

sierra research



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**Design and Operation of an
Instrumented "Chase Car" for
Characterizing the Driving
Patterns of Light-Duty
Vehicles in Customer Service**

prepared for:

**U.S. Environmental Protection Agency
Certification Division**

February 28, 1992

prepared by:

Sierra Research, Inc.
1521 I Street
Sacramento, California 95814
(916) 444-6666

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**Under Contract No. 68-C9-0053
Work Assignments 1-03 and 1-04**

February 28, 1992

prepared by:

**Thomas C. Austin
Robert G. Dulla
Francis J. DiGenova**

**Sierra Research, Inc.
1521 I Street
Sacramento, CA 95831
(916) 444-6666**

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1. Summary

With funding provided by the U.S. Environmental Protection Agency and the California Air Resources Board, Sierra Research has developed an instrumented "chase car" that, with the use of a behind the grill mounted laser rangefinder, is capable of recording major speed changes of vehicles it follows without maintaining a constant following distance or matching the acceleration characteristics of the vehicle being followed. The chase car is also equipped with systems designed to provide second-by-second information on its own speed, longitudinal acceleration, lateral acceleration, roadway grade, engine load, roadway type, and level of congestion. By following randomly selected vehicles traveling along road routes known to be representative of a particular area, the chase car collects information that characterizes the full range of operating conditions experienced on public roadways.

Initial operation of the chase car was in the Greater Metropolitan Los Angeles area where approximately 100 routes were driven. Over 200 routes were then driven in Baltimore, Maryland. During 1992, additional data collection is anticipated in Los Angeles and possibly other areas. Through analysis of the data collected by the chase car and supplemental data on vehicle activity at "trip ends" and "soak time" between trips, the current operational characteristics of light-duty vehicles can be compared to the operational characteristics embodied in the "LA4" driving cycle, used in the Federal Test Procedure for light-duty vehicles since the 1972 model year.

After the construction of one or more driving cycles that represent the operating characteristics recorded by the chase car, tests of a representative sample of vehicles can be used to determine whether such cycles produce emissions results that are significantly different from the emissions produced using the LA4 cycle.

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2. Introduction

In January 1990, the Mobile Source Division of the California Air Resources Board (CARB) issued a Request For Proposals for "Characterization of Driving Patterns and Emissions from Light-Duty Vehicles in California". The RFP called for the development of new driving cycles to represent light-duty vehicle travel during peak morning, peak afternoon, and off-peak periods. Also during 1990, amendments were made to the Clean Air Act (§206(h)) requiring the U S Environmental Protection Agency (EPA) to "review and revise as necessary the regulations . regarding the testing of motor vehicles and motor vehicle engines to insure that vehicles are tested under circumstances which reflect the actual current driving conditions under which motor vehicles are used, including conditions relating to fuel, temperature, acceleration, and altitude "

In response to the CARB RFP, Sierra Research, Inc (Sierra) proposed, and was eventually awarded a contract, to use an instrumented "chase car" to collect speed vs time data while following randomly selected vehicles operating in the Greater Metropolitan Los Angeles Area. The original scope of work under Sierra's contract with CARB called for the use of a chase car instrumented only to record its own speed-time profile. 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 their driving patterns.

Having been given the responsibility for conducting the review of the light-duty driving cycle mandated by the recent Clean Air Act amendments, EPA's Certification Division issued "work assignments" to Sierra to supplement the chase car effort being performed for CARB. Under Work Assignment 1-03 of Contract No 68-C9-0053, Sierra was required to perform an evaluation of data collection methods that could be employed to record vehicle operation in customer service. The evaluation was to consider instrumentation options for vehicles driven by randomly selected motorists in addition to instrumentation options for "chase cars" designed to follow other vehicles. In addition to the conceptual evaluation under Work Assignment 1-03, Work Assignment 1-04 directed Sierra to develop and field test a complete vehicle. Development of a methodology for constructing representative driving cycles from the chase car data was also required.

Following this introductory section, Section 3 summarizes the advantages and limitations of chase cars and sets forth Sierra's recommended approach for characterizing light-duty vehicle driving patterns through the use of chase car data supplemented with data collected from "trip end" surveys, motorist surveys, and instrumented vehicles being driven in routine customer service. Section 4 describes the chase car instrumentation package developed by Sierra. Section 5 presents the results of field tests conducted using the chase car to follow another instrumented vehicle in traffic. Section 6 covers chase car operational

procedures, including the protocol used to determine which vehicles will be followed. Section 7 describes the route selection methodology being used to determine where the chase car is driven. Section 8 describes the data analysis technique proposed for translating information collected by the chase car into driving cycles that represent customer service.

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3. Advantages and Limitations of Chase Cars

Two approaches available for characterizing the operation of vehicles in customer service are 1) to collect data from instrumented vehicles driven by a variety of motorists, and 2) to collect data using an instrumented "chase car" that follows randomly selected motorists. The two driving cycles currently used by EPA and CARB for determining compliance with emissions and fuel economy standards for light-duty vehicles are the Urban Dynamometer Driving Schedule, commonly referred to as the "LA4", and the "Highway" cycle. Generally speaking, 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 chase car data.

The LA4 was developed using an instrumented vehicle driven over a specific, 13 mile long road route (the LA4 road route) believed to be representative of travel in Los Angeles in terms of the fraction of time spent at various combinations of speed and load. Different drivers drove the route in different elapsed times. The data selected for cycle development was based on the one trip over the route that came the closest to the average time for all drivers. As a result, portions of the speed-time trace generated by one particular driver, driving one particular car, during one particular trip over the route were used to construct the 7.5 mile cycle that has been used to certify light-duty vehicles since the 1972 model year*. The Highway cycle was developed using an instrumented chase car that followed other vehicles in traffic during 1,050 miles of operation over non-urban roadways. Using pieces of the speed-time trace generated by the chase car, a 10.2 mile long cycle was constructed that matched the average speed, stops per mile, and major speed deviations per mile for all of the data recorded by the chase car**.

As discussed below, neither of the techniques previously used for cycle development provide assurance that the resultant cycle adequately represents light-duty vehicle operation in customer service.

Practical Considerations

Regardless of the technique used to collect data, there are several practical considerations that need to be addressed. The emissions from

* R.E. Kruse and T.A. Huls, "Development of the Federal Urban Driving Schedule," U.S. Environmental Protection Agency, SAE paper no. 730553, May 1973.

** T.C. Austin, et al., "Passenger Car Fuel Economy During Non-Urban Driving," U.S. Environmental Protection Agency, SAE paper no. 740592, August 1974.

passenger cars and light trucks are known to be strongly affected by operating mode. In order for a driving cycle to represent a composite of operation in customer service, it must encompass a wide range of operating modes and initial conditions.

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 a particular 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 assumed to be 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.

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, it is apparent that the development of a representative driving cycle must involve the characterization of vehicle operation over a wide range of roadway 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 emissions 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.

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

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 cause the average to be what it is. If

the length of the cycle needed to achieve the proper average is excessive, weighting factors of less than 10 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 how 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 other vehicles in 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 is 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 is the case with the LA4, the Highway cycle also 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 measurement of speed-time profiles. Implicit in the analysis of speed-time data and its subsequent translation into a dynamometer driving cycle has been the assumption 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 with 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 equipped with 3-way catalysts, could cause emissions to increase by a factor of 100. 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. However, representativeness of the sample would be an obvious concern. Motorists willing to participate in a diary data collection effort may not be representative of 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 of diary data collection efforts. Representativeness of sample would remain a potential problem. Expecting motorists to accurately remember times and mileages could be a serious problem. As with the case of diary data, detailed speed-time information would not be available. However, the technique has some promise 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 have their behavior affected (e.g., reduced 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 vehicles can be approximated without the need for volunteers who know they are involved in some sort of 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 to follow are selected on a random basis and whether the time and location of chase car operation adequately represents travel in the area. However, if representative routes have been identified, 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 their behavior.

Recommended Approach

Based on the considerations outlined above, Sierra recommended that both CARB and EPA use a multifaceted data collection effort to characterize light-duty vehicle operation in routine customer service. To characterize speed-time profiles on public roadways, Sierra recommended using a chase car instrumented (with a radar- or laser-based system) to measure the speed-time profile of other vehicles without following them in a close or consistent manner. To ensure representative traffic conditions, it was recommended that road routes for the chase car to follow be randomly selected from a validated transportation model after the routes had been "trip-weighted". To overcome the problem with recording trip end behavior, Sierra recommended obtaining supplemental data from a trip end survey involving visual observation of trip origins and destinations. To overcome the problem with knowing soak times between trips, Sierra recommended collecting survey information from a random sample of motorists stopped at Highway Patrol roadblocks or interviewed during refueling operations at service stations. To obtain additional information on soak times and to provide a cross check on the chase car data, Sierra also recommended that some data be obtained from instrumented vehicles owned by motorists who volunteer to operate their vehicle with a retrofitted instrumentation package.

In response to these recommendations, Radian Corporation was issued a work assignment by EPA to develop a simple instrumentation package for retrofit onto vehicles owned by motorists who volunteer to participate when they are approached at vehicle inspection and maintenance (I/M) test facilities in Baltimore, Maryland, and Spokane, Washington. CARB issued a Request for Proposals to have data on instrumented vehicles collected in California as well. Sierra pursued the development of a more sophisticated chase car instrumentation package than had been contemplated under the original version of the scope of work for CARB and continued with its efforts to define representative road routes and operating protocol for chase car data collection in the Los Angeles, California and Baltimore, Maryland areas.

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4. Chase Car Specifications and Instrumentation

Under Sierra's original scope of work for CARB, the concept for the chase car involved using a vehicle with a relatively high power/weight ratio that would be instrumented to record road speed once per second while closely following other vehicles in traffic, especially during major speed deviations. With the availability of additional funding for chase car development by EPA, it became possible to pursue alternative concepts for capturing the speed-time profile of other vehicles. In addition, a decision was made to pursue the development of an instrumentation system for determining roadway grade.

Vehicle Selection

Once the decision was made to pursue the development of a system to measure the relative speed of vehicles being followed without maintenance 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 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 Continental Town Car were identified as two vehicles with a large space behind the grill. Of these two, the Caprice provided easier access to the behind the grill space and substantially lower cost at nearly the same power/weight ratio. The Caprice was also considered to be a somewhat less conspicuous looking 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 to 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 (3.23:1). A picture of the vehicle is shown in Figure 1.

Laser Rangefinder Development

The initial efforts on alternative instrumentation packages involved an investigation of a forward-looking, "same lane" radar system to record the relative speed of a vehicle being followed. Police-type radars

Figure 1
Chevrolet Caprice Chase Car



proved to be inadequate because of accuracy problems at speed differentials below about 10 mph. This limitation is fundamental to doppler-based radar systems which operate on the principal of a radar signal's frequency shift 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 more difficult the task of estimating speed. 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.

One system that initially looked the best was a special purpose radar system called "VORAD" designed for use as a collision avoidance/smart highway device. The VORAD system is designed to accurately measure relative speed differences between the instrumented vehicle and the vehicle being followed in order to ensure that a safe driving distance is maintained. Although the VORAD system is not yet commercially available, several prototype systems were already under evaluation. Concerns about the radar beam being detected by radar detector equipped vehicles combined with problems in negotiating the timely availability of a system for Sierra's use ultimately caused efforts to be focussed on a laser-based system.

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 rangefinder-based speed measurement system designed to compete with hand-held police radar units. By measuring time of flight of an eye safe, 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 1 foot on average. If the return signals indicate a variable range, the instrument automatically switches to speed-measuring mode and attempts to determine relative speed in mph. Discontinuities in range measurements are an indication that the laser beam has moved off of the target and no speed is computed. When there are no discontinuities, the laser, after about 1-3 seconds (depending on the relative speed), indicates "lock on" to a target. Figure 2 shows a picture of the hand-held system.

Figure 2
Laser Atlanta Hand-Held Laser Gun



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 Sierra's 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 2 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 as the chase car negotiates hills and curves. Sierra signed an agreement with Laser Atlanta for the development of a vehicle-mountable system that would measure distance to within 1 foot over a range of 2-200 feet.

Figure 3 shows the custom laser rangefinder developed by Laser Atlanta installed in the Caprice. The rectangular box above the two lens 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 a "head up" display of target relative speed in the video picture, along with an illuminated reticle which shows where the laser and camera are aimed. The laser light is infrared and not visible to the naked eye.

Figure 3
Custom Laser System Mounted in Chase Car

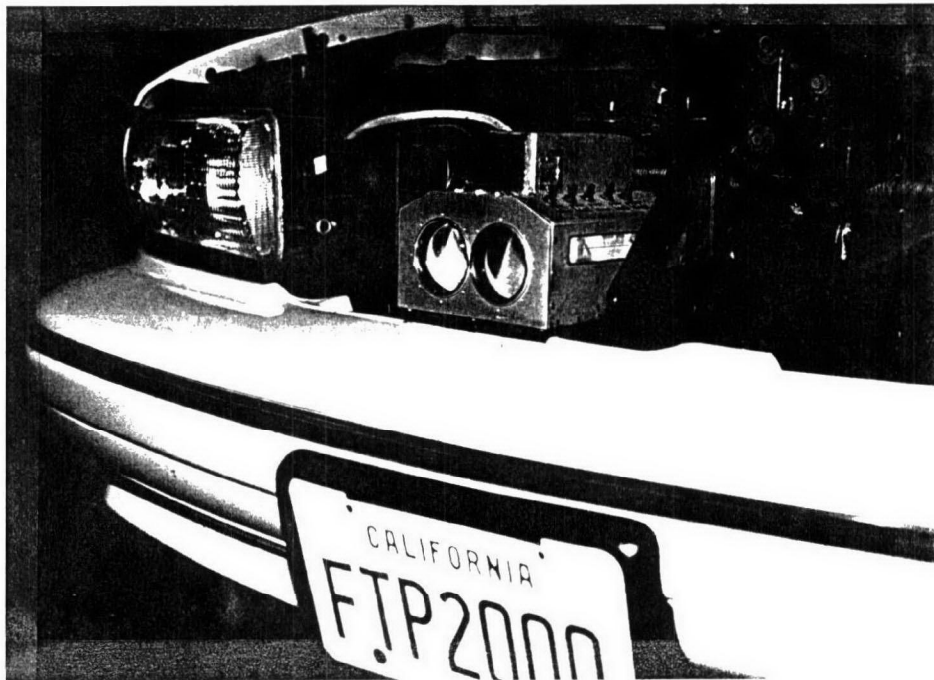


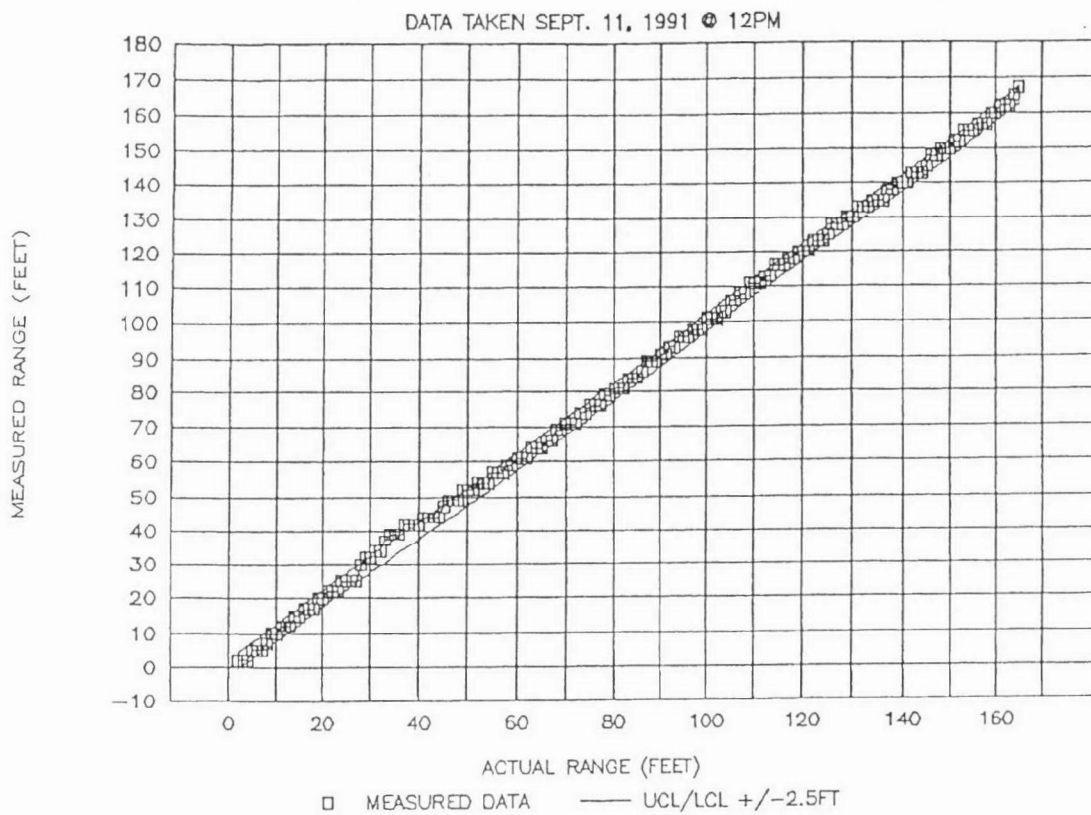
Figure 4 shows a front view of the car with the hood closed. Note that a small section of grill has been cut out to eliminate any obstruction of the laser gun, receiver, or camera.

Figure 5 shows the results of Laser Atlanta's final test of the distance measurement accuracy of the system. Several software changes from the original version of the system were required after Sierra's test results

Figure 4
Frontal View of Chase Car With Laser Rangefinder Installed



Figure 5
Laser Rangefinder Distance Measurement Accuracy



indicated larger distance measurement error and problems getting the system to lock on to moving targets. As shown in the figure, distance measurements are accurate to within about 2.5 feet, except for a minor discontinuity in the 30-40 foot range. The cause of the discontinuity is thought to be some internal interference that has not been precisely identified. As discussed in more detail in Section 5, the data filtering method being employed to process laser data will minimize the effects of the discontinuity. Even without filtering, the discontinuity has a modest effect on the calculated speed/time profile of vehicles being followed. For example, when a vehicle accelerates away from the chase car through the 30-40 range, an instantaneous overestimate of the distance between the vehicles of 2 feet would cause a true 6 mph/sec acceleration (a commonly observed rate) to instantaneously appear to be 7.4 mph/sec, followed by an instantaneous 4.6 mph/sec acceleration rate during the next second. With digital filtering of the laser data, the effect of distance measurement error can be substantially reduced.

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 D.C. voltage (0-5 volts) that is proportional to speed.

Manifold Air Pressure Measurement

A standard GM manifold air pressure (MAP) sensor produces a D.C. 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 with 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.

Results reported by the manufacturer of the "G-Analyst" accelerometer system (a system that was evaluated and rejected) indicate that pitch response for passenger cars varies from about 1.0-2.5 degrees per g, depending on the stiffness of the suspension. Because the maximum acceleration/deceleration rates for the chase car seldom exceed 0.5 g, a maximum pitch response of about 1 degree is expected. (In terms of accelerometer readings, this translates to only about 0.01 g of acceleration in the plane of the roadway.)

Figure 6 illustrates the correlation between the acceleration calculated from the vehicle speed sensor output compared to the acceleration measured by the longitudinally oriented accelerometer when the vehicle is driven on a known approximately level road in downtown Sacramento, California. As the figure indicates, there is some "noise" in the data due to vibration but there is, nevertheless, excellent correlation between the two. By elevating one end of the vehicle, the accelerometers were able to predict the grade within 1%.

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. Figure 7 shows an 8mm camcorder installed between the front and rear seats. The infrared focussing system used on this particular model (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 adaptor, plugged into the power supply system described below.

Figure 6
Correlation Between Computed and Measured Longitudinal Acceleration

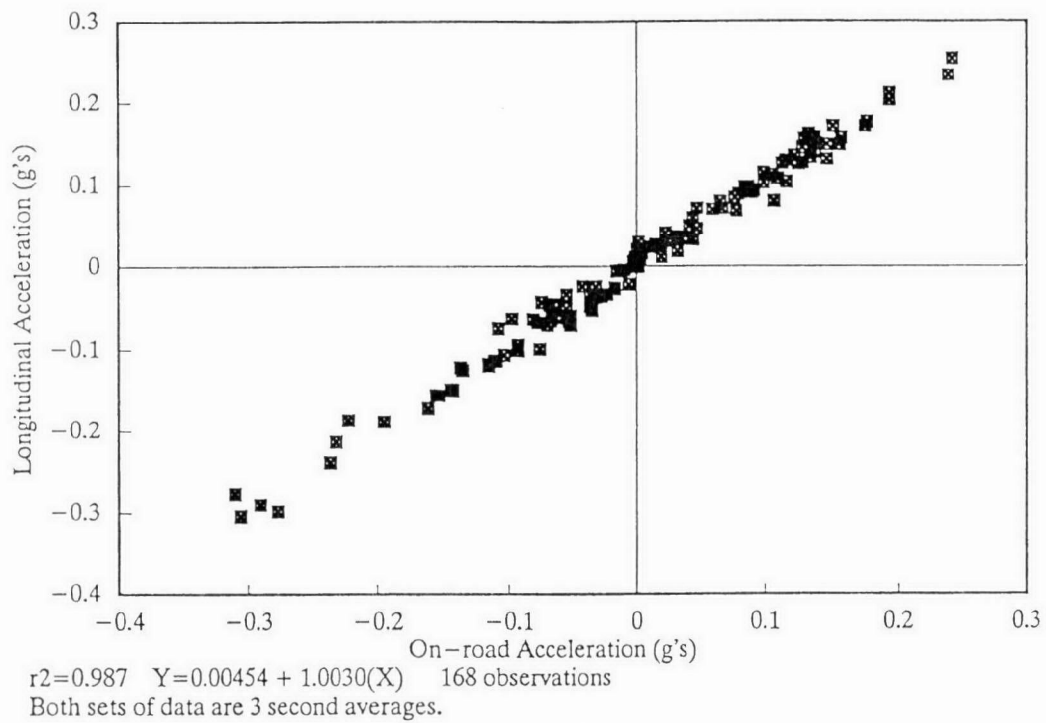


Figure 7
8mm Camcorder Installation



Manually recorded observations are obtained through the use of a switch box with 4 rotary switches and 1 toggle switch to classify and record conditions as they change. Figure 8 shows a picture of the switchbox in its initial configuration. 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). Figure 9 shows pictorial representations of each level of service copied from a U.S. Department of Transportation publication. (These pictures are mounted on the chase car dashboard for reference by the observer.)

Figure 8
Switchbox Used by Observer

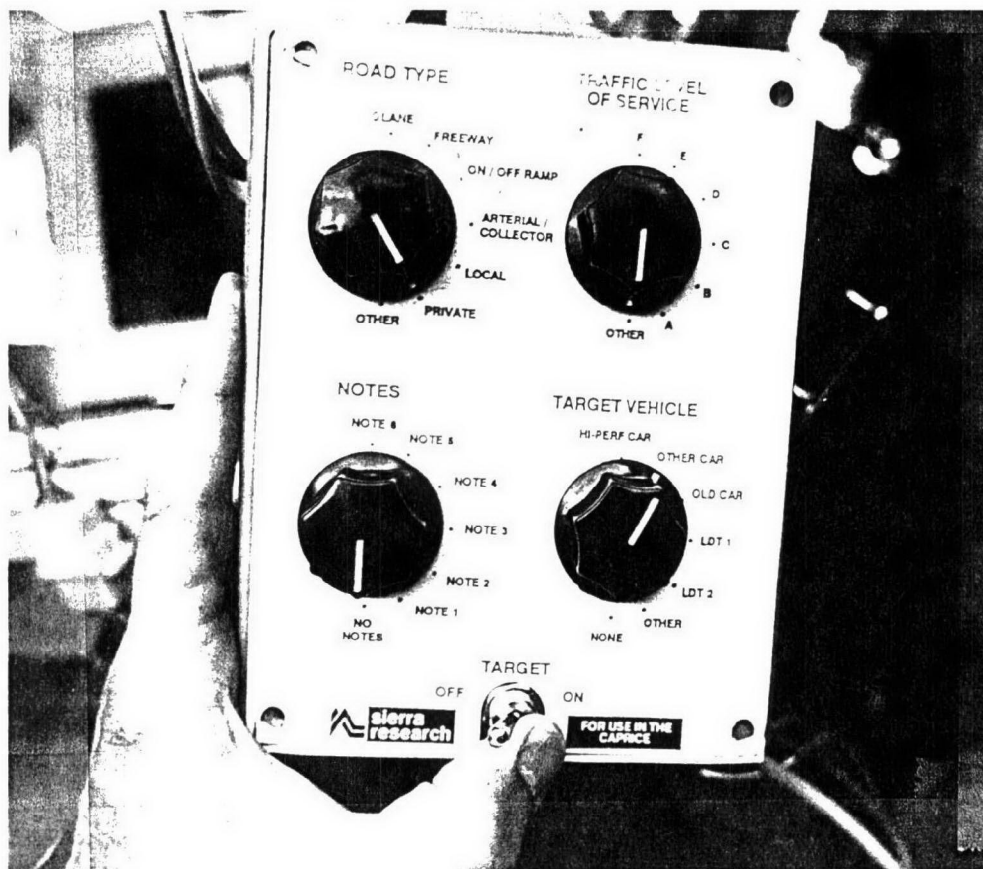


Figure 9
 Illustrations of the U.S. DOT
 Level of Service Classification Scheme

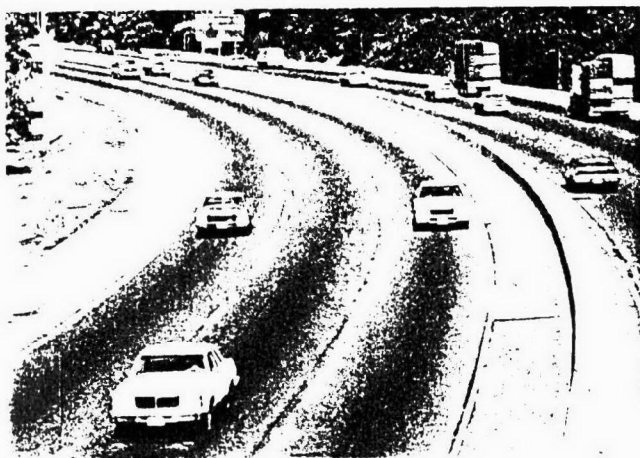


Illustration 3-5. Level-of-service A.



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



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

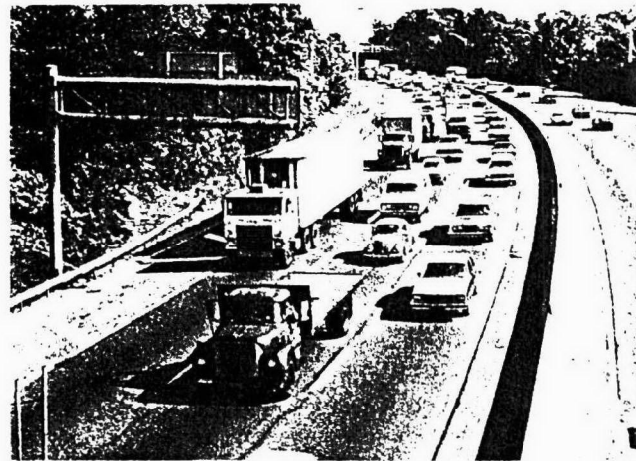


Illustration 3-9. Level-of-service E.



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

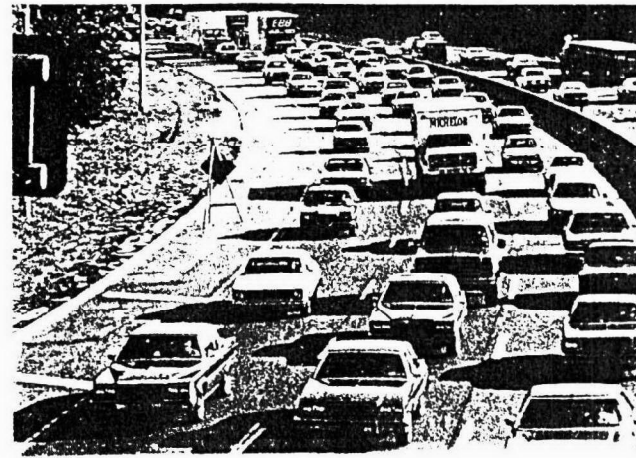


Illustration 3-10. Level-of-service F.

- Target Vehicle - used to indicate the type of vehicle being followed. The seven selections shown in the figure are high performance car, other car, old car, light-duty truck 1, light-duty truck 2, other and none. This rotary switch can only produce a signal when the toggle switch is on, indicating the laser is aimed at a target vehicle.
- Notes - a total of 6 "flags" are available to record the occurrence of an unusual condition.

Data Acquisition System

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

- chase car speed,
- chase car manifold air pressure,
- chase car lateral acceleration,
- chase car longitudinal acceleration,
- roadway type,
- level of service,
- target vehicle type,
- target vehicle range,
- target vehicle speed, and
- a series of "flags"

To sample, digitize and record these data streams at least once each second, Sierra installed a Metrabyte model DAS-8 data acquisition system in an IBM-compatible portable computer. The system accepts up to 8 analog 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 identified by Sierra were the Dell 316LT (80386 processor), Epson 286LT, and Packintell model LA3540 286. Each was equipped with a 20-40 MB internal hard disk and a 1.44 MB diskette drive. As shown in Figure 10, the computers were mounted on a foam pad placed in the center of the front seat. (The monitor shown in the picture displays the image produced by the laser-mounted camera, allowing the observer to determine when the laser is on target.)

During several weeks of shakedown testing, a variety of power supply failures, screen failures, and system crashes occurred using the Epson and the Dell onboard the Caprice. After resolution of an initial problem of the computer not retaining the date and time when shut off, the Packintell functioned without failure for over 1,000 miles of on road operation.

For future data collection efforts, Sierra is planning to further modify the Packintell computer to increase its reliability. Because it is one

Figure 10
Chase Car Passenger Compartment
Showing Portable Computer Equipped With
Data Acquisition System



of the few portable computers with two expansion slots, it is possible to install a solid state disk emulator (in addition to the data acquisition card) that uses battery backed-up memory chips. After booting the computer from the hard disk and starting up the data acquisition program, data can be written to the disk emulator and no reads of or writes to the hard disk will be required while the vehicle is in motion.

The software is configured to sample and store data from each of the ten inputs once per second. Two date-coded data files are created with a time stamp on each entry; one for the analog data and one for the laser data received over the RS-232 link. Table 1 is an example of what the data file looks like for the eight channels of analog data. The file header identifies the type of data being stored in each column.

Although data is stored once per second, the sampling, averaging, and scaling done prior to data storage depends on the input being monitored. In the case of the accelerometers, it was determined by trial and error that an average of ten samples each second was needed to damp out noise created by the action of the vehicles suspension system as it traverses roadway irregularities. A scale factor and an offset is also 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, often

Table 1
Sample Analog Data File Created With Labtech Notebook

```
"Sierra Research"
"Caprice"
"The time is 12:07:22.20."
"The date is 09-30-1991."
"AVG LONG" "AVG LAT" "SPEED" "MAP" "SW#1" "SW#2" "SW#3" "SW#4" "DURATION" "cuntime" "time"
"g/s" "g/s" "MPH" " " "POSITION" "POSITION" "POSITION" "POSITION" "SECS" "secs" " "
0.0258 -0.0492 -0.1 36.7 2 1 1 0 0 43645 00:12:07:24.539
0.0325 -0.0357 -0.1 35.7 2 1 1 0 1 43646 00:12:07:25.539
0.0303 -0.0369 -0.2 36.0 2 1 1 0 2 43647 00:12:07:26.539
0.0270 -0.0365 -0.0 36.0 2 1 1 0 3 43648 00:12:07:27.539
0.0292 -0.0367 -0.2 36.5 2 1 1 0 4 43649 00:12:07:28.539
0.0301 -0.0369 -0.1 36.3 2 1 1 0 5 43650 00:12:07:29.539
0.0280 -0.0392 -0.1 37.4 2 1 1 0 6 43651 00:12:07:30.539
0.0305 -0.0336 0.1 38.1 2 1 1 0 7 43652 00:12:07:31.539
0.0305 -0.0416 -0.0 37.0 2 1 1 0 8 43653 00:12:07:32.539
0.0509 -0.0420 -0.2 38.0 2 1 1 0 9 43654 00:12:07:33.539
0.0761 -0.0408 0.1 45.4 2 1 1 0 10 43655 00:12:07:34.539
0.1715 -0.0344 4.5 50.9 2 1 1 0 11 43656 00:12:07:35.539
0.1686 -0.0431 6.1 56.7 2 1 1 0 12 43657 00:12:07:36.539
0.1670 -0.0256 8.1 54.1 2 1 1 0 13 43658 00:12:07:37.539
0.1514 -0.0363 10.5 49.8 2 1 1 0 14 43659 00:12:07:38.539
0.1281 -0.0183 12.3 56.8 2 1 1 0 15 43660 00:12:07:39.539
0.1095 -0.0351 14.2 46.4 2 1 1 0 16 43661 00:12:07:40.539
0.0446 -0.0525 15.2 47.0 2 1 1 0 17 43662 00:12:07:41.539
0.0800 -0.0234 16.5 51.0 2 1 1 0 18 43663 00:12:07:42.539
0.0880 0.0069 17.2 52.1 2 1 1 0 19 43664 00:12:07:43.539
```

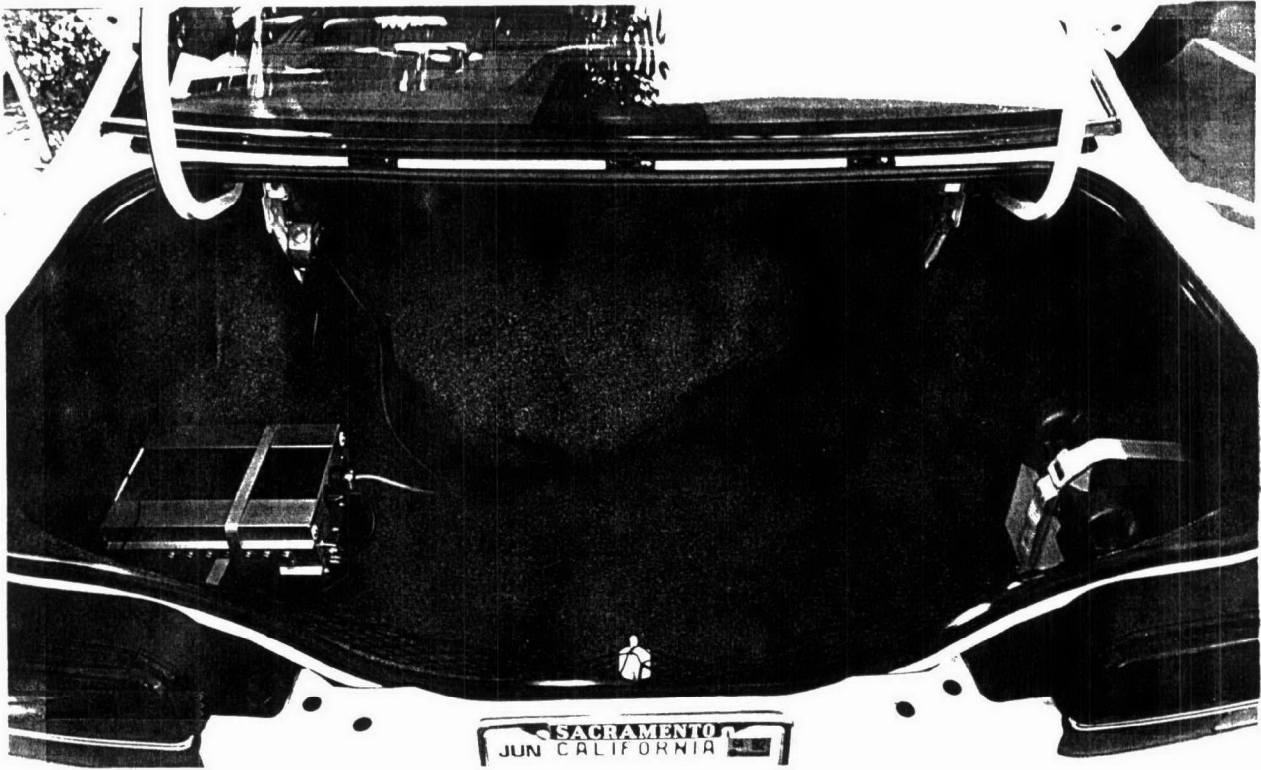
adjusted by a scale factor. For example, the speed output is calibrated to record and display the speed in mph.

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 inverter (Tripp-Lite model PV-1000 FC). Connected to the inverter 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 or not the vehicle's engine is running. In addition, the system is used to provide a more stable voltage for the laser rangefinder. 110 volt output is used to power the 8mm camcorder. Figure 11 shows the orientation of the

Figure 11
AC/DC Power Supply System



marine battery, inverter, and 12 volt power supply in the trunk of the Caprice. Figure 12 is a close up of the inverter and the 12 volt power supply.

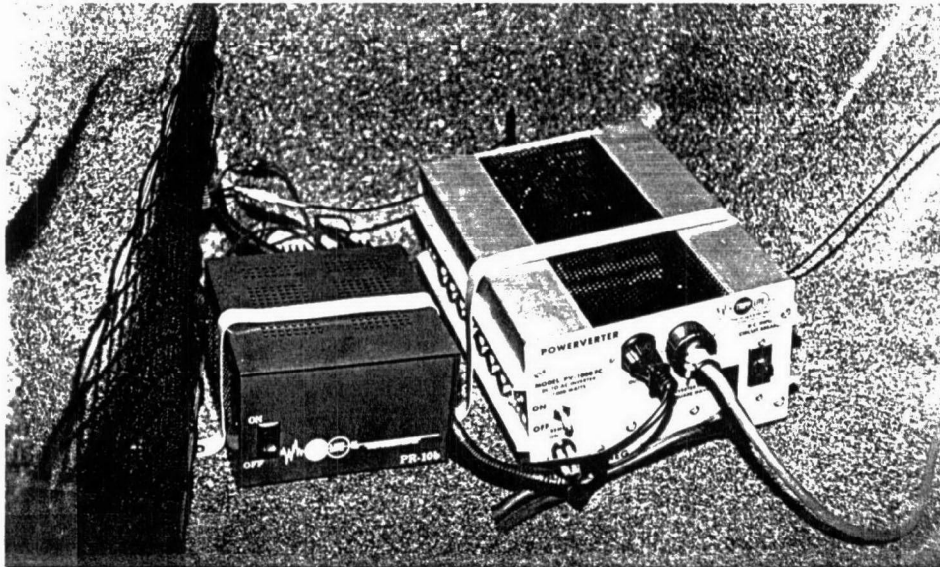
By monitoring the voltage of the marine battery at the beginning of every day, it was determined that the vehicle's alternator is capable of maintaining a full charge while the inverter and regulated power supply are used during routine operation.

Miscellaneous

Several miscellaneous features have been 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 or in resolving 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, 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

Figure 12
Power Supply System
Close-Up



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 multimeter, a spare computer and data acquisition system, a spare switchbox and a fire extinguisher.

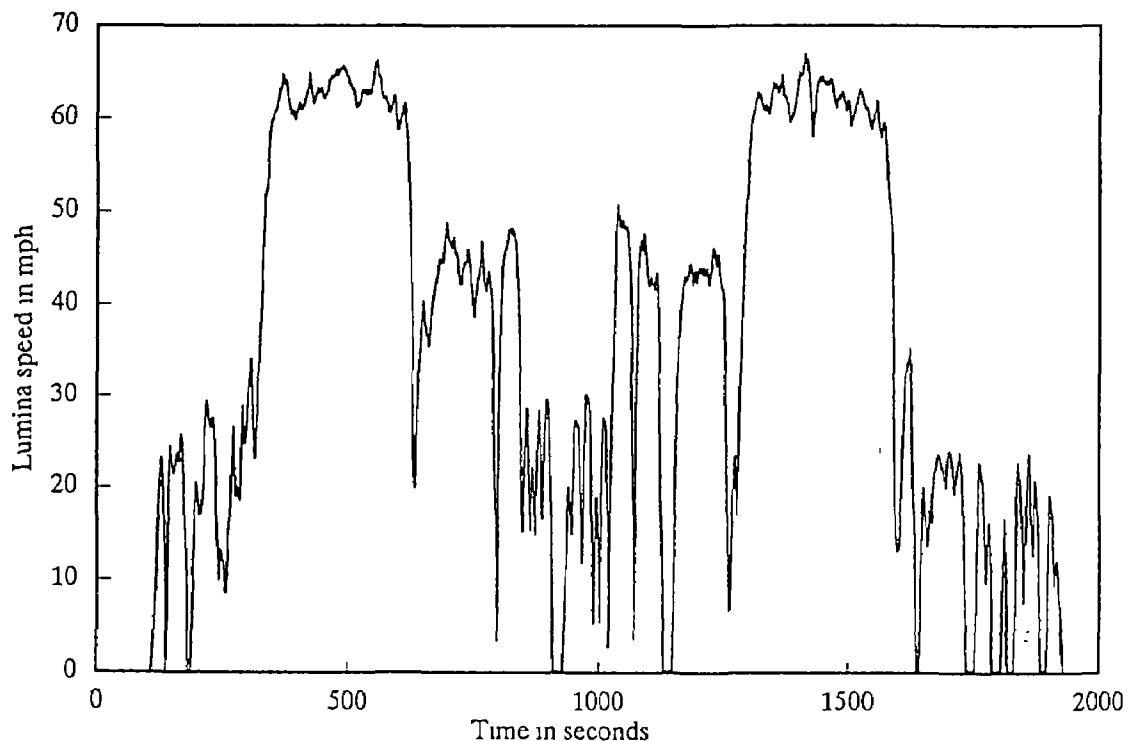
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5. Field Testing

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 13 shows the speed-time trace generated by the Lumina over one of the standard road routes used by Sierra in Sacramento, a common commuting route for individuals who work in downtown Sacramento. The route starts at Sierra's office in downtown Sacramento, goes south on Interstate 5 to the Greenhaven/Pocket residential area, and then returns to downtown along the same route run in the opposite direction. The particular trip shown in Figure 13 having been made during off-peak conditions, the first and second halves of the speed-time trace are almost mirror images of one another.

Figure 13
Target Vehicle Speed-Time Trace
For Downtown/Greenhaven/Downtown Road Route



Target is an instrumented Chevrolet Lumina.

Figure 14 shows a portion of the trip during which 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 and the other is the speed-time trace of the chase car adjusted to account for the relative speed difference measured by the laser. Differences in the traces in the 60 mph range were subsequently determined to be caused by calibration differences of the speed sensing circuitry. (The Lumina speed measurement was high by approximately 2 mph at 60 mph. Adjusting for this calibration error, the laser estimated speed of the Lumina is more accurate than indicated by the raw data.) The trace based on the laser data was generated using the Savitzky-Golay digital filter (described in Section 8)

Figure 15 is an enlargement of the portion of the trace shown in Figure 14. The individual data points are estimates of Lumina speed based on the laser data collected by the chase car and the solid line is the speed-time trace recorded onboard the Lumina. Although estimate errors greater than 1 mph are apparent at some points, major speed deviations appear to be estimated with reasonable accuracy. Figure 16 shows

Figure 14
Target Vehicle Speed-Time Trace
Compared to Laser-Based Estimate

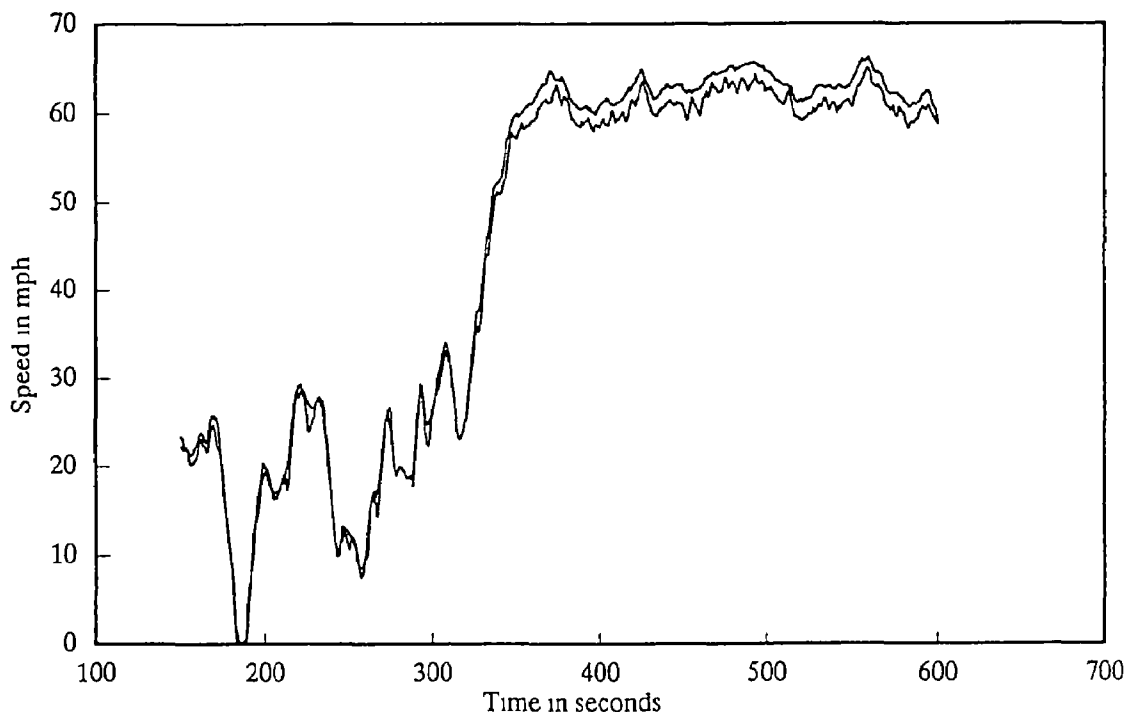


Figure 15
Target Vehicle Speed-Time Trace
Compared to Individual Laser Data Points

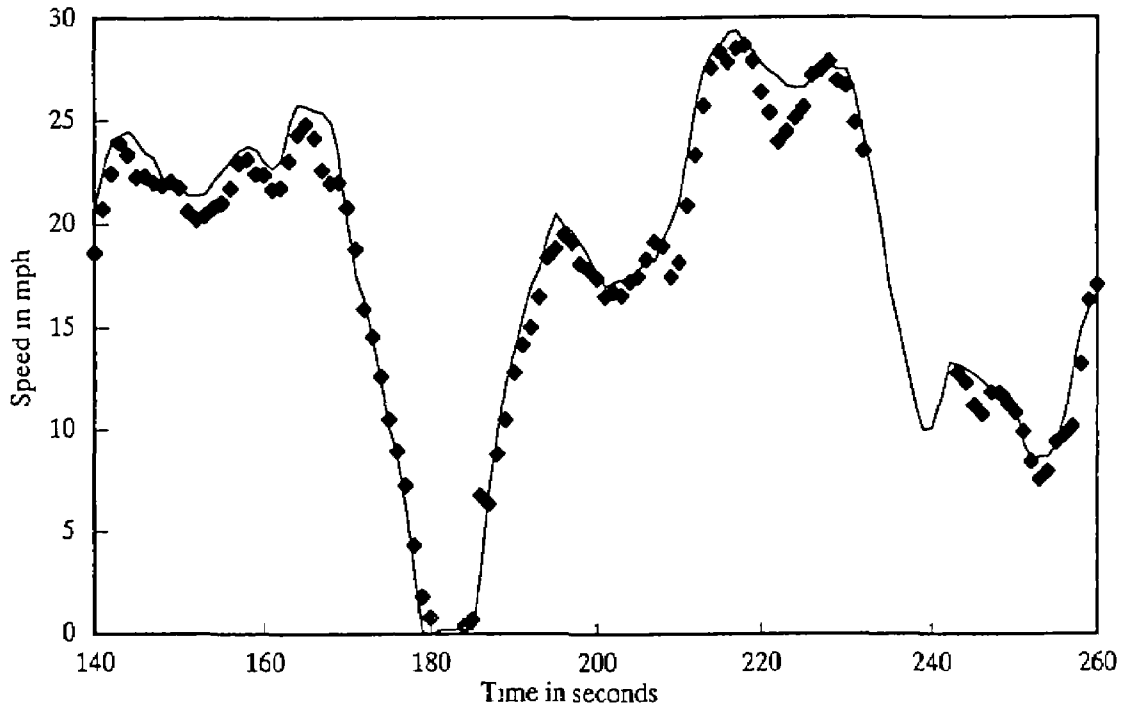
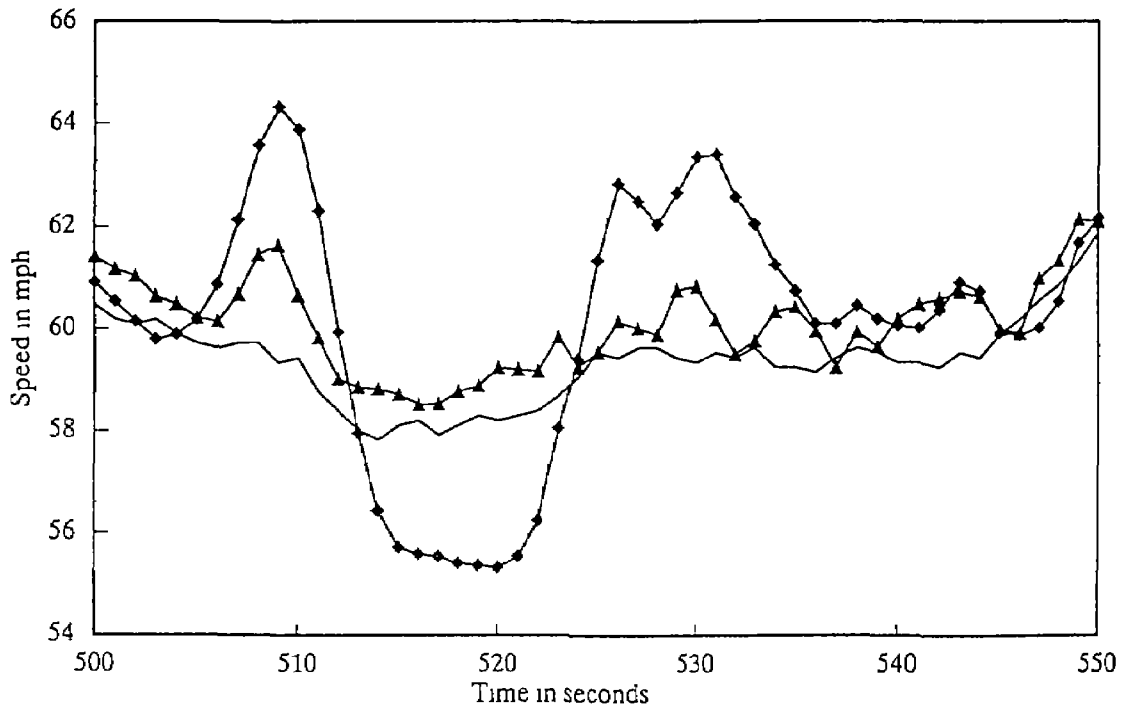


Figure 16
Target Vehicle Speed-Time Trace
Compared to Chase Car Speed-Time Trace
and Laser-Based Target Vehicle Estimate

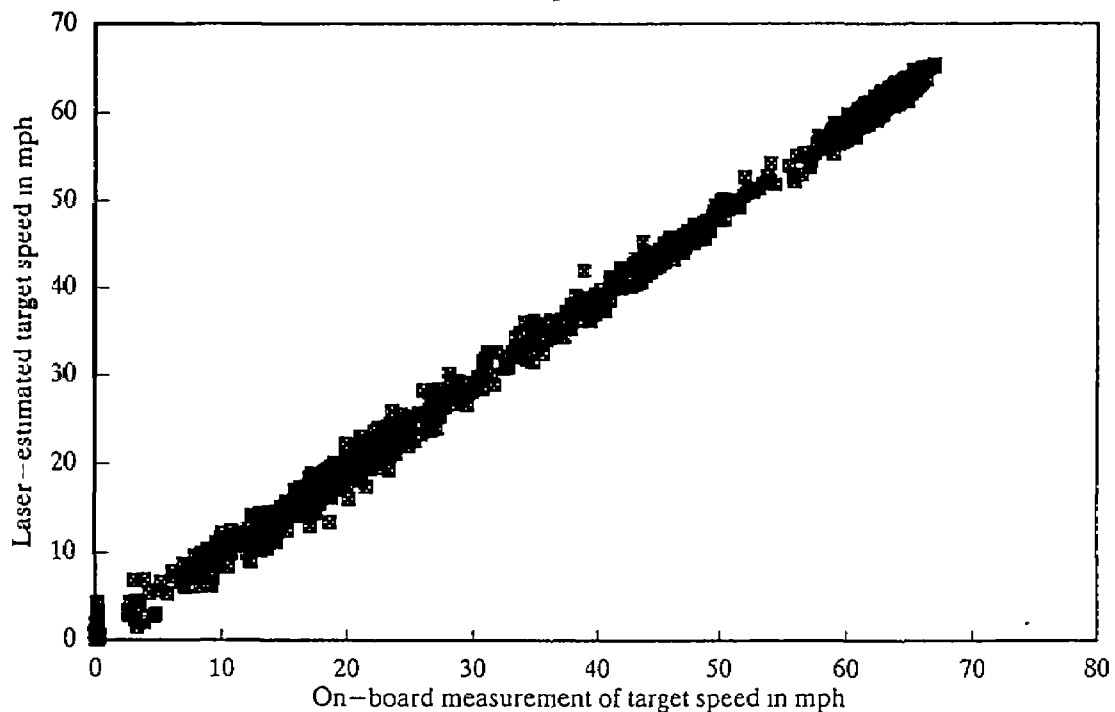


Plain solid line is on-board measured speed of target car (Lumina)
Line with diamonds is speed of Caprice. Line with triangles is laser estimate of target car speed

similar data for a higher speed portion of the trace with the Lumina speed-time trace adjusted slightly to account for the calibration error of its speedometer. In addition, Figure 16 shows the speed-time trace of the chase car itself, unadjusted by the laser data. As the figure shows, the laser data made it possible to estimate the speed of the target vehicle within 1-2 mph while the chase car speed deviated from the target vehicle speed by much more. (The difference between the chase car speed and the target vehicle speed during this portion of the trip was associated with the driver of the chase car speeding up to prevent a third vehicle from pulling in behind the target vehicle and then slowing down to restore a more comfortable following distance.)

Figure 17 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.

Figure 17
Laser Estimated Speed vs Actual Speed
of a Target Vehicle



Target is an instrumented Chevrolet Lumina.

Laser is installed in an instrumented Chevrolet Caprice which is following the Lumina.

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.

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6. Route Selection

As of the preparation of this report, funding has been established for data collection in Los Angeles, California (CARB funding) and Baltimore, Maryland (EPA funding). The methodology used for the initial selection of representative road routes in the Los Angeles area was somewhat different from the improved methodology ultimately used to select representative routes in Baltimore. In both Los Angeles and Baltimore, routes were selected to represent typical weekday operation. Weekends, holidays, and days with significant rainfall were avoided. From personal observations, it is obvious that travel under such conditions is significantly different. Resource and time constraints do not make it possible to obtain a statistically robust data set for each of these conditions; therefore, the decision was made to concentrate on typical weekday travel, clearly the highest priority category. In addition, weekday travel without precipitation is clearly associated with the most significant air pollution episodes.

Overview of Initial Los Angeles Methodology

In order to select the initial routes that the chase car followed, Sierra obtained the current trip generation matrices 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. Sierra stratified the OD pairs by trip length before selecting a representative sample of trips (OD pairs). All of the OD pairs were ranked by trip length and then sorted into 100 bins with an equal number of OD pairs. The most frequent and second most frequent OD pair within each bin was selected for each travel period of the day. In all, 600 OD pairs (200 each for each of the three periods of operation) were selected to represent travel in the Los Angeles area. To put this number in perspective, it should be noted that the three trip generation matrices contain information on more than 28 million trips.

This methodology ensured that the average length of the selected trips was equal to the average length of all trips contained in the trip generation matrix. It also ensured that the distribution of selected trip lengths correctly represented the distribution of trip lengths contained in the trip generation matrix. To confirm that the methodology was successful, the average trip length of the selected trips was computed and compared to the average for the trip generation matrix for each period of operation. In each case, the average trip lengths are essentially identical.

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. Sierra further translated the node numbers detailing each trip into road routes on a map with street names. About 100 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.

The above-described routes selected from the OD pairs represent interzonal 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. However, Sierra 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 a recent motorist survey. 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, Sierra selected specific locations to begin and end the interzonal trips so that a reasonable distribution of trip end locations was achieved and so that 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 associates a certain number of intrazonal trips occurring with each zone that appears to be roughly proportional to the number of interzonal trips associated with the zone. (We are not clear on precisely how the number of intrazonal trips is computed.) 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. Because SCAG uses an estimate

that the average intrazonal trip length is one-half the diameter of the TAZ in which it occurs within each selected TAZ, the chase car crew was directed to drive one-third very short trips (minimum 2 blocks), one-third trips approximately equal in length to one-half the zone diameter, and one-third trips nearly as long as the zone diameter. The number of intrazonal routes run was about 10% of the total intrazonal plus interzonal trips

Overview of Baltimore Methodology

Sierra obtained the trip generation matrices from the MinUTP transportation planning model employed by the Baltimore Regional Council of Governments. That model, however, has not been configured to provide travel estimates for different periods of time (i.e., peak versus off-peak). Instead, it provides travel estimates for a 24-hour period during a typical weekday. An additional distinction between the two communities is that SCAG tracks the daily trip productions and attractions for five trip purposes, whereas, Baltimore only tracks three trip purposes

SCAG

- Home-Based Work Trips
- Home-Based Shopping Trips
- Home-Based Other Trips
- Non-Home-Based Work Trips
- Non-Home-Based Non-Work Trips

Baltimore

- Home-Based Work Trips
- Home-Based Non-Work Trips
- Non-Home-Based Trips

The three trip generation matrices provided by SCAG did not distinguish among trip types. That is because the UTPS model cannot distinguish among trip types after they have been assigned* to the road network. The trips must be assigned in order to determine the distance between origin and destination zones. In contrast, Baltimore provided separate trip generation matrices for each trip type. Evidently, the MinUTP model is capable of tracking trip types after the assignment process.

Despite the differences in the trip generation matrices (i.e., trip type versus time of day), the initial methodology used to select trips in Baltimore was essentially the same as the Los Angeles methodology. The

* The assignment process determines the specific routes that trips will follow through the road network. The methodology used to select routes is designed to minimize the distance and time required to get from the origin zone to the destination zone.

trip generation matrix was ranked by trip length and trips were selected so that the distribution of selected trip lengths represented the distribution of trip lengths contained within the matrix. This approach ensured that the average trip length of the selected trips equaled the average of all trips. Using that methodology, a total of 600 trips was selected from the more than 6 million trips contained in the trip generation matrices.

MinUTP determined the network links to be followed on all interzonal trips. Sierra translated the node numbers of those links into routes on maps with road names. Upon completion of this exercise, it was apparent that an inadequate number of trips to and from the downtown area had been selected. Further analysis uncovered two problems with the original methodology. Because the model starts all trips from the centroid of a TAZ, the previous methodology introduced a bias in favor of selecting routes from TAZs of larger geographic area. As a result, too few routes were selected from small TAZs, which are the TAZs that are the most densely populated. In addition, the original route selection methodology failed to include any routes with low trip frequency. In Baltimore, there is such an extreme difference in population density between the downtown and outlying areas that the undersampling of routes beginning or ending in the downtown area was obvious. To correct the problem, routes were randomly selected from a trip-weighted compilation of routes within the modelling domain. Analysis of the random sample confirmed that it still had the proper average trip length. In addition, the amount of travel associated with the densely populated downtown area was in the proper proportion. (All future work in Los Angeles will use routes selected using this same approach.)

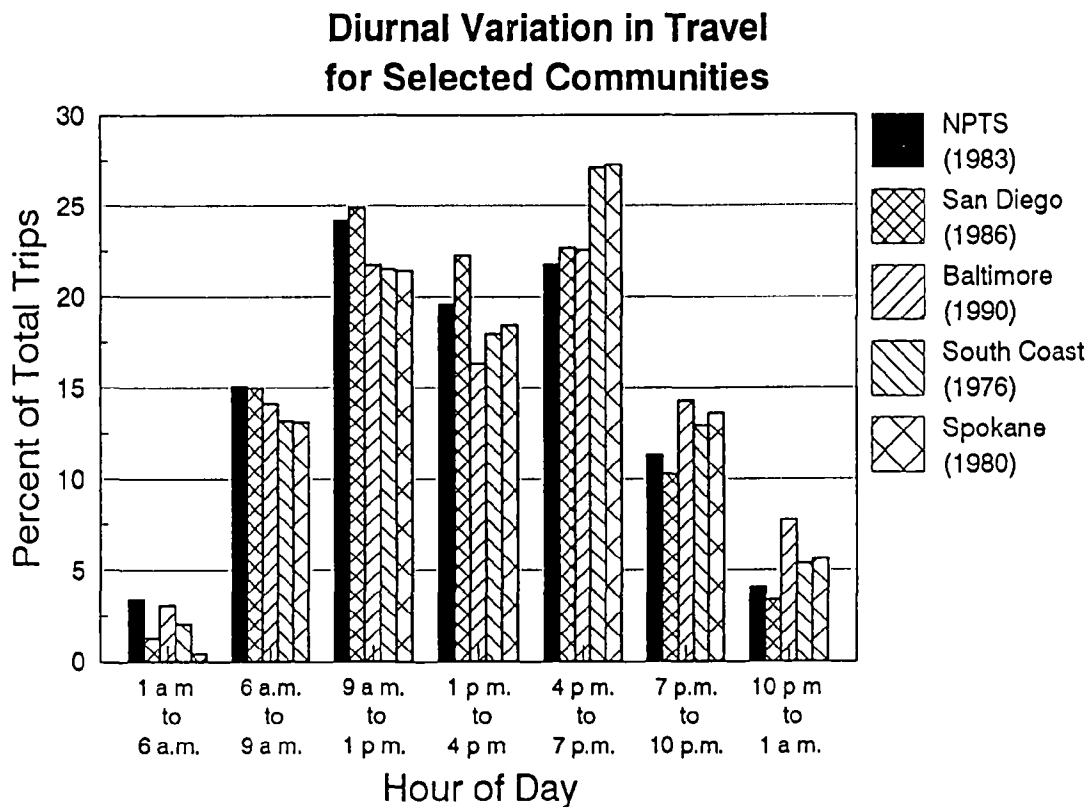
Unlike SCAG, the Baltimore Regional Council of Governments agreed to determine the routes followed for the intrazonal trips that Sierra selected. Unlike interzonal trips, there was no estimate available of the length of intrazonal trips. However, estimates of the average trip duration were available. The specific methodology employed to select intrazonal routes was to stratify the TAZs into bins on the basis of average intrazonal trip duration and select a random sample from each bin so that the average of the sample matched the average of all of the zones.

Finally, after all of the routes were selected and mapped, it was necessary to determine how to distribute them across the hours of the day. In the South Coast, the time definitions of the periods of operation aided that process. The a.m. and p.m. peaks provided enough detail on when to travel those routes, and Sierra used trip survey data provided by SCAG to determine the frequency of off-peak travel during the remaining 19-hour period. A similar approach was needed to distribute travel on a diurnal basis, by trip type, in the Baltimore area.

Unfortunately, the Baltimore Regional Council of Governments have no information on diurnal travel activity by trip type. The only data available for Baltimore on diurnal travel activity were based on 1990 traffic counts collected by the Maryland Department of Transportation. Those data, however, only track aggregate travel activity.

Given the fact that no local data were available to diurnally distribute the trips by purpose, a comparison of the aggregate travel trends observed in Baltimore, the 1984 NPTS, and several communities across the U S. was made To provide a uniform basis of comparison, the hourly data reported by several of the communities was aggregated to the hourly increments reported by the NPTS and is illustrated in Figure 18 The figure shows that while there is some variation in aggregate travel activity across the observed communities, that in general the levels of activity are relatively consistent More importantly, the levels of activity reported in the NPTS are generally consistent with those observed in Baltimore

Figure 18



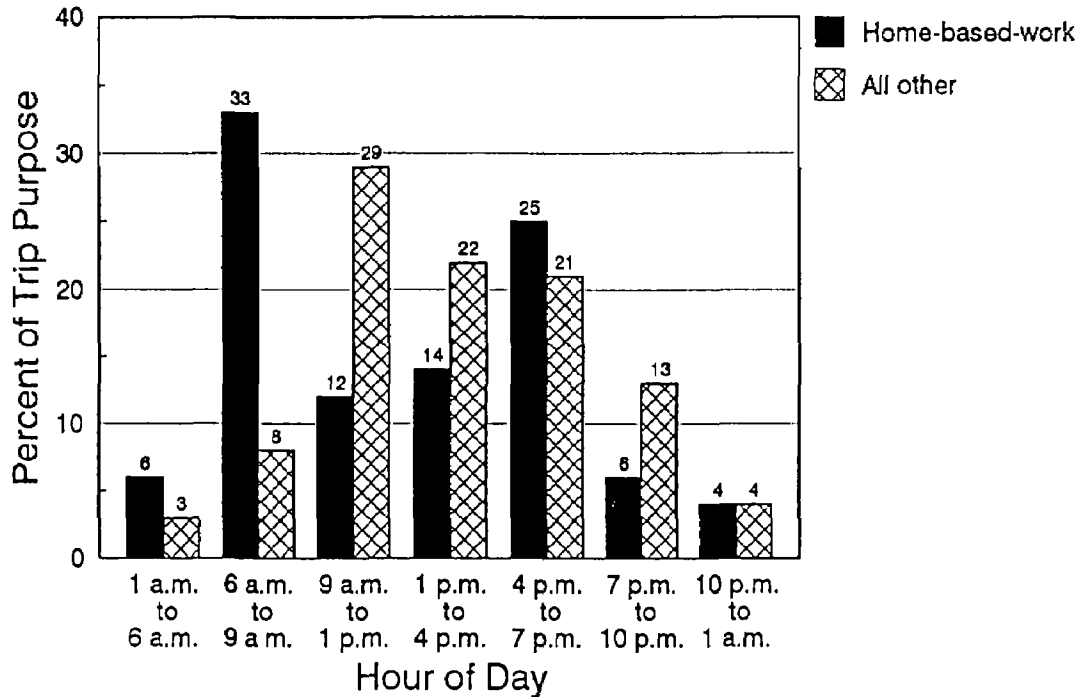
Note Based on local data and the 1983 National Personal Transportation Study The local data includes a mix of traffic count and survey data.

The 1984 NPTS data was therefore used to diurnally distribute the Baltimore trips

Figure 19 provides a summary of diurnal allocation by trip purpose based on the NPTS data

Figure 19

Recommended Allocation of Baltimore Trips by Purpose and Time of Day



Note: Based on data reported in the 1984
National Personal Transportation Study

To meet logistical constraints in planning and driving routes, some of the off-peak hours were aggregated. For home-based-work trips, the 1-6 a.m. off-peak period was retained in order to capture some of the early morning commute trips. The remaining off-peak periods were aggregated as shown in Table 2.

Table 2

Proposed Diurnal Allocation of Baltimore Trips (Percent of Trips within Trip Category)

	Home-Based Work	All Other
1 a.m. - 6 a.m.	6	-
6 a.m. - 9 a.m.	33	8
9 a.m. - 4 p.m.	26	51
4 p.m. - 7 p.m.	25	21
7 p.m. - 1 a.m.	10	20
	100	100

###

7. 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 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 is using GM's approach of following individual vehicles during major speed changes and accelerations, but then picking up other vehicles to follow when one vehicle being followed leaves the pre-selected road route or when there is any indication that motorists sense they are being followed.

Driving Protocol

Trip Beginnings and Ends - Each chase trip begins in or adjacent to the parking area that is closest to the centroid of the Traffic Analysis Zone (TAZ) indicated on the map for that particular trip. Acceptable parking areas include 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 begins when the chase car first begins moving on a public street.

Each chase trip ends at the parking area, as defined above, that is closest to the end-point TAZ centroid. Data recording ends when the chase car leaves the public street, or parks along the curb.

Standard Technique for Selection of Target Vehicles - Target vehicles are selected at random from a pool of candidates that are near the instrumented chase car and travelling in the same direction on the same route. Candidate vehicles include cars and light trucks, except those pulling trailers and emergency vehicles. Motorcycles, buses, and medium and heavy trucks will be excluded from consideration, as will any vehicle 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 can determine the frequency with which such vehicles ideally would have been targeted. Based on the perceptions of the chase car crew, 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 depends on the level of traffic. On busy surface streets with traffic in front of the chase car, the chase car crew finds 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 is subtracted per 10 mph of speed before deciding which white vehicle is closest. After selecting the nearest white vehicle, the chase car moves into the lane it is travelling in, if not already in that lane. The target vehicle will be the vehicle immediately in front of the chase car after that maneuver, which vehicle may or may not be the white vehicle.

On more lightly travelled surface streets, follow the first candidate vehicle that the chase car approaches or that passes the chase car.

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

Although there may be some concern that the focus on white cars will introduce 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 only uses white cars to select the lane of traffic to move into, and then only in certain circumstances. White cars are not used to select the lane of travel on lightly travelled surface streets or on freeway on-ramps or when the initially selected vehicle has been lost. White cars are primarily used to select the lane of travel on busy surface streets, where it is less likely that the vehicle in front of the chase car after the lane change will actually be a white car. Subsequent data analysis will make it possible to determine whether a disproportionate number of white cars ended up being target vehicles. 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 is positioned behind a candidate vehicle, the vehicle becomes a "target" for the laser.

range-finder. Target acquisition is indicated by the proper position of the chase car in the same lane as the target and at a reasonable range (less than 300 feet). When the target has been acquired, the observer records the target type using the rotary selector switch and records the start of chase by turning on the target switch.

Following a Target - The chase car driver attempts to remain behind the target, approximately matching its accelerations and decelerations, to the extent possible without arousing suspicion by the target driver, disrupting traffic or creating a safety hazard. The chase car makes lane changes with the target vehicle only when it appears that the target vehicle is making a passing maneuver, and not preparing to turn off the route. The distance of the chase car behind the target is to be not more than about 300 feet and not less than a safe following distance (approximately one car length for each 10 mph, depending on conditions). For instance, in free-flowing traffic on wet pavement, maintain a following distance greater than on dry pavement. In very slow stop-and-go traffic, it is permissible to "tailgate" the target.

If, at any time, the target acquisition is lost or is about to be lost even momentarily, e.g., around a sharp curve or at a sharp grade change, the observer immediately turns off the target switch, turning it on again only if it is clear that the target has been reacquired with the laser range finder.

Deselection of a Target - Each selected target is followed as long as reasonably possible. If a target cannot be followed safely through a lane or speed change, or if it appears to be deviating from the preplanned route, it is deselected and a new target chosen. (As discussed in Section 8, the potential bias associated with losing aggressive drivers is addressed during data analysis.) In that case, the vehicle immediately in front of the target vehicle becomes the new target if it is a candidate vehicle and if it is in laser range. If there is no vehicle within laser range when the original target is lost, then the protocol for initial selection of a target vehicle is employed.

The target is also deselected if it stays in a queue of vehicles apparently waiting to make a turn off of the preplanned route. If a third vehicle comes between the target and the chase car, a new target is selected using the standard protocol unless the third vehicle moves away before a new target is identified and acquired, in which case the original target is reacquired and chase of that target is resumed. The percentage of target vehicles that are reacquired previous targets will be estimated during data analysis.

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

If the driver of the target vehicle exhibits erratic behavior, such as sudden stops or starts, or apparent nervousness about being followed (e.g., by frequent reference to the rear view mirror), this may create a safety hazard. If such erratic behavior or anxiety is detected, the chase of that vehicle is ended immediately and a new target is selected.

Chase Car Travel at Other Times - At all times when the chase car is not following a target, the chase car is driven in a fashion that approximately matches the general flow of through traffic, i e., travelling faster than some vehicles and slower than a similar number of vehicles (excluding vehicles that are merging right or traveling slowly in order to exit), consistent with safe driving practices Lane changes are made by the chase car only as required to acquire a target, to follow a target, to change routes, 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 is missed, data recording is ended immediately. The chase car is driven back to a point on the route before the miss occurred, previous driving conditions (e g , lane, speed) are re-established in the correct direction, and data recording resumes at the point where the miss occurred

Equipment Operating Procedures

A variety of "check lists" are used to assist in achieving consistent and efficient data collection during routine operation The check lists are printed on 5"x7" laminated cards that are held together by a clip installed on the dashboard of the vehicle The applicable card is rotated to the first position in the stack

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 inverter 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 inverter
- ___ Disconnect cables and remove computer and camcorder
- ___ Turn off and disconnect phone

8. Data Processing

By the end of each day in the field, all of the data files are copied to high density (1.44 MB) diskettes. These diskettes are used to transfer the trip files to Sierra's in-house VAX computer system. The trip files on the portable computer hard disk are retained until the diskettes have been successfully copied to the VAX. To further reduce the chances that any data are lost, the original diskettes are archived and files copied to the VAX system are backed up onto 8mm tape.

Trip Data Analysis

An ever expanding SAS program is being used to screen the data recorded during each trip for obvious errors (e.g., laser range discontinuities, out of range accelerometer measurements, etc.) and compute descriptive statistics for both the chase car and target vehicles. The program is also designed to digitally filter range measurements from the laser rangefinder. 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.

The descriptive statistics produced by the program include 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 each second from successive speed measurements),
- distribution of road grade intervals (based on the difference of total acceleration, measured by accelerometer 10 times per second and averaged over 3 seconds, and on-road acceleration, calculated every second by differentiating speed measurements and averaging over three seconds), and
- PKE (positive kinetic energy of acceleration per mile)

Where possible, each of the above-listed statistics is computed separately for total travel by the chase car, travel by the chase car when it is not following a target vehicle, travel by the chase car when it is following a target vehicle, total target vehicle travel, and the composite of the chase car and the target vehicles

In addition to the above-listed statistics, speed-time traces will be plotted for each route. More detailed analyses, including consideration of differences between different types of target vehicles, are possible with minor modifications to the software. However, the data collection effort may have to be expanded for such analyses to be worthwhile.

Digital Filtering of Laser Range Finder Data - The laser range finder used for the data collection in Baltimore and the initial data collection in Los Angeles was designed and configured to provide, at intervals of one second, measurements of the range or distance in feet to the target vehicle ahead and relative speed of the target vehicle in mph. If there is no target or the range finder is unable to "lock on" a reading of either range or speed, for whatever reason, the laser provides a default output of "9999".

Currently, only range data from the laser, together with speed data collected from the instrumented chase car, are used to analyze kinematics of the target vehicle. In particular, the relative speed of the target vehicle is computed by smoothing and differentiating the range data for each second through the use of a Savitzky-Golay digital filter, and adding to that the speed of the chase vehicle to obtain the absolute speed of the target vehicle. A nine-point digital filter is used with a cubic/quartic polynomial first derivative. As described in the original paper by Savitzky and Golay*, this technique is analytically equivalent to performing a linear least square best-fit of a cubic or quadratic polynomial to nine equally-spaced data points (nine successive range measurements at one second intervals), differentiating the polynomial, evaluating it at the center of the nine points, and then successively advancing the time window one second, as with a moving average.

Optimal configuration of the digital filter in the current application, has required some experimentation. A nine-second analysis has been found to provide the best compromise between a filter which is able to capture the main features of a hard acceleration or deceleration that may be as brief as 2-3 seconds, while still providing an objective "best fit" smoothing of discrete range data. In addition, optimization in the current application has required the recognition of a slight delay (between one-half and one second) between the time the laser measurement is made and evaluated and when the data are retrieved over an RS232 serial interface line by Labtech Notebook, an on-board data logging program running on a laptop computer. This delay is accommodated by

* "Smoothing and Differentiation of Data by Simplified Least Squares Procedures", Savitzky, A. et al, Analytical Chemistry, Vol. 36, No. 8, July 1964, p. 1627-1639.

applying the digital filter to successive ranges of data that are centered on times that precede the second of interest by one second

Quality Control Checks - Before data from a particular road route are included in the computation of descriptive statistics, the second-by-second speed data are checked to identify likely problems. Acceleration or deceleration rates in excess of the capabilities of the chase car are 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 is 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.

Video Tape Analysis

Review of the video tapes will be used to double check apparent errors identified during second-by-second data analysis of acceleration rates. Review of the tape will indicate whether a data stream with out-of-range acceleration could conceivably have been valid. In addition, the video tape will be used to determine the reason for any other questionable characteristics of the speed/time trace for each trip. Depending on the length of time periods with obvious speed data problems, substitute speed estimates can be computed from available accelerometer data. However, it is expected that this approach will be limited to periods of less than 10 seconds of apparent data errors.

Review of the video tapes will also be 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 is caused by aggressive or unsafe behavior on the part of the target vehicle driver can be estimated. During this same review process, the number of times that previous targets are re-acquired can also be determined.

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