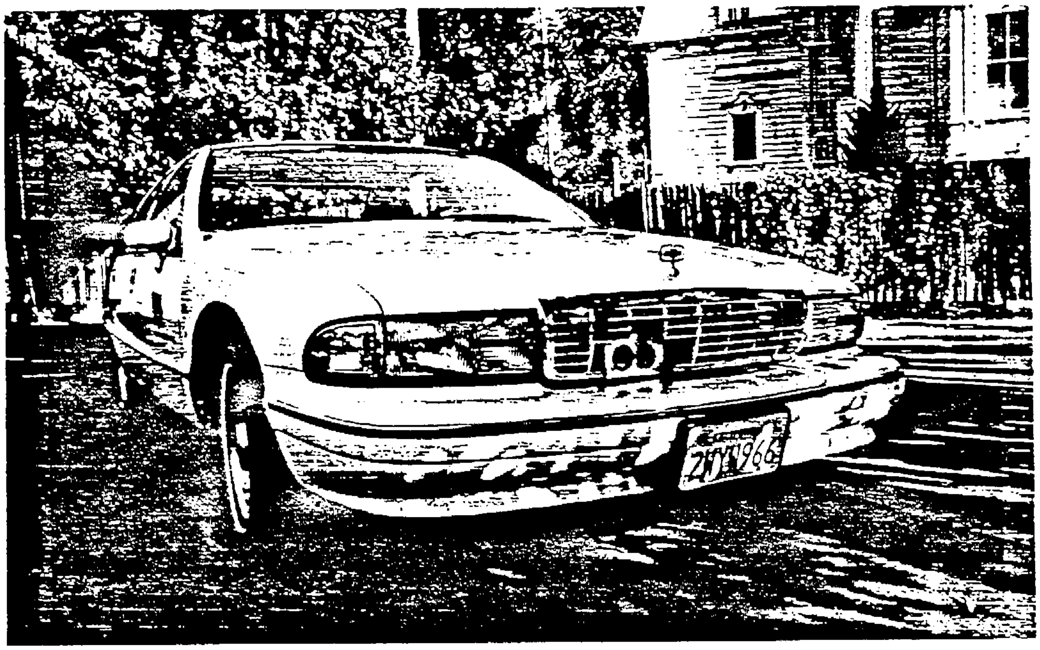


Figure 5
View of Chase Car With Hood Closed



With the vehicle's hood closed, the lenses of the laser system are visible through a small opening that has been cut into the grill, but only by viewing the vehicle from the front. The system is not visible to other motorists as they drive by the chase car, and the system does not appear to be noticed when drivers in front of the chase car glance in their rear view mirrors. Based on tests conducted by Sierra, individual distance measurements are accurate to within about ± 1 foot.

3.3 Chase Car Speed Measurement

A standard GM pulse-generator-type speed sensor on the transmission produces a signal whose frequency is proportional to speed. A lead spliced into the wire between the sensor and the speedometer is routed into the passenger compartment and connected to a custom circuit, based on a frequency-to-voltage integrated circuit package, that converts the frequency signal to a DC voltage (0-5 volts) that is proportional to speed. Experience with this system indicated a problem with voltage spikes at vehicle speeds below 10 mph. This led to the development of a supplemental speed measurement system, which is described in detail in Appendix A.

The supplemental speed measurement system utilizes a set of four driveshaft mounted magnets and the pickup coil from an aftermarket speedometer. The pulses generated each time a magnet on the drive shaft passes the pickup coil are conditioned, using a Schmidt trigger, and then counted, using the counter/timer chip on a commercial analog-to-digital converter (A/D) board which is described, along with the data acquisition system, later in this report. As shown in Appendix A, the performance of the speed measurement system installed on the chase car has been validated through the use of coast down data and comparisons with accelerometer based speed estimates. Low speed accuracy problems with the OEM speed sensor were eliminated with the custom system used to record driveshaft rotation.

As configured, the data logging program polls the counter on the A/D board once per second to determine the number of pulses observed in the previous second, i.e., the number of times that a magnet has passed the pickup coil. The number of magnet passages past the coil is four times the number of revolutions of the drive shaft which, based on the rear axle ratio, is 3.08 times the number of revolutions of the rear axle. Assuming no tire slip and using a measured tire circumference of about 83 inches, the nominal pulse rate at 60 mph for this system is about 157 per second. Measurements at a nominal speed of 60 mph over a fixed-length highway drive, the same drive used to calibrate the original hybrid speed sensor, confirm an actual pulse count of approximately this number, with slight deviation due to an effective tire circumference slightly different from the static measurement. This frequency-to-speed relationship implies a minimum measurable speed (corresponding to one pulse per second) of 0.38 mph, which is also the precision of speed measurements.

3.4 Collection of Additional Chase Car Data

Measurement of Brake Application - A separate input channel stores one "bit" of data each second to document whether the chase car brake pedal is depressed.

Manifold Air Pressure Measurement - A standard GM manifold air pressure (MAP) sensor produces a DC voltage (0-5 volts) that is proportional to pressure. Output of the sensor is directed into the passenger compartment through leads spliced into the connection between the MAP sensor and the vehicle's ECU.

Road Grade Measurement System - An additional instrumentation feature of the chase car is a Sierra-designed roadway grade and acceleration measurement system. The system consists of two Lucas NovaSensor unidirectional accelerometers mounted perpendicular to one another and oriented to record acceleration in the plane of the vehicle floor pan. One accelerometer is aligned parallel to the longitudinal centerline of the car and the other is aligned in the lateral direction. During operation on level roadways, the lateral accelerometer indicates when the chase car is turning and the longitudinal accelerometer produces a signal that is approximately proportional to the rate of change in speed measured by the pulse generator on the output shaft of the transmission. When the vehicle is not on a level road, the difference between the rate of change in speed in the longitudinal direction (measured by the transducer on the transmission) and the longitudinal acceleration measured by the longitudinal accelerometer indicates the roadway grade.

The way that the system works can be understood by considering what happens when the nose of the vehicle is elevated. When the vehicle is not moving, both accelerometers are calibrated to read 0 ±0.01 g on a level surface. If the vehicle was lifted by its front bumper, and hung vertically, the longitudinal accelerometer would read 1.0 g. If the vehicle was lifted by its rear bumper, and hung vertically, the longitudinal accelerometer would read -1.0 g. When the vehicle is moving along a non-zero grade roadway at a constant speed, the longitudinal acceleration indicated by the accelerometer is equal to the sine of the roadway angle from horizontal (e.g., on a 30° angle, the accelerometer would read 0.5 g). As noted above, when the vehicle is accelerating or decelerating, the difference between the rate of change in speed in the longitudinal direction (measured by the first derivative of the signal from the speed transducer on the transmission) and the total acceleration measured by the longitudinal accelerometer indicates acceleration due to the roadway grade, i.e, the component in the plane of the roadway of the acceleration due to gravity.

Due to roadway irregularities and vehicle vibrations, substantial care is required in the collection and analysis of accelerometer data to evaluate grade. With accelerometers sampled at 10 Hertz and a post processing algorithm that screens out transient changes in apparent grade, the current system can, while moving, measure road grades to an accuracy of a few percent of grade. More detailed information on the grade measurement system is available in a report prepared for the Mobile Source Division.[12]

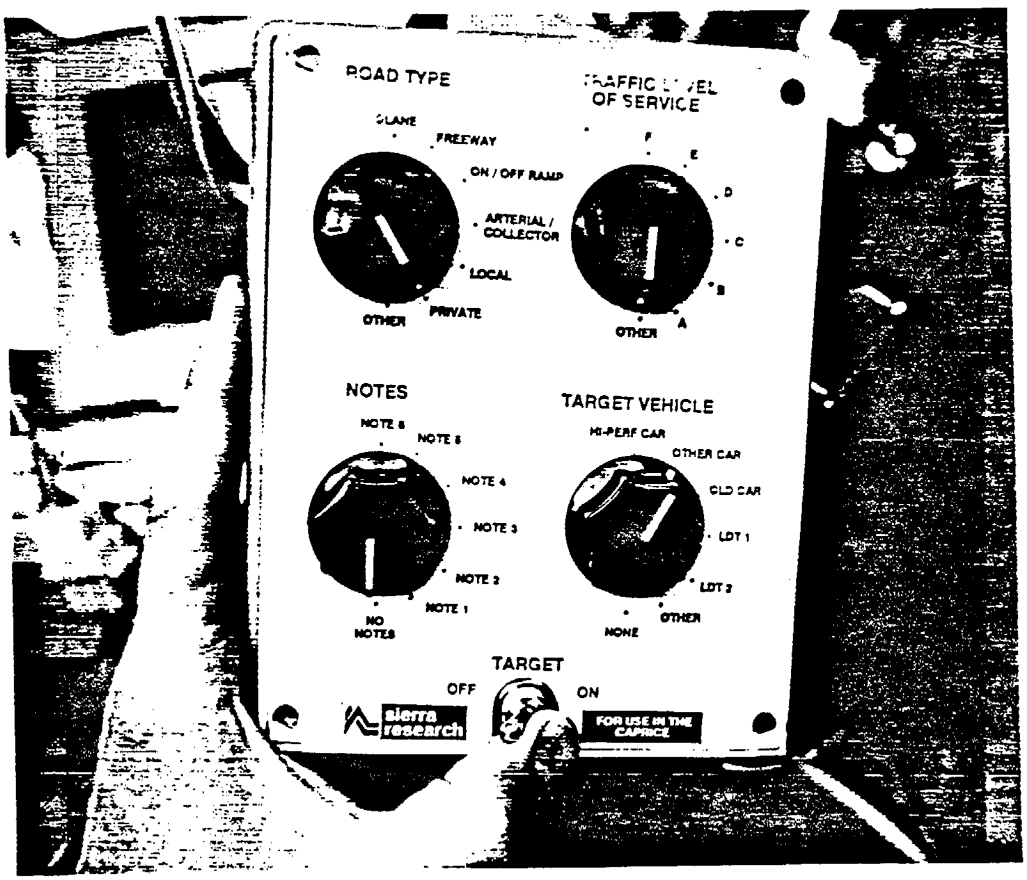
Visual Observations - The chase car was equipped with two independent systems for recording information regarding roadway type, traffic congestion, and type of vehicle being followed. An 8mm camcorder was installed between the front and rear seats. The infrared focussing system used on the camcorder (Sony CCD-F70) was able to focus on traffic in front of the vehicle instead of the vehicle windshield. By using a wide angle conversion lens (0.7x), the effective focal length of the lens was changed to 6 mm. Although this is still not adequate to cover the full width of the windshield, it provides a reasonable view of traffic in adjacent lanes. The camcorder is powered by an AC adapter, plugged into the power supply system described below.

Manually recorded observations were obtained through the use of a switch box with 4 rotary switches and 1 toggle switch to classify and record conditions as they change. As shown in Figure 6, each rotary switch has seven positions and produces a unique voltage for each switch position. The purpose of each switch is described below:

- Road Type - used to indicate diamond lane, freeway, on/off ramp, arterial/collector, local, private and other.

- Level of Service - used to describe six separate levels of traffic density (passenger cars/mile/lane): A through F. An additional switch position is provided to characterize any "other" conditions (such as extreme congestion caused by a major traffic accident). As shown in Figure 7, pictorial representations of each level of service (copied from a U.S. Department of Transportation publication) were mounted on the chase car dashboard for reference by the observer. Based on the view through the windshield, the observer selected the level of service representation that was closest to the observation.

Figure 6
Switchbox Used for Recording Visual Observations



- Target Vehicle – used to indicate the type of vehicle being followed. The seven selections available are high performance car, other car, old car, light-duty truck 1, light-duty truck 2, other and none. (Performance cars were defined as those which would accelerate from 0–60 mph in about 8 seconds or less. A list of popular models with such capability was provided for the study

Figure 7
Illustrations of the U.S. DOT
Level of Service Classification Scheme

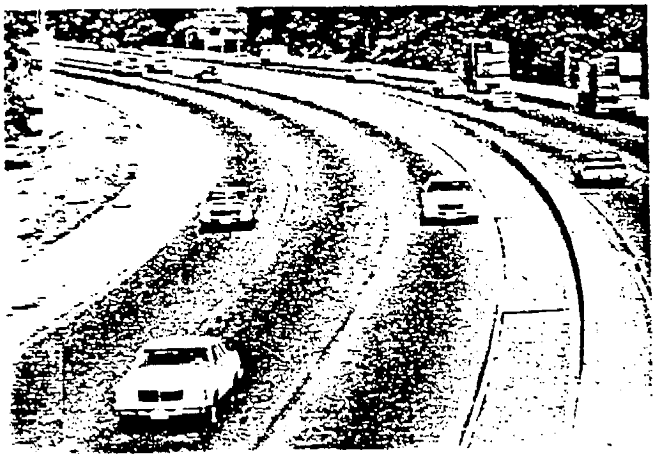


Illustration 3-5. Level-of-service A.

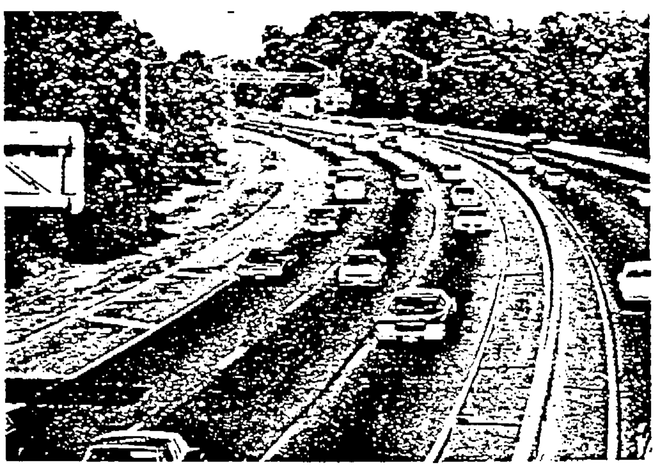


Illustration 3-6. Level-of-service B.

Illustration 3-7. Level-of-service C.

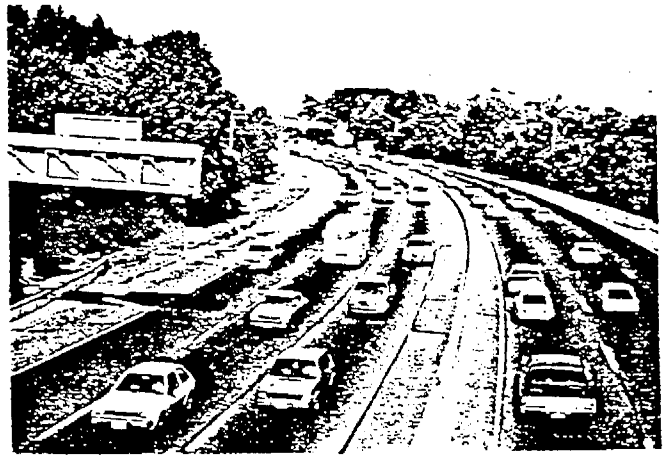


Illustration 3-8. Level-of-service D.

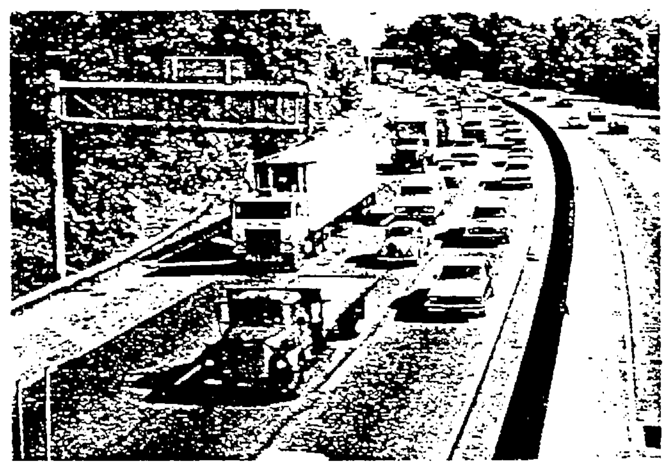


Illustration 3-9. Level-of-service E.

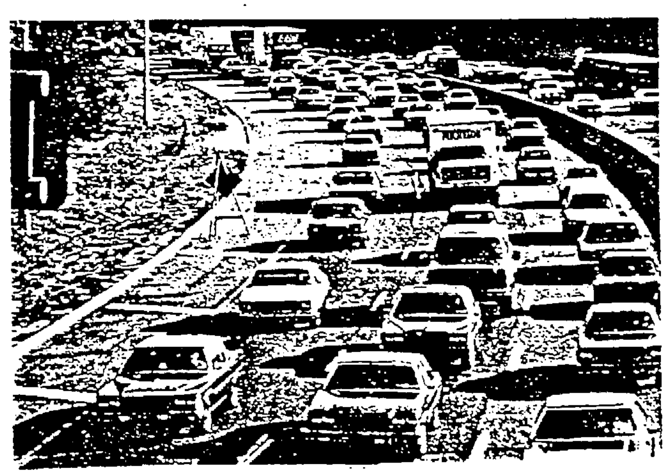


Illustration 3-10. Level-of-service F.

by drivers and observers who were not avid car enthusiasts. "Old cars" were vehicles definitely identifiable as pre-1973 models. The LDT1 category was used for mini-pickups and mini-vans. The LDT2 category was used for heavier pickups and vans.) This rotary switch can produce a signal only when the toggle switch is on, indicating the laser is aimed at a target vehicle.

- Notes - a total of six "flags" are available to record the occurrence of an unusual condition.

The voltages output from each switch are digitized using an on-board data acquisition system described in the following section.

3.5 Data Acquisition System

As outlined above, there are, in addition to the video recording, twelve different data streams being generated and stored during routine operation of the chase car:

- chase car speed via OEM speed transducer,
- chase car speed via driveshaft-mounted speed transducer,
- chase car manifold air pressure,
- chase car lateral acceleration,
- chase car longitudinal acceleration,
- road type,
- level of service,
- target vehicle type,
- target vehicle range,
- target vehicle speed,
- chase car brake light status (brake light "on" or "off"), and
- a series of "flags".

To sample, digitize and record these data streams at least once each second, a Metrabyte model DAS-8 data acquisition system was installed in an IBM-compatible portable computer. The system accepts up to eight analog inputs, up to three digital inputs, and one RS-232 input. Digitized analog data and RS-232 data outputs are controlled by a program called Labtech Notebook. Because the Metrabyte system requires a computer with an IBM-compatible expansion slot, the selection of computers was limited. Three alternatives were identified. Each was equipped with a 20-40 MB internal hard disk and a 1.44 MB diskette drive. The computers were mounted on a foam pad placed in the center of the front seat.

During several weeks of shakedown testing, a variety of power supply failures, screen failures, and system crashes occurred using two of the computers onboard the Caprice. A Packintell model LA3540 (80286 CPU) proved the most reliable and functioned without failure for over 1,000 miles of on-road operation. To further enhance reliability, the computer was subsequently retrofitted with a 1.44 megabyte, solid state, disk emulator (ROMDISK) manufactured by Curtis, Inc. This was feasible on the Packintell computer as it is one of the few portable computers with two expansion slots. After booting the computer from the hard disk and starting up the data acquisition program, data are written to the disk emulator. Thus, no reads of or writes to the hard disk are required while the vehicle is in motion.

The software is configured to sample and store data once per second from each of the ten inputs, except for the accelerometers which, as noted earlier, are sampled ten times per second. All data, including block-averaged accelerometer data, are then scaled and stored at one value per second. A scale factor and an offset are used so that the data from the accelerometers are stored in "g's". In the case of the other outputs, the value stored is the last value read, usually adjusted by a scale factor. For example, the speed output is calibrated to record and display the speed in mph. All scaled outputs are simultaneously stored to non-volatile ROMDISK and displayed in real time for confirmation by the observer.

Power Supply System - During shakedown testing of the instrumentation system, some variations in sensor readings obtained through the data acquisition system were observed as the load changed on the vehicle's electrical system. It is suspected that this was caused by variations in the reference voltages supplied to the data acquisition system by the computer power supply. Measurements of the voltage available from the vehicle's electrical system showed variations within the range of 12-14 volts depending on electrical system load and whether the battery was being charged by the alternator.

To provide a stable source of DC power for the computer, a supplemental power supply system was installed in the vehicle's trunk. A 12 volt, deep cycle marine battery was installed in the trunk and connected to the vehicle's alternator through an underhood-mounted isolator. The marine battery was configured to power a 1000 watt, frequency compensated DC-to-AC invertor (Tripp-Lite model PV-1000 FC). Connected to the invertor was a 12 volt/10 amp regulated power supply (Tripp-Lite model PR-10b). Using this system, DC voltage to the computer is maintained at close to 12.8 volts regardless of the load on the vehicle's electrical system, and irrespective of whether the vehicle's engine is running. In addition, the system is used to provide a more stable voltage for the laser range finder. the 110 volt output is used to power the 8mm camcorder and the laptop computer. By monitoring the voltage of the marine battery at the beginning of every day, it was determined that the vehicle's alternator is capable of maintaining a full charge while the invertor and regulated power supply are used during routine operation.

Miscellaneous - Several miscellaneous features were incorporated in the chase car to improve the overall safety and efficiency of its operation. A transportable cellular phone is installed to enable the crew to maintain communications with the office. This feature has proven useful in resolving minor equipment problems and questions regarding road routes. To minimize the possibility that the chase car is mistaken for a law enforcement vehicle, no external antenna is used with the phone.

To further minimize the possibility that passing motorists notice either the camcorder or other equipment, as well as to avoid being mistaken for a law enforcement vehicle, all windows of the vehicle behind the front doors have been tinted to achieve 80% light extinction. This type of tinting is not uncommon on California vehicles and it makes it very difficult for passing motorists to see into the vehicle from the rear or to notice the silhouette of the camera from the front.

Equipment carried onboard the vehicle includes miscellaneous hand tools, electrical repair equipment, a digital multimeter, a spare computer and data acquisition system, a spare switchbox, a fire extinguisher, and other safety equipment.

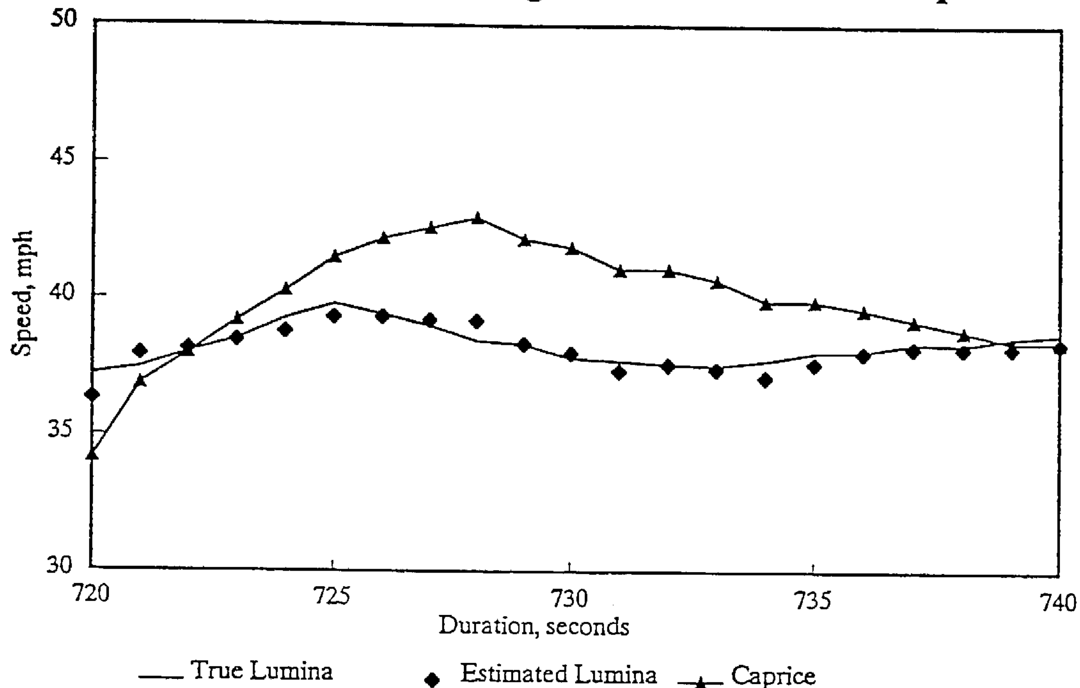
System Validation - To evaluate the effectiveness of the chase car instrumentation system, a second vehicle, a Chevrolet Lumina, was equipped with a similar speed, MAP, and acceleration measurement system, but no laser. The Caprice chase car was then used to follow the Lumina in traffic with the laser system activated.

Figure 8 shows an example of data collected during operation of the two vehicles when the chase car was able to maintain an almost continuous laser lock on the Lumina. One of the speed-time traces was generated by the Lumina, one was generated by the Caprice chase car, and the other was the speed-time trace of the target car adjusted to account for the relative speed difference measured by the laser. The trace based on the laser data was generated using the Savitzky-Golay digital filter (described below). As the figure shows, the laser data made it possible to estimate the speed of the target vehicle to within 1-2 mph despite the fact that the chase car speed deviated from the target vehicle speed by much more.

Figure 9 shows the overall correlation between the laser-based estimates of target vehicle speed and the actual target vehicle speed as measured by the target vehicle speed sensor. The conclusion drawn from the data collected was that the laser-based system is capable of measuring major speed changes of a target vehicle with reasonable accuracy, but incapable of accurately representing the high frequency, minor speed deviations of the target vehicle. This limitation of the system appears to be due to the design limit on distance measurement resolution associated with the fact that the system records all laser pulse time-of-flight measurements in discreet "bins" that are about 2 feet in width. Notwithstanding this limitation, the laser-based system does offer the ability to capture major speed deviations without the need for the chase car to follow the target vehicle in a close and consistent manner in order to duplicate its acceleration or deceleration. (The fact that the laser data did not allow the speed-time trace of the target vehicle to be computed precisely was accounted for in the development of the driving cycle, as discussed in Section 8.)

Figure 8

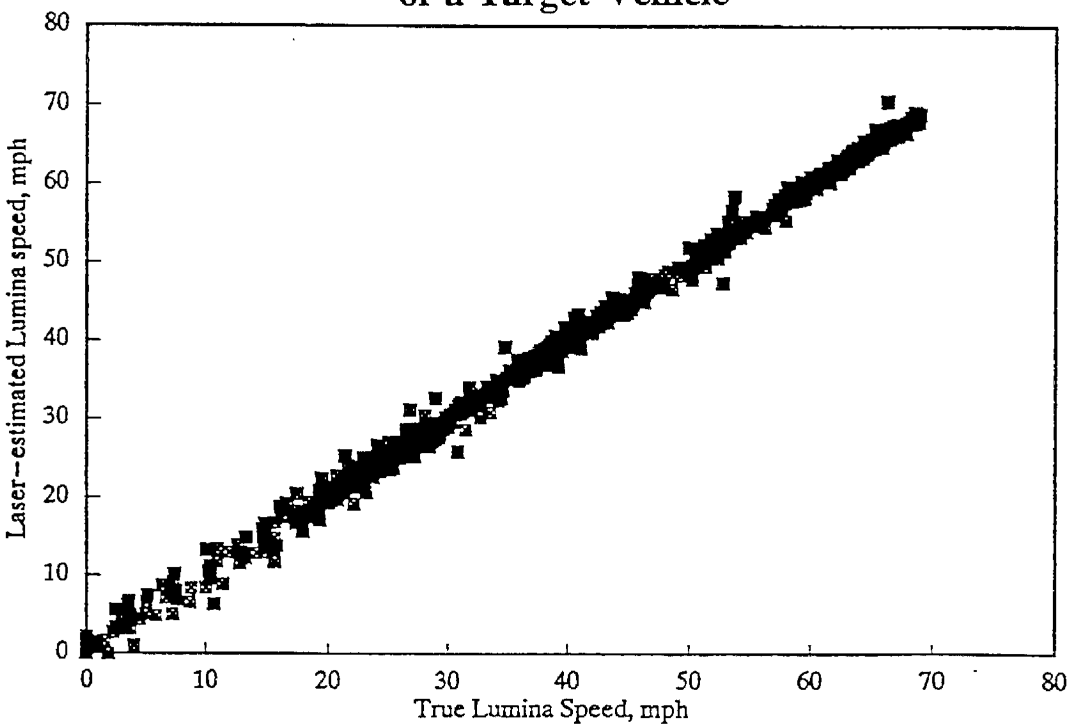
Target Vehicle Speed-Time Trace Compared to Chase Car Speed-Time Trace and Laser-Based Target Vehicle Estimated Speed



Sacramento drive No. 08132.PRN

Figure 9

Laser Estimated Speed vs. Actual Speed of a Target Vehicle



4. COMPARISON OF CHASE CAR DRIVERS

During the course of the contract, an experiment was conducted to compare characteristics of the drivers used during the primary data collection effort with those of other drivers, and examine the effects of driving different cars. The experiment entailed collecting and analyzing second-by-second data for 10 drivers, three of whom were routinely involved in driving the chase car to follow randomly selected vehicles. A total of 66 trips were driven, all over the same 18-mile route, using two instrumented late-model cars. Results were analyzed by comparing descriptive statistics of the drives, by driver and car, with emphasis on those statistics expected to be most closely associated with differing emissions, e.g. maximum rates of acceleration and speed.

4.1 Background

In previous chase car studies, individual drivers have been followed from the start to the end of a route, a protocol that has the potential to introduce biases with regard to the representativeness of the drivers and routes. The current study sought to reduce these potential biases by preselecting routes according to a stratified random sampling procedure designed to provide a representative selection of routes, and then choosing and following "targets of opportunity" according to a protocol designed to minimize bias. In order to preserve the representativeness of route selection, each second of driving on each route is included in the overall description of "composite" driving. For those times when no target existed, chase car drivers were instructed to drive according to the prevailing traffic to the extent that was possible. Experience to date suggests that drive statistics from data collected in this way may be based on substantial fractions of time when no target data are available. During these times, the composite drive statistics may be determined in part by the chase car drivers' behavior. It is therefore important to ensure that the composite drive is not unduly influenced by the driving habits of the chase car drivers. Of particular concern would be any characteristics, such as a tendency to drive in an overly aggressive or overly passive manner, that might be expected to bias the composite driving statistics in a way that could unduly influence vehicle emissions. This experiment was therefore designed to help assess the significance of this concern.

4.2 Experimental Protocol

The main purpose of the experiment was to compare driving behaviors of chase car drivers with those of other drivers, with emphasis on those parameters expected to be most closely associated with differences in emissions. A secondary objective was to examine the effect of driving different cars.

A set of experimental parameters related to vehicle speed and acceleration was chosen for examination based on each measure's expected close association with emissions[13,14,15,16,17] and/or its common usage to compare driving patterns[18]. The selected parameters are maximum instantaneous speed; overall average speed; average speed when moving (defined here as the average of all speeds in excess of 0.5 mph); PKE (positive kinetic energy of acceleration per unit mass per unit distance driven); maximum instantaneous acceleration; and number of seconds of "hard" acceleration (defined here as rates that exceed 0.15 g's or 3.3 mph/sec, which is the maximum rate of acceleration in the LA-4 driving cycle).

The primary subjects of the experiment were three chase car drivers who performed all of the driving in field studies that were conducted in Los Angeles and, under a separate contract with EPA, in Baltimore, Maryland and Spokane, Washington. These chase car drivers are referred to herein as drivers number 1, 2 and 10. (Driver number 10 was added as a chase car driver in Spokane only, toward the end of the field study.) Seven other drivers whose behaviors were examined in the current experiment are identified as drivers number 3 through 9.

For reasons of practicality, all ten drivers in the current experiment were selected from Sierra's employees. A mix of six male and four female drivers was chosen, matching approximately the 52/48 split in the general population of licensed drivers[19]. (Most of the chase car driving was done by drivers number 1 and 2, a female and male, respectively.) The ten test drivers ranged in age from 31 to 53, with an average age of 40. By comparison, the average age of U.S. drivers is about 41 years[20].

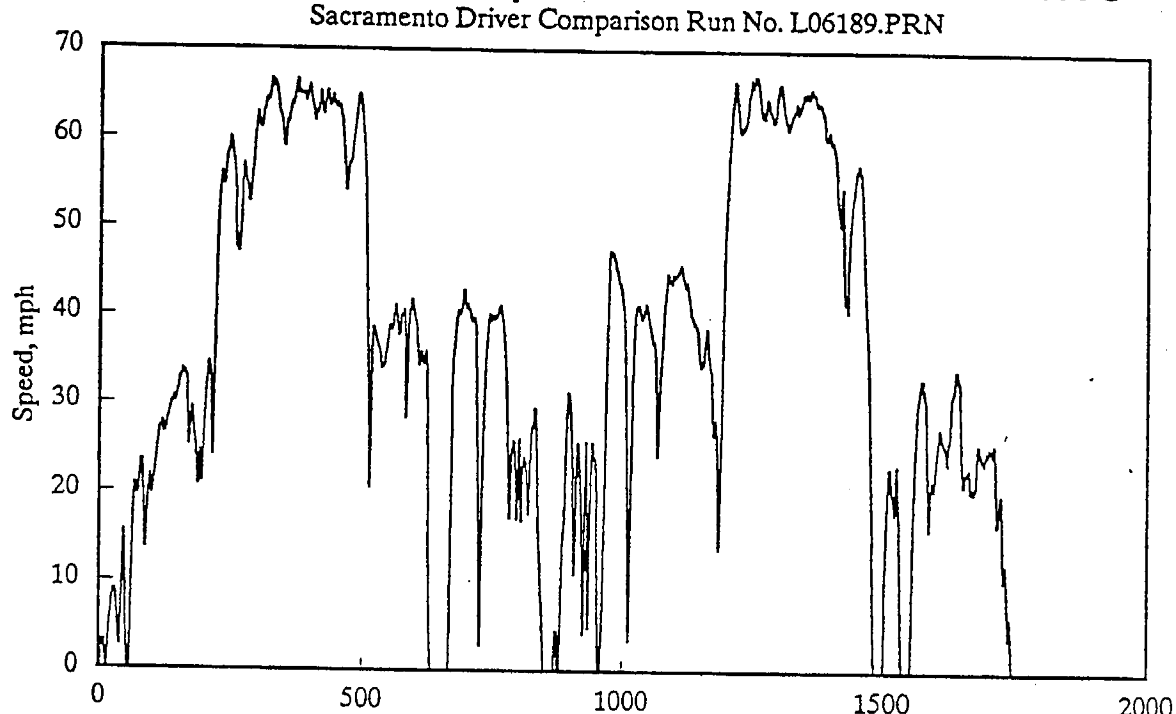
In order to eliminate differences between routes as a source of variation, all drivers were asked to drive the same test route. The route, a round trip of about 18 miles between downtown Sacramento and a more suburban location, was selected to provide a mix of both city and freeway driving. In order to minimize differences in traffic congestion as an influence on driving characteristics, all drives were conducted during off-peak hours, between 9:30-11:30 am and between 1:00-3:30 p.m. A typical time-speed trace for the test route, from Run No. L06189, is shown in Figure 10.

All drivers were given the same directions to the end point and were instructed to "drive as you normally would." Drivers were further instructed to stop at the end point without turning off the engine (which would terminate data acquisition), wait five seconds, and then return to the trip's starting point by the reverse route. This is reflected in the near mirror-image symmetry of Figure 10. For each driver, the first run was discarded from the analysis to allow for potentially unusual driving behavior that could occur while learning the route. In addition, several drives were discarded because the test driver missed a turn. A total of 66 drives were retained for analysis.

Figure 10

Typical Time–speed Trace for Test Drive

Sacramento Driver Comparison Run No. L06189.PRN



Driver No. 4, MAXMPH=67.3, AVGMPH=36.2, MOVMPH=38.9
PKE=0.314 m/sec/sec, MAXGS=0.295, HRDACLS=50 secs.

All of the driving was done using two vehicles*. About half of the drives (35 of 66) were made using a 1991 Chevrolet Lumina with 3.1 L V-6 engine and automatic transmission. The remaining 31 drives were made using a 1991 Chevrolet Caprice with 5.0 L V-8 engine and automatic transmission geared for towing. The Caprice, which was the chase car for all field studies, is a larger and heavier vehicle than the Lumina, but it has a similar power-to-weight ratio and was found to provide only slightly poorer wide open throttle performance (0-60 mph in 12 seconds vs. 11 seconds for the Lumina). Each vehicle was equipped with a data acquisition system designed to measure and record vehicle speed (and other parameters) on a second-by-second basis. Vehicle speeds were measured and recorded to an accuracy of at least one mile per hour.

* To gain some insight into the effects of a different vehicle, an attempt was made to have each of the ten drivers drive each of the two test cars at least three times. This goal was met for all drivers except number 7, who drove the Lumina only twice. (These are the net number of drives after discarding the first run from each driver and all drives with missed turns.)

Data were collected between June 4 and September 4, 1992. Second-by-second data on vehicle speeds were reduced to summary data and plotted using a desktop computer running Lotus 1-2-3. Statistical comparisons were computed using SAS, primarily with the SAS procedure "GLM." The number of routes per car driven by each driver is shown in Table 1.

Table 1

Number of Routes Driven*
by Driver (within Group) and by Car

Driver Number	Number of Routes Driven, by Car Type: Caprice	Lumina	All Cars
Chase Car Drivers			
1	3	3	6
2	3	3	6
10	3	3	6
All	9	9	18
Other Drivers			
3	3	3	6
4	3	4	7
5	6	2	8
6	3	3	6
7	3	3	6
8	5	4	9
9	3	3	6
All	26	22	48
All Drivers	35	31	66

* Excluding the first run for each driver, and any drives with missing turns.

Each drive was described in terms of the six parameters listed below. The first three are related to speed and the last three are related to acceleration.

- MAXMPH – the maximum speed achieved during the drive, in mph;
- AVGMPH – average speed, in mph (includes times when the vehicle was stationary with engine idling);

- MOVMPH – the average speed while moving, in mph. This is the same as AVGMPH except that speeds of 0.5 mph or less, including all idling times, are excluded. To the extent that idling and slow (0.5 mph or less) "creeping" are required vehicle maneuvers that are beyond the discretion of individual drivers to avoid, MOVMPH is presumed to provide a more realistic measure of driver-to-driver differences in speed preference than AVGMPH.

- PKE – the positive kinetic energy of acceleration per unit mass, per unit distance of the drive, in meters per second squared. This is a measure of the work performed to accelerate the vehicle per unit mass and per unit of distance travelled.

- MAXGS – the maximum acceleration, in g's. MAXGS is the maximum value of instantaneous acceleration as calculated from the difference-centered approximation equation for acceleration:

$$\text{acceleration } @t_2 = \frac{(\text{speed } @t_3)-(\text{speed } @t_1)}{t_3 - t_1}$$

  where t_1, t_2 and t_3 are three successive seconds of data.*

  MAXGS is expressed in g's, the average acceleration at the surface of the Earth due to gravity ($1 \text{ g} = 32.15 \text{ ft/sec}^2$).

- HRDACLS – number of seconds of "hard" acceleration or acceleration in excess of 0.15 g's (3.3 mph/sec). This threshold is the maximum acceleration in the LA-4 drive cycle. Accelerations beyond this level are sometimes described as "off-cycle" and associated emissions are presumed to be relatively high.

4.3 Results

Summary statistics for all drives are shown in Table 2. Following the table, Figures 11-16 show summary statistics for each drive, plotted by driver. In the figures, each drive is represented as one point, with different symbols used to represent different cars. The figures show a mixed pattern of results. A few drivers are seen to be fairly consistent in certain parameters from drive to drive: for example, maximum speed (shown in Figure 11) is relatively low for driver number 6 and relatively high for driver number 9, compared to the average for all drives (solid horizontal line).

A notable feature of the data is the effect of the vehicle being driven upon maximum acceleration (Figure 15). While some overlap is evident

*This formula for computing acceleration rate was used during this comparison of chase car drivers. However, acceleration was also computed from each second to the next as soon as the improved speed measuring system described in Appendix A was completed.

Table 2

Summary of Statistics for all Drives*
(n=66)

Statistic	Mean	Standard Deviation**	Minimum	Maximum
MAXMPH (mph)	68.9	3.7	60.7	76.9
AVGMPH (mph)	36.3	1.4	32.9	39.1
PKE (m/sec^2)	0.33	0.03	0.25	0.41
MOVMPH (mph)	38.7	1.2	35.5	41.0
MAXGS (g's)	0.27	0.04	0.19	0.36
HRDACLS (secs)	45.0	18.8	8	94

* The four columns of statistics were computed based on all drives. For example, "MAXMPH" of 68.9 mph under the column "Mean" is the mean of the maximum values from all 66 drives. The "MAXMPH" under the column "Maximum" is the maximum value selected from the list of maxima from each drive.

** Sample standard deviation

between the maximum accelerations experienced with the Caprice as compared to the Lumina, all ten drivers experienced their highest maximum accelerations with the higher-performance Lumina (triangle symbol) and their lowest maximum run accelerations with the lower-performance Caprice (square symbol). Driver number 3 had consistently high accelerations with both cars and, notably, had higher accelerationswith the Caprice than most other drivers had with the Lumina. This result suggests that, with the possible exception of driver number 3, most drivers do not exercise maximum vehicle performance in their normal driving, but do tend to have a higher maximum acceleration rate when driving a car that affords higher acceleration.

The hypotheses that the respective driving statistics differ significantly by driver and car were further tested by analyzing each of the driving parameters using the analysis of variance (ANOVA) procedure. Because sample sizes differed, the ANOVA was performed using the SAS procedure GLM (General Linear Model), rather than the simpler SAS ANOVA procedure. The effects of driver (nested within driver group) and car type were evaluated by examination of variance ratios, or "F-ratios," and by the comparison of means. Results of the analyses are summarized in Table 3. In reviewing these results and considering their

Figure 11

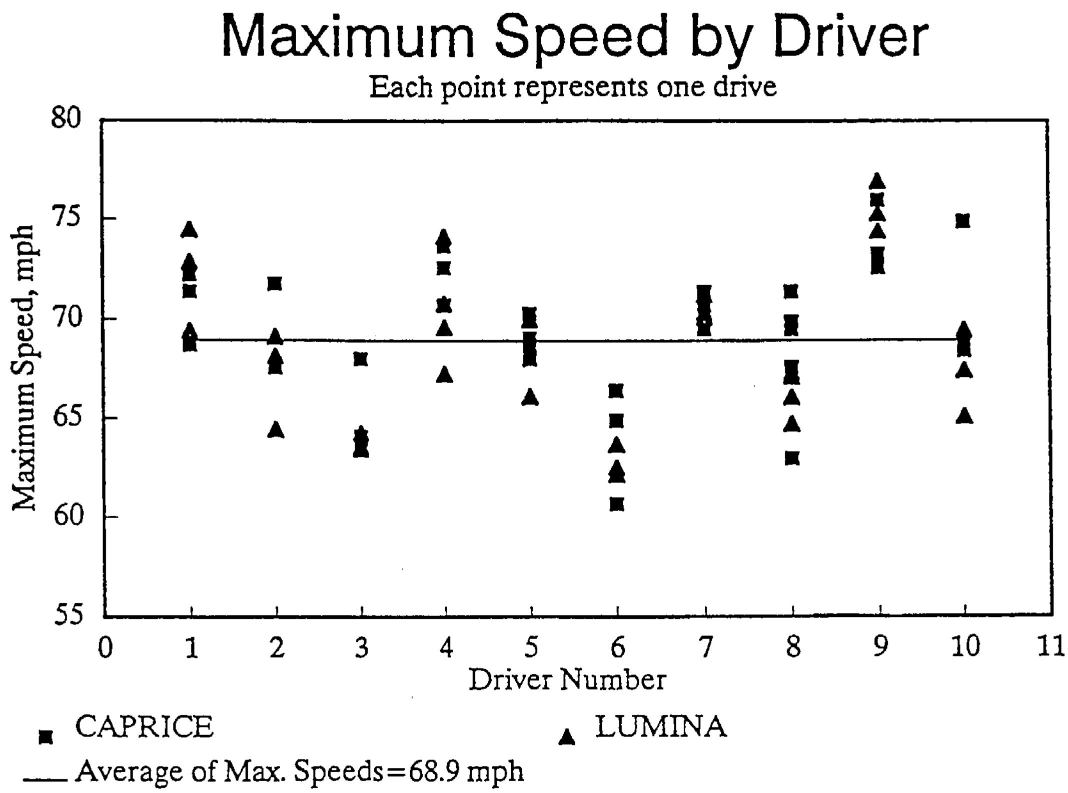


Figure 12

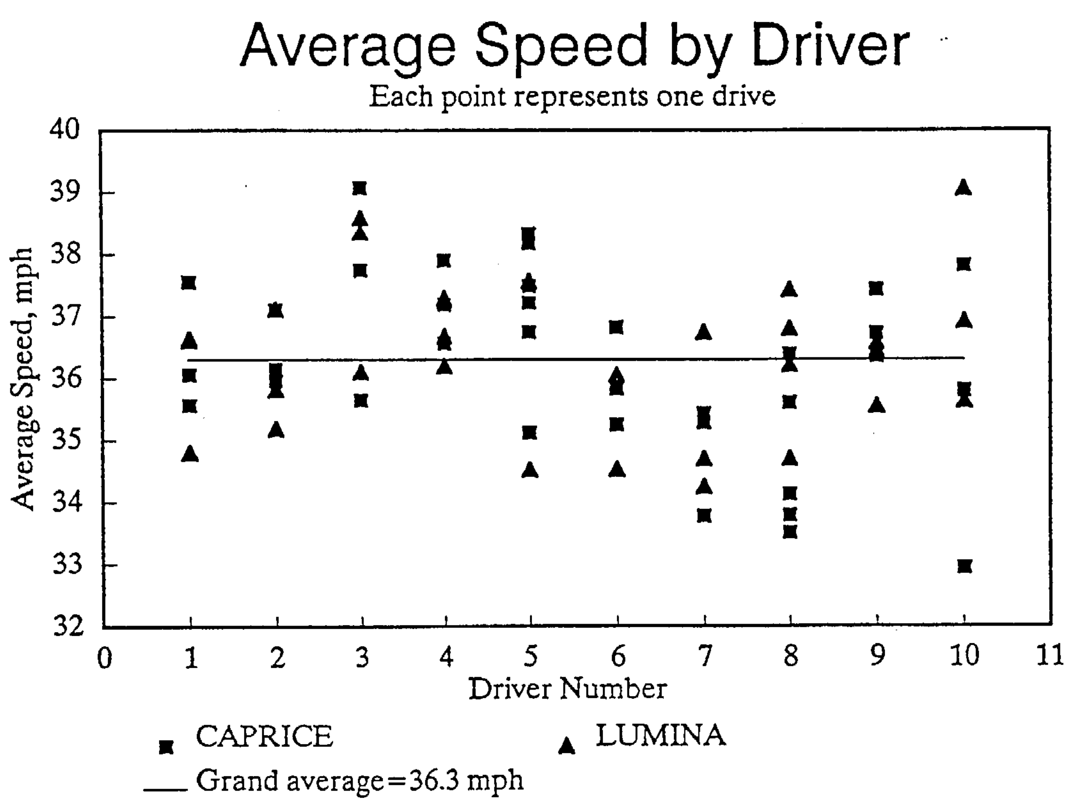


Figure 13

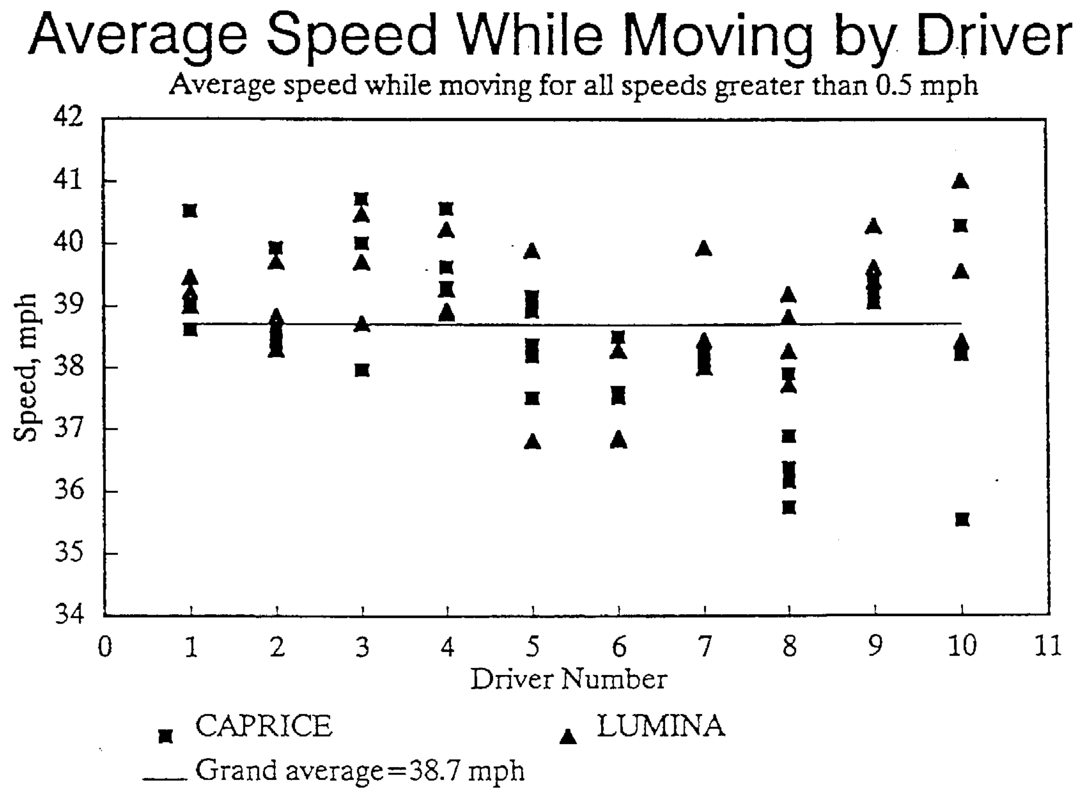


Figure 14

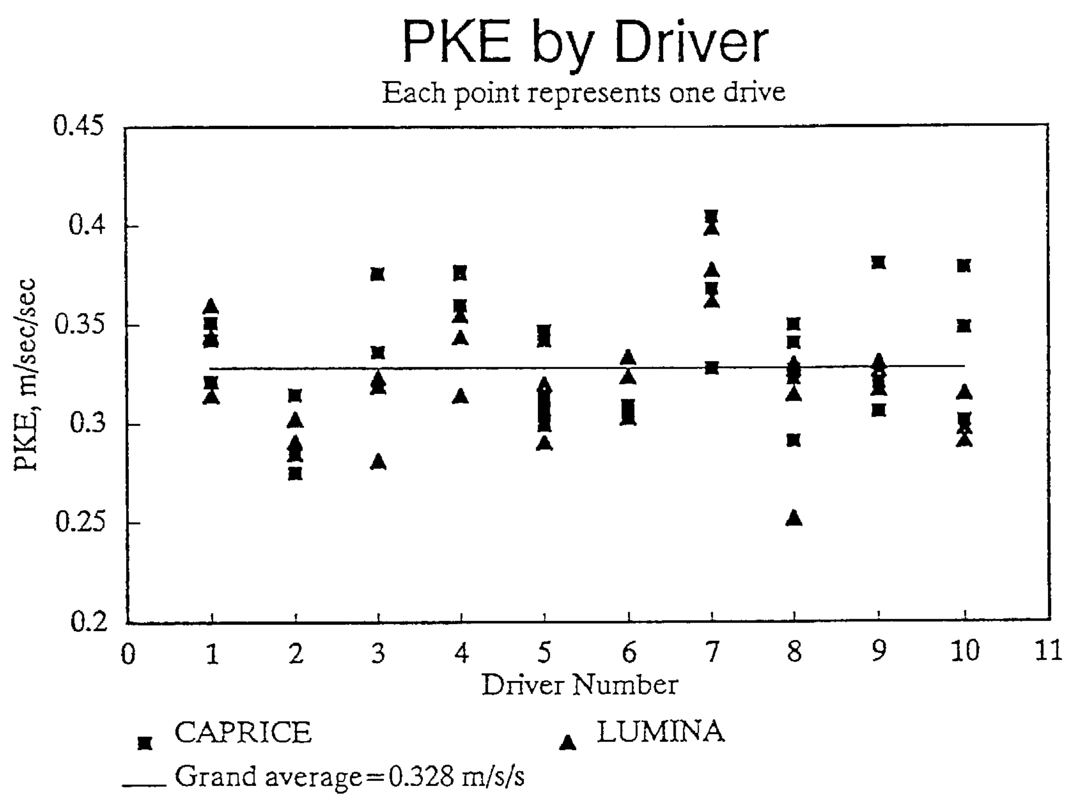


Figure 15

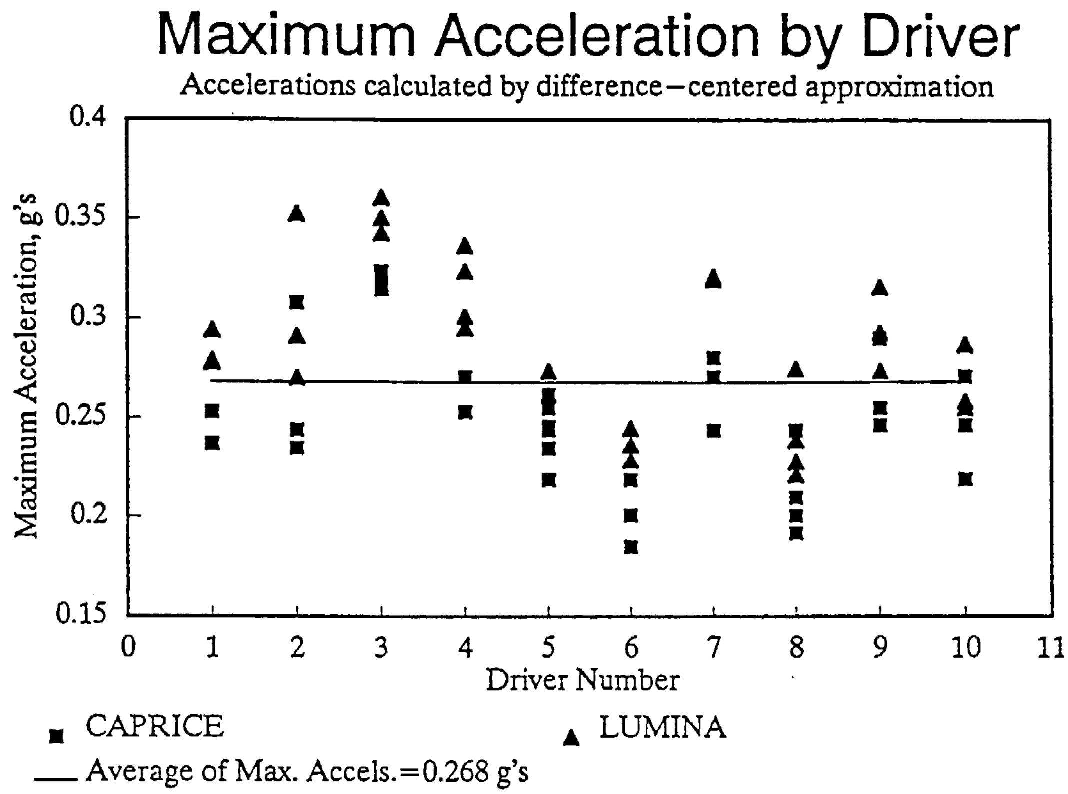


Figure 16

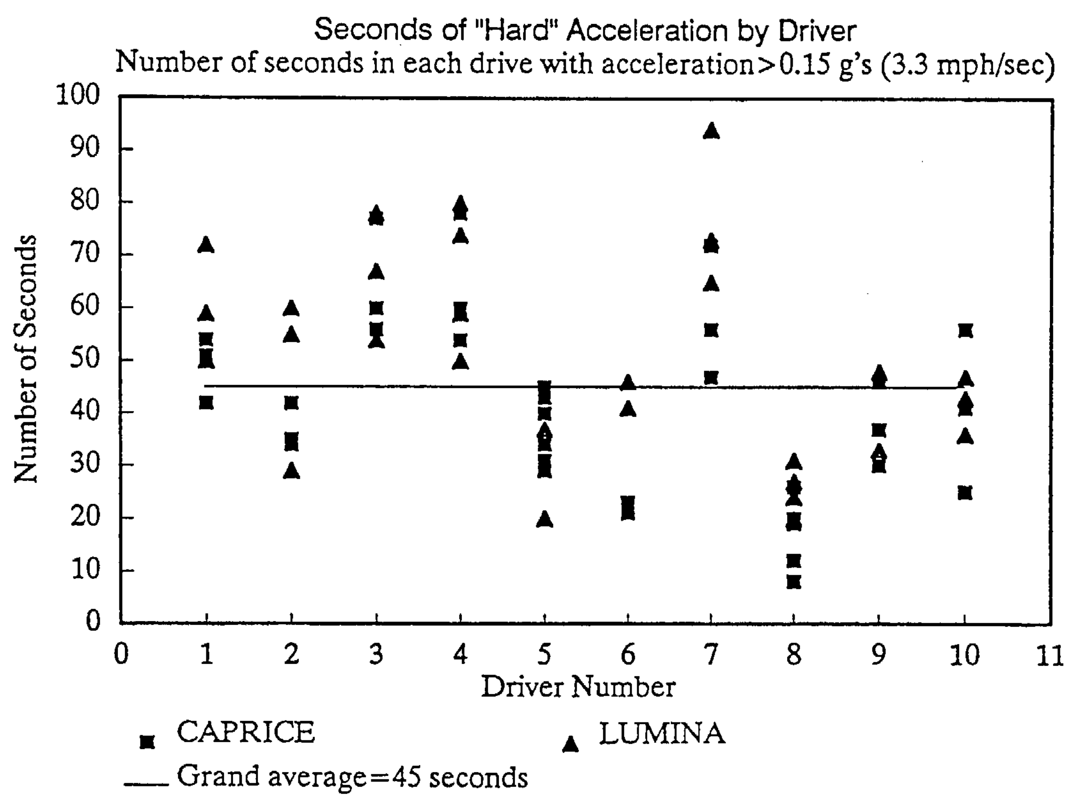


Table 3

Summary of Results of ANOVA of Driving Parameters, by Driver and Car

Parameter	Fraction of Variance Explained (r^2)	Driver Effect F-value	Driver Effect Prob.*	Car Effect F-value	Car Effect Prob.*
MAXMPH	0.72	15.58**	0.0001	3.73	0.0586
AVGMPH	0.31	2.78**	0.0094	0.06	0.8094
PKE	0.51	5.78**	0.0001	4.49**	0.0385
MOVMPH	0.43	4.32**	0.0003	2.54	0.1164
MAXGS	0.82	21.84**	0.0001	55.06**	0.0001
HRDACLS	0.75	17.71**	0.0001	7.04**	0.0104

* All probabilities are SAS Type I probabilities.

** F-values that exceed the critical value at the 0.05 level.

application beyond the conditions of the experiment, it is important to keep in mind that the sample size was limited and that several experimental variables, notably the route, traffic levels (as determined by driving times), and vehicle type were controlled.

Examination of the F-values in Table 3 suggests two important results. First, significant differences existed between drivers for all six of the parameters examined. Second, significant differences for the two cars were apparent for only those parameters related to vehicle acceleration, i.e. PKE, MAXGS and HRDACLS, and not for the other three parameters that were related to vehicle speed. An examination of potential interactive effects between driver and car (not shown and not discussed further in this report) did not show any significant effects either.

To further identify where significant differences were shown to exist between drivers, the Tukey-Kramer multiple comparison test[21] was applied; results are summarized in Table 4. Based on all possible pairwise comparisons of means, this table shows, for each parameter, the driver numbers for which the parameter mean is significantly less at the 0.05 level than that for the driver number shown in column 1. For example, the first entry, "3,6,8" under MAXMPH in Row 1, indicates that the mean value of MAXMPH for driver 1 is significantly greater (at the 0.05 level) than that for drivers 3,6 and 8 (only), when simultaneously considering all pairwise combinations. Although each pairwise

Table 4

Pairwise Comparison of Differences
in Mean Statistics for all Drivers
Showing Only Comparisons Where Mean for
"Driver Number" is Significantly Greater

Driver Number*	MAXMPH	AVGMPH	MOVMPH	PKE	MAXGS	HRDACLS
1	3,6,8	–	8	2	8,6	5,6,8
2	6	–	–	–	8,6	8
3	–	7,8	6,8	–	1,2,4,5,6, 7,8,9,10	2,5,6, 8,9,10
4	3,6,8	–	6,8	2	5,6,8,10	2,5,6, 8,9,10
5	3,6	–	–	–	–	–
6	–	–	–	–	–	–
7	3,6	–	– –	2,3,5 6,8,10	5,6,8,10	5,6,8, 9,10
8	6	–	–	–	–	–
9	2,3,5,6, 7,8,10	–	6,8	–	6,8	–
10	3,6	–	–	–	6	8

* The table shows entries for only those pairwise comparisons of statistics for which the mean for "Driver Number" (in the first column) exceeds that of the driver(s) whose number is entered in the table, e.g. the MAXMPH for driver number 2 is significantly greater than that for driver number 6 (only). See text for description of statistical tests.

comparison has a mirror image (e.g., the mean for driver number 3 of MAXMPH is significantly less than the corresponding value for driver 1), the image is not shown in the table in order to draw attention to the member of the pair expected to be associated with the higher emissions.The results of pairwise comparisons of drivers shown in Table 4 may be confirmed qualitatively by referring to Figures 10-15. In terms of relative speeds and accelerations, driver numbers 6 and 8 tended to be the least "aggressive," with relatively low maximum speeds and accelerations. Conversely, driver numbers 4 and 7 tended to have relatively high maximum speeds and accelerations. Driver number 7 also had markedly higher PKE than most others. Driver number 9 had relatively high maximum speed but low maximum accelerations while driver number 3 had the converse, high accelerations but low maximum speed. The remaining group of drivers, numbers 1,2,5 and 10, which includes all three chase car drivers, tended to be relatively moderate in all of the measures of speed and acceleration.

It is important to note in the foregoing comparisons that absence of a significant effect in the multiple comparison test cannot demonstrate that no effect is present. It is possible that the experimental set-up was insufficiently powerful to detect a significant difference, due, for example, to the relatively small sample size and high variability in the data. It is encouraging, therefore, that significant differences can be observed between drivers for certain combinations of the test statistics, as this tends to affirm the sensitivity of the experimental set-up and the choices of parameters being compared. Finally, it is noteworthy that the comparison of statistics between respective pairs of the three chase drivers showed only one significant difference, which was the higher PKE of driver number 1 compared to driver number 2.

A more direct comparison can be made between chase car drivers and other drivers by comparing them as groups. Because a vehicle-related effect has already been shown (see Table 3), a two-effects model is again considered, which simultaneously examines the effects of car and group. Means are compared using Tukey's Studentized Range Test. Results of the means comparison are summarized in Table 5.

The data in Table 5 show that for all of the parameters except PKE, the chase car drivers, when grouped, do not differ significantly from the other drivers grouped (or the tests are not sufficiently sensitive to distinguish differences between the two groups). For the parameter PKE, the chase car drivers differed significantly (at the 0.05 level) from the other drivers; chase drivers had, on average, a lower PKE (by 4%) for the route.

With respect to the effect of car, significant differences were seen in the maximum acceleration rate and in the number of seconds of hard acceleration. In both cases, the Lumina showed greater accelerations than the Caprice. No significant vehicle effects were seen in the means of PKE or any of the three measures of vehicle speed.

Table 5

Comparison of Driving Statistics
by Driver Group and by Car
Using Tukey's Studentized Range Test

Parameter	Effect of Driver Group: Mean for Chase Car Drivers*	Mean for Other Drivers**	Effect of Car: Mean for Caprice	Mean for Lumina
MAXMPH (mph)	69.5	68.7	69.3	68.4
AVGMPH (mph)	36.3	36.3	36.2	36.3
PKE (m^2/s)	0.318***	0.332***	0.332	0.323
MOVMPH (mph)	39.0	38.6	38.5	39.0
MAXGS (g's)	0.268	0.267	0.249***	0.288***
HRDACLS (secs)	46.2	44.6	40.7***	49.9***

* Significant at the 0.05 level.
** Chase car drivers were Numbers 1, 2 and 10.
*** Other (non-chase car) drivers were numbers 3-9.

4.4 Discussion

The purpose of this experiment was to determine whether chase car drivers differ from other drivers with respect to certain driving characteristics that are expected to be related to emissions. In particular, it was of interest to determine whether chase car drivers had a discernible tendency to be more or less aggressive than other drivers. A secondary objective was to test for any effects due to the type of vehicle being driven. The following specific conclusions are drawn from the experimental dataset:

- For a limited sample of driving under partially controlled conditions, significant differences were noted between drivers in selected emission-related driving characteristics. For certain statistics, differences were also noted between cars.

- Simultaneous pairwise comparison of statistics from all of the test drivers, accounting for the vehicle effect, showed that some drivers tended to drive at significantly higher or lower speeds and/or with significantly higher or lower accelerations than others. The three chase car drivers tended not to fall into these categories, i.e., they tended to be neither more aggressive nor less aggressive than other drivers by most of the measures considered.

- Driving statistics for the three chase car drivers were indistinguishable from each other with the exception of PKE, for which driver number 1 was significantly higher than driver number 2.

- Compared as groups, the chase car drivers and other drivers were not significantly different based on five of the six measures of driving characteristics expected to be related to emissions. With regard to the sixth measure, PKE (positive kinetic energy per unit mass per unit distance), the chase car drivers as a group tended to drive significantly different (slightly less aggressively) than the other drivers.

- With respect to the effect of the vehicle being driven, significant differences were seen in the maximum acceleration rate and in the number of seconds of hard acceleration. In both cases, the Lumina showed greater accelerations than the Caprice. No significant vehicle effects were seen in the means of PKE or any of the three measures of vehicle speed.

- Most drivers did not exercise maximum vehicle performance in their normal driving, but did tend to have a higher maximum acceleration rate when driving the higher performance car.

Based on a very limited sample of drivers and test drives and using six selected measures of driving behavior, these results suggest that it is possible to discern differences between drivers in the selected parameters; however, in general, the chase car drivers tended to be neither more nor less aggressive than other drivers.

###

5. ROUTE SELECTION AND CHASE CAR OPERATIONAL PROCEDURES

5.1 Route Selection

In order to select the routes that the chase car followed, the current trip generation matrices were obtained from the Urban Transportation Planning System (UTPS) model employed by the Southern California Association of Governments (SCAG) to track travel activity in the Greater Metropolitan Los Angeles Area. The current UTPS model for the Los Angeles area is configured to estimate travel for three separate periods of operation during a typical week day in 1985: the a.m. peak (6:30–8:30 a.m.), the p.m. peak (3:30–6:30 p.m.) and the off–peak (the other 19 hours of the day). Each period of operation has a separate trip generation matrix. The trip generation matrix specifies the number of trips that occur both between and within all of the 1,655 Traffic Analysis Zones (TAZs) that make up the modeling domain of the South Coast. The matrix lists the number of trips that take place between origin and destination zones (interzonal trips) and within the same zone (intrazonal trips). All interzonal trips begin and end at a centroid, the population–weighted center of a TAZ.

SCAG developed an estimate of the typical route that would be followed between each origin–destination pair (OD pair) and included that trip distance for each OD pair contained in the trip generation matrix. Routes were randomly selected from a trip–weighted compilation of routes within the modeling domain covered by the SCAG transportation model. SCAG identified the specific links that the selected trips followed in the computerized network of road links (intersection to intersection) that have been coded to represent the South Coast road system. The node numbers detailing each trip were further translated into road routes on a map with street names. Ninety of these routes were then run, with the routes selected by time of day based on the profile of a.m. peak, p.m. peak, and off–peak travel for the region. Eleven routes were run during the a.m. peak period, 23 routes were run during the p.m. peak period, and 56 routes were run during off–peak periods (primarily mid–day). The travel in each time period was within 1% of SCAG's estimate for the areawide travel distribution. Although many of the routes were very well traveled (e.g., over portions of the Interstate and State highway system), some routes represented lesser traveled roadways (as was intended). The only problem Sierra identified with the routes is that they did not appear to adequately represent routes used by business travelers and tourists (e.g., to and from major airports and tourist attractions like Disneyland). This was assumed to be due to the routes being determined from surveys of local residents.

The above–described routes selected from the OD pairs represent <u>interzonal</u> travel between TAZs on that portion of the Southern California roadway network that SCAG coded into the UTPS model. Such travel is over "collectors" and more heavily traveled roadways. Travel over "local" roadways (e.g., within subdivisions), the roads that would be traversed to get from the centroid onto the road network coded into the model, is not specifically identified by the UTPS model. Sierra, therefore, selected local roads to be followed between the centroid and the ending link on the road network. Starting and ending points for these trips were selected based on the results of the motorist survey performed with the assistance of the California Highway Patrol and described in the next section of the report. For example, interzonal trips during weekday mornings usually have an origin in a residential area and a destination in an employer parking lot. Based on an on-site survey of each TAZ, specific locations were selected to begin and end the interzonal trips so that a reasonable distribution of trip end locations was achieved and the overall length of each trip was not significantly affected.

The routes followed by intrazonal trips (i.e., within a specific TAZ) are also not specified by the UTPS model. The model assumes that all intrazonal trip lengths are equal to one half the diameter of the TAZ in which they occur. In addition, the model assumes a certain number of intrazonal trips occurring within each zone that appears to be roughly proportional to the number of interzonal trips associated with the zone. The methodology used in selecting the routes of these trips was to stratify all intrazonal trips into bins on the basis of trip length (i.e., one-half TAZ diameter) and to select a random sample of TAZs from each bin so that the average trip length of the sample matched the average of all TAZs.

Origins and destinations for intrazonal trips will more frequently involve residence-to-residence travel or travel between residences and shopping locations. As in the case of the interzonal trips, the specific locations to begin and end each trip were selected so that the overall distribution of trips by trip end location matches the available survey data. SCAG estimates that intrazonal trips make up roughly 10% of all trips in the Los Angeles area; therefore, the number of intrazonal routes run was about 10% of the total intrazonal plus interzonal trips. Because SCAG estimates that the average intrazonal trip length is one-half the diameter of the TAZ in which it occurs, the chase car crew was directed to drive one-third of these trips very short (minimum 2 blocks), one-third approximately equal in length to one-half the zone diameter, and one-third nearly as long as the zone diameter.

Figure 17 shows the approximate location of the interzonal routes driven during the course of the data collection effort. Tables 6 and 7 show the percentage of time and distance for all routes combined as a function of roadway type and "Level of Service" (described in Section 3) observed during data collection. The distribution of travel by roadway type matches the SCAG estimates for the area quite closely, based on analysis performed by ARB staff.

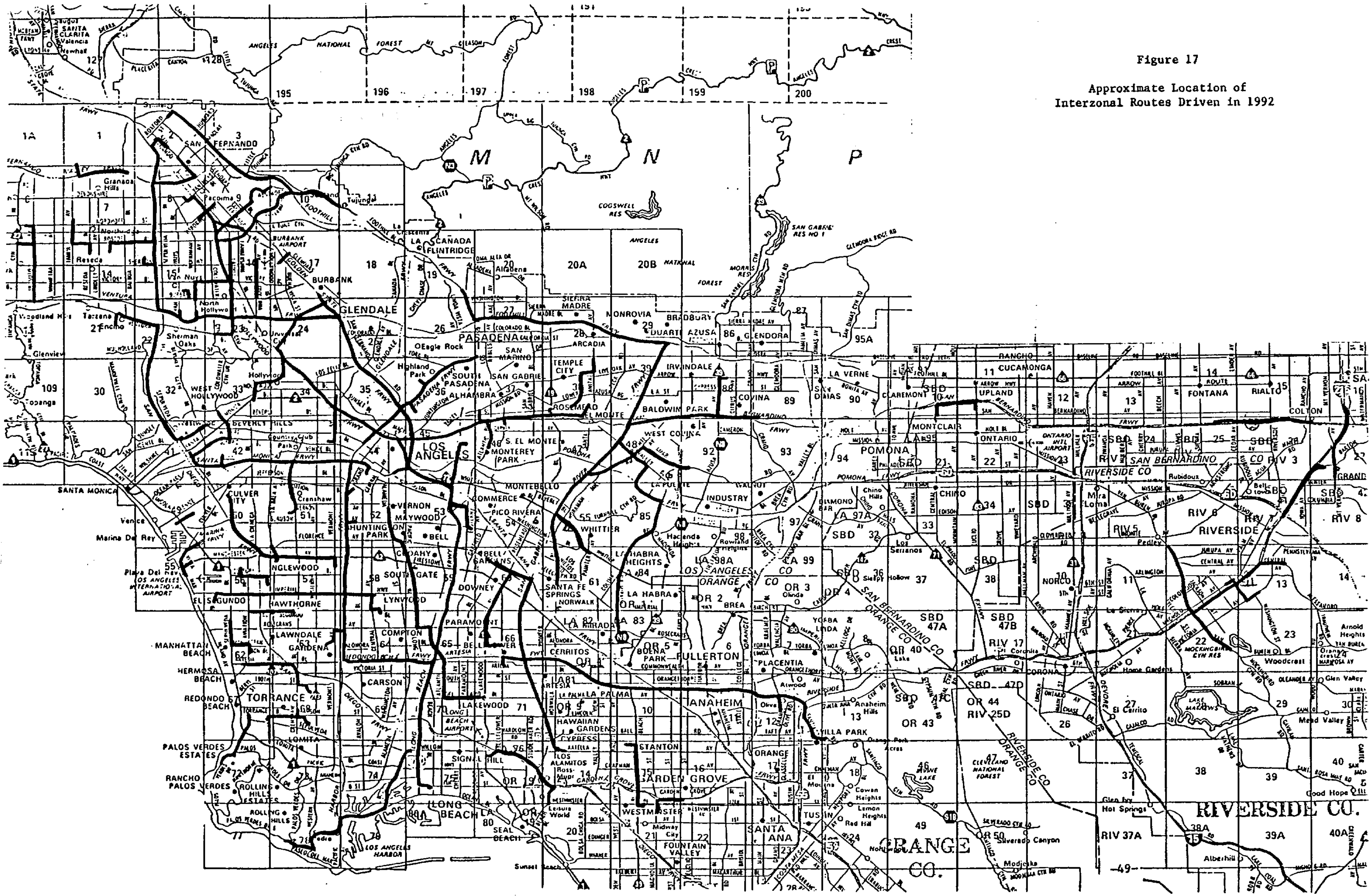


Figure 17

Approximate Location of Interzonal Routes Driven in 1992

Table 6

Availability of Data by Facility Type and Level of Service

Los Angeles, 1992

Table of Facility Type by Level of Service
Number of Seconds of Data

Facility Type	Level of Service Unknown	A	B	C	D	E	F	Row Total	Row Percent
Unknown	102	0	0	0	0	0	0	102	0.1%
Major Arterial *	0	1514	3912	3098	2316	893	58	11791	11.7%
Primary Arterial *	0	10305	8157	6641	3327	1226	711	30367	30.1%
Secondary Arterial *	0	3897	2444	2275	968	522	0	10106	10.0%
Grey Arterial *	0	0	30	30	0	0	0	60	0.1%
Other Arterial *	0	1885	1176	263	120	61	0	3505	3.5%
On Ramp, Meter On	0	56	160	180	81	59	195	731	0.7%
On Ramp, Meter Off	0	37	35	24	35	15	11	157	0.2%
On Ramp, Meter-Bypass Lane	0	0	17	58	30	0	0	105	0.1%
On Ramp, Meter Disconnected	1	4	74	83	0	0	0	162	0.2%
On Ramp, No Meter	0	242	141	128	3	59	89	662	0.7%
Off Ramp	0	343	451	570	556	54	232	2206	2.2%
Freeway to Freeway Ramp	0	55	335	214	174	337	230	1345	1.3%
Other Transition	0	7	26	0	0	0	0	33	0.0%
Private	0	89	14	44	14	0	0	161	0.2%
Local	0	1379	0	10	0	0	0	1389	1.4%
Collector	2	7766	1160	403	74	6	0	9411	9.3%
Freeway	0	734	2247	7174	4442	5045	8631	28273	28.0%
Carpool	0	0	0	0	0	1	0	1	0.0%
No Video Art/Col	0	204	40	0	0	0	0	244	0.2%
Column Total	105	28517	20419	21195	12140	8278	10157	100811	
Column Percent	0.1%	28.3%	20.3%	21.0%	12.0%	8.2%	10.1%		

* Major Arterial = 6 or more lane divided streets
Primary Arterial = 4 lane divided, or center turn lane, or 3 lane one-way streets
Secondary Arterial = 4 lane undivided or 2 lane one-way streets
Grey Arterial = Unusual Arterial Design
Other Arterial = 2 lane, heavily used, may have center turn lane

Table 7

Los Angeles, 1992
Distance Driven by Facility Type

Facility Type	Distance Traveled (miles)	Percent of Total Distance
Unknown	0.00	0.0%
Major Arterial	69.16	8.7%
Primary Arterial	191.01	24.1%
Secondary Arterial	59.92	7.6%
Grey Arterial	0.20	0.0%
Other Arterial	25.10	3.2%
On Ramp, Meter On	2.71	0.3%
On Ramp, Meter Off	1.40	0.2%
On Ramp, Meter-Bypass Lane	0.94	0.1%
On Ramp, Meter Disconnected	1.56	0.2%
On Ramp, No Meter	4.85	0.6%
Off Ramp	15.43	1.9%
Freeway to Freeway Ramp	17.72	2.2%
Other Transition	0.26	0.0%
Private	0.27	0.0%
Local	6.34	0.8%
Collector	43.05	5.4%
Freeway	351.29	44.3%
Carpool	0.01	0.0%
No Video Art/Col	1.64	0.2%

Total = 792.86 miles

5.2 Chase Car Operational Procedures

The chase car technique being used by Sierra is somewhat different from the chase car techniques previously used by General Motors and EPA. GM attempted to follow an individual vehicle from the beginning of its trip to its final destination. EPA attempted to have its drivers flow along with traffic, passing as many vehicles as passed them. Both of the previously used techniques were subject to criticism. By attempting to follow another vehicle from trip beginning to trip end, the GM approach increased the risk that motorists would see that they were being followed and alter their behavior. By its design, the approach previously used by EPA would be insensitive to extremes in driving behavior. In addition, none of the chase cars used in previous studies were capable of precisely measuring the speed-time profiles of other vehicles on the road. In addition, these approaches did not account for the possible influence of road grade.

Because acceleration rates are a significant concern, Sierra used GM's approach of following individual vehicles during major speed changes and accelerations, but then picked up other vehicles to follow when a vehicle being followed left the pre-selected route or when there was any indication that motorists sensed that they were being followed.

Trip Beginnings and Ends - Each chase trip began and ended in or adjacent to a parking area that was close to the centroid of the Traffic Analysis Zone (TAZ) indicated on the map for that particular trip. In choosing trip end locations, consideration was given to the time of day, the type of trip likely to be occurring then, and major origins and destinations within the zone. For example, most a.m. trips began in residential areas, whereas most p.m. peak trips began in commercial areas. The chase car team had final discretion to deviate from the maps as necessary to adjust for conditions not apparent on the map. Acceptable parking areas included private residences, apartment building parking lots, shopping center parking lots, roadside business parking lots, service station aprons, and on-street, curbside parking. Actual data recording began when the chase car first started moving on a public street. Data recording ended when the chase car left the public street, or parked along the curb.

Standard Technique for Selection of Target Vehicles - Target vehicles were selected at random from a pool of candidates near the instrumented chase car and travelling in the same direction on the same route. Candidate vehicles included cars and light trucks, except vehicles pulling trailers and emergency vehicles. Motorcycles, buses, and medium and heavy trucks were also excluded from consideration, as were any vehicles being driven in an erratic or unpredictable manner, as evidenced by sudden stops and starts, unsafe speeds, unsafe lane changes, etc. Although it would be desirable to have detailed information on the speed-time profiles generated by vehicles being driven in an erratic, unsafe manner, the collection of such data was considered impractical. To get a sense of the possible significance of such vehicles, detailed review of the video tapes determined the frequency with which such vehicles ideally would have been targeted. Such vehicles represented less than 1% of all target vehicles.

The method for selecting the target vehicle at the beginning of a new roadway link depended on the level of traffic. On busy surface streets with traffic in front of the chase car, the chase car crew found the closest white vehicle in front of an imaginary line passing through the center of the chase car and perpendicular to the direction of travel. For vehicles in the same lane as the chase car, one car length was subtracted per 10 mph of speed before deciding which white vehicle was closest. After selecting the nearest white vehicle, the chase car moved into the lane the white car was travelling in, if it was not already in that lane. The target vehicle was defined as the vehicle immediately in front of the chase car after that maneuver, which vehicle might have been the white vehicle.

On lightly travelled surface streets, the chase car followed the first candidate vehicle that the chase car approached or that passed the chase car.

On freeways, data collection began, if possible, by following the candidate vehicle that was on the on-ramp immediately in front of the chase car, onto the freeway and into whatever lane it went. If there was no candidate vehicle in front of the chase car on the on-ramp, then the chase car merged into freeway traffic and selected a target vehicle according to the standard protocol described above. If it became necessary to select another target vehicle, the first candidate vehicle encountered in the same lane as first used was selected, if it was in laser range. If the first vehicle encountered in the same lane was not a candidate vehicle, i.e., not a light-duty vehicle or a light-duty truck, or if the vehicle was not in laser range, then the target vehicle was selected using the standard protocol.

Although there may be some concern that the focus on white cars introduced some sample bias (due to the possible relationship between driver demographics/aggressiveness and color choice), it is important to recognize that the technique for selecting target vehicles uses white cars to select the lane of traffic to move into, and then only in certain circumstances. White cars were not used to select the lane of travel on lightly travelled surface streets or on freeway on-ramps or when the initially selected vehicle had been lost. White cars were primarily used to select the lane of travel on busy surface streets, where it was less likely that the vehicle in front of the chase car after the lane change was actually a white car. It also should be recognized that other potentially more random vehicle selection techniques (e.g., the selection of vehicles based on license plate numbers) proved impractical in the field.

Acquisition of the Target Vehicle - Once the chase car was positioned behind a candidate vehicle, the vehicle became a "target" for the laser range finder. Laser lock generally occurred immediately when the range to the target vehicle was less than 300 feet. When the laser was locked on, the observer recorded the target type using the rotary selector switch and the start of chase by turning on the target switch.

Following a Target - To the extent possible, the chase car driver attempted to remain behind the target, approximately matching its accelerations and decelerations, without arousing suspicion by the target driver, disrupting traffic or creating a safety hazard. The chase car made lane changes with the target vehicle only when it appeared that the target vehicle was making a passing maneuver, not preparing to turn off the route. The distance between the chase car and the target was generally kept to not more than about 200 feet and not less than a safe following distance (approximately one car length for each 10 mph, depending on conditions). In free-flowing traffic on wet pavement, the chase car drivers maintained a following distance greater than on dry pavement. In very slow stop-and-go traffic, the chase car drivers would often follow the target very closely, i.e., "tailgate".

If, at any time, the target acquisition was lost or was about to be lost even momentarily, e.g., around a sharp curve or at a sharp grade change, the observer immediately turned off the target switch, turning it on again only if the laser range finder output showed clearly that the target had been reacquired.

Deselection of a Target - Each selected target was followed as long as reasonably possible. If a target could not be followed safely through a lane or speed change, or if it appeared to be deviating from the chase car's preplanned route, it was deselected and a new target chosen. In that case, the vehicle immediately in front of the target vehicle became the new target if it was a candidate vehicle and within laser range. If there was no vehicle within laser range when the original target was lost, then the protocol for initial selection of a target vehicle was employed.

The target was also deselected if it stayed in a queue of vehicles apparently waiting to turn off the preplanned route. If a third vehicle came between the target and the chase car, a new target was selected using the standard protocol unless the third vehicle moved away before a new target was identified and acquired, in which case the original target was reacquired and chase of that target was resumed.

If the chase car had to change lanes or turn to exit a given roadway in order to follow a preassigned route, the current target was dropped and a new target was selected as soon as possible, using the basic target vehicle selection protocol.

Due to safety concerns, a target was deselected if the driver of the target vehicle exhibited erratic behavior, such as sudden stops or starts, or apparent nervousness about being followed (e.g., by frequent reference to the rear view mirror). When such erratic behavior or anxiety was detected, the chase of that vehicle was ended immediately and a new target was selected. Fewer than 0.5% of target contacts were lost for this reason.

Chase Car Travel at Other Times - At all times when the chase car was not following a target, the chase car was driven in a fashion that approximately matched the general flow of through traffic, i.e., travelling faster than some vehicles and slower than a similar number of vehicles (excluding vehicles merging right or traveling slowly in order to exit), consistent with safe driving practices. Lane changes were made by the chase car only as required to acquire a target, to follow a target, to change routes, or to match the general flow of through traffic, or as required by road or safety considerations.

In the event that a turn or a freeway exit was missed, data recording was ended immediately. The chase car was driven back to a point on the route before the miss occurred, previous driving conditions (e.g., lane, speed) were re-established in the correct direction, and data recording resumed at the point where the miss occurred.

Equipment Operating Procedures - A variety of "check lists" were used to assist in achieving consistent and efficient data collection during routine operation. The check lists were printed on 5"x7" laminated cards held together by a clip installed on the sun shade of the vehicle. The applicable card was rotated to the first position in the stack. The check lists reminded the driver and the operator of the steps to follow in turning on equipment, starting data collection, and backing up data files. .

The "Start of Day" check list contains the following items:

- __ Clean windshield and laser lens if necessary.
- __ Plug in cellular phone and turn on.
- __ Install computer and connect cables.
- __ Install and aim camcorder; confirm lens set to widest angle.
- __ Turn on laser, monitor, and camcorder with invertor switch.
- __ Insert fresh 8mm tape with date on label and set camcorder counter to zero.
- __ Start computer; check that at least 5 MB of free space remains on hard disk.
- __ Check clock and date on computer and camcorder.
- __ Insert fresh 1.44 MB diskette with date label and check for "no files" and 1.4 MB free.
- __ Start Labtech Notebook.
- __ Start car; set switch box to "Note 6"; run "GO" to start recording data and check for reasonable readings from all sensors and laser.
- __ Escape out of Labtech Notebook.

The "Start of Trip" check list contains the following items:

- __ Check fuel level.
- __ Make Post-it note with turns.
- __ Start camcorder.
- __ Check camcorder counter reading and read out loud.
- __ Display date on camcorder and read out loud and log.
- __ Display time on camcorder and read out loud and log.
- __ Read chase car odometer and log.
- __ State location; destination and route number.
- __ Confirm laser switches on.
- __ Confirm computer is running Labtech Notebook and ready to start recording data.
- __ Confirm switchbox set correctly for start of run with laser switch set to "OFF".
- __ Run "GO" and tell driver to drive away when traffic is clear.

The "Along the Route" check list contains the following items:

__ Call out laser ON/OFF.
__ Call out vehicle type.
__ Call out roadway type changes.
__ Call out Level of Service changes.
__ Call out speed limit signs and actual speed.
__ Call out obvious grades.
__ Activate other "Notes" when unusual events occur (e.g., forced detour off route; forced to make unplanned stop for vehicle related problem; etc.)
__ Activate "Note 6" when problems are significant enough to abort run.

The "End of Trip" check list contains the following items:

__ Hit escape key to stop data collection and call out.
__ Read time on camcorder out loud and log.
__ Read chase car odometer and log.
__ State location; destination and route number.
__ Stop camcorder.
__ Pop tape out of camcorder and write run number on label; replace tape if sufficient time remains for next run.
__ "Quit" Notebook.
__ Note size of last two .PRN files.
__ Check remaining space on diskette; install fresh diskette if necessary.
__ Copy last two .PRN files to diskette in a: drive.
__ Write run number on diskette.

Finally, the "End of Day" check list contains the following items:

__ Remove 8mm tape from camcorder and activate write protect tab.
__ Confirm day's data files are on 1.44 MB diskette(s) and diskette(s) labeled with date and run numbers; reconcile written log with number of .PRN files written to diskette(s).
__ Reconcile number of trips on diskette label and number of trips on 8mm tape label.
__ Turn off computer.
__ Turn off invertor.
__ Disconnect cables and remove computer and camcorder.
__ Turn off and disconnect phone.

###

6. TRIP END DATA COLLECTION AND ANALYSIS

As noted in Section 2, one limitation of collecting vehicle operation data using a chase car is that "trip ends" (the beginning and ending portion of a trip) are difficult to capture. A field study of trip end activity was therefore used to supplement the data collected by chase car.

Over 2,800 trip ends were observed in Sacramento, California, at a wide variety of parking facilities. These included trip ends in different residential parking categories (e.g., garages, on-street parking spaces, etc.), as well as nonresidential categories (e.g., parking garages, shopping malls, drive-thru service lanes, etc.). For each observation, times were recorded for four separate modes of operation: idle, reverse, cruise and queue (e.g., 1-2 mph). In addition, random roadside surveys of motorists were conducted in both Sacramento and the San Francisco Bay Area to determine the frequency of vehicle starts and ends in the same parking categories.

6.1 The Need to Characterize Trip-ends

To accurately represent urban area driving, a representative driving cycle must include all portions of an "average" vehicle trip within the urban area, including those portions not occurring on the normal roadway network. Off-network operations occur at both the beginning and the end of the trip (collectively referred to as trip ends). Depending on the parking area, there may be significant periods of operation before a vehicle enters or after it exits the roadway network. These periods are expected to vary considerably by time of trip and parking location.

During this study, a trip beginning was defined as each time a vehicle's engine was started (unless the start immediately followed a stall) and a trip end as each time the engine was turned off. This definition differs somewhat from the manner in which a trip is defined in most transportation-related studies and models. Such studies usually categorize trips based on their origin and purpose. Common trip types include home-work, home-shopping, home-other, work-other, other-other. These types of groupings, however, often ignore intermediate stops made during linked trips. For example, a motorist who stops at a gas station on the way to work would usually be counted as making a single home-work trip, and vehicle operation at the gas station would be overlooked. In the present analysis, the linked trip would instead be separated into two distinct trips, each with a trip beginning and a trip end. This approach thus provides a more accurate method for developing representative trip end segments.

Observations of residential, parking lot and on-street parking indicate there are four specific modes of non-network vehicle operation: idle, reverse, cruising and queuing (sometimes referred to as "creeping"). Not all four modes occur for every trip end. For example, some motorists may park their vehicle so that they do not need to put the vehicle into reverse when exiting the parking location. However, an average driving cycle would include components for all four of these operating modes.

To determine "average" vehicle trip end behavior, it is necessary to collect sufficient data and utilize an appropriate weighting scheme to construct statistically valid driving cycle segments for both the beginning and end of the trip. This section of the report details the methodology used to accomplish this objective, and presents the results of the analysis. In particular, this section focusses on the methods used to ensure the representativeness of the data collected. The individual steps in this effort are discussed below.

6.2 Study Design

As a first step to the analysis, a thorough review of available literature was conducted, but revealed no existing data on trip end times or mode of operation. However, the review indicated there were several sources of national and local information that could be used to design methods for the collection and analysis of trip end data. Based on the results of the review, a decision was made to conduct a detailed field study of average times for the beginning and end of trips in urban areas.

Sacramento Survey Design – Sacramento, California, was selected as the location for an initial trip end study. This community was selected for convenience (Sierra's offices are located in Sacramento), and because it was believed to be reasonably representative of many large U.S. urban areas. The goals of the Sacramento study included the following:

1. development of a study methodology that could be used in other cities to collect similar data;

2. collection of sufficient local data to allow construction of statistically representative driving cycle segments for vehicle trip end operations in the local urban area; and

3. aggregation of local data into regimes that could be compared to data collected in other areas, to determine whether Sacramento-derived trip end driving cycle segments were representative of other cities as well.

Available Information – Available information from relevant local and national studies were used to design the Sacramento trip ends study. This information included the following:

- National travel data (from the 1983–1984 Nationwide Personal Transportation Study[22], or NPTS) on trip distribution by purpose. The data are summarized below in Table 8.* The NPTS data can be used to target those trip purposes estimated to result in the majority of total urban trips and VMT.

Table 8

Overall Vehicle Trip Distribution By Purpose (1983-84 National Travel Survey)*

Trip Purpose	% Trips	% VMT
To/from work	27.8	30.1
Work-related business	2.9	4.2
Work Subtotal	30.7	34.3
Shopping	20.0	13.4
Doctor/dentist	1.2	1.5
Other family/personal	18.3	15.5
Family/Personal Subtotal	39.5	30.4
Civic/educational/religious	5.9	4.1
Vacation	0.2	2.1
Visit friends/family	9.9	13.5
Pleasure driving	0.4	1.1
Other social/recreational	12.1	13.3
Social/Recreational Subtotal	22.6	30.0
Miscellaneous	1.3	1.2
Total	100.0	100.0

* Available preliminary data show 1990 trip percentages in the work, family/personal and social/recreational categories to be within 10% of the 1983-1984 percentages shown in the table.

*A similar study was also conducted in 1990. However, little data were available from the 1990 study at the time of survey design.

The data show the following five trip types account for almost 90% of all travel:

work-related	= 27.8% trips	30.1% VMT
shopping	= 20.0%	13.4%
other family/personal business	= 18.3%	15.5%
visit friends/family	= 9.9%	13.5%
other social/recreational	= 12.1%	13.3%
TOTAL	= 88.1%	85.8%

Unlike the historical transportation planning methodology previously discussed, the NPTS data were treated identically to the approach used in this analysis, i.e., each segment of a linked trip was considered a separate trip. Thus, the percentages shown above accurately reflect the frequency of trips as defined herein.

- A map and inventory of downtown parking facilities, including ownership and limited occupancy rate data, for the City of Sacramento.[23]

- A copy of the "Downtown Economic Study", prepared by Cambridge Systematics for the City of Sacramento in June 1989.[24] This study, which addressed the economic effects of raising the price of downtown parking, included data on the distribution of parking and pedestrian activity in downtown by trip purpose.

- A summary of population, housing unit and population density data (based on 1990 census data) for Sacramento County, disaggregated into 22 separate planning districts.[25]

- A listing of the distribution of dwelling unit types (divided into single-family residences, 2-4 units, 5+ units, and mobile homes) for 25 slightly different planning districts within Sacramento County.[26]

- Housing, population and employment data, disaggregated by census zone, for Sacramento County.[27]

- Detailed information on the location of all large multi-residential developments in the Sacramento area, from a local firm associated with the real estate industry[28].

- Two additional references used by traffic engineers to estimate trip generation rates from a variety of residential, commercial and other facilities. These include the ITE Trip Generation Report (published by the Institute of Traffic Engineers) and the National Cooperative Highway Research Program (NCHRP) Report 187[29]. However, review of the references indicates the data have limited usefulness for the current study due to the way in which they are expressed (e.g., trips/1,000 sq.ft. of floor space).

General Survey Methodology - The NPTS distributions were used to target Sierra's survey of trip end times. To reduce survey requirements, the following simplifying assumptions were made:

- All shopping or other non-commute trip ends at residences were assumed to have the same time-in-mode characteristics, regardless of trip purpose or time of day, since congestion was not expected to be a significant factor in residential areas except at large, multi-family dwellings. Commute peak-period trip end characteristics were expected to possibly vary from the non-commute trips due to the higher level of congestion.

- All trips beginning or ending at family/friends' houses, or for "pleasure driving", were assumed to be accurately represented by data collected on residential trip beginnings and endings.

- All social/recreational trips made in the "other" subcategory were assumed to be to a variety of events and locations, and under varying traffic conditions, resulting in a wide distribution of parking facilities and mode times. This was also assumed to be true of shopping-related and "other family/personal business" trips. Although some of the same parking facilities may be used for all three types of trips, the distribution of trips among all types of parking facilities was assumed to be somewhat different for each trip type.

- Civic/educational/religious trips were also assumed to be made to a variety of parking facilities and activities. It was assumed that the average time mode characteristics for these trips can be adequately represented by the data collected on the "other" category of trips, as defined below.

- It is obvious that a high percentage of vehicle trips either begin or end at the driver's residence. However, the NPTS data were not disaggregated in a manner that it made it possible to quantify the percentage. Based on estimates provided by Sierra employees, it was assumed that 100% of to/from work, civic/educational/religious, social/recreational and other trips, and 80% of family and personal business trips, begin or end at home. Based on these assumptions, 45% of all trip beginnings and 45% of all trip endings were estimated to occur at home.

- The other 20% of family and personal business trips were assumed to be evenly divided between trips that begin or end at work (e.g., noontime travel), or at locations related to other similar trip purposes (i.e., such trips are strung together).

The trip purpose categories shown previously in Table 8 needed to be translated into trip end location categories and sampling times for survey purposes. Three general trip end categories were identified for sampling purposes:

1. <u>Residential</u> (for trip ends occurring at home) - Based on the above assumptions, this category is estimated to account for

approximately 50% of all trip ends. Except for large multi-residential developments, it was expected that mode times for these trips would be independent of the degree of traffic congestion. Therefore, there would be no need to sample for both peak and off-peak traffic conditions, other than at the larger multi-residential units. (However, limited data would be collected to check this assumption.)

2. Employment (for trip ends at employment-related parking facilities) - This category is estimated to account for roughly 19% of all trip ends. Mode times in this category would be sampled only during peak traffic conditions.

3. Other (for trip ends at parking spaces used by vehicle drivers who are shopping or on other social, family or personal business) - This category is estimated to account for approximately 31% of all trip ends. As mentioned previously, trip distributions among types of parking facilities for the three sub-categories included in this "other" category needed to be determined. Both peak and off-peak sampling was expected to be required in this category.

Collection of Time-in-Mode Data - To facilitate the accurate collection of time-in-mode data from multiple modes of vehicle operation (e.g., idle, reverse, cruising and queuing), a programmable HP-41CX calculator with a built-in "stopwatch" function was used. Although there are only four different modes of operation, there may be multiple occurrences of some modes during a single trip end. For example, a vehicle exiting a parking lot onto a busy street may have several instances of cruising and queuing, depending on the level of vehicle activity in the lot and other factors. The use of the HP-41CX allowed the recording of a large number of mode times using only a few simple keystrokes, which could subsequently be accessed from the calculator's memory and recorded on a written summary sheet after each trip end observation was completed.

Sierra Pilot Survey - The validity of the assumptions outlined above, the use of NPTS distributions for targeting trip categories in Sacramento and the methodology for collecting time-in-mode data were initially tested by a limited survey conducted by Sierra employees on their own personal travel. Employees were asked to record the type of parking facilities used and to time each trip end mode for each of their trips during the course of one week. Data collected from this limited survey were analyzed to check the above assumptions, prior to beginning a full-scale survey of trip end behavior in Sacramento. It is acknowledged that the pilot survey may have been influenced both by the non-representativeness of the subject population, and the fact that drivers surveyed their own driving habits, potentially resulting in changes to those habits during the survey period. However, the pilot survey was primarily used to target the types of parking facilities to be sampled in the full-scale survey. Any bias introduced by the pilot survey methodology did not affect the results of the full-scale survey because the frequency of trip end activity by facility type was determined independently.

For the pilot study, either the vehicle driver or a passenger was required to operate the calculator while entering or exiting parking facilities. Although some difficulties were encountered during the pilot survey in operating the calculator while driving, this methodology proved to work well in recording trip end data during subsequent field surveys.

Results of the Pilot Survey – 276 start-up and 276 exit observations were made by a total of 14 Sierra employees during the pilot survey. Table 9 compares the estimates presented above (based on the NPTS) with the actual results of the pilot survey. The data show excellent correlation between the estimated and actual results for the employment-related trip ends. However, the pilot survey showed a much lower percentage of residential trip ends than expected from the NPTS results. It is not known how much of this difference is actually due to differences between trip generation rates in Sacramento and the areas sampled in the NPTS, versus the effect of the non-representativeness of the surveyed population in the pilot study.

Table 9

Comparison of Trip End Distributions During the Pilot Survey

Parking Location	Assumed Trip Ends (%)	Pilot Survey Trip Ends (%)
Residential	50%	37%
Employment	19%	20%
Other	31%	43%
Total	100%	100%

Table 10 provides a more detailed breakdown of the frequency of trip ends by parking location in the pilot survey. The data presented in the table show a wide distribution of trips across a considerable range of parking facilities. Review of the data shows that approximately one-half of the residential trip ends occurred in the residential on-street category, with the other half divided among the remaining residential parking categories of garages, driveways and parking spaces (e.g., in multi-residential facilities). About three-quarters of all employment parking occurred in employee parking lots, with one-quarter in on-street parking spaces. Finally, the "other" parking category is disaggregated into many separate types of parking facilities, with grocery store lots, commercial parking lots and other single-purpose lots being the most frequently used facilities in this overall category.

The frequency distribution of trip ends based on the subcategories noted above could be significantly affected by the composition of the survey sample (i.e., the use of Sierra employees). These results are

Table 10

Frequency of Trip Ends During Pilot Survey
(by Type of Parking Facility)

Parking Facility	Starts	Ends
On Street Work	5.1%	5.4%
On Street Other	4.3%	3.6%
On Street Residential	18.5%	18.1%
Residential Garage	10.5%	10.5%
Residential Driveway	4.3%	4.3%
Residential Parking Space	3.3%	3.6%
Employee Parking	14.5%	14.1%
Drive-Thru Window	0.0%	0.0%
Gas Station Pump	1.8%	1.8%
Small Strip Mall	4.3%	4.3%
Grocery Store	6.9%	6.9%
Commercial Parking Lot	5.8%	6.1%
Major Mall	3.2%	2.9%
Parking Garage	1.9%	2.2%
Employee/Customer Parking Lot	1.5%	1.5%
Other Single Purpose Lot	13.0%	14.1%
Other Multi-Purpose Lot	0.0%	0.0%
Miscellaneous	1.1%	0.4%
Total	100.0%	100.0%

summarized here simply for comparison to the weightings developed subsequently and should not be used for other purposes.

Full Survey Design – The information shown in Table 10 can be used to design a data collection program that provides a level of sampling effort in each category commensurate with actual trip end distributions. This ensures that sufficient observations are made in those types of parking locations with the highest frequency of trip ends, to attempt to maximize the accuracy of the survey results. The effort required for sampling each of these categories is discussed in greater detail below.

Residential – Because this category is estimated to account for 37-50% of all trip ends, it is very important to obtain accurate time-in-mode data for residential locations. However, this category was expected to be difficult to sample representatively, for the following reasons:

1. A large percentage of trips involve travel to/from single family residences. These were expected to be hard to observe, due to low housing densities, non-uniform travel times, problems with finding suitable points of observation and other factors.

2. There could be large differences in mode times, depending on the type of residential dwelling units, type of parking facilities, lot sizes (e.g., length of driveways), etc.

Given these concerns, population and housing unit density data were used to select three planning areas of Sacramento that represented low, medium and high densities of residential development. Within each planning area, a survey subarea encompassing approximately 1,000 housing units was established. The private firm cited previously was contacted to provide information on the size of all large multi-residential areas located in each subarea. These data, along with the Sacramento Area Council of Governments (SACOG) dwelling unit distributions, were used to gauge the representativeness of the subarea, and to target individual residential parking areas for study. Based on a review of local zoning maps, non-residential (e.g., commercial, light industrial, etc.) areas were excluded from the subarea.

In each of the three subareas, an initial target of 200 trip beginnings and 200 trip endings was selected. It was initially intended that sufficient data would be collected during both peak and off-peak periods to determine if mode times were independent of period of operation (as theorized) for all but the large multi-residential units. However, several factors combined to require a change in survey methodology. These factors included the following:

- Actual off-peak trip ends proved difficult to observe due to the low level of residential trips occurring during these periods.

- Anecdotal evidence supplied by survey workers indicated little difference in peak and off-peak congestion in the surveyed locations.

- Residential trip start times were significantly affected by ambient temperature levels, as discussed later in the section. This temperature effect obscured any peak/off-peak differences.

As a result of these factors, most residential observations were obtained during peak periods, and peak and off-peak observations were averaged for all residential locations.

The residential survey was initially intended to be distributed across dwelling unit types based on available SACOG data (e.g., 63.0% single-family homes, 11.8% 2-4 unit residences, 21.6% multi-unit 5+ buildings and 3.5% mobile homes). Target sampling percentages were somewhat re-distributed to ensure that sufficient data were obtained from a representative range of multi-residential units. Also, subsequent sampling efforts showed it was easier to collect multi-residential trip end data, due to the higher level of trip generation associated with these facilities. Single-family residential observations, particularly in the low population density subarea, were difficult to obtain. This resulted in fewer than planned observations in this category.

Table 11 summarizes the number of residential trip ends observed in the three subareas by parking category. Due to the observation difficulties described above, actual observations were curtailed below the initial target of 200 trip beginnings and 200 trip ends in each subarea. The table also reflects the regrouping of the residential data into parking category type, rather than type of dwelling unit. This was done during the course of the study to more easily weight the data in developing overall urban average trip end segments (beginning and end).

Table 11

Residential Trip End Observations in Sacramento

Subarea Description	Residential Category	Number of Trip Starts/Ends
Orangevale	On-street	11/10
	Garage	13/5
	Driveway	54/59
	Parking Space	40/33
City of Sacramento	On-street	50/27
	Garage	17/2
	Driveway	59/28
	Parking Space	32/45
Arden/Arcade	On-street	20/11
	Garage	9/9
	Driveway	39/20
	Parking Space	68/46

Employment - Of the three general categories, this accounts for the smallest percentage of trip ends. Mode times, however, were expected to be longer than residential mode times, thus increasing the importance, from an emissions standpoint, of this category. As a result of the downtown parking study, excellent information was available on parking supply in the Sacramento core area; however, there was a complete absence of such information for the remainder of Sacramento County.

Because of this, the trip end sampling program for work-related trips focussed primarily on the downtown area.

For downtown Sacramento, trip ends at approximately 20 parking lots and garages were surveyed. These were selected to represent a wide distribution of facility sizes, and ownership and usage characteristics (e.g., public, private or commercial). Roughly 30 trip beginnings and 30 trip endings were surveyed at each lot. Table 12 lists the number of available parking spaces and trip ends observed at each facility. The table also includes the number of observations made at on-street spaces.

Parking structures represented a special sampling problem due to the large percentage (about 40%) of total downtown parking spaces they encompass, and difficulties in obsêrving mode times in such structures. Expected longer cruise times increased the necessity to accurately sample such lots. Therefore, short-range radio transceivers were used by the survey team to communicate during trip end observations of vehicles chosen at random entering and exiting the parking structures.

For commute trips to and from non-downtown areas, three commuter-related representative subareas were selected, based on the employment density information provided by SACOG. This selection process was similar to that of residential subareas. First, employment densities were calculated for each of the planning areas for which residential population densities were also available. Based on those data, three planning areas, in addition to the downtown core area, were selected as representing low, medium and high employment density areas.

Using a methodology similar to that used for the residential category, subareas were established in each of the three employment planning areas. Trip end observations were made among four parking categories: a) small lot (0-20 spaces); b) medium lot (21-100 spaces); c) large lot (101-500 spaces); and d) major lot (greater than 500 spaces). Initially, it was intended to include non-residential on-street parking spaces and parking garages as two additional parking categories. Field observations, however, found none of these in the selected non-downtown subareas, resulting in the elimination of these categories.

It was also originally intended to separate the observations into commute and non-commute categories by time of day. Commute trip ends were to be defined as those occurring during morning and evening peak commute periods (7:30-9:00 a.m. and 4:00-6:00 p.m.). As detailed below, however, this methodology was altered during the course of the survey work.

Other - Little data are available on customer-related parking supply anywhere in Sacramento County. (The downtown parking study included an inventory of <u>total</u> parking supply, for both commute and other purposes.) Therefore, field observations were conducted at the same facilities selected for the commute survey. This was done to minimize the amount of actual fieldwork required, and because it was impossible to determine by field observations the incidence of commute parking versus parking for each of the three trip purpose subcategories included in the "other"

Table 12

Downtown Sacramento Trip End Observations

Parking Facility Description (Address/Type)	Number of Parking Spaces	No. of Trip End Observations (Starts/Ends)
6th & K/Public Garage	1,935	32/30
11th & L/Public Garage	948	29/29
13th & I/Public Garage	876	36/37
10th & I/Public Garage	621	32/40
6th & I/Commercial Garage	523	32/31
8th & J/Commercial Garage	329	30/30
16th & K/Private Garage	271	30/30
2nd & N/Public Lot	182	31/37
4th & J/Public Lot	164	32/32
7th & N/Private Lot	164	31/30
9th & H/Private Lot	135	30/31
15th & Capitol/Private Lot	122	30/31
13th & I/Commercial Lot	96	31/33
15th & L/Private Lot	58	31/39
10th & H/Private Lot	40	32/36
13th & G/Private Lot	30	30/31
11th & I/Commercial Lot	29	31/30
14th & H/Public Lot	167	31/31
16th & I/Private Lot	13	3/22*
On-Street Parking	–	59/59

* A decision was made to reduce trip end observations at this lot due to the low level of parking activity.

(or non-commute) category (shopping, other business and other social). This was due to the following reasons:

1. non-uniform arrival times (e.g., not all commuters arrive at work by 8 a.m. each day and non-commute trips occur throughout the day in varying frequencies);

2. non-uniform parking times due to both the trip purpose and the consumer habits (e.g., the length of time spent at the grocery store) of individual motorists; and

3. the multi-use nature of many of the parking facilities among the three non-commute subcategories.

Because of these factors, and the need to accurately weight the mode times for the three trip purposes, a list was initially developed of representative types of parking facilities that might be visited during one of these three types of trips. This list was produced by combining personal observations with the results of the Sierra pilot survey and the trip generation rates contained in the NCHRP Report 187. (This was actually done in conjunction with the methodology outlined above for selection of the commute-related facilities to be sampled, since preliminary field observations revealed the need to observe both commute and non-commute trip ends at the same parking facilities.)

The next step was to conduct sufficient observations at a number of parking facilities to allow computation of average mode times for each facility type. It was initially believed that mode times might vary considerably between peak and off-peak conditions, requiring trip end times to be collected for both conditions. Subsequent field observations, however, in the high-density subarea revealed no consistent differences in trip end times between peak and off-peak periods. As discussed above for residential observations, this comparison was hampered by difficulties in observing off-peak trip ends. This resulted in insufficient data to support a finding of statistically significant differences in peak and off-peak trip end times. In addition, there were substantial temperature-related effects that acted to obscure any possible peak/off-peak effects.

The original plan was also to compare customer (i.e., non-commute) trip end data to commute-related data to determine if there were significant differences in mode times. Subsequent field observations showed that it was very difficult to distinguish between the two types of parking activities. The only method of separating such activities was to assume only commute parking occurred during the morning and evening peak commute periods (7:30-9:00 a.m. and 4:00-6:00 p.m.) and only non-commute parking occurred during the off-peak periods. Since, as indicated above, there was no consistent difference in trip end times between the two periods, it was concluded that there were no readily apparent differences in customer and commuter trip end times. As a result, these were subsequently recategorized simply as nonresidential trip ends.

The non-downtown data collection effort focussed on determining the validity of the assumption that mode times for vehicles entering and exiting the facilities were similar to the more extensive data collected in the downtown area. Sampling targets of 30 trip beginnings and 30 trip endings for each of the four parking categories outlined above were initially selected for each subarea. The actual number of trip ends observed depended on several factors, including the types of facilities located in each subarea and the ease of observation at each facility selected. Table 13 summarizes the number of nonresidential observations made at individual facilities in each subarea.

Table 13

Trip Ends Observed at Retail Facilities in the Sacramento Urban Area

Subarea Description	Parking Facility Description	Parking Category	Number of Trip Starts/Ends
Folsom City	Major mall lot	500+	56/55
	Single purpose lots	21-100	33/32
	Multi-purpose lot	21-100	40/42
	Multi-purpose lot	101-500	48/42
	Gas station	-	13/11
	Drive-thrus	-	15
Arden/Arcade	Super mall (8,700 spaces)	500+	60/59
	Single purpose lot	1-20	0/9
	Drive-thru	-	11
Citrus Heights	Major mall	500+	44/45
	Single purpose lots	21-100	14/11
	Single purpose lot	101-500	18/ 0
	Multi-purpose lot	101-500	50/52
	Multi-purpose lot	21-100	41/39
	Gas station	-	7/6
	Drive-thru	-	4

Observation Protocol - For all trip end observations, the sampling protocol was very similar to the methodology used in the pilot survey. The only difference was these observations were made on a remote basis to introduce as little bias as possible into the survey results. In most cases, drivers did not know they were being observed. To further reduce the possibility of bias, field personnel were instructed that, if questioned, they should explain that they were taking a survey, but not to tell drivers that their driving movements were being timed. Initial field experience seemed to indicate that some drivers were bothered by the presence of survey staff in parking lots. Subsequently, personnel were equipped with standard orange safety vests commonly worn by road construction and other workers. This appeared to "legitimize" the survey personnel, and ease drivers' concerns.

Vehicles were chosen at random for observation as start-ups occurred within a lot or at a residence, or as vehicles exited the roadway network into the parking facility being observed. The greatest difficulty in observing vehicles occurred in residential areas, particularly those with single-family dwelling units, due to low housing densities and infrequent trip ends.

In the smaller parking lots, field personnel were able to observe all entrances into the lot (i.e., trip ends), start-ups in the lot (i.e., trip beginnings) and ensuing vehicle movements relatively easily. Vehicles were simply observed from a single vantage point, or followed on foot if necessary. For the bigger lots and the residential observations, survey staff used bicycles to follow the vehicles being observed. In some cases, this resulted in drivers realizing they were being observed, causing them to change their driving habits. If this happened, field personnel were instructed to terminate the observation. Overall, however, a very small percentage of observations were required to be terminated in this manner.

Summary of Sacramento Data Collection Efforts - Table 14 summarizes the data collected in Sacramento. Each "trip end" included in the table consists of either a trip beginning or ending. The table shows that residential observations accounted for approximately 25% of all trip ends observed in Sacramento. These observations were split relatively equally among the three residential subareas sampled in the study.

Survey efforts in the nonresidential category were focussed on the downtown area in order to gather sufficient data to ensure statistically valid results. The table shows that the majority (59%) of such observations occurred in the downtown area. After this goal was accomplished, remaining resources were devoted to collecting data in the other subareas to determine whether similar trip end times were occurring in the remainder of the urban area. Approximately equal numbers of trip ends were observed in the low- and medium-density subareas (e.g., 19% and 16% of total non-residential observations, respectively). About 6% of these observations were made in the high-density subarea, primarily at the largest shopping mall in the Sacramento area.

Table 14

Summary of Trip End Data Collection Efforts in Sacramento

Trip Type	Location	Trip Ends Observed (Starts/Ends)
Residential	Orangevale	118/107
	City of Sacramento	158/102
	Arden/Arcade	136/86
	Residential Subtotal	412/295
Nonresidential	Downtown Sacramento	618/657
	Arden/Arcade	60/79
	Folsom City	190/197
	Citrus Heights	174/157
	Nonresidential Subtotal	1,042/1,090
Total Observations		1,454/1,385

Trip Frequency Survey - The final step of the Sacramento portion of the trip ends study involved the collection of data that could be used to determine the frequency distribution of trip ends by type of parking facility used. The following possible approaches to obtain these data were considered:

1. Use of the NPTS data. NPTS respondents were asked where they drove on the previous day. The final report summarized survey results into the general categories noted previously in Table 8. If more disaggregated data were available, it could possibly be redistributed into the current analysis' parking categories.

2. Development of a brand-new "day-after" trip survey, similar to the NPTS, that could be given to vehicle owners in Sacramento and other cities of interest. Motorists would be asked to note every single location that they had driven the preceding day. These data would then be used to construct a new trip end database.

When contacted, Federal Highway Administration (FHWA) staff indicated that transmittal of 1983-84 NPTS data would be delayed, for an unspecified period, due to workload constraints. In addition, the original questionnaires could not be accessed due to confidentiality concerns and it was believed they had been destroyed. Fortunately, the second approach appeared to have several advantages, including the following:

- It would be based on data collected in the city being analyzed.
- It would be based on current travel patterns.
- Since the questionnaire would be designed specifically for this study, possible data misinterpretation would be minimized.
- Additional questions could be incorporated into the survey instrument, to assist in accurately weighting mode times collected for trip ends.

Due to the detailed nature of such a survey, it requires personal interviews with a representative cross-section of motorists. Possible ways to ensure representativeness include a random telephone survey, a survey of motorists patronizing locations visited by a representative distribution of drivers (e.g., at gas stations), or a survey administered on a roadside basis in conjunction with other survey efforts (e.g., the random roadside emissions survey program conducted by the California Bureau of Automotive Repair, or BAR).

After considering the approaches outlined above, the third method was selected. BAR staff were contacted to determine if they were conducting any random roadside emissions inspections. Subsequently, field personnel were able to administer trip frequency surveys at random roadside locations in both the Sacramento and San Francisco Bay urban areas. In Sacramento, surveys given to 60 motorists provided detailed information on 269 trips. Roughly 250 motorists were surveyed in the Bay area, resulting in trip end data on a total of 1,074 trips. Table 15 summarizes the type of information collected. The parking categories (by type and size of parking facility) used in the frequency survey are identical to those used to categorize individual trip end observations. This was designed to allow easy matching of trip end frequencies with average trip end times for each category, as shown later in this section.

<u>Los Angeles Survey Design</u> - The trip end survey for the Los Angeles area was designed similarly to that described above for Sacramento. Several factors, however, combined to limit the scope of the L.A. study effort relative to that in Sacramento. These factors included the following:

1. Fewer data were available on housing and employment patterns in the Los Angeles area. Significant delays were also encountered in obtaining what data were available, resulting in little advance time for planning the Los Angeles fieldwork.

2. The Los Angeles area is much larger and somewhat less homogeneous on a socio-economic basis than Sacramento. This made it hard to select sampling subareas that would be representative of average vehicle trip end conditions in urban Los Angeles.

3. Los Angeles has much higher population and employment densities.

Table 15

Information Collected in Trip Frequency Survey

1. Type of residence:

   a. single family
   b. mobile home or trailer
   c. multi-family (2-4 units)
   d. multi-family (5+ units)
   e. other

2. Location of residential parking:

   a. garage
   b. driveway
   c. on-street
   d. multi-residential space
   e. other

3. Trip information for each trip taken on previous day:

   a. travel date
   b. day of week
   c. time of day
   d. trip length (minutes and/or miles)

4. Trip origin and destination information:

   a. home
   b. work
   c. school or church
   d. gas station
   e. grocery store
   f. restaurant
   g. other store (specify type)
   h. professional building
   i. entertainment facility (specify type)
   j. other (specify type)

5. Type of parking used at trip destination:

   a. on-street parking
   b. residential garage
   c. residential driveway
   d. residential space
   e. employee parking lot
   f. drive-thru window
   g. gas station pump
   h. other single-purpose lot (specify type)
   i. small strip mall lot
   j. grocery store mall lot
   k. commercial parking lot
   l. major shopping mall lot
   m. parking garage
   n. employee and customer lot
   o. other multi-purpose lot (specify type)

6. Estimated size of parking lot or garage (if used):

   a. 1- 20 spaces
   b. 21-100 spaces
   c. 101-500 spaces
   d. greater than 500 spaces
   e. not sure

4. Sampling of some densely populated subareas in Los Angeles was not possible due to concerns about the safety of field personnel.

Survey Goal – The goal of the Los Angeles portion of the study was to collect enough data for a statistically valid comparison to the Sacramento data. Thus, survey efforts in Los Angeles focussed on determining whether the Sacramento results could be considered valid for Los Angeles as well. This allowed the targeting of trip ends and subareas in Los Angeles that could be compared directly to the same trip end categories and similar locations in Sacramento.

It was decided to focus on areas of higher population and employment densities, in part due to higher overall densities in Los Angeles. It was also felt that if there were significant differences between Sacramento and Los Angeles trip end times, they would most likely occur in higher density zones as a result of increased traffic activity and congestion. Selection of such sampling subareas was thus intended to result in the collection of "worst case" trip end times.

Subarea Selection – Based on the above methodology, higher-density residential and nonresidential subareas were selected for sampling in Los Angeles. The chosen subareas and their respective densities were:

Residential:

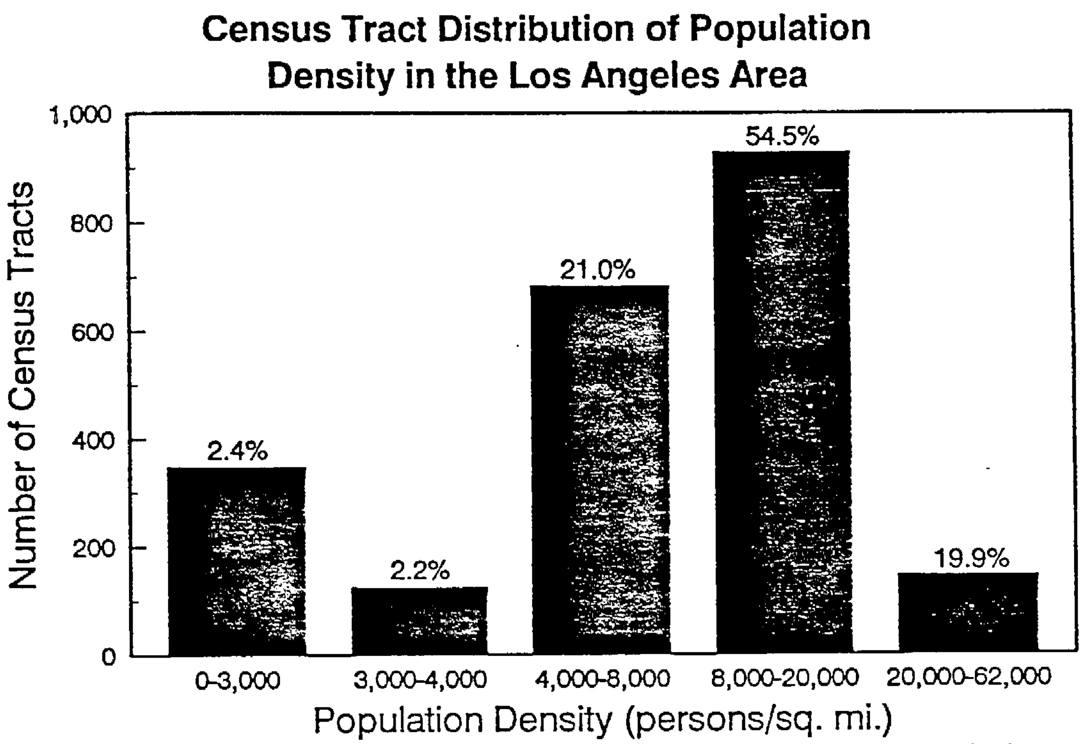
- Westwood (4,000–22,000 persons/sq. mi., depending on the portion of the subarea selected)
- Santa Monica (20,000 persons/sq. mi.)
- Hermosa Beach (14,000 persons/sq. mi.)

Commute/Other:

- Seal Beach/Huntington Beach (1,000–3,000 employees/sq. mi.)
- Belmont Shore/Long Beach (3,000–6,000 employees/sq. mi.)
- Beverly Hills (19,000 employees/sq. mi.)

These subareas were picked based on 1987 population and employment density data (by census tract) supplied by the Southern California Association of Governments (SCAG)[30]. The Los Angeles residential and employment densities are much higher than the high-density zones selected in Sacramento. The densities of the areas selected for study, particularly the employment densities, are not the highest in Los Angeles. They were selected, however, as representing the median range of densities in L.A. Figures 18 and 19 show frequency distributions of population and employment densities in Los Angeles, by census tract. Comparison of the figures to the densities shown above reveals that the selected subarea densities fall within the median of each density grouping. In fact, over 75% of Los Angeles population live in census tracts in the same density range (4,000–20,000 persons/sq. mi.) as the subareas selected for residential observations. Although there are areas in Los Angeles with much higher population densities,

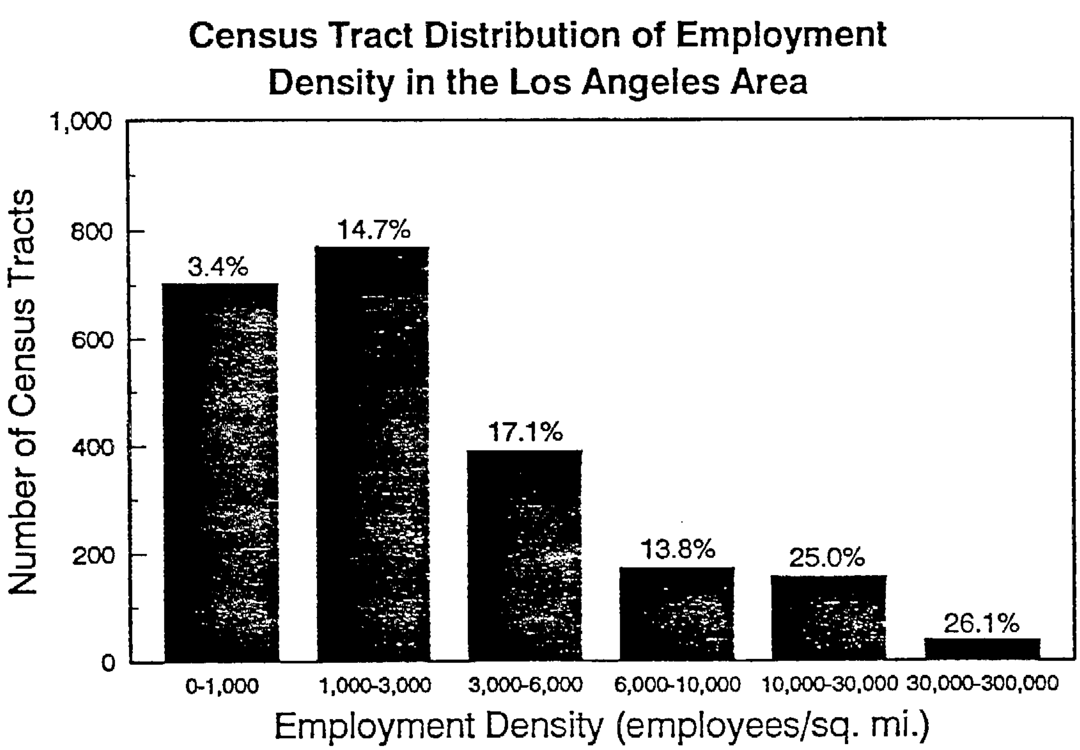
Figure 18



Note: Based on 1987 population data provided by Southern California Association of Governments.

Figures at the top of each bar correspond to the percentage of total LA population in each category.

Figure 19



Note: Based on 1987 employment data provided by Southern California Association of Governments.

Figures at the top of each bar correspond to the percentage of total LA employment in each category.

these were excluded due to concerns regarding observer safety, low trip end frequencies or other factors.

Table 16 shows the number of residential trip ends observed in the selected subareas. The percentage of observations by parking category varies considerably among the subareas, reflecting the distribution of parking within each area. However, the weighting factors applied to each category of parking (e.g., garage) were independently developed.

Table 16

Residential Trip End Observations in Los Angeles

Subarea Description	Residential Category	Number of Trip Starts/Ends
Westwood	On-street	52/40
	Garage	1/0
	Driveway	31/36
	Parking Space	0/0
Hermosa Beach	On-street	62/20
	Garage	26/19
	Driveway	35/12
	Parking Space	4/3
Santa Monica	On-street	54/10
	Garage	11/9
	Driveway	4/0
	Parking Space	22/23

The higher employment density areas in Los Angeles were also judged unsuitable for sampling purposes due to various reasons. In particular, facilities in these areas were mainly parking garages. As described in detail later in this section, the study results showed that parking garages of differing sizes have surprisingly similar trip end times. Thus, parking garage observations are considered representative of higher density areas as well.

Trip ends were observed in parking lots and garages located in various commercial core areas in the Los Angeles area. Table 17 lists the number of available parking spaces and trip ends observed for each parking lot or garage that was sampled. It is believed that a high

Table 17 Commercial Core Area Trip End Observations in the Los Angeles Area		
Parking Facility Description (Address/Type)	Number of Parking Spaces	Number of Trip End Observations (Starts/Ends)
Beverly Hills:		
Beverly Boulevard/ Private Lot	17	14/15
Los Angeles:		
Main St. & Macy/Commercial Lot	approx. 300	16/16
Santa Monica:		
15th St./Commercial Lot	35	14/22
1st & Elm/Commercial Garage	500+	29/29
1st & Pacific/Commercial Garage	500+	30/30
Ocean & Elm/Commercial Garage	319	31/34
Broadway & Chestnut/Public Garage	400+	31/30
Long Beach Blvd. & Broadway/ Private Garage	300+	17/21
Long Beach Blvd. & 1st/Public Lot	approx. 150	9/4*
Promenade & 1st/Public Lot	approx. 125	31/30
On-Street Parking	-	85/67

* Observations were halted due to concerns about observer safety.

percentage of these trip ends were made by commuter vehicles. The table also shows the number of observations made at on-street parking spaces in these areas.

Table 18 summarizes the trip end observations made at shopping-related parking facilities in the three Los Angeles retail-related subareas. Efforts were made to sample parking lots of a wide variety of different sizes.

Table 18

Trip Ends Observed at Retail Facilities in the Los Angeles Area

Subarea Description	Parking Facility Description	Parking Category	Number of Trip Starts/Ends
Seal Beach/ Huntington Beach	Major mall lot	500+	53/43
	Major mall lot	500+	22/20
	Single-purpose lots	1-20	61/39
	Single-purpose lot	101-500 (225)	30/30
	Single-purpose lot	500+	30/32
	Multi-purpose lots	21-100	122/124
	Multi-purpose lots	101-500	61/60
Long Beach/ Belmont Shores	Single-purpose lot	1-20	30/ 9
	Single-purpose lot	21-100	29/30
	Gas station	-	60/61
	Drive-thru	-	32

Los Angeles Data Collection Summary - Table 19 provides a summary of the Los Angeles trip end data. The table shows that about 2,100 total trip ends were observed. Roughly 23% were residential observations, 30% were recorded in commercial core locations and 47% were at retail shopping facilities and other customer-oriented locations.

Overall, more than 4,800 trip ends were observed in Sacramento and Los Angeles combined. These included the following observations:

- 1,181 (24.1%) residential trip ends;
- 1,881 (38.4%) commercial core trip ends; and
- 1,835 (37.5%) shopping or other customer-related trip ends.

This represents a substantial database, particularly since it appears that no previous data of this sort have ever been collected. How these data were weighted to construct average trip end segments for the two communities is described later in this section.

Table 19

Summary of Trip End Data Collection Efforts in Los Angeles

Trip Type	Location	Trip Ends Observed (Starts/Ends)
Residential	Westwood	84/76
	Hermosa Beach	127/54
	Santa Monica	91/42
	Residential Subtotal	**302/172**
Nonresidential	Commercial Core Parking	307/299
	Torrence	53/43
	Seal Beach/Huntington Beach	326/305
	Belmont Shore/Long Beach	119/132
	Nonresidential Subtotal	**805/779**
Total Observations		1,107/951

6.3 Trip End Weighting Methodology

The survey data collected in Sacramento and Los Angeles provide considerable information on trip end times for individual vehicles and facilities. A key question regarding these data is how to use them to develop trip end driving cycle segments representative of all urban vehicle trips. To do this, appropriate weighting factors are needed to construct overall average trip end mode times. These weighting factors are available from the results of the frequency surveys given in Sacramento and the San Francisco Bay area. Outlined below is a description of how the data were used to produce overall average trip end times for the Sacramento and Los Angeles urban areas.

Sacramento Trip End Weightings – The first step in weighting the trip end data involved simple arithmetic averaging of trip end times for each type of parking within each subarea. In addition, data from each parking lot category were further disaggregated into the following lot sizes: 1–20, 21–100, 101–500 and greater than 500 spaces. All data for each parking category were then averaged across subareas. After computing average mode times by category, the averages were weighted together to compute mode times for an average trip beginning and trip ending using the results of the frequency surveys in Sacramento and San Francisco. Table 20 compares the results of the two surveys with data collected during the 1983–84 NPTS, as an indication of whether the two surveys accurately represent travel in the two communities. The table presents the distribution, by trip purpose, of total trips estimated by each survey.

Table 20

Comparison of Sacramento and San Francisco Trip End Surveys to 1983-84 Nationwide Personal Transportation Study (NPTS)

	Percentage of Total Trips		
Trip Purpose	Sacramento	San Francisco	NPTS
Work-Related	32.3%	41.4%	30.7%
Family/Personal	43.5	29.8	39.5
Social/Recreational	19.7	23.9	22.6
Civic	4.5	4.6	5.9
Other	-0-	-0-	1.3

The table shows the Sacramento data, in terms of percent of trips made, compare very favorably with the results of the NPTS. Estimated trip percentages are within 10% for the three major categories of trips (i.e., work, family and social). The San Francisco results show a somewhat higher percentage of work-related trips and a lower percentage of family/personal trips. Reasons for these differences are unknown.

Tables 21 and 22 provide a more detailed summary of the results of the two trip frequency surveys, disaggregated by general parking category and trip end type (beginning and end). Several categories are actually a composite of even more disaggregated distributions among types and sizes of parking lots. The two surveys show similar but not identical trends in the frequency of trips beginning and ending at the various parking categories.

After collecting the frequency data, it was necessary to choose which database to use in weighting the trip end times collected in Sacramento. Advantages of the Sacramento database include the following:

- The frequency data were collected in the same urban area in which the trip end observations were made.
- The close correlation between the Sacramento and NPTS data suggests the data are representative of national travel characteristics (although national trends could have changed since the NPTS was conducted in 1983-1984).

Advantages of the San Francisco database include the following:

- The San Francisco data were collected at ten different sites throughout the Bay area, versus three locations in Sacramento. This suggests the San Francisco data may be more representative of an overall urban area than the Sacramento data.

Table 21

Frequencies of Trip Beginnings in
Sacramento and the San Francisco Bay Area

Category	Sacramento # Trips	Sacramento Frequency	San Francisco Bay # Trips	San Francisco Bay Frequency	Composite Frequency
On Street Residential	18	6.7%	126	11.7%	10.7%
Residential Garage	34	12.6	93	8.7	9.5
Residential Driveway	36	13.4	114	10.6	11.2
Residential Space	15	5.6	76	7.1	6.8
Other On Street	12	4.5	178	16.6	14.1
Employee Parking	14	5.2	11	1.0	1.9
Drive-Thru Window	2	0.7	9	0.8	0.8
Gas Station	7	2.6	27	2.5	2.5
Commercial Parking Lot	17	6.3	23	2.1	3.0
Parking Garage	3	1.1	5	0.5	0.6
Shopping Lot	109	40.5	392	36.5	37.3
Other	2	0.7	20	1.9	1.6
Total	269	100.0%	1,074	100.0%	100.0%

- The San Francisco database is four times larger than Sacramento's, supporting the suggestion of better statistical accuracy.

The use of each of these databases has advantages over the other. Consideration was also given to combining the results of the two surveys to construct one larger trip frequency database. This approach was rejected due to a concern that merging the databases might be biased (i.e., the resulting data would not be representative of either the Sacramento or San Francisco Bay areas.) Instead, the Sacramento and the

Table 22

Frequencies of Trip Ends in Sacramento and the San Francisco Bay Area

Category	Sacramento # Trips	Sacramento Frequency	San Francisco Bay # Trips	San Francisco Bay Frequency	Composite Frequency
On Street Residential	21	7.8%	127	11.8%	11.0%
Residential Garage	31	11.5	91	8.5	9.1
Residential Driveway	37	13.8	110	10.2	10.9
Residential Space	12	4.5	78	7.3	6.7
Other On Street	13	4.8	179	16.7	14.3
Employee Parking	14	5.2	12	1.2	1.9
Drive-Thru Window	2	0.7	9	0.8	0.8
Gas Station	7	2.6	27	2.5	2.5
Commercial Parking Lot	17	6.3	23	2.1	3.0
Parking Garage	3	1.1	5	0.5	0.6
Shopping Lot	111	41.2	394	36.7	37.6
Other	1	0.4	19	1.8	1.5
Total	269	100.0%	1,074	100.0%	100.0%

San Francisco frequency data were each used separately to weight the Sacramento trip end times. This methodology allowed the computation of two estimates of overall residential trip beginning and trip end times. Results of both weighting approaches are presented in later in this section.

<u>Los Angeles Trip End Weightings</u> - The methodology used to weight the trip end observations collected in Los Angeles was modeled after the Sacramento methods; however, the use of population and employment densities to weight the observed trip end times was not employed in Los Angeles. As indicated previously, L.A. trip end observations were focussed on higher density areas, with the goal being to determine

whether the Sacramento results were valid for Los Angeles as well. The Los Angeles urban area is simply so large and so diverse that it was impossible, within the resources available under the contract, to adequately sample a wide enough range of subareas to ensure the final results are statistically representative of the entire area.

The average trip end times collected in Los Angeles were multiplied by the trip frequencies collected in Sacramento to develop overall urban average trip end times using those frequency weightings. The results of this methodology are described later in this section.

Time Between Trips – Motorists participating in the roadside surveys conducted in Sacramento and the San Francisco Bay area were also asked to provide information on the time of day and duration of each trip made during the preceding day. The resulting data can be used to calculate times between trips, thus providing a means to estimate the fraction of trip starts occurring in the cold start mode.

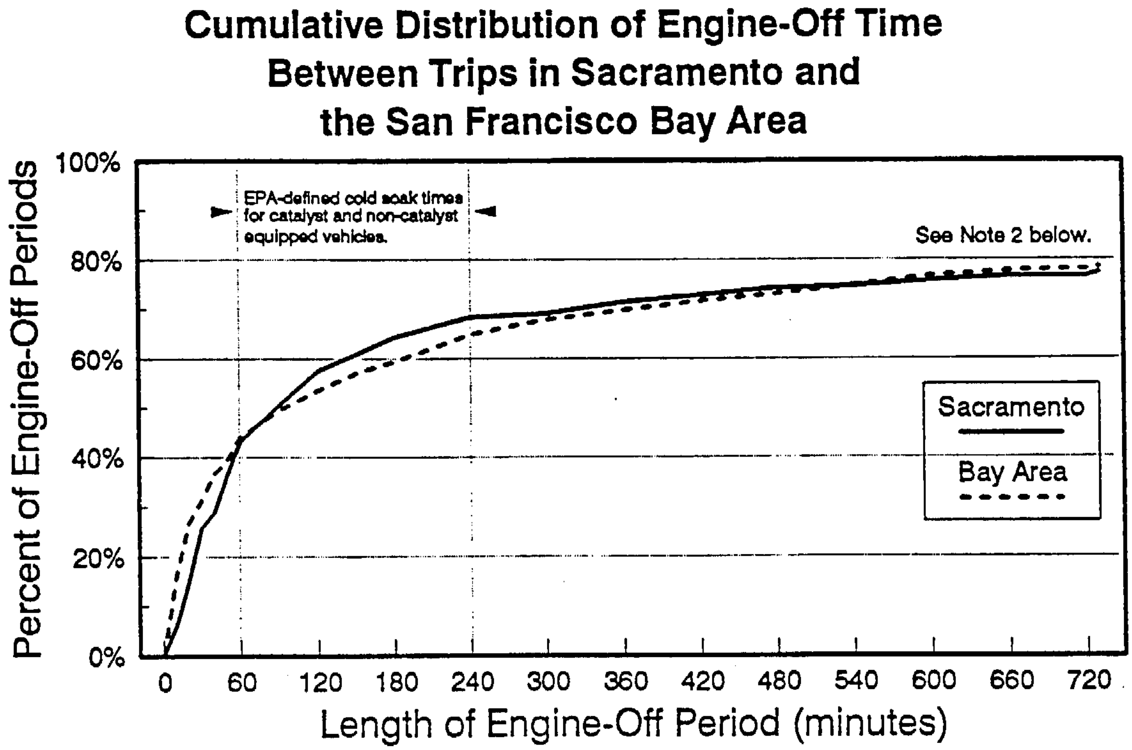
Review of data from the Sacramento survey shows that, on average, each motorist made 4.6 trips on the day preceding the survey. This number is similar to the 5.0 trips/day computed from the San Francisco survey data. The average trip lasted 14.4 minutes in Sacramento and 16.0 minutes in the Bay area. Not counting overnight cold soaks, the average time between trips (i.e., engine–off time) was 109.8 minutes in Sacramento and 124.4 minutes in San Francisco.

The Bay area averages may be somewhat high due to the lack of accurate trip end times for several sales people that participated in the San Francisco survey. Because of this, times for trips made by these individuals were not included in the Bay area averages reported above. The number of trips reported by such individuals, however, was well above average, with one sales person reporting a total of 52 trips on the previous day. Excluding these data thus resulted in a higher average time between trips and a lower average trip time than if these data were able to be included.

Combining the Sacramento and Bay Area data results in an average trip time of 15.6 minutes and an average engine–off time between trips of 121.2 minutes. When accounting for the exclusion of the sales–related Bay Area trips, it appears that reasonable values would be 15 minutes for an average trip time and 120 minutes (2 hours) for an average time between trips for the surveyed population.

In addition to the average time between trips, it is also important to evaluate the daily distribution of times between trips recorded in both locations. This is particularly important from an emissions standpoint, since emissions generated when a vehicle has been sitting for an extended period of time (i.e., cold start emissions) can be several times greater than those produced during a hot start. Figure 20 presents the daily distribution of both the Sacramento and Bay Area data. The two datasets have very similar distributions, with about one-half of the engine–off periods being 90 minutes or less in duration. Roughly 22% of the engine–off periods occur overnight, and are therefore not included in the figure, since their exact length is unknown.

Figure 20



Note 1: Data based on roadside surveys administered to motorists at several locations in Sacramento and the Bay Area.

Note 2: The roughly 22% of daily engine-off periods which occur overnight are not accounted for by the lines shown on the figure.

Both EPA's and ARB's emissions models assume that a cold start occurs whenever a catalyst-equipped vehicle is allowed to sit for more than one hour prior to restart, or a non-catalyst equipped vehicle is allowed to sit for more than four hours. One- and four-hour lines are shown on Figure 20 for reference; however, these one- and four-hour cold start periods do not appear to be based on a significant amount of data collected by either agency. Nevertheless, in the absence of better data, it appears reasonable to assume that cold starts will result when the time between trips is more than one hour, since the large majority of the in-use fleet is now equipped with catalysts. Using this definition, Figure 20 indicates that 56% of motor vehicle starts in Sacramento and the San Francisco Bay Area should be considered to be cold starts.

Given the steep distribution of starts occurring in the 0–60 minute range, further study of the engine-off time required for the engine and emissions control system (e.g., the catalyst) to drop into cold start mode appears to be warranted. For example, if a cold start were redefined to be one that occurs after an engine-off period of 45 minutes or more, the estimated fraction of cold starts in Sacramento and the Bay Area would climb to roughly 64%. If, instead, the cold-start period were extended to 90 minutes, estimated cold starts would drop to approximately 50%. This potential swing in the fraction of cold starts becomes very significant from an air quality standpoint when the large differences in hot and cold start emission rates are taken into account.

6.4 Trip End Times in Sacramento and Los Angeles

As described above, a large number of trip end data were collected in Sacramento and Los Angeles. Given the study objective of constructing statistically representative driving cycle segments for trip beginning and end, the analysis of the data focussed on two goals. The first was to collect sufficient data to ensure the accuracy of average trip end times computed from the data within an acceptable level of confidence. The second was to compute trip end averages, based on the data collected, representative of overall trips in the urban areas being sampled. These goals are discussed in more detail below.

Determination of Appropriate Sample Sizes - Preliminary data analysis was initiated during the collection effort, to provide guidance regarding the quantity of data needed to ensure the statistical accuracy of average trip end times computed from the data. Initial observations indicated that trip end times in the sample appeared to be log normally distributed. An example of this distribution is shown in Figure 21. Based on the central limit theorem, however, the distribution of sample means (by parking facility) within each parking category should tend to be normally distributed. Accordingly, the following formula was used as a guide regarding the sample size needed for each trip category. The formula is based on the standard deviation seen in the data and the desired degree of confidence.

$$n = \frac{[z(\alpha/2)(\sigma)]^2}{E^2}$$

where:

n = number of samples required

$z(\alpha/2)$ = critical value of z

σ = standard deviation

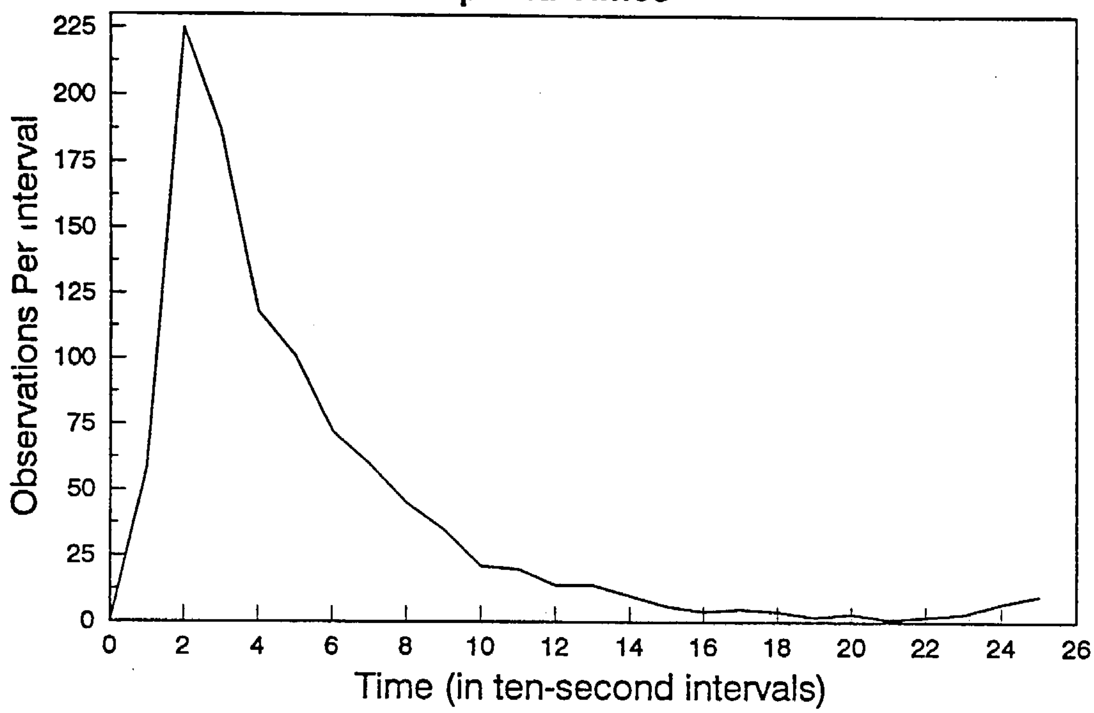
E = maximum error of the estimate of the population mean such that there is a probability of $(1-\alpha)$ that the sample mean differs from the mean of the total population by less than E

Thus, for the trip end study, E becomes the amount of acceptable error in average trip end times. The initial goal was a maximum acceptable error of five seconds at a 95% degree of confidence. The critical value of z for a normal distribution was obtained from a standard statistical table. For a 95% confidence interval, the critical value of z is equal to 1.960.

Based on these values and standard deviations computed on an ongoing basis from the collected data, it was possible to determine the number of samples required to achieve the desired degree of confidence. This method was used to target the total number of samples per parking category.

Figure 21

Distribution of Sacramento Trip End Times



To simplify the calculation, only total trip end times (starts and ends) for each trip category were evaluated, not individual times for the four trip end modes previously identified (i.e., idle, reverse, queue and cruise). This provided an easy means of determining whether there had been sufficient observations in each category.

This approach was used to target the acceptable number of observations per category. For most categories, total required trip ends were well within the original number of projected observations; in some of the categories, however, relatively large standard deviations resulted in the need for unacceptably large sample sizes in order to maintain the program goals of a five-second maximum error within a 95% degree of confidence. Larger degrees of error were also experienced in certain categories due to relatively small sample sizes resulting from observational difficulties noted previously. Reversing the above formula provides a means of calculating the error (E) for each of the parking categories based on the final number of observations made, and the standard deviation of the observations. Table 23 shows the results of this calculation for the Sacramento trip end data, based on both a 90% and a 95% confidence interval.

Table 23

Estimated Sacramento Trip End Observation Error

Parking Category	Trip End Mode	Number of Observations	Observation Error (seconds) 95% Degree of Confidence	Observation Error (seconds) 90% Degree of Confidence
Residential On-Street	Start	81	30.9	25.9
	End	48	9.4	7.9
Residential Garage	Start	39	27.2	22.8
	End	16	7.7	6.4
Residential Driveway	Start	152	12.5	10.5
	End	107	8.6	7.2
Residential Parking Space	Start	140	9.4	7.9
	End	124	4.6	3.8
Other On-street	Start	54	3.2	2.7
	End	47	4.4	3.7
Drive-thru Window	Start	*		
	End	30	37.5	31.5
Gas Station	Start	20	8.0	6.7
	End	17	5.5	4.6
Commercial Parking Lot	Start	343	3.3	2.8
	End	383	3.1	2.6
Parking Garage	Start	221	7.3	6.1
	End	227	5.8	4.9
Shopping Parking Lot	Start	324	6.0	5.0
	End	323	6.8	5.7
Other Parking	Start	81	15.4	12.9
	End	63	7.7	6.4

* Vehicle operations at drive-thru windows were categorized as trip endings only since the vehicle engines were never shut off.

The table shows that observed trip end times in most parking categories had an estimated error of less than 8 seconds. A weighting scheme identical to that used to weight the trip end times (i.e., using surveyed trip frequency percentages) was also used with the data shown in Table 23 to estimate the overall degree of error in the final trip end averages. Estimated errors calculated in this manner are presented below, along with average trip end times for both Sacramento and Los Angeles.

<u>Sacramento Trip End Averages</u> - Based on the Sacramento observations described earlier, trip end times for each type of parking category were averaged arithmetically. The resulting average residential trip end times are shown in Table 24. A more detailed summary of the residential trip end times, including individual mode times (for idle, reverse, cruise and queue) is contained in Appendix B.

Table 24

Average Residential Trip End Times in Sacramento (in seconds)

Parking Category	Trip End Mode	Subarea Averages: Orangevale	City of Sacramento	Arden/ Arcade	Overall Average
On-street	Start	39.3	80.1	84.2	75.6
	End	34.5	10.9	16.1	17.0
Garage	Start	93.4	76.0	92.4	87.2
	End	35.7	21.6	15.4	22.5
Driveway	Start	44.1	85.4	58.0	63.7
	End	26.0	31.9	14.8	25.4
Parking Space	Start	76.4	66.2	62.1	67.1
	End	24.5	40.7	27.0	31.3

The data presented in the table show there are significant differences in average residential trip end times among the subareas sampled. The differences, however, are not consistent, nor is there an apparent relationship between the trip end times and population density. A complicating factor is the effect of changes in ambient temperature, which is described in more detail below. As with the peak/off-peak comparisons discussed previously, this temperature effect effectively masks any density/trip end time correlation that may exist. Insufficient data were collected to statistically separate the effects of the two factors; therefore, all Sacramento residential trip end times were simply averaged together to compute a single start and end time for each parking category.

Similarly to the residential data, average nonresidential trip end times for Sacramento are shown in Table 25. In addition, data from the parking lot categories shown in the table were further disaggregated into lot size according to the following categories: 1–20 spaces, 21–100 spaces, 101–500 spaces and greater than 500 spaces. The disaggregated data, including individual mode times (for idle, reverse, cruise and queue) are also contained in Appendix B.

Table 25

Average Nonresidential Trip End Times in Sacramento (in seconds)

Parking Category	Trip End Mode	Nonresidential Subareas: Folsom City	Citrus Heights	Arden/ Arcade	Downtown	Overall Average
On-street	Start	–	–	–	18.2	18.2
	End	–	–	–	23.7	23.7
Drive-thru Window	Start	–	–	–	–	–
	End	222.5	230.1	251.3		233.9
Gas Station	Start	25.4	32.8	–	–	28.0
	End	13.6	25.8	–	–	17.9
Commercial Parking Lot	Start	–	–	–	51.8	51.8
	End	–	–	–	37.7	37.7
Parking Garage	Start	–	–	–	110.1	110.1
	End	–	–	–	84.4	84.4
Shopping Parking Lot	Start	50.7	65.3	113.9	–	67.8
	End	43.3	45.1	81.4	–	50.9
Other Parking	Start	52.1	75.5	–	–	65.9
	End	29.5	27.3	29.5	–	28.7

The data shown in Tables 24 and 25 reveal considerable differences in trip end times, depending on the type of parking facility used. Trip end times for nonresidential on-street spaces are among the shortest observed, for both starts and ends. Not surprisingly, the highest average trip end time of roughly four minutes occurs at drive-thru windows. (This time correlates very well with an estimate of drive-thru times at fast food restaurants in Los Angeles previously reported by Sierra in an analysis of emissions from drive-thru lanes[31]. That analysis reported average times of 4.09 and 3.25 minutes for off-peak and peak period drive-thru operations, respectively, based on data from over 1,400 such restaurants in the L.A. area provided by restaurant owners.)

Very high trip start and end times are also seen at parking garages and shopping parking lots. In addition, all residential categories have relatively high start times. According to survey personnel, these data reflect the extended times often observed at residences where vehicles were left idling unattended or while waiting for passengers.

The average times shown these tables can also be compared to the degree of observation errors previously presented in Table 23. Not surprisingly, this comparison shows that the largest degree of error occurs in the categories with the highest trip end times. These include trip start times at residential on-street spaces and garages, and drive-thru window times. It is interesting, however, that parking garages and shopping parking lots have a relatively low degree of error even though their average trip end times are fairly high. These data support anecdotal observations made by field survey personnel that trip end times in these facilities were relatively independent of facility size.

Repark and Cruise-Through Operations - Two unique categories of vehicle trip ends were also encountered during field observations. So-called "repark" operations consisted of vehicles that never entered the road network after start up at a parking facility. This included those driven to another parking location within the same lot, e.g., at a shopping mall. There were also some cases of residential starts where the vehicle was simply shifted to a different parking location at the residence. For the purposes of the trip ends study, repark operations were counted as trip starts. Mode times for reparks were included in the computation of average trip start times.

So-called "cruise-through" operations involved vehicles that entered a parking facility, but were never parked. Such instances included vehicle stops to drop off or pick up passengers, and vehicles driven through a parking lot looking for a parking space. Cruise operations were counted as trip ends for study purposes, and their mode times included in average trip end computations.

The phenomenon of repark and cruise-through activities were initially identified in the pilot survey described earlier. Subsequent field observations revealed a small but significant fraction of such trip end operations. Table 26 summarizes the number and frequency of repark and cruise operations observed in Sacramento.

The table shows that about 4.5% of all trips are expected to include either repark or cruise-through operations. The percentage of each type of operation refers to the frequency of repark or cruise-through activities for that particular category. For example, the table shows that 1.5% of all residential trip starts involve reparks, and 3.7% of all nonresidential trip ends involve cruise-throughs.

Table 26

"Repark" and "Cruise-Through" Operations in Sacramento

Type of Operation	Residential	Nonresidential	Total
	——— % of Trips Affected ———		
Repark	6 (1.5%)	5 (0.5%)	11 (0.8%)
Cruise	12 (4.1%)	40 (3.7%)	52 (3.8%)
Total	18 (5.5%)	45 (4.1%)	63 (4.5%)

EPA observed a similar repark phenomenon during a study of driving habits conducted in Columbus, Ohio, in 1983-84[32]. This involved the loan of instrumented vehicles to program participants. Analysis of the resulting data showed a small percentage of extremely short trips. EPA staff theorized that "these extremely short trips likely represent such things as driving from one store to another at a shopping mall or switching car position on a driveway." According to the final report, trips of less than 0.01 miles (53 feet) accounted for 2.3 percent of all trips made by the loaner vehicles. This is significantly higher than the repark percentage seen in the Sacramento trip end data. Due to study design, however, the EPA data were likely not representative of overall repark frequencies in the Columbus study area. Thus, while the EPA study provides independent confirmation of the existence of a significant percentage of such vehicle operations, the repark frequency observed in the current trip end study is considered more representative of actual urban rates.

Frequency-Weighted Trip End Times - Tables 27 and 28 present the results of weighting the trip end times shown in Tables 24 (residential) and 25 (nonresidential), by the trip frequencies previously presented in Table 21 (trip beginnings) and Table 22 (trip ends). Table 28 is based on trip end frequency data collected in the Sacramento area, while Table 29 is based on San Francisco Bay area weightings. The tables present both mean mode times and weighted mode times (mean x frequency) for each parking category. Review of the individual weighted means allows the reader to see the contribution of each mode and parking category to the overall weighted trip end times.

The data shown in Tables 27 and 28 also reflect the fact that the trip frequency data were disaggregated into one more category than the trip end time observations. The trip frequency data include the category of employee parking, which was not disaggregated in the trip end data

Table 27

Sacramento Tripend Data Weighted by Sacramento Frequency Data

07/28/92

START-UP

SACRAMENTO FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
12	4.46%	On Street	54	18.18	0.81	54	9.91	0.44	20	5.35	0.09	19	4.84	0.08	27	9.18	0.20
18	6.69%	On Street Res.	81	75.58	5.06	81	61.32	4.10	29	9.64	0.23	77	11.29	0.72	1	7.00	0.01
34	12.64%	Res Garage	39	87.24	11.03	39	55.65	7.03	37	22.52	2.70	38	10.49	1.29	0	0.00	0.00
36	13.38%	Res Driveway	152	63.70	8.52	152	44.84	6.00	123	14.28	1.55	145	7.50	0.96	3	7.57	0.02
15	5.58%	Res Parking Space	140	67.14	3.74	140	31.61	1.76	127	10.23	0.52	140	21.68	1.21	40	15.97	0.25
14	5.20%	Employee Parking	343	51.83	2.70	343	18.79	0.98	261	10.06	0.40	342	21.13	1.10	104	14.24	0.22
2	0.74%	Drive-Thru Window															
7	2.60%	Gas Station Pump	20	27.96	0.73	20	7.96	0.21	3	14.32	0.06	20	13.28	0.35	6	15.22	0.12
17	6.32%	Commercial Lot	343	51.83	3.28	343	18.79	1.19	261	10.06	0.48	342	21.13	1.33	104	14.24	0.27
3	1.12%	Parking Garage	221	110.05	1.23	221	14.32	0.16	203	10.33	0.11	221	56.67	0.63	196	33.34	0.33
109	40.52%	Shopping	323	67.83	27.49	323	15.41	6.24	265	10.60	3.52	321	34.85	14.03	174	16.87	3.68
2	0.74%	Other	81	65.94	0.49	81	27.67	0.21	67	10.08	0.06	81	23.58	0.18	36	14.28	0.05
269		TOTALS =	1454	687.28	65.07	1454	306.27	28.32	1135	127.47	9.71	1404	226.44	21.87	587	147.91	5.16

EXIT ROADWAY

SACRAMENTO FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
13	4.83%	On Street	47	23.74	1.15	33	6.09	0.21	30	15.51	0.48	44	9.91	0.45	2	6.61	0.01
21	7.81%	On Street Res.	48	16.99	1.33	46	8.05	0.60	11	5.04	0.09	48	7.16	0.56	3	15.32	0.07
31	11.52%	Res Garage	16	22.48	2.59	16	6.02	0.69	0	0.00	0.00	16	16.46	1.90	0	0.00	0.00
37	13.75%	Res Driveway	107	25.42	3.50	105	11.49	1.55	36	6.88	0.32	104	11.89	1.59	2	14.86	0.04
12	4.46%	Res Parking Space	124	31.29	1.40	121	7.38	0.32	21	13.20	0.10	124	21.02	0.94	6	17.31	0.04
14	5.20%	Employee Parking	383	37.68	1.96	341	4.65	0.22	51	10.93	0.08	383	23.10	1.20	135	25.75	0.47
2	0.74%	Drive-Thru Window	30	233.94	1.74	14	0.45	0.00	0	0.00	0.00	30	41.26	0.31	29	199.25	1.43
7	2.60%	Gas Station Pump	17	17.89	0.47	14	2.84	0.06	1	17.71	0.03	17	13.95	0.36	1	9.56	0.01
17	6.32%	Commercial Lot	383	37.68	2.38	341	4.65	0.26	51	10.93	0.09	383	23.10	1.46	135	25.75	0.57
3	1.12%	Parking Garage	227	84.36	0.94	222	8.20	0.09	40	9.31	0.02	227	68.98	0.77	206	6.31	0.06
111	41.26%	Shopping	323	50.94	21.02	292	9.13	3.41	42	13.25	0.71	323	36.98	15.26	48	26.81	1.64
1	0.37%	Other	63	28.69	0.11	56	4.25	0.01	15	5.70	0.01	63	18.70	0.07	17	18.00	0.02
269		TOTALS =	1385	611.10	38.57	1260	73.20	7.42	247	108.46	1.92	1379	292.51	24.86	449	365.53	4.38

Table 28

Sacramento Tripend Data Weighted by San Francisco Bay Area Frequency Data

07/28/92

START-UP

BAY AREA FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
178	16.57%	On Street	54	18.18	3.01	54	9.91	1.64	20	5.35	0.33	19	4.84	0.28	27	9.18	0.76
126	11.73%	On Street Res.	81	75.58	8.87	81	61.32	7.19	29	9.64	0.40	77	11.29	1.26	1	7.00	0.01
93	8.66%	Res Garage	39	87.24	7.55	39	55.65	4.82	37	22.52	1.85	38	10.49	0.89	0	0.00	0.00
114	10.61%	Res Driveway	152	63.70	6.76	152	44.84	4.76	123	14.28	1.23	145	7.50	0.76	3	7.57	0.02
76	7.08%	Res Parking Space	140	67.14	4.75	140	31.61	2.24	127	10.23	0.66	140	21.68	1.53	40	15.97	0.32
11	1.02%	Employee Parking	343	51.83	0.53	343	18.79	0.19	261	10.06	0.08	342	21.13	0.22	104	14.24	0.04
9	0.84%	Drive-Thru Window															
27	2.51%	Gas Station Pump	20	27.96	0.70	20	7.96	0.20	3	14.32	0.05	20	13.28	0.33	6	15.22	0.11
23	2.14%	Commercial Lot	343	51.83	1.11	343	18.79	0.40	261	10.06	0.16	342	21.13	0.45	104	14.24	0.09
5	0.47%	Parking Garage	221	110.05	0.51	221	14.32	0.07	203	10.33	0.04	221	56.67	0.26	196	33.34	0.14
392	36.50%	Shopping	323	67.83	24.76	323	15.41	5.62	265	10.60	3.17	321	34.85	12.64	174	16.87	3.32
20	1.86%	Other	81	65.94	1.23	81	27.67	0.52	67	10.08	0.16	81	23.58	0.44	36	14.28	0.12
1074		TOTALS =	1454	687.28	59.79	1454	306.27	27.65	1135	127.47	8.14	1404	226.44	19.06	587	147.91	4.93

EXIT ROADWAY

BAY AREA FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
179	16.67%	On Street	47	23.74	3.96	33	6.09	0.71	30	15.51	1.65	44	9.91	1.55	2	6.61	0.05
127	11.82%	On Street Res.	48	16.99	2.01	46	8.05	0.91	11	5.04	0.14	48	7.16	0.85	3	15.32	0.11
91	8.47%	Res Garage	16	22.48	1.90	16	6.02	0.51	0	0.00	0.00	16	16.46	1.39	0	0.00	0.00
110	10.24%	Res Driveway	107	25.42	2.60	105	11.49	1.15	36	6.88	0.24	104	11.89	1.18	2	14.86	0.03
78	7.26%	Res Parking Space	124	31.29	2.27	121	7.38	0.52	21	13.20	0.16	124	21.02	1.53	6	17.31	0.06
12	1.12%	Employee Parking	383	37.68	0.42	341	4.65	0.05	51	10.93	0.02	383	23.10	0.26	135	25.75	0.10
9	0.84%	Drive-Thru Window	30	233.94	1.96	14	0.45	0.00	0	0.00	0.00	30	41.26	0.35	29	199.25	1.61
27	2.51%	Gas Station Pump	17	17.89	0.45	14	2.84	0.06	1	17.71	0.03	17	13.95	0.35	1	9.56	0.01
23	2.14%	Commercial Lot	383	37.68	0.81	341	4.65	0.09	51	10.93	0.03	383	23.10	0.49	135	25.75	0.19
5	0.47%	Parking Garage	227	84.36	0.39	222	8.20	0.04	40	9.31	0.01	227	68.98	0.32	206	6.31	0.03
394	36.69%	Shopping	323	50.94	18.69	292	9.13	3.03	42	13.25	0.63	323	36.98	13.57	48	26.81	1.46
19	1.77%	Other	63	28.69	0.51	56	4.25	0.07	15	5.70	0.02	63	18.70	0.33	17	18.00	0.09
1074		TOTALS =	1385	611.10	35.97	1260	73.20	7.14	247	108.46	2.92	1379	292.51	22.17	449	365.53	3.75

since there was no way to determine parking purpose during trip end observation. To resolve this mismatch, trip end times collected in commercial lots were assumed applicable for employee parking facilities as well. This was based on the presumption that most of the observed commercial lot trip ends were commuter-related. As a result, the number of observations and the mean times shown in the tables are identical for these two parking categories. The observation totals shown in each table have also been adjusted to account for this "double counting" of commercial lot observations.

Review of the data in the two tables shows that a large fraction of the overall trip end times can be attributed to the weighted shopping trip ends. This is due to a combination of the high frequency of such trips and the relatively high trip end times associated with this parking activity. As a result, over 40% of the total start and over 50% of total end times result from the Sacramento shopping category weighting. Using the San Francisco frequency weightings results in similar contributions of more than 40% to trip starts and more than 50% to trip end times.

Overall, trip start and end times are estimated at 65.07 and 38.57 seconds, respectively, when Sacramento trip frequencies are assumed. If San Francisco trip weightings are used, start and end times are estimated at 59.79 and 35.97 seconds, respectively. The results of the two weightings thus agree within 10% of one another. Also, as discussed below, the average values for each survey fall within the error band of the other survey, at both the 90% and 95% confidence intervals. Because of this, and since the Sacramento data are considered more valid for the trip ends study, the remainder of the analysis will focus exclusively on Sacramento-weighted results.

Weighted Error of the Mean - The same method can also be used to weight the error for each individual parking category previously shown in Table 23. Table 29 presents the results of this methodology. As with the weighted sample means, the table shows the individual contribution to the error of the mean by each mode and parking category. The table presents the weighted error at both the 90% and 95% confidence intervals. At a 95% confidence level, the weighted error is computed to be 11.06 seconds for trip starts and 6.91 seconds for trip ends. Sacramento trip start and end times are thus estimated (at the 95% confidence interval) to be equal to 65.07 ± 11.06 seconds, and 38.57 ± 6.91 seconds, respectively. The table shows that over 70% of the weighted error in trip start times comes from three parking categories: on-street residential, residential garage and shopping. If residential driveways are added, these categories account for more than 85% of the weighted error of the trip start mean and over 80% of the trip end mean.

This methodology only accounts for the degree of error in estimated trip end times. A second source of potential error in the overall results of the analysis is the sampling error contained in the trip frequency survey data. Quantifying the effect of this source of error is more difficult; however, it is possible to get a sense of its relative magnitude by comparing the results of the Sacramento and San Francisco Bay Area surveys. Although roughly four times as many observations were

Table 29

Frequency-Weighted Errors of the Mean for Sacramento

07/29/92

SACRAMENTO FREQUENCY DISTRIBUTION

START-UP

CATEGORY	# TRIPS/ CATEGORY	FREQUENCY	# OBS	MEANS	WEIGHTED MEANS	STANDARD DEVIATION	ERROR OF THE MEAN @90% CONFIDENCE	WEIGHTED ERROR OF THE MEAN	ERROR OF THE MEAN @95% CONFIDENCE	WEIGHTED ERROR OF THE MEAN
On Street	12	4.46%	54	18.18	0.81	11.93	2.67	0.12	3.18	0.14
On Street Residential	18	6.69%	81	75.58	5.06	141.66	25.89	1.73	30.85	2.06
Res Garage	34	12.64%	39	87.24	11.03	86.69	22.84	2.89	27.21	3.44
Res Driveway	36	13.38%	152	63.70	8.52	78.68	10.50	1.40	12.51	1.67
Res Parking Space	15	5.58%	140	67.14	3.74	56.71	7.88	0.44	9.39	0.52
Employee Parking	14	5.20%	343	51.83	2.70	31.42	2.79	0.15	3.33	0.17
Drive-Thru Window	2	0.74%								
Gas Station Pump	7	2.60%	20	27.96	0.73	18.31	6.74	0.18	8.02	0.21
Commercial Lot	17	6.32%	343	51.83	3.28	31.42	2.79	0.18	3.33	0.21
Parking Garage	3	1.12%	221	110.05	1.23	55.51	6.14	0.07	7.32	0.08
SHOPPING	109	40.52%	323	67.83	27.49	54.94	5.03	2.04	5.99	2.43
Other	2	0.74%	81	65.94	0.49	70.61	12.91	0.10	15.38	0.11
TOTAL =	269		1454	687.28	65.07			9.28		11.06

SACRAMENTO FREQUENCY DISTRIBUTION

EXIT ROADWAY

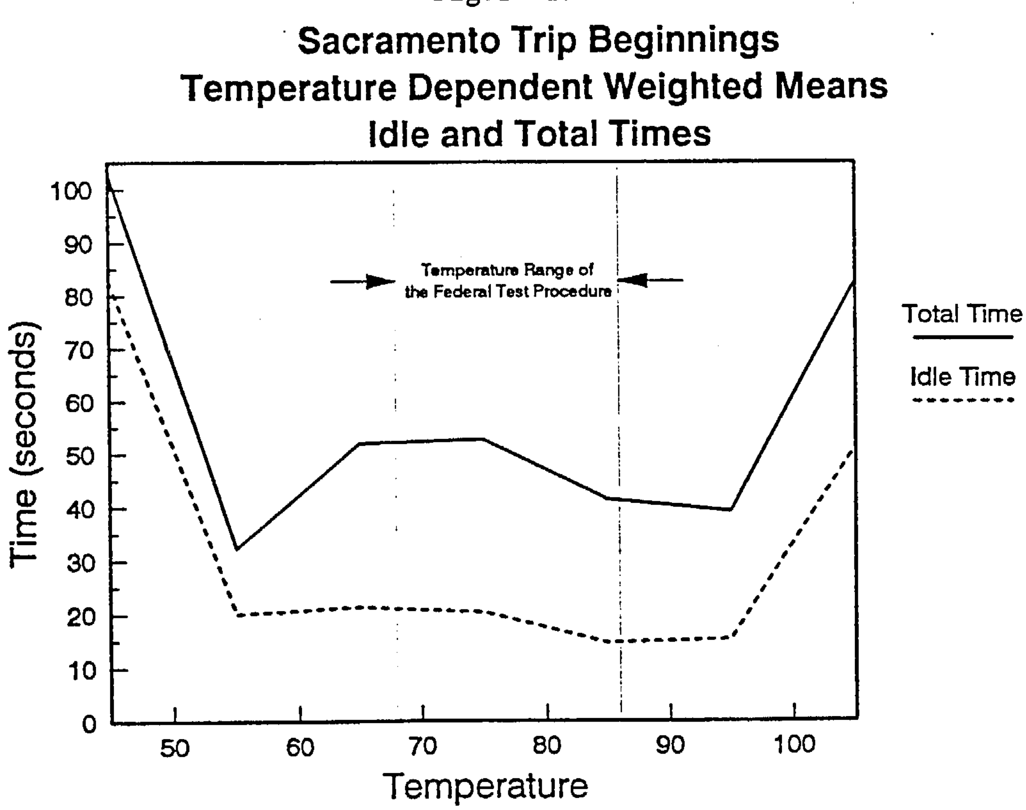
CATEGORY	# TRIPS/ CATEGORY	FREQUENCY	# OBS	MEANS	WEIGHTED MEANS	STANDARD DEVIATION	ERROR OF THE MEAN @90% CONFIDENCE	WEIGHTED ERROR OF THE MEAN	ERROR OF THE MEAN @95% CONFIDENCE	WEIGHTED ERROR OF THE MEAN
On Street	13	4.83%	47	23.74	1.15	15.40	3.70	0.18	4.40	0.21
On Street Residential	21	7.81%	48	16.99	1.33	33.05	7.85	0.61	9.35	0.73
Res Garage	31	11.52%	16	22.48	2.59	15.63	6.43	0.74	7.66	0.88
Res Driveway	37	13.75%	107	25.42	3.50	45.54	7.24	1.00	8.63	1.19
Res Parking Space	12	4.46%	124	31.29	1.40	25.84	3.82	0.17	4.55	0.20
Employee Parking	14	5.20%	383	37.68	1.96	31.31	2.63	0.14	3.14	0.16
Drive-Thru Window	2	0.74%	30	233.94	1.74	104.72	31.45	0.23	37.47	0.28
Gas Station Pump	7	2.60%	17	17.89	0.47	11.51	4.59	0.12	5.47	0.14
Commercial Lot	17	6.32%	383	37.68	2.38	31.31	2.63	0.17	3.14	0.20
Parking Garage	3	1.12%	227	84.36	0.94	44.55	4.86	0.05	5.80	0.06
SHOPPING	111	41.26%	323	50.94	21.02	62.64	5.73	2.37	6.83	2.82
Other	1	0.37%	63	28.69	0.11	31.00	6.42	0.02	7.66	0.03
TOTAL =	269		1385	611.10	38.57			5.80		6.91

collected in the Bay Area survey, differences between sampled trip end percentages and resulting weighted trip end times are fairly small. Given this result, and the limited resources available for this analysis, it is concluded that it would not be productive to expend the effort required to produce a significant improvement in survey representativeness. A very large sample size would be required to make a significant difference in survey results.

Temperature Effects – Part of the reason for the relatively large degree of error computed for residential observations is the variance in ambient temperatures that occurred during the course of the Sacramento field study. Based on field reports that average vehicle idling times appeared to rise significantly during both cold and hot weather, an analysis was conducted of the effect of changes in ambient temperature on trip end times.

The extended idling times appeared to be related to passenger comfort (i.e., to heat or cool the interior of the vehicle prior to driving). It would thus be expected that if such an effect were to occur, it would be during trip starts but not ends. This presumption is supported by the Sacramento data. Analysis of the data showed no significant correlation between temperature and trip end times, while trip start times did appear to correlate positively with ambient temperature. Figure 22 presents both idle mode and total trip start times, weighted by trip frequency and disaggregated into 10°F temperature ranges.

Figure 22



Care must be taken in interpreting the data shown in the figure. The apparent dip in trip times in the 50°–59°F range is an anomaly caused by insufficient observations within that range. This anomaly results from the weighting methodology used to construct overall trip end times combined with the absence of nonresidential observations in this range. For example, trip starts within the "shopping" category account for about 36% of the total trip start weighting, but the average start time in this category is computed as zero due to the lack of any such trip ends in this temperature range. Review of actual trip end data shows that, contrary to what is presented in Figure 22, elevated trip start times were also observed in the 50°–59°F range.

The figure shows a significant rise in average trip start times due to increased vehicle idling below 50°F and above 100°F. (This increase actually occurs below 60°F, as explained above.) Conversely, trip starts, particularly during the idle mode, appear to have relatively consistent times in the temperature range between 50°F and 100°F (actually between 60°F and 100°F).

Extremely limited data are available for the extreme temperature ranges shown in Figure 22. The 40°–49°F trip start data consist of just 38 observations and the 50°–59°F data of just 19 observations, while only 40 trip starts were observed at temperatures greater than 100°F. Less than 7% of all trip start observations occurred in these three temperature ranges. Therefore, a few lengthy starts would tend to skew the average times shown in the figure. For example, one trip start in the 40°–49°F range lasted for over 430 seconds. As a result, it accounted for over 35% of the total start time weighting for that temperature range.

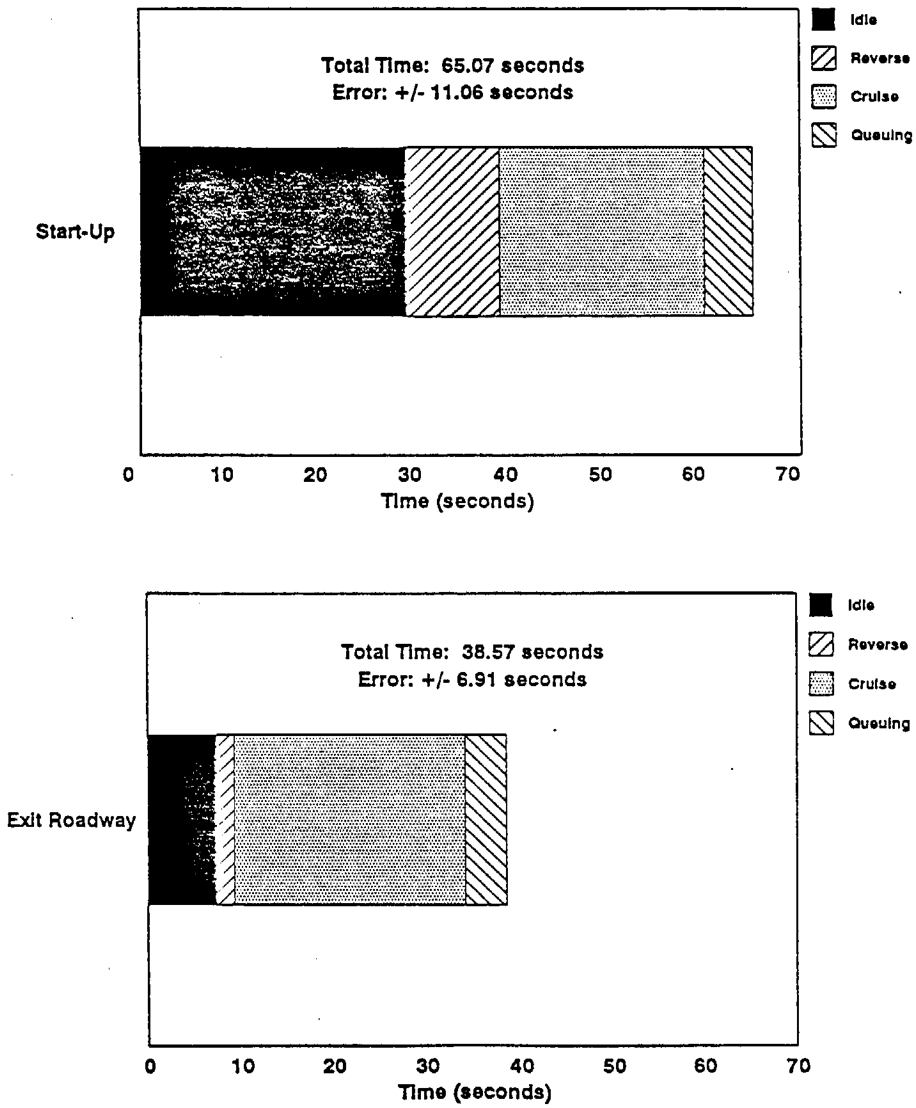
Because of the limited data, it was decided that all data collected in Sacramento, across the entire temperature range, should be used to construct final reported average trip end times. In other words, all data were used because there were not sufficient data available to determine if any data points (even the 430 second start time) are true outliers, or if they simply represent very low frequency trip ends. Accordingly, all assembled data were assumed to be representative of trip end times in Sacramento, and used to calculate the overall average times reported above.

It was also recognized, however, that the extended idling periods observed during cold– and hot–temperature events were not representative of an average Sacramento vehicle trip occurring in the 68°–86°F temperature range of the Federal Test Procedure. Therefore, as discussed below, data collected in the outlying temperature ranges (below 60°F and above 100°F) were eliminated from the data base prior to construction of a representative driving cycle for Los Angeles.

<u>Sacramento Summary</u> – The overall results of the Sacramento trip end observations are summarized in Figure 23. The figure shows estimated average mode and total times for both trip starts and ends in Sacramento. Also shown are estimated error bars for each estimate, based on a 95% confidence interval. Review of the figure reveals that vehicle idling accounts for almost 50% of the total off–network trip

Figure 23

Overall Sacramento Tripend Results



start time of roughly 65 seconds. Cruising activities are responsible for another third of the average start times. For trip ends, vehicle cruising accounts for over 60% of the total off-network operating time of about 36 seconds. Idling is responsible for another 20% of trip end times. Reverse and queuing modes are each responsible for a small percentage of all trip end operations.

Los Angeles Trip End Averages - Table 30 presents the average trip end times for each parking category observed in Los Angeles. These data can also be compared to similar data collected in Sacramento. Figures 24 and 25 provide a graphical comparison of trip end averages (unweighted by trip frequencies) in Sacramento and Los Angeles. The figures show relatively close correlation between data from the two areas for many

Table 30

Average Los Angeles Trip End Times by Parking Category
(in seconds)

Parking Category	Trip Start	Trip End
Residential On-Street	34.93	22.44
Residential Garage	73.25	25.51
Residential Driveway	41.27	20.04
Residential Parking Space	60.47	26.55
Nonresidential On-Street	23.28	15.90
Drive-thru Window		238.80
Gas Station	27.96	18.31
Commercial Parking Lot	63.60	46.25
Parking Garage	108.74	82.33
Shopping Parking Lot	57.35	43.98
Other Parking	–	–

parking categories. The largest differences occur among the residential categories, which have Sacramento trip end times significantly greater than those of Los Angeles. This is apparently due to the following two factors:

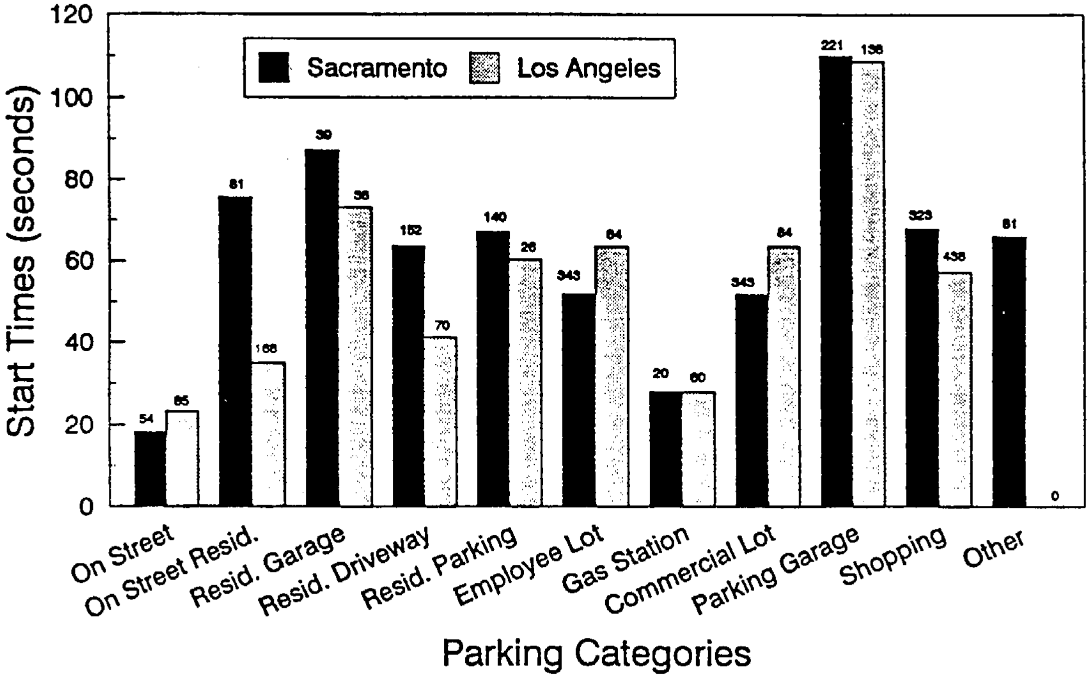
- Unlike the Sacramento data, Los Angeles trip end times are not significantly affected by ambient temperature variations, due to a lack of observations in the extreme temperature ranges. For example, no trip ends were observed in Los Angeles at temperatures in excess of 90°F.

- The sampling of only higher residential density areas in Los Angeles appeared to result in lower trip end times, due to such things as shorter driveways and less frequency of unattended idling of vehicles. (This conclusion is the opposite of the initial assumption: that higher density areas would have longer trip end times.)

Figure 24 shows that the combination of the above factors resulted in significantly shorter start times in L.A. for on-street residential parking and residential driveways. Trip start times for the other parking categories are relatively uniform between Sacramento and Los Angeles. Figure 25 shows that all of the trip end times are fairly consistent between the two urban areas.

Figure 24

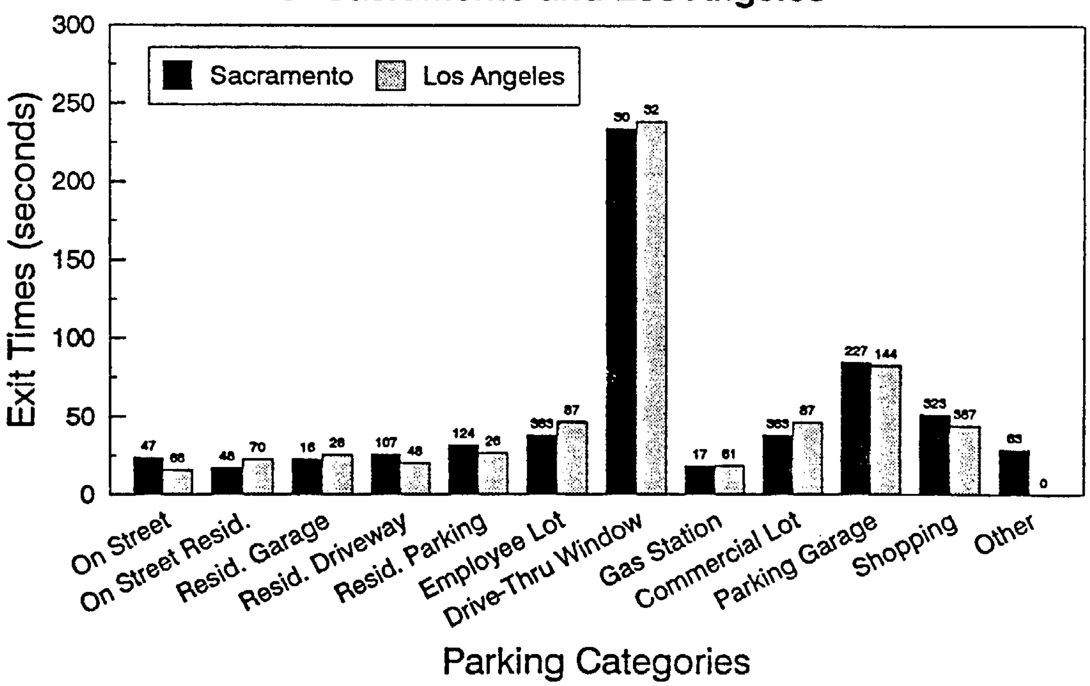
Trip Beginning Times by Parking Category for Sacramento and Los Angeles



Note: Number of observations shown at top of bars.

Figure 25

Trip End Times by Parking Category for Sacramento and Los Angeles



Note: Number of observations shown at top of bars.

Weighting the trip end averages shown in Table 30 by the Sacramento trip frequencies produces the data presented in Table 31. In addition to the same commercial lot/employee parking conversion performed on theSacramento data, the Los Angeles data also required a further adjustment. Because no trip end times were recorded for the "other" parking category, trips in this category were zeroed out. Trip percentages in the remaining categories were then renormalized to compute the frequencies shown in Table 31.

As with the weighted Sacramento data, the Los Angeles data show a large contribution to overall trip end times from the shopping category. Residential trip ends also contribute significantly to the total weighting, due to higher trip frequencies associated with these categories. Overall, trip start and end times are estimated at 54.44 seconds and 36.18 seconds, respectively, when Sacramento trip frequencies are assumed. Table 32 summarizes the comparison of the Sacramento and Los Angeles data.

The table shows the average Los Angeles trip end times fall within the error range of the Sacramento data. This is particularly true in trip ending times, where the overall mean between the two areas is less than three seconds apart. It is also apparent that most of trip starts and ends are spent in the idle and cruise modes. Reverse and queue operations account for little of the total trip end times in either Sacramento or Los Angeles.

<u>Exclusion of Temperature Extremes</u> – As indicated previously, ambient temperature was found to have a significant effect on the trip start times observed in Sacramento. Accordingly, it was decided to exclude data recorded during extreme temperatures prior to developing trip end segments representative of an average trip in Sacramento under FTP conditions. Review of the data revealed that elimination of observations taken at less than 60°F or greater than 100°F would eliminate most data outliers while still keeping 94% of the entire data set.

Another approach would be to use only data collected within the FTP temperature range (i.e., 68°–86°F); however, this would provide only about 1,000 usable observations, or roughly 38% of all data collected in Sacramento. This number is insufficient to ensure statistically representative results. In addition, much of the data outside the FTP range appear unaffected by ambient temperature. Therefore, the larger 60°–100°F temperature range was selected as a compromise between ensuring an adequately sized data base, and eliminating data not representative of FTP conditions. Implicit in the exclusion of temperature extremes is the fact that a driving cycle based on the remaining trip end characteristics may not adequately represent cold weather conditions under which most CO violations occur. In most areas, the exclusion of data collected above 100°F is not relevant to most days, even during the ozone season.

Table 31

Los Angeles Tripend Data Weighted by Sacramento Frequency Data

07/28/92

START-UP

SACRAMENTO FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
12	4.49%	On Street	85	23.28	1.05	85	10.93	0.49	63	9.25	0.31	85	5.30	0.24	2	8.42	0.01
18	6.74%	On Street Res.	168	34.93	2.35	168	25.53	1.72	61	8.28	0.20	164	6.40	0.42	1	25.76	0.01
34	12.73%	Res Garage	38	73.25	9.33	38	48.72	6.20	38	15.20	1.94	38	9.33	1.19	0	0.00	0.00
36	13.48%	Res Driveway	70	41.27	5.56	70	23.95	3.23	63	12.97	1.57	69	5.40	0.72	2	11.15	0.04
15	5.62%	Res Parking Space	26	60.47	3.40	26	34.27	1.93	25	14.30	0.77	26	11.02	0.62	2	18.58	0.08
14	5.24%	Employee Parking	84	63.60	3.33	84	18.38	0.96	76	9.54	0.45	84	21.59	1.13	59	21.36	0.79
2	0.75%	Drive-Thru Window															
7	2.62%	Gas Station Pump	60	27.96	0.73	60	9.79	0.26	18	9.03	0.07	59	11.32	0.29	18	14.40	0.11
17	6.37%	Commercial Lot	84	63.60	4.05	84	18.38	1.17	76	9.54	0.55	84	21.59	1.37	59	21.36	0.96
3	1.12%	Parking Garage	138	108.74	1.22	138	15.35	0.17	118	13.30	0.13	138	42.43	0.48	131	41.70	0.44
109	40.82%	Shopping	438	57.35	23.41	438	14.02	5.72	379	10.45	3.69	434	29.95	12.12	152	24.69	3.50
2	0.00%	Other *	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
267		TOTALS =	1107	554.45	54.44	1107	219.32	21.86	841	111.86	9.69	1097	164.33	18.57	367	187.42	5.94

EXIT ROADWAY

SACRAMENTO FREQUENCY DATA		CATEGORY	TOTAL			IDLE MODE			REVERSE MODE			CRUISE MODE			QUEING MODE		
#TRIPS/ CATEGORY	FREQUENCY		# OBS	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN	# OBS/ MODE	MEAN	WEIGHTED MEAN
13	4.85%	On Street	68	15.90	0.77	68	6.26	0.30	18	11.82	0.15	68	6.51	0.32	0	0.00	0.00
21	7.84%	On Street Res.	70	22.44	1.76	68	6.94	0.53	27	14.77	0.45	70	9.93	0.78	2	2.46	0.01
31	11.57%	Res Garage	28	25.51	2.95	28	9.21	1.07	6	5.45	0.14	28	14.84	1.72	1	8.35	0.03
37	13.81%	Res Driveway	48	20.04	2.77	45	4.49	0.58	5	11.02	0.16	48	7.54	1.04	4	86.93	1.00
12	4.48%	Res Parking Space	26	26.55	1.19	25	6.29	0.27	8	10.48	0.14	26	17.28	0.77	0	0.00	0.00
14	5.22%	Employee Parking	87	46.25	2.42	79	11.00	0.52	17	12.70	0.13	87	23.29	1.22	51	17.89	0.55
2	0.75%	Drive-Thru Window	32	238.80	1.78	1	20.06	0.00	2	4.86	0.00	32	27.26	0.20	31	217.39	1.57
7	2.61%	Gas Station Pump	61	18.31	0.48	58	2.95	0.07	5	9.73	0.02	61	11.65	0.30	3	61.97	0.08
17	6.34%	Commercial Lot	87	46.25	2.93	79	11.00	0.63	17	12.70	0.16	87	23.29	1.48	51	17.89	0.67
3	1.12%	Parking Garage	144	82.33	0.92	142	9.01	0.10	57	17.29	0.08	144	50.55	0.57	141	16.38	0.18
111	41.42%	Shopping	387	43.98	18.22	353	4.52	1.71	59	9.54	0.60	387	34.93	14.47	50	26.90	1.44
1	0.00%	Other *	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
268		TOTALS =	951	586.36	36.18	867	91.73	5.78	204	120.36	2.03	951	227.07	22.86	283	456.16	5.52

* "Other" was omitted from the frequency calculations for Los Angeles because there were no observations in this category.

Table 32

Comparison of Average Trip End Times in Sacramento and Los Angeles

Trip End Mode	Trip Start Times (in seconds) Sac'to	L.A.	Trip End Times (in seconds) Sac'to	L.A.
Idle	28.32	21.86	7.42	5.78
Reverse	9.71	9.69	1.92	2.03
Cruise	21.87	18.57	24.86	22.86
Queue	5.16	5.94	4.38	5.52
Total Mean	65.07	54.44	38.57	36.18
Error of the Mean (at 95% confidence)	11.06	10.00	6.91	6.40

An adjustment was made similar to that made to the Sacramento data prior to construction of representative trip end segments from the Los Angeles data. All trip end observations recorded at ambient temperatures of less than 50°F were eliminated from the final L.A. data set. There were two reasons for using this temperature rather than the 60°F cutoff used in Sacramento: first, observations taken in the 50°–59°F range in Los Angeles appeared to be unaffected by ambient temperature; second, a significant percentage (i.e., 9%) of the total L.A. trip start observations were recorded within this temperature range. This undoubtedly reflects the lower average ambient temperatures in Los Angeles during the study period.

Table 33 compares the final trip end mode times calculated for Sacramento and Los Angeles. As discussed previously, no attempt was made to ensure that the data collected in the L.A. area were representative of overall vehicle trips. In fact, observation areas were selected in Los Angeles with the objective of observing "worst case" trip end times, i.e., those with the longest average times. In spite of this, the values shown in the table are surprisingly close. It is therefore concluded that the trip end segments constructed from the Sacramento data, which are considered representative of the entire Sacramento urban area, can be considered a reasonable approximation of overall average trip end times in Los Angeles as well.

Relatively low percentages of time are spent in the reverse and queuing modes and these modes are similar to idle. Considering these facts and the degree of error shown in Table 33, it is concluded that these times can be rounded off to 30 seconds of idle followed by 30 seconds of cruise at trip start up, and 30 seconds of cruise followed by 10 seconds of idle at trip end, as shown in Table 34.

Table 33

Comparison of Temperature-Corrected Trip End Times in Sacramento and Los Angeles

Trip End Mode	Trip Start Times (in seconds) Sac'to	Trip Start Times (in seconds) L.A.	Trip End Times (in seconds) Sac'to	Trip End Times (in seconds) L.A.
Idle	24.60	21.71	6.77	5.75
Reverse	9.61	9.68	2.03	1.97
Cruise	22.06	18.59	23.49	22.34
Queue	5.29	5.94	4.42	5.55
Total Mean	61.55	54.32	37.89	35.62
Error of the Mean (at 95% confidence)	9.85	n/a	7.11	n/a

Table 34

Recommended Trip End Drive Cycle Segments

Trip End Mode	Time (in seconds)
Trip Start - Idle	30
Trip Start - Cruise	30
Trip End - Cruise	30
Trip End - Idle	10

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7. CHASE CAR DATA ANALYSIS

By the end of each day in the field, all of the data files created during travel along the preselected road routes had been copied to high density (1.44 MB) diskettes. These diskettes were used to transfer the trip files to Sierra's in-house VAX computer system.

A custom FORTRAN program was used to screen the data recorded during each trip for obvious errors (e.g., laser range discontinuities, out of range accelerometer measurements, etc.) and to compute descriptive statistics for each route, for both the chase car and target vehicles. The program was also designed to digitally filter and differentiate range measurements from the laser range finder. Using the digitally filtered range data, the program produces a composite trip, defined in terms of speed and time, of the chase car supplemented with data collected from target vehicles. In computing composite trip statistics, speed estimated for the target vehicle is substituted for the chase car speed whenever it is available;* however, the program is structured to ensure that accelerations are not computed across the transition from chase car to target vehicle or target vehicle to chase car. In addition, stops per mile are computed only from the chase car to avoid counting the same stop twice, or missing a stop during the transition from the chase car speed data to the target vehicle speed data.

7.1 Digital Filtering of Laser Range Finder Data

Second-by-second range data from the laser and speed data from the instrumented chase car were used to analyze the kinematics of the target vehicle. (If there was no target or the range finder was unable to "lock on" a target, the laser provided a default value of "9999.") In particular, the relative speed of the target vehicle was computed by simultaneously smoothing and differentiating the laser-based range data for each second through the use of a Savitzky-Golay (SG) cubic and quadratic digital filter, and adding to that the speed of the chase car to obtain the absolute speed of the target vehicle. A seven-point (i.e., seven second) digital filter was used. As described in the original paper by Savitzky and Golay[33], this technique is analytically equivalent to performing a linear least squares best fit of a cubic or quadratic polynomial to seven equally spaced data pcints, and then evaluating the polynomial at the centerpoint. This technique was applied successively in the FORTRAN screening program, advancing the

*Analysis of the data indicated that a target vehicle was being followed 55.5% of the time. At other times, there was no car or light truck in front of the chase car (a common occurrence in residential areas). Because the laser could not always track target vehicles around curves and over bumps, laser data were recorded 50.9% of the time.

time window one second each time to evaluate the relative speed at the centerpoint of the window. To evaluate the speed in the first three and last three seconds at the start and end of each continuous set of laser data, Gorry's method of endpoints[34], an extension of the SG approach, was used.

Optimal configuration of the digital filter in the current application has required some experimentation and testing with data from a target of known and varying speed and chase car (the Lumina and Caprice data described earlier). The seven second filter was found to provide the best compromise between capturing the main features of a hard acceleration that may be as brief as 2–3 seconds, while still providing an objective "best fit" smoothing of discrete range data.

One of the critical elements in the digital filtering of laser range data has been the choice of either quadratic or cubic smoothing functions. The cubic function, having four parameters, provides the closest fit to the data and is the best function to use when relative target speeds are changing rapidly, or if accurate target speed estimation is the only criterion. However, discretization errors introduced by the laser range bins are not fully screened out by the cubic function. As a result, estimates of target vehicle PKE (positive kinetic energy of acceleration) were found to be overestimated when using cubic smoothing alone. The quadratic function, with only three parameters, provides more severe smoothing, which tends to limit discretization errors and provide accurate PKE values for the target vehicle when target speeds are high but relatively constant, e.g., when cruising behind the target on a high speed freeway. However, the quadratic function tended to smooth out important features of the target performance, such as hard accelerations and hard decelerations. Accordingly, a compromise approach was developed that provides for computing both the cubic and quadratic functions for all laser speed estimates, but using the cubic function only for those times when the predicted relative speeds from the two functions differ by more than 2 mph, i.e., when the speeds are changing rapidly and the quadratic function provides a poor fit. At all other times, the quadratic function is used.

7.2 Quality Control Checks

Before data from a particular road route were included in the computation of descriptive statistics, the second-by-second speed data were checked to identify likely problems. Acceleration or deceleration rates in excess of the capabilities of the chase car were one of the criteria used to flag potential problems. Any occurrence of low speed (0–10 mph) accelerations in excess of 0.4 g or high speed (>55mph) acceleration in excess of 0.2 g was used to flag a probable error. (Intermediate acceleration rates are used for intermediate speeds.) Computed target vehicle acceleration rates are flagged if they exceed 0.6 g in the 0–30 mph range. Lower acceleration rate thresholds are used at higher speeds with the lowest threshold being 0.2 g for accelerations occurring in the 90–100 mph range. Deceleration rates for both the chase car and target vehicles are flagged if they exceed 1.0 g.

7.3 Video Tape Analysis

Review of the video tapes was used to double check possible errors (flagged values) identified during second-by-second data analysis of acceleration rates. Review of the tapes indicated whether a data stream with out-of-range acceleration could conceivably have been valid. In addition, the video tapes were used to determine the reason for any other questionable characteristics of the speed-time trace for each trip.

Review of the video tapes was also used to determine how often the chase car was unable to maintain contact with vehicles being driven in an unsafe or aggressive manner. By reviewing a large subset of the trips, the percentage of the time that target loss was caused by aggressive or unsafe behavior on the part of the target vehicle driver was estimated to be less than 1%. During this same review process, the number of times that previous targets were re-acquired was also determined, i.e., the number of distinct targets was determined.

7.4 Descriptive Statistics

As noted earlier, a FORTRAN program was used to calculate descriptive statistics for each route. Following that analysis, a SAS program was used to compute overall statistics (for all routes). The overall descriptive statistics produced by the SAS program included the following:

- average speed;
- average speed while moving;
- percent idle time;
- stops per mile;
- percent time on various road types;
- percent time with various traffic levels of service;
- distribution of instantaneous acceleration rates (calculated from successive speed measurements) using the difference-centered approximation;
- distribution of road grade intervals; and
- PKE (positive kinetic energy of acceleration per mile).

Where possible, each of the above-listed statistics was computed separately for total travel by the chase car, travel by the chase car when it was not following a target vehicle, travel by the chase car when it was following a target vehicle, total target vehicle travel, and the composite of the chase car and the target vehicles. Table 35 summarizes some of the descriptive statistics computed for all of the data collected in Los Angeles during 1992, including trip ends, compared to the LA4 driving cycle.

As the table shows, the LA4 cycle has a lower average speed and higher number of stops per mile than the vehicle operation observed in Los Angeles during 1992. The maximum speed on the LA4 was fairly close

Table 35

Driving Characteristics
Observed in Los Angeles During 1992
Compared to the LA4 Driving Cycle

Parameter	LA4	1992 Data
Average Speed	31.6 km/hr 19.6 mph	42.9 km/hr 26.6 mph
Maximum Speed	91.5 km/hr 56.7 mph	129.5 km/hr 80.3 mph
Average Maximum Speed of All Routes	n.a.	90.0 km/hr 55.8 mph
Percent Idle	19.0	14.4
Stops Per Mile	2.41	1.26
Maximum Acceleration Rate	1.48 m/s^2	3.62 m/s^2
Average Maximum Acceleration Rate of All Routes	n.a.	2.55 m/s^2

to the average maximum speed for all of the individual routes driven; however, significantly higher maximum speeds were observed on many routes, including a maximum speed of 80 mph. Even the average maximum acceleration rate observed during the chase car operation was substantially higher than the maximum acceleration rate on the LA4.

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8. CYCLE DEVELOPMENT

8.1 Objectives

Emissions related to tropospheric air pollution are of interest only when emitted at times and places where they are likely to contribute to violations of the ambient air quality standards. Watson[35] postulated that an emissions driving cycle based on morning peak traffic in urban areas might be needed to describe vehicle activity contributing to photochemical smog, the maximum concentrations of which typically occur in the late afternoon during warm sunny weather after vehicle emissions have undergone a complex series of photochemical reactions.

Although temporal differences in driving patterns could be determined from the data collected during chase car operation, the cycle development effort was specifically intended to produce a cycle representative of all driving occurring in the Los Angeles area. This approach was based on the knowledge that the highest concentrations of photochemical oxidants in Southern California (and many other areas) result from multi-day atmospheric stagnation episodes or long-range, long-duration transport of pollution from upwind areas. Under such conditions, pollutants emitted throughout the day contribute almost equally to peak ozone levels occurring on the following day. In addition, analysis of ambient CO data in Southern California suggests that violations of the ambient air quality standards result from CO emissions occurring over a wide geographic area and timeframe.[36]

Although the goal of the cycle development effort was a "self-weighting" cycle, it was recognized that the cycle should encompass a very wide range of vehicle operation in order to ensure that the effect of "rare events" with extremely high emission levels would not be excluded. As discussed earlier, the increase in emissions associated with high load operation of gasoline-fueled light-duty vehicles is so large that the cycle development phase of the effort was initiated with the expectation that weighting factors might have to be applied to a segment of the final cycle in order to capture vehicle operating conditions causing extremely high emissions levels, while keeping the total length of the cycle reasonable (i.e., not substantially increasing the time required to test each vehicle.)

8.2 Analysis of Velocity-Acceleration Distributions

A variety of approaches to developing driving cycles using speed-time data collected from instrumented vehicles or chase cars has been used previously. As described earlier, the LA4 cycle was constructed using the speed-time trace from one of several trips over the road route that most closely matched the average speed of all of the trips. A more sophisticated approach was used in constructing the EPA Highway driving cycle in that segments of speed-time traces were selected (by trial and error) to match the overall statistics for stops per mile and "major speed deviations" per mile in addition to average speed. The most comprehensive procedure previously used for selecting segments of speed-time traces to match a larger sample of data was that used by Watson during the development of a cycle to represent driving conditions during morning peak traffic periods in Melbourne, Australia.

Watson constructed the Melbourne Peak Cycle using a quasi-random selection of segments of individual trips made by an instrumented vehicle until the total travel time exceeded the 15-minute duration that had been established as the target trip length. The trip segments Watson used were the speed-time profiles between stops that were at least 100 meters in length. Watson called these segments "microtrips". (Such segments in the LA4 driving cycle have previously been referred to as "hills".)

Watson used randomly selected microtrips to identify three cycles that best matched the statistics for the total data set for a number of "arbitrarily selected" parameters that included mean velocity, RMS acceleration, RMS speed, PKE, and disaggregated velocity probabilities. He then used a trial and error approach, swapping microtrips between the best cycles, to reduce the difference between the 15-minute cycles and the entire data set. Although Watson described the parameters he tried to match as being "arbitrarily selected", it appears from his paper that he was actually trying to develop the best possible match to the entire data set based on a representation of the data set that Watson referred to as a "velocity acceleration probability density function" or "VAPDF". As shown in Figure 26, a VAPDF is a three-dimensional plot of the frequency of vehicle operation at all possible combinations of speed and acceleration. In the text below, these plots are referred to as "Watson Plots". This shape of the three dimensional surface is affected by axis scaling and the selected bin size. Bin widths of 10 km/hr and 0.5 m/sec^2 were selected to achieve about a 10 by 10 (100 cell) grid covering the expected range of speed and positive acceleration rates encountered in routine driving. This bin size was also expected to be sufficient to distinguish between operating conditions that most drivers would consider noticeable (i.e., significant). Figure 26 is the Watson plot for the LA4 driving cycle.

As shown in Figure 26, about 17% of the LA4 cycle falls into the 0 speed, 0 acceleration bin (idle). The second largest peak occurs in the vicinity of 40 km/hr (25 mph) and 0 acceleration (cruise). The maximum speed on the velocity-acceleration surface falls into the 90 km/hr (56 mph) bin (the frequency has dropped to zero at the 100 km/hr bin). The maximum acceleration rates are in the 1.5 m/sec^2 bin (dropping to zero frequency at 2 m/sec^2).

Of all of the cycle construction techniques used previously, selecting segments of speed-time traces to match the velocity acceleration frequencies observed for a large sample of vehicle operation would seem to best represent vehicle operation in customer service. This approach provides a cycle that reflects the full range of observed vehicle speeds and loads while simultaneously providing the appropriate proportion of operation in each velocity-acceleration bin. By using actual segments

Figure 26

Velocity Acceleration Probability Density Function (Watson Plot) for the LA4 Cycle

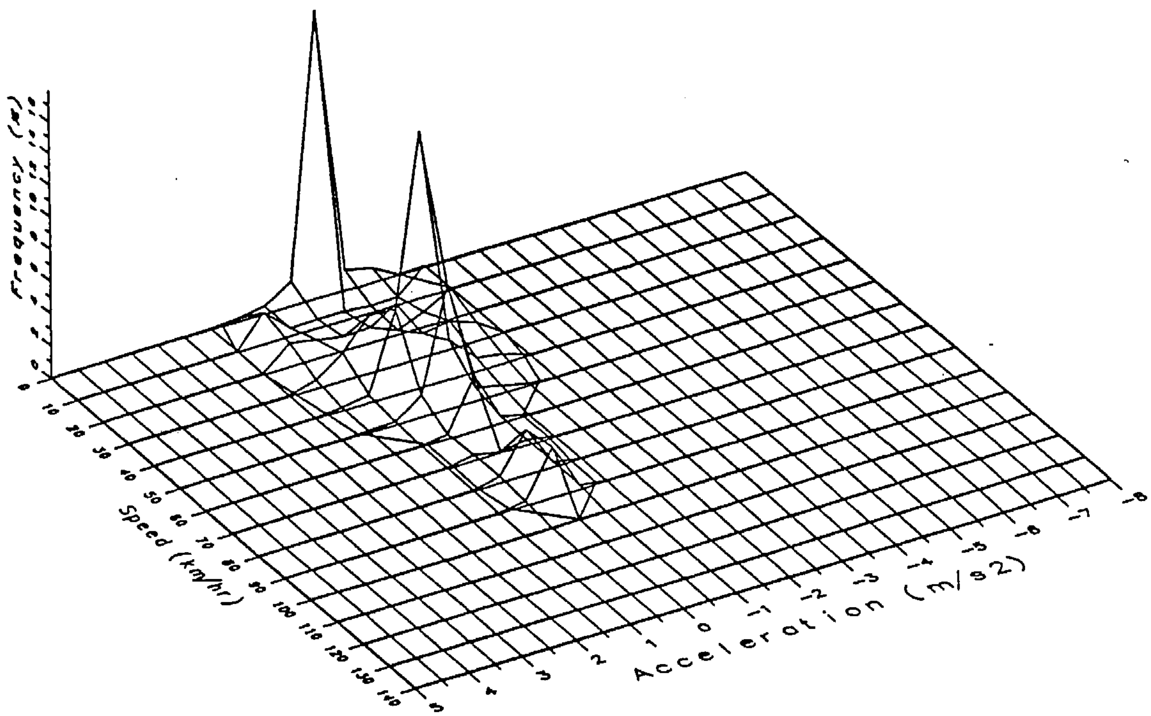


Figure 27 presents the Watson Plot for the data collected in Los Angeles during 1992, including trip end information collected separately. Comparing Figures 26 and 27, a number of differences between the 1992 data set and the LA4 cycle are obvious. The envelope of maximum acceleration and deceleration rates is much broader in the 1992 data set, since the maximum acceleration rates observed in customer service were as high as 3.6 m/s^2 and the maximum acceleration rate on the LA4 is about 1.5 m/s^2. Even greater variation is apparent in the maximum deceleration rates. In addition, the range of speeds observed in customer service extends to 130 km/hr (80 mph) vs 90 km/hr (57 mph) for the LA4. Although the percent time at idle is nearly the same, the secondary peak is much lower and at a slightly higher cruising speed of 60 km/hr (37 mph).

Figure 27

Watson Plot for All 1992 LA Data

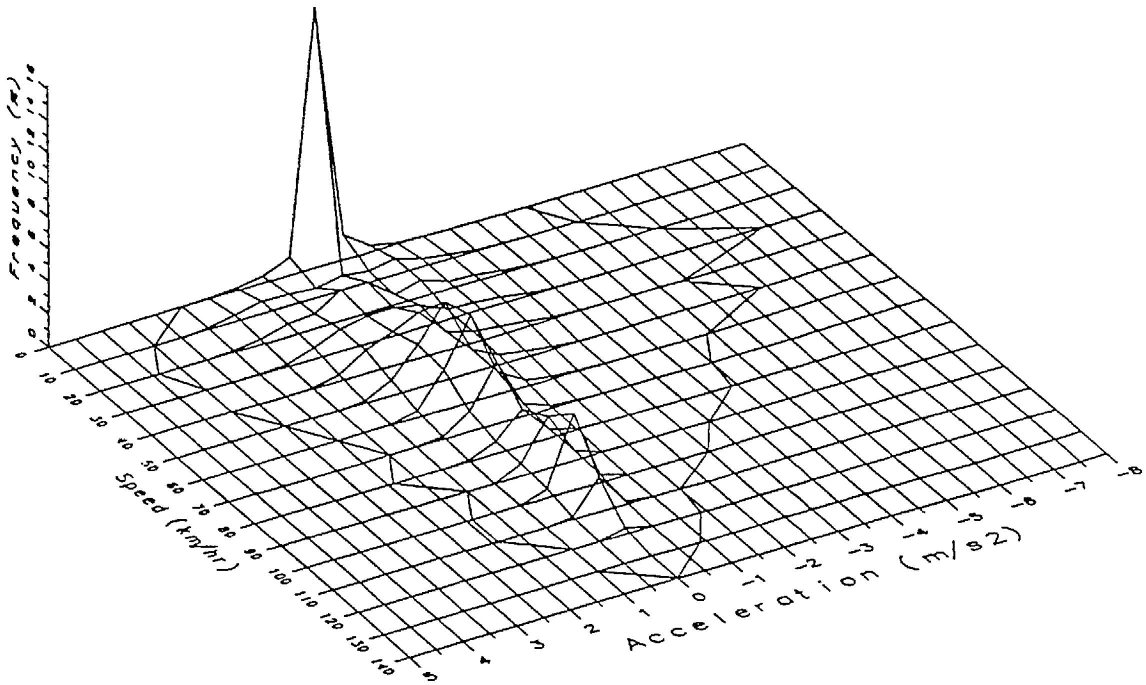


Figure 28 is another plot of the 1992 Los Angeles data set with the boundary of maximum acceleration and deceleration rates plotted at a frequency of 0.1%. This substantially reduces the area covered by the boundary line because very infrequent acceleration and deceleration events are not shown (although they are kept in the data set and still used to calculate other statistics). Figure 29 is a similar plot of the 1992 Los Angeles data without the inclusion of the trip end activity. As a result, the percent time at idle is somewhat lower. (A description of how trip-end activity was addressed appears at the end of the next subsection.)

8.3 Cycle Construction Methodology

From the chase car data collected in Spring 1992, the sample was broken into "microtrips" (with a microtrip being defined as the travel occurring between adjacent stops, including the leading period of idle). Although the "composite" data (with the target vehicle speed-time profile substituted for the chase car speed-time trace when available) were used to generate the Watson Plots for the entire data set, only chase car data were used to generate the set of microtrips. Target vehicle data were ignored in generating the set of microtrips because targets were often acquired or lost in the middle of a microtrip. By using composite data, the microtrips would contain discontinuities

Figure 28

Watson Plot for All 1992 LA Data With Boundaries Set at 0.1% Frequency

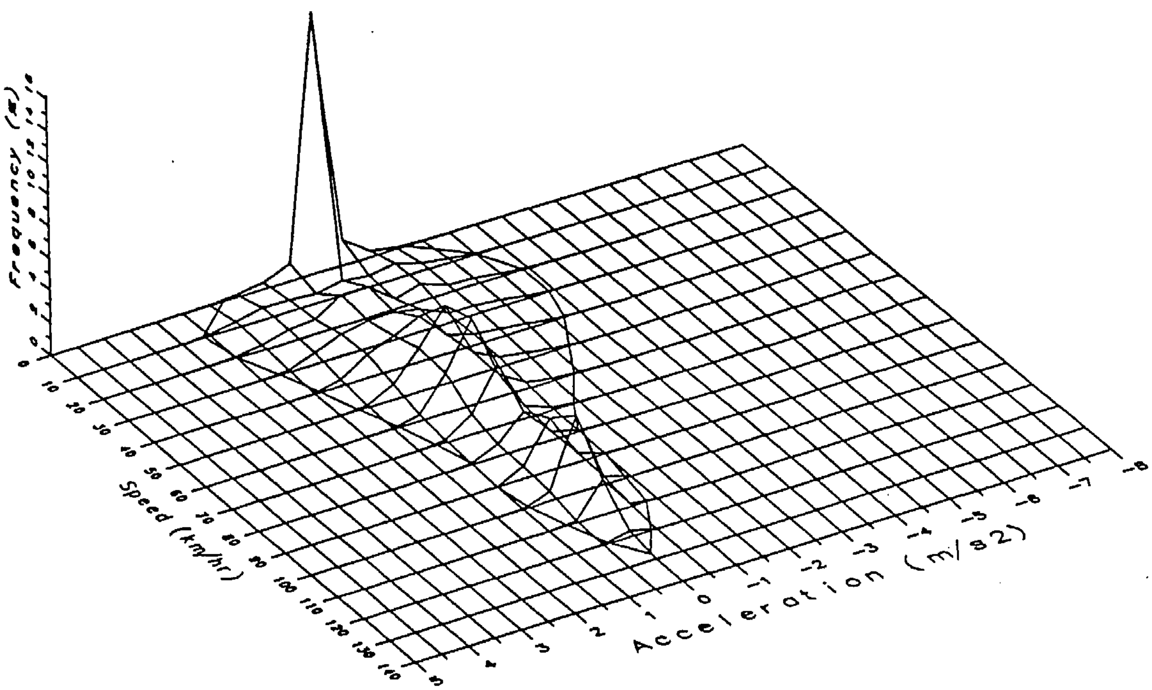
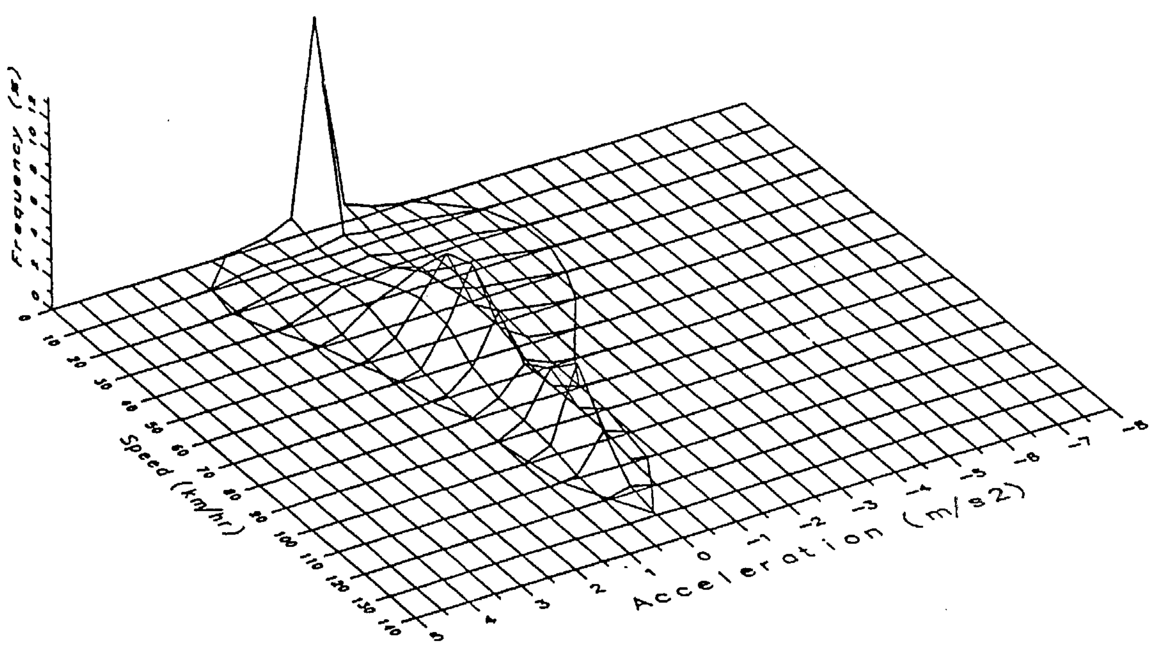


Figure 29

Watson Plot for All 1992 LA Data With 0.1% Boundaries and No Trip-Ends



associated with the switch between chase car speed-time profile and target speed-time profile. By using only target vehicle data, whole microtrips would not usually be available. An additional reason for excluding target vehicle data from the series of microtrips used to develop a cycle was to eliminate concerns regarding the accuracy of the speed-time trace generated from the digital filtering of laser data. This concern was limited to the representativeness of the speed-time trace in terms of the minor speed changes occurring from second-to-second (as opposed to any concern with laser data going into the proper speed-accel bin).

The construction of a driving cycle from chase car microtrips did not bias the results toward the driving habits of the individual chase car drivers. The target profile of vehicle operation was based on composite data and, as described in more detail below, the chase car speed-time profiles were selected to match the target profile, rather than just chase car operation. There is bias toward the individual chase car drivers resulting from the fact that more than half of the travel occurred without data being collected on a target vehicle. However, as discussed in the previous section, traffic often constrained the operation of the chase car even when the laser was not locked onto a target. Under conditions where traffic did not constrain the operation of the chase car, the "average" characteristics of the individual chase car drivers provides assurance that the speed-time profiles are not skewed towards particularly aggressive or sedate driving.

Another indication of the representativeness of the chase car speed-time profile is the similarity between the statistics computed from the data set for the chase car only and the composite (chase car/target vehicle) speed-time profile. Analysis showed that the average PKE for chase car alone was 3858.7, while the composite PKE was 3929.3. The mean values of the maximum route speed and maximum route acceleration for the chase car were within 7% of the composite values.

There were 833 microtrips in the sample of 102 routes. Given a target cycle time on the order of the LA-4 cycle (≈20 min), a methodology was developed to determine the combination of microtrips totaling about 20 minutes that best represented the entire data set.

To match the speed/accel frequency distribution of the entire 1992 data set, one simple approach would be to evaluate all possible combinations of the 833 microtrips that totaled roughly 20 minutes. Although it might not be obvious, this approach was computationally impractical. The mean time for a microtrip was roughly 2 minutes. Thus, for a target cycle time of 20 minutes, roughly 10 microtrips (20/2) are needed. The number of unique combinations of 10 microtrips from a population of 833 are:

$$\#\text{COMBINATIONS} = 833! \;/\; [10! - (833-10)!] = 4.2 \times 10^{22}$$

Assuming a high-speed computer could evaluate the "fit" of the selected cycle to the population speed/accel frequency in one second, it would take 1,300,000,000,000,000 years to evaluate all combinations of microtrips in the database.

Obviously, an approach that was less computationally exhaustive was required. Three approaches for microtrip selection were evaluated:

1. Random
2. Best Incremental
3. Hybrid

Random - The random approach simply selects microtrips at random from the population of 833 without replacement until the target cycle time (20 minutes) is reached. (Without replacement means that once a microtrip is randomly selected, it is removed from the sample of remaining microtrips that can be selected). The problem with the random approach is that many randomly generated cycles need to be generated to approach the best fit that could be achieved by evaluating all combinations of microtrips.

Best Incremental - The best incremental approach interactively selects and builds a sample of microtrips that "incrementally" best fit the target VAPDF surface. For example, all 833 microtrips were scanned and the single microtrip that best matched the VAPDF was determined. This microtrip was removed from the sample of remaining microtrips. The remaining microtrips were then scanned and the microtrip that produced the best fit when added to the first was selected. This process was repeated until the target time was reached.

Conceptually, the best incremental approach may appear reasonable, but the problem is that the longest microtrips are, individually, much better fitting than shorter microtrips. This method results in only one or two microtrips being selected before the target time is reached.

Hybrid - The "hybrid" method used was a quasi-random approach that combined random and best incremental selection techniques in a manner that optimized the ability of the best incremental concept to find better-fitting trips than simple random selection, but with much less bias toward longer trips.

The hybrid approach was constructed as follows. First a "seed" sample of microtrips for some subset of the cycle target time (e.g., 5 minutes) was selected completely at random. After the seed sample time was reached, subsequent microtrips were selected using the best incremental approach. By creating a seed sample of microtrips onto which trips were added, the best incrementally fitting trips that remained were not simply the longest trips.

Comparative evaluation of several hundred cycles using the random and hybrid approaches and the single cycle generated from the best incremental method clearly showed that the hybrid approach had the best ability to pick a cycle of microtrips that best fit the population VAPDF.

Starts - Representative selection of the start portion of the cycle was accomplished by comparing the first 120 seconds of each of the 102 routes to the VAPDF generated from the initial 120 seconds of all the routes. (The "start" portion of the cycle was set at 120 seconds based on typical catalyst "light-off" times for late-model three-way catalyst vehicles.) The start portion of each of the routes was ranked based on its fit to the start VAPDF. The two best routes were retained and used in a modified version of the hybrid method. Instead of simply starting with a random seed of microtrips, the start portions of the two best routes were used as the initial part of the seed. The remaining portion of the seed was filled randomly as before. When inserting these starts, the speed-time traces of the two routes were not simply truncated at time=120 seconds. Instead, the speed-time traces of the start routes were included out to the next stop, usually between 2-3 minutes. Similarly, when the seed sample time and the total cycle time were reached, the remainder of the "current" microtrip being added was included.

Some 18,000 cycles were then generated using the modified hybrid approach. Seed sample times from 2 through 10 minutes at 1 minute increments were evaluated. One thousand cycles were generated for each seed time/start route series (9 seed times x 2 best start routes).

Figure 30 shows the Watson Plot for the cycle that best matched the entire data set (not including trip ends), which is henceforth referred to as the "LA92" cycle. It can be compared to the plot for all 1992 LA data shown in Figure 29. The difference between Figure 29 and Figure 30 is plotted in Figure 31. Summing the differences at each point, the best-fit cycle matched the target surface area within 22%. Tables 36 and 37 are the tabular versions of Figures 30 and 31.

Since the cycle that best fit the data base collected by the chase car did not include "trip ends", it was necessary to add portions of idle and low speed cruise to both ends of the selected microtrips to match the trip end behavior observed during the separate trip end survey. Consistent with the patterns of trip end behavior observed in the field survey, 30 seconds of idle and 30 seconds of low speed operation were added to the beginning of the cycle and 30 seconds of low speed and 10 seconds of idle were added to the end of the cycle. Based on estimates provided by the trip end observation team, typical off-street, low-speed operation involved speeds averaging about 15 mph. A search of the entire data base located a micro trip of 30 seconds length, with an average speed of 15.8 mph.

Figure 32 is the speed-time trace for the selected cycle (after trip ends were added) compared to the LA4. Perhaps the most striking difference is the higher speed operation that occurs on the LA92 cycle. Another significant difference is that over five minutes of operation occur before the vehicle is first accelerated to freeway speeds on the LA92 cycle (vs. about three minutes on the LA4).* Table 38 shows how key parameters for the LA92 compare to the LA4 and the entire 1992 LA data set.

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*It should be noted that the high speed microtrip with the acceleration from idle beginning at 323 seconds was actually driven on a high-speed arterial, not a freeway. However, travel on this stretch of roadway was representative of that observed on freeways.

Figure 30

Watson Plot for Best-Fit ("LA92") Cycle

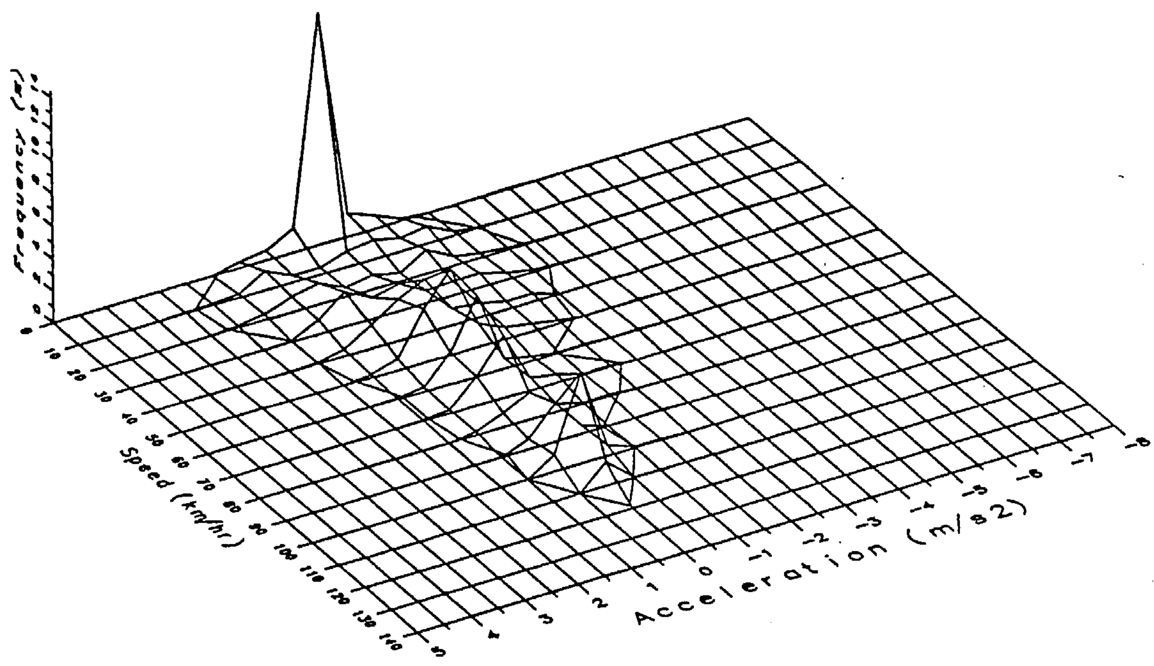


Figure 31

Watson Plot for Difference Between "LA92" Cycle and Entire Data Set

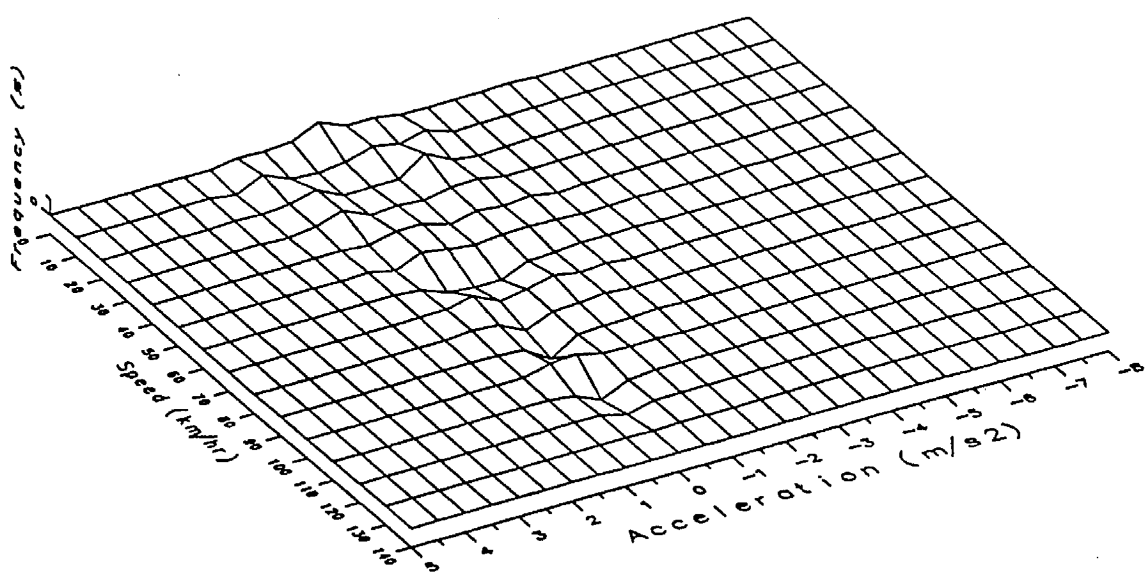


Table 36

Speed/Accel Frequency Distribution (%)

Cycle HSD-289

Speed/Accel Frequency Distribution (%)

ACL BIN (m/s2)	SPD BIN (kph) 0	< 10	< 20	< 30	< 40	< 50	< 60	< 70	< 80	< 90	<100	<110	<120	<130	<140	Row Totals
-8.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-6.5	0.000	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.075
-6.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.5	0.000	0.000	0.000	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.075
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-4.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-4.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-3.5	0.075	0.000	0.000	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150
-3.0	0.000	0.000	0.075	0.075	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.225
-2.5	0.000	0.075	0.150	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.374
-2.0	0.000	0.225	0.299	0.449	0.524	0.225	0.075	0.150	0.000	0.075	0.000	0.000	0.000	0.000	0.000	2.021
-1.5	0.150	1.048	0.599	0.898	0.524	0.524	0.075	0.075	0.150	0.000	0.075	0.000	0.000	0.000	0.000	4.117
-1.0	0.823	0.823	1.497	0.898	0.898	0.749	0.299	0.524	0.075	0.000	0.075	0.000	0.000	0.000	0.000	6.662
-0.5	1.422	1.198	0.524	0.823	1.048	1.497	0.674	0.823	0.524	0.524	0.674	0.075	0.000	0.000	0.000	9.805
0.0	14.371	0.973	0.898	1.722	3.368	5.389	5.090	3.967	1.722	2.395	5.763	1.497	0.000	0.000	0.000	47.156
0.5	1.497	0.449	0.599	1.347	2.620	3.368	2.021	1.871	0.898	0.674	1.048	0.000	0.000	0.000	0.000	16.392
1.0	0.599	0.449	1.347	2.171	1.497	0.749	0.299	0.225	0.225	0.000	0.000	0.000	0.000	0.000	0.000	7.560
1.5	0.374	1.198	0.973	0.898	0.449	0.225	0.075	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.266
2.0	0.000	0.225	0.374	0.075	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.749
2.5	0.000	0.150	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.299
3.0	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.075
3.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Col Totals	19.311	6.886	7.485	9.581	11.003	12.874	8.683	7.710	3.593	3.668	7.635	1.572	0.000	0.000	0.000	100.000

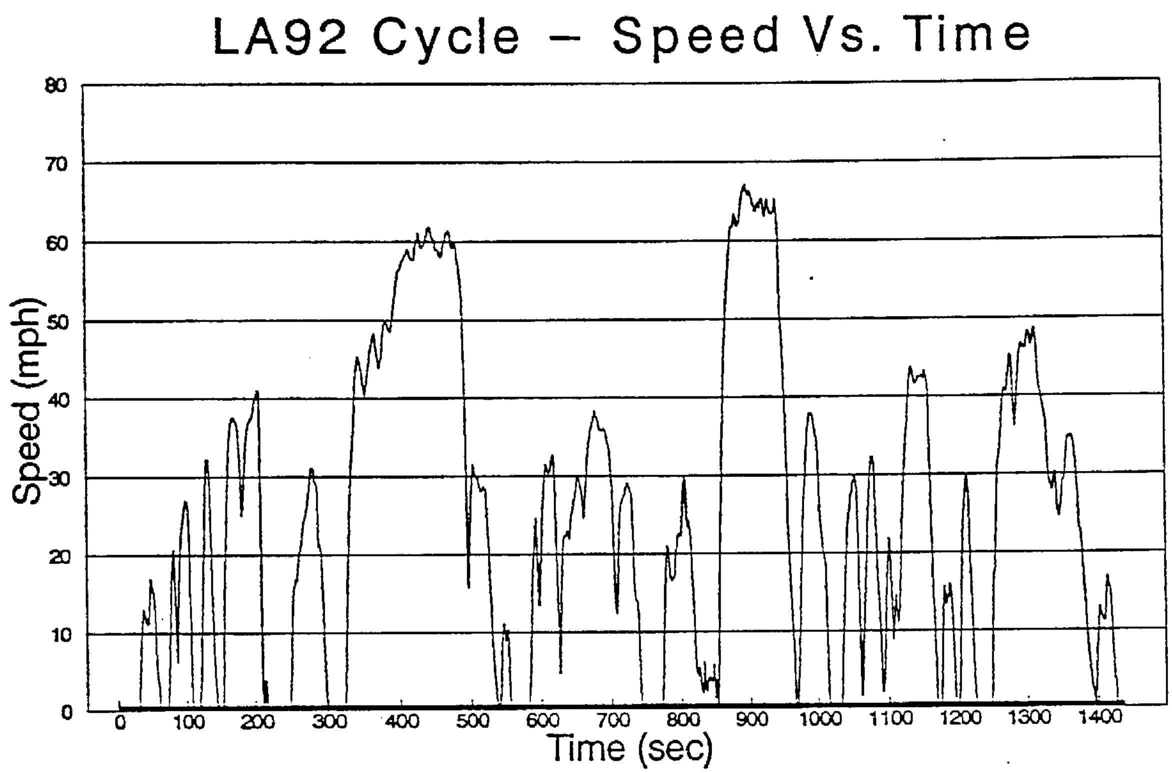
Table 37

Difference Between Cycle H5D-289 and Target Surface LA2FREQT
Speed/Accel Frequency Distribution (%)

	SPD BIN (kph)																
ACL BIN (m/s2)	0	< 10	< 20	< 30	< 40	< 50	< 60	< 70	< 80	< 90	<100	<110	<120	<130	<140	Net Totals	Abs Totals
-8.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-6.5	0.000	0.000	0.000	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.074	0.074
-6.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.5	0.000	0.000	0.000	0.000	0.000	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.074	0.074
-5.0	0.000	0.000	-0.001	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.002	0.002
-4.5	0.000	0.000	0.000	-0.002	-0.001	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.004	0.004
-4.0	0.000	-0.001	-0.006	-0.007	-0.003	-0.002	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.020	0.020
-3.5	0.074	-0.008	-0.023	-0.015	-0.009	0.070	-0.001	-0.002	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.085	0.202
-3.0	0.000	-0.041	-0.010	-0.007	-0.045	-0.023	0.062	-0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.067	0.191
-2.5	-0.007	-0.038	-0.065	-0.040	-0.142	-0.065	-0.026	-0.006	-0.004	-0.003	0.000	0.000	0.000	0.000	0.000	-0.395	0.395
-2.0	-0.024	-0.102	-0.165	-0.027	0.157	0.029	-0.010	0.125	-0.012	0.070	-0.002	0.000	0.000	0.000	0.000	0.039	0.722
-1.5	0.012	0.502	0.077	0.285	-0.033	0.076	-0.131	-0.004	0.120	-0.016	0.066	0.000	0.000	0.000	0.000	0.953	1.320
-1.0	0.358	0.133	0.934	0.212	0.120	0.028	-0.187	0.307	-0.043	-0.068	0.053	-0.009	-0.001	0.000	0.000	1.837	2.453
-0.5	0.289	0.412	-0.179	-0.087	-0.228	-0.117	-0.924	-0.092	-0.096	-0.126	0.097	-0.145	-0.030	-0.001	0.000	-1.226	2.823
0.0	0.963	-0.019	-0.179	0.055	0.279	0.088	-0.867	-0.362	-0.804	-1.180	0.478	-0.907	-0.425	-0.047	0.000	-2.926	6.653
0.5	0.259	-0.220	-0.253	-0.105	0.290	0.372	-0.738	0.445	0.040	-0.178	0.392	-0.201	-0.038	-0.005	0.000	0.059	3.537
1.0	0.140	-0.136	0.553	0.663	-0.126	-0.322	-0.140	0.046	0.126	-0.035	-0.014	-0.004	0.000	0.000	0.000	0.751	2.306
1.5	0.193	0.571	0.131	0.100	-0.003	0.056	0.018	0.045	-0.007	0.000	-0.001	-0.001	0.000	0.000	0.000	1.102	1.125
2.0	-0.030	-0.194	-0.015	-0.098	0.018	-0.018	-0.011	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	-0.349	0.385
2.5	0.000	0.028	0.033	-0.039	-0.014	-0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.118
3.0	0.000	0.058	-0.033	-0.009	-0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.102
3.5	0.000	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001	0.001
4.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Net Totals	2.227	0.944	0.797	0.953	0.258	0.240	-2.956	0.498	-0.681	-1.536	1.068	-1.266	-0.494	-0.053	0.000	0.000	
Abs Totals	2.348	2.463	2.657	1.825	1.470	1.343	3.116	1.440	1.254	1.676	1.102	1.266	0.494	0.053	0.000		22.505

Figure 32

Speed-Time Profile for "LA92" Cycle
vs. LA4 Cycle



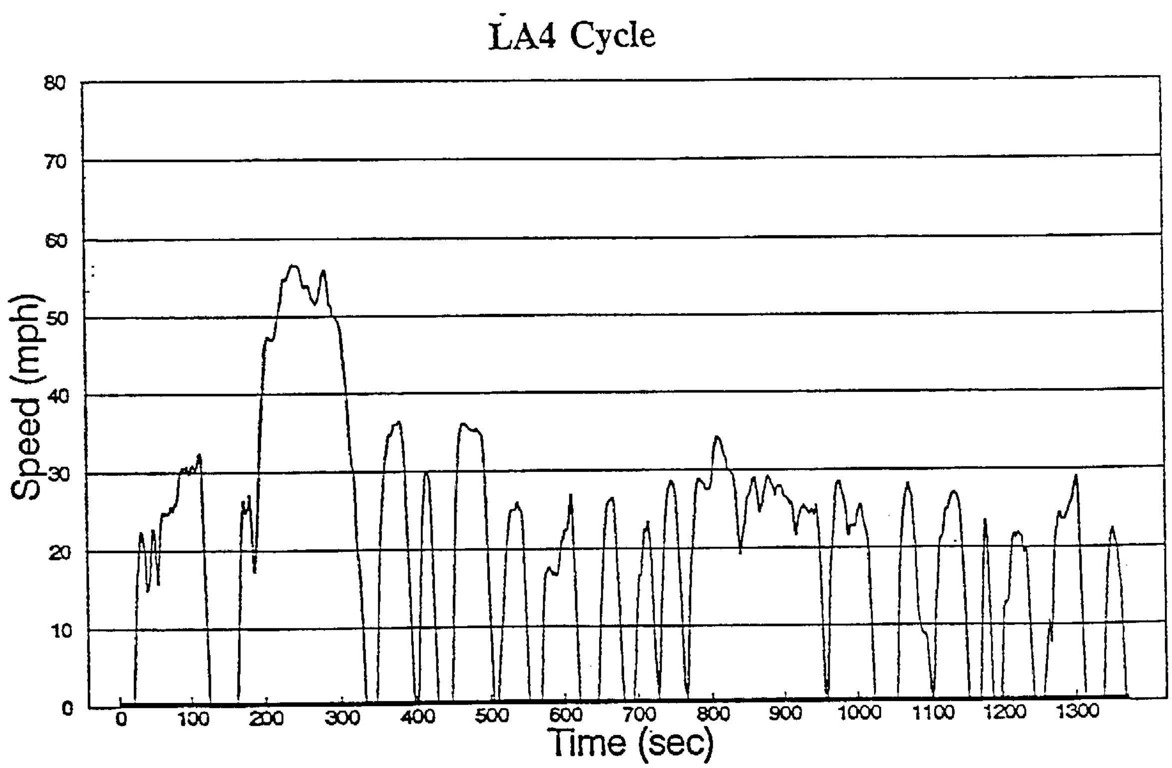


Table 38

Best Cycle Representing Driving Characteristics Observed in Los Angeles During 1992 vs. Entire Data Set and LA4 Driving Cycle

Parameter	LA4	Entire Data Set	Best Cycle "LA92"
Average Speed	31.6 km/hr 19.6 mph	42.9 km/hr 26.6 mph	40.0 km/hr 24.8 mph
Maximum Speed	91.5 km/hr 56.7 mph	129.5 km/hr 80.3 mph	108.1 km/hr 67.0 mph
Average Maximum Speed of All Routes	n.a.	90.0 km/hr 55.8 mph	n.a.
Percent Idle	19.0	14.4	16.4
Stops Per Mile	2.41	1.26	1.52
Maximum Acceleration Rate	1.48 m/s^2	3.62 m/s^2	3.02 m/s^2
Average Maximum Acceleration Rate of All Routes		2.55 m/s^2	n.a.
Cycle Length	12.0 km 7.5 miles	n.a.	16.0 km 9.9 miles

8.4 Representativeness Testing

After identifying the combination of microtrips that best fit the VAPDF for the entire sample of data collected in Los Angeles, the VEHSIME computer model was used to determine if vehicle emissions predicted for the best-fit cycle match the emissions predicted for the entire data set.

At the beginning of the contract, the most current engine map data contained in the model were for mid-1970s vintage engines equipped with oxidation catalysts. During the course of the contract, Sierra constructed additional maps for vehicles equipped with three-way catalysts based on chassis dynamometer data collected by EPA. Sierra also developed a cold start simulation subroutine based on modal emissions data collected by EPA.

Table 39 shows the results of using VEHSIM to estimate hot start emissions for a late-model vehicle equipped with a 3.3L Chrysler engine. As the table shows, the emissions predicted for the entire 1992 LA data set are within 20% of the emissions predicted for the 10-mile, LA92 cycle.

Table 40 shows the VEHSIME results for two different engines on the LA92 cycle and the LA4 cycle. As the table shows, both engine maps generate significantly higher CO and NOx emissions for the LA92 cycle. Review of the second-by-second output indicates that very large increases in emissions occur approximately 850 seconds into the cycle, when the speed increases to the maximum for the cycle.

Table 39

Computer Model Comparisons of Hot Start Emissions on LA92 Cycles vs. Entire 1992 LA Data Set (grams/mile)

	Hydrocarbons		Carbon Monoxide		Oxides of Nitrogen	
Engine	Entire DataSet	LA92 Cycle	Entire DataSet	LA92 Cycle	Entire DataSet	LA92 Cycle
3-Way Catalyst Chrysler 3.3L	0.18	0.20	1.33	1.60	0.54	0.54
Average Change LA92 vs. All		+11%		+20%		0%

Table 40 Computer Model Comparisons of Hot Start Emissions on LA4 and LA92 Cycles (grams/mile)						
	Hydrocarbons		Carbon Monoxide		Oxides of Nitrogen	
Engine	LA4	LA92	LA4	LA92	LA4	LA92
3-Way Catalyst Chrysler 3.3L	0.18	0.20	0.86	1.60	0.20	0.54
Ox Catalyst Buick 3.8L	0.18	0.15	0.35	1.36	1.56	2.66
Average Change LA92 vs. LA4		-6%		+187%		+120%

Dynamometer test results for a representative sample of vehicles will be required to verify the emissions effects indicated by the VEHSIME model. However, the changes in emissions predicted by the model are directionally consistent with the changes in emissions that would be expected from a driving cycle that subjects vehicles to higher speeds and loads than occur on the LA4.

During initial dynamometer testing conducted by ARB, one deceleration contained in the initial version of the LA92 cycle was found to be difficult to follow on a chassis dynamometer. This deceleration, beginning 206 seconds into the cycle required the vehicle to slow from 41 mph to 0 mph in 4 seconds (-0.5 g). This was the only "panic stop" included in the trace. To make the cycle easier to drive, the deceleration was altered to make it equal to the next most severe deceleration in the cycle by extending the trace into the adjacent idle period for two seconds.

Appendix D contains the second-by-second tabulation of the final cycle with the altered deceleration rate.

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