

**DATA COLLECTION FOR DRIVING CYCLE DEVELOPMENT:
EVALUATION OF DATA COLLECTION PROTOCOLS**

FINAL, OCTOBER, 1999

by

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Prepared as part of the CAMP Initiative
Funded by:
California Department of Transportation
T.O. 16

1. BACKGROUND	1
1.1. STUDY OBJECTIVES	1
2. BACKGROUND FOR THE CHASE CAR METHOD	2
2.1. CHASE CAR TECHNOLOGY	4
2.1.1. Chase Car Selection.....	4
2.1.2. Range-Finder Laser.....	5
2.1.3. Chase Car Speed Measurement System.....	5
2.1.4. Road Grade Measurement System.....	7
2.1.5. Visual-Observation Equipment.....	7
2.2. CHASE CAR PROTOCOL	10
2.3. VARIABILITY IN THE CHASE CAR DATA	11
2.3.1. Regional Variability	11
2.3.2. Missing Target Car Data.....	16
2.3.3. Driver Variability	18
2.4. DIFFERENCE IN DRIVING BEHAVIORS ACROSS REGIONS	22
3. INSTRUMENTED VEHICLES	45
3.1. CITY SELECTION	46
3.2. DATA COLLECTION PROTOCOL.....	46
3.3. TECHNOLOGY	47
3.4. NUMBER OF VEHICLES IN STUDY.....	48
3.5. DIFFERENCES IN THE ANALYSES.....	48
3.6. COMPARISONS OF DRIVING DATA COLLECTED BY TWO DIFFERENT PROTOCOLS	49
4. THE GPS PROTOCOL.....	57
4.1. REVIEW OF THE LEXINGTON STUDY	57
4.1.1 Results from Data Retrieval Operation.....	59
4.1.2 Base Map and Map Matching Analysis.....	62
4.1.3 Attitudinal Survey	63
4.2. REVIEW OF THE LEXINGTON BENCH TEST	65
4.2.1 Percents of valid records.....	67
4.2.2. Positional accuracy	68
4.3. CONCERNS WITH THE GPS PROTOCOL.....	68
4.3.1. Potential loss in driving information of short trips	69
4.3.2. Potential loss in driving information in certain areas and facility types.....	69
4.3.3. Non-Zero Speeds measured while the vehicle is at stationary	70
4.3.4. GPS Vs Differential GPS	70

4.3.5. Accuracy of base map.....	70
4.3.6. Automatic Collection of GPS data.....	70
4.3.7. Location to install GPS receiver.....	70
4.3.8. Power Supply.....	71
4.3.9. Communication Problems between PTS Software and the GPS receiver.....	71
4.3.10. Potential Protocol Improvement via Intelligent Transportation System (ITS).....	71
5. CONCLUSIONS	72
5.1. IMPROVEMENTS TO THE CHASE CAR METHOD	72
5.1.1. Route Choice and Sampling.....	73
5.1.2. Lane Choice	76
5.1.3. Treatment of Missing Data.....	77
5.1.4. Vehicle.....	77
5.1.5. Technology.....	77
5.1.7. Locations and Timing of the Data Collection.....	80
5.2. GLOBAL POSITIONING SATELLITES (GPS)	80
5.3. TECHNOLOGY COMBINATIONS.....	81

1. BACKGROUND

Significant efforts have been undertaken to collect data describing driving behavior in the United States for the purpose of constructing emissions cycles. Two primary methods have been employed to collect data: the use of a chase car to mimic driver behavior and record speed and acceleration data from sample vehicles, and the installation of onboard instrumentation in vehicles to record speed and acceleration data. New concepts are also being developed, for instance using global positioning satellite (GPS) technology to record vehicle movements on trips taken by a population of interest.

The purpose of the study was to evaluate the potential biases associated with the use of current chase car protocols as well as identifying and recommending solutions to problems in the actual data used to determine driving cycles. To evaluate potential biases in the chase car protocol, data collected in Los Angeles, CA in 1992 as well as chase car data from Baltimore, MD and Spokane, WA were examined. The chase car protocol itself was also investigated. Consideration was given to the relative advantages and disadvantages of instrumented vehicle and chase car data.

1.1. Study Objectives

The current study has several objectives: 1) to review and evaluate the current chase car protocol; 2) to review and compare instrumented vehicle data to chase car data; 3) to evaluate GPS technology for use in future data collection procedures; and, 4) to recommend refinements to the existing chase car protocol. The object is to suggest adjustments to the current chase car protocol and to explore several possible new data collection methods.

2. BACKGROUND FOR THE CHASE CAR METHOD

It has long been acknowledged that the Federal Test Procedure (FTP) does not adequately reflect normal driving patterns, yet for many years the FTP has formed the basis for mobile source emissions inventory estimations. In 1990, the California Air Resources Board (CARB) initiated a project aimed at constructing new driving cycles to better represent actual driving behavior, and thus improve mobile source emissions modeling (Gammariello *et al*, 1996). To accomplish this, driving data, specifically speed-time profiles, were collected on road networks in the Greater Metropolitan Los Angeles area in April and May of 1992 resulting in a database known as LA92. This was accomplished by using what is commonly referred to as the chase car protocol.

In this protocol, a chase car installed with a range-finder laser system collects second-by-second speed-time profiles from hundreds of target vehicles assumed to represent typical driving behavior. In the LA study the chase car followed predefined routes “locking-on” to target vehicles with the laser while simultaneously collecting data on such variables as road grade, type of vehicle targeted, road facility type and level of service (LOS), in addition to speed and acceleration (Austin *et al*, 1993).

The chase car protocol used to collect the LA92 data was a refined version of past protocols used by General Motors (GM) and the US Environmental Protection Agency (EPA). GM’s protocol involved a chase car following a vehicle from its trip beginning to its trip end, attempting to match the target cars’ major speed changes, accelerations and decelerations. Two primary concerns arose when using this protocol. First, the potential for detection and resultant behavioral change by the target car driver was considered problematic. Second, the crudeness of acceleration and deceleration event measures likely resulted in inaccuracies in the data. The chase cars employed in the GM and EPA studies were not instrumented with the range-finder laser technology used in the LA study. Instead, the data collected in these studies were dependent on the chase car drivers’ abilities to accurately match speed and acceleration of target vehicles. The protocol and technology employed by EPA were similar to that of GM. Additionally, EPA’s method could not account for the possible effects of changing road grades (Austin *et al*, 1993).

In addition to the LA92 data, chase car data has also been collected in Baltimore, MD (B92), and Spokane, WA (S92). Los Angeles (LA), Baltimore, and Spokane were specifically chosen to represent driving in different parts of the country and under different conditions. Table 1 illustrates the primary features of these locations that made them attractive for these studies (Carlson and Austin, 1997).

Although all three sets of data were collected using the same protocol, to date only LA92 has been used as a stand-alone data set in developing driving cycles (*i.e.*, development of the UC). Possible regional differences in driving have not yet been considered in emissions cycles.

Table 1. Cities Chosen for Chase Car Data Collection

	<i>Population Level</i>	<i>Public Transport</i>	<i>Isolation Level</i>
<i>Baltimore, MD</i>	High	Good	Not Isolated
<i>Los Angeles, CA</i>	High	Very Poor	Not Isolated
<i>Spokane, WA</i>	Low	Very Poor	Isolated

To date, there has been some, albeit limited analysis of the chase car data (Austin *et al*, 1993), including computation of descriptive statistics as well as presentation of the distribution of instantaneous acceleration rates and the distribution of road grade intervals for the LA92 database. Additional investigation also included a comparison of driver behavior, using different drivers, three of whom were chase car drivers in the LA, Spokane and Baltimore studies. The limitations of this driver behavior study, which the authors note, include the small number of non-random drivers sampled (three in the chase car driver group and seven in the public driver group) and the possibility that important variation in driver behavior is masked because traffic levels, routes and vehicle types were controlled. The results of the study indicated: 1) that a significant difference in driving behavior in average speeds and accelerations occurred when drivers used a high performance vehicle instead of a standard passenger car; and, 2) that driving behavior between chase car drivers as a group and public drivers as a group did not differ significantly in average speeds or accelerations (Austin *et al*, 1993). This second conclusion contradicts previous research (Holmén and Niemeier, 1998) that used a random set of drivers and found significant differences in driving patterns.

Since collecting the LA92 data, both CARB and EPA have used it in creating driving cycles. EPA constructed facility-specific cycles using LA92 in conjunction with S92 and B92. The EPA used average speed, acceleration frequency, trip length and level of service (LOS) variables in creating its cycles. The CARB constructed the Unified Cycle (UC), also using the LA92 data. Average speed, acceleration frequency and trip length, but not LOS, were used in developing the trip-based UC cycle. Additionally, CARB constructed what is known as the Unified Correction Cycles (UCCs) using the LA92 data to derive speed correction factors for speeds between 10 mph and 50 mph. Because LA92 contains limited data for the higher and lower speed ranges, CARB supplemented it with 1992 instrumented vehicle data collected by the EPA in Baltimore, MD, Spokane, WA and Atlanta, GA. The instrumented vehicle data were used for speeds between 0 and 10 mph and 55 and 75 mph.

2.1. Chase Car Technology

The chase car is an instrumented vehicle that records second-by-second data as it follows a pre-determined route within a selected city. When possible, the chase car uses a laser to record the relative distance between it and a target vehicle. With this information, it is possible for second-by-second speed and acceleration data to be estimated for the target vehicle. In addition to the laser, the chase car is equipped with video recording equipment and manual recording equipment for visual observations made by the driver and observer.

This section summarizes the selection of the chase car and other technology used for collecting driving data in the LA92 project. Some potential biases and errors that may be caused by these technologies are also discussed. In particular, the following are described: 1) the selection of the chase vehicle, 2) the specifications of the range-finder laser, 3) the chase car speed management system, 4) the road grade measurement system, and 5) the visual observation equipment on-board the chase vehicle. These technologies were investigated because they affect target driver perception and the precision of the data recorded for target vehicles. Additionally, they distinguish accelerations and decelerations due to changing road grade from driver-induced accelerations and decelerations, and they help verify traffic conditions and record information concerning facility types, congestion levels and the type of target vehicle being recorded.

2.1.1. Chase Car Selection

In collecting the LA92 data, criteria were used to select the chase car. The first priority was that the chase car must have enough room between the grill and the radiator/condenser to install a range-finder laser system. The second and third priorities were that the chase car should be inconspicuous and have a high power-to-weight ratio. Two candidates were identified: the Lincoln Town Car and the Chevrolet Caprice. The Chevrolet Caprice was selected because the space behind the grill was easiest to access, the vehicle had a “somewhat” less conspicuous appearance than the Lincoln, particularly from the front, and the vehicle price was substantially lower, while providing nearly the same power-to-weight ratio as the Lincoln (Austin *et al*, 1993).

It was important that the chase car itself not be an influential factor on the driver behavior of the general population. Although thought to have a less conspicuous appearance than the Lincoln Town Car, the Chevrolet Caprice is also a popular model for police vehicles. Clearly, the most important implication of identifying the chase car as a police vehicle is that drivers may drive in a less aggressive manner or may

even change lanes to let the chase car pass them. As a result, the data collected from the chase car may not truly represent natural driving behavior.

To try to address this problem, the Chevrolet Caprice was specially ordered with aluminum wheels, white sidewall tires and tinted rear glass. The color white was selected because it is the most common color for light-duty vehicles and because it results in less heat build-up in the trunk and passenger compartments (Austin *et al*, 1993). The chase car was also ordered with a trailer-towing package consisting of higher rate springs and a higher rear-end ratio (3.08:1) to improve mobility performance. All of the windows behind the front seat were 80 percent tinted to reduce the visibility of a video camera installed inside the vehicle (Austin *et al*, 1993). Figure 1 shows a front view of the Chase Car.

2.1.2. Range-Finder Laser

The range-finder laser system used in the LA92 chase car is a single beam laser designed to measure the distance between the chase and target vehicles. Figure 1 shows the position of the laser system installed in the chase car. The system can be seen through a small cut on the grill from a front view. According to Sierra Research, Inc. (SR), who performed the LA92 study, “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 view mirrors” (Austin *et al*, 1993, p. 24). The system provides range readings twice per second. Testing of the range-finder system revealed that the system provided range measurement with a precision of ± 1 foot (Austin *et al*, 1993). This may cause corresponding errors in the estimated target car speeds of up to 2 feet/second (1.36 mph).

2.1.3. Chase Car Speed Measurement System

A GM pulse-generator-type speed sensor was used to collect speed measurements. However, this system sometimes produced spikes in speed readouts, especially for speeds below 10 mph (Austin *et al*, 1993). To compensate for this, SR developed a supplemental speed measurement system that provided more accurate readings and did not generate spikes. The system was comprised of four-mounted shaft magnets and a pick-up coil. A pulse from a magnet was generated every time the magnet passed the pick-up coil. A counter/timer chip recorded these pulses. The count was then translated to speed as follows: four pulses equaled one revolution of the shaft, which was equal to 3.08 times the rear axle revolution. The chase-car wheel static circumference was 83 inches, and assuming no tire slippage occurred, 165 pulses translated to a speed of 60 mph (Austin *et al*, 1993).

Figure 1

Field testing by SR revealed that the actual pulse count was close to 165. The slight difference between the theorized and the actual pulse count was believed to be caused by the difference in dynamic tire circumference from that of the tire circumference in a static state. Therefore, SR concluded that the system could estimate the speed of the chase car with a precision of 0.38 mph. The error of the range finder laser and the speed measurement system together indicate that target speeds could be estimated with a precision of 1.74 mph (0.38 mph + 1.36 mph). It should be noted that, in this system, the estimated speed is the average speed of the past second, not an instantaneous speed.

2.1.4. Road Grade Measurement System

The road grade measurement system, custom-designed by SR, was used to create a distribution of the road grade intervals experienced during chase car runs (Austin *et al*, 1993). It consisted of two Lucas NovaSensor unidirectional accelerometers mounted perpendicular to each other. One was installed parallel to the lateral direction, and the other parallel to the longitudinal direction of the chase car. The former is used to estimate the lateral acceleration occurring when the chase car turns, while the latter is used to estimate the longitudinal acceleration of the vehicle, which is the combination between the speed acceleration due to the driver and the acceleration due to the roadway grade. The difference between the longitudinal acceleration measured from the road grade measurement system and the speed acceleration estimated from the speed car measurement system is the grade of the roadway.

When the vehicle is moving, the system can estimate the road grade with a precision of a few percent of grade (Austin *et al*, 1993). It should be note that the estimated grade represents the road grade that the chase car is driving on, which is lagged from that of the target vehicles. The amount of elapsed time depends on the speeds and distances between the target and chase cars.

2.1.5. Visual-Observation Equipment

The chase car was installed with a video camera and a switch box for recording data such as type of road, level of service (LOS) and target vehicle type based on visual observation. A camcorder (Sony CCD-F70), installed between the front and back seats, was used to record the traffic in front of the chase car, including a partial view of traffic in adjacent lanes. The tapes recorded from the video camera were used primarily to verify the data retrieved from the other data acquisition systems.

The switch box had four rotary switches to collect the following data:

- type of roadway
- level of service (LOS)
- type of target vehicle
- unusual conditions that might have occurred.

Each rotary switch had seven positions, each position having a unique voltage. The first switch identified the type of roadway from seven categories: diamond lane, freeway, on/of ramp, arterial/collector, local, private and other. The LOS switch categorized LOS into 7 levels from A to F plus an “other” condition, “such as extreme congestion caused by a major traffic accident” (Austin *et al*, 1993, p. 27). To specify the LOS, the observer used the Highway Capacity Manual (HCM) illustrations shown in Figure 2 to classify traffic conditions. The vehicle-type switch was used to classify the types of target vehicles followed. Vehicles were classified into six categories: high-performance, other (includes standard passenger vehicles), old, light-duty truck 1, light-duty truck 2, and none. The last rotary switch was used to make note of unusual conditions, up to six incidents, that might have occurred during the data collection period.

Data collected via the observer-controlled switchbox may contain the results of human errors or unconscious biases. Some of the data collected were largely subjectively evaluated. Subjective decisions were made by agreement between the observer and the chase car driver and thus, were dependent on their knowledge and the reference material provided to them. Other driver-observer pairs may classify the same realization differently. For instance, review of the LA92 video recordings indicated that LOS guidelines were inconsistently applied and that sometimes the observer and driver disagreed on the appropriate LOS to record. In other words, a road segment appeared to be LOS A on the videotape but would be recorded as LOS C, or when on the same facility type (at different times), traffic conditions classified as LOS A previously might be classified as LOS C. It also appeared that the observer and driver often forgot to update the LOS when entering a new facility type or approaching new traffic densities on the same facility. When the driver-observer pair erred, they seemed to consistently err on the side of higher LOS levels, rather than lower. This indicates that congestion may not be as severe on the chosen routes as was recorded. Sierra found no significant difference between SAFDs in LOS A-C when developing EPA's freeway driving cycle with this data (Carlson and Austin, 1997). For Arterial/Collector cycles, Sierra found similarities in average speeds in LOS A and B, C and D, E and F and grouped them

accordingly, to develop only three cycles (Carlson and Austin, 1997). The videotapes indicate this could be an artifact of the data recording procedure rather than a reflection of actual driver behavior.

Figure 2

The use of the same photograph to categorize LOS for all types of roadways in the LA92 project conflicts with the conventional approach, which utilizes different classifications for different types of roadways. Figure 2 actually illustrates operational LOS characteristics for a freeway. To specify LOS on a freeway, the HCM provides quantitative criteria to specify LOS using the (vehicle/mile/lane) or average travel speed (mph). The recommended scheme for classifying LOS on ramps is similar to that used for freeways, but with different density thresholds. The HCM provides methods for categorizing LOS for arterials and collectors, using an average-through-travel measure. Referencing the series of illustrations used to classify LOS on freeways would certainly result in at least some misclassification of LOS on arterials and collectors as well as on ramps (Niemeier *et al*, 1998). The HCM does not outline standard methods for assigning LOS on local roads, private roads or for diamond lanes.

2.2. Chase Car Protocol

There are two instructions in the current chase car protocol that are important for the purposes of: 1) the target car selection protocol for busy surface streets and freeways, and 2) the data collection protocol for chase car drivers when target vehicles are not available. In the first, when entering a new roadway, the target car selection protocol calls for the chase car driver to follow the first vehicle encountered in front that is in the same lane as the closest white vehicle. Specifically, the closest white vehicle is defined as, “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” (Austin *et al*, 1993, p. 53). If the chase car is in the same lane as a white vehicle and more than one white vehicle is present, “one car length is subtracted per 10 mph of speed before deciding which white vehicle is the closest” (Austin *et al*, 1993, p. 53). In the field application of the selection process can be complex under rapidly changing traffic conditions, making execution of the protocol difficult. Review of the LA92 tapes showed that the chase car protocol was inconsistently applied, particularly with respect to the employment of the “white car protocol.” Many targets were not acquired even though the video suggests it was possible to acquire them. Both the driver and observer seemed to have difficulty managing the complicated route structure given a lack of familiarity with the route/area. This seemed to impact the attention given to acquiring targets. This suggests that the target car selection protocol may require refinement of certain elements essential to the data collection process to avoid important biases.

With regard to point 2, data collection in the absence of target cars, the chase car protocol calls for drivers to “drive in a fashion that approximately matches the general flow of through traffic,” driving, “faster than some vehicles and slower than a similar number of vehicles” (Austin *et al*, 1993, p. 54).

In the absence of target vehicles, the chase car records its own vehicle movement data. These data are then used to replace missing target data points in the database. This creates what is known as the “composite” trace, which is a combination of target and “non-lock” chase car data that is then used to create Speed Acceleration Frequency Distributions (SAFDs) or Watson Plots, the cornerstone of driving cycle development. From LA92 and other chase car databases, it is clear that relatively little data is actually obtained from the target vehicles and thus, the driving behavior of the chase car drivers becomes very important.

2.3. Variability in the Chase Car Data

To conduct further analysis of the chase car method, we evaluated three different areas of variability that could arise in data collection: 1) the variability between driving data collected in different cities; 2) the variability in the amount and type of missing data in each city’s data set; and, 3) the variability in driving behavior between “non-lock” chase and target car drivers.

2.3.1. Regional Variability

To examine regional variation, we considered the composite data from B92, S92 and LA92 with respect to different variables: LOS and facility type. The S92 and B92 databases contain the same type of data and variables as LA92. B92 includes 191,119 seconds of data, representing 218 routes. S92 contains 175,137 seconds over 249 routes. LA92 contains 102 chase car routes, resulting in 100,709 records (seconds) of data. Each database contains 24 variables, recorded on a second-by-second basis.

2.3.1.a. Variation in LOS

In each of the above studies, the chase car observer assigned a LOS based on his/her view through the windshield of the chase vehicle. The observer used a switchbox mounted on the chase car’s dashboard to manually record the LOS (Austin *et al*, 1993). Table 2 shows the variability in the assigned LOS in chase car data collected in different cities.

Table 2. Percent Seconds Spent in Each Level of Service (LOS)

	LOS (% seconds)					
	A	B	C	D	E	F
<i>Baltimore</i>	46.6	25.3	16.5	7.5	2.4	1.7
<i>LA</i>	28.3	20.3	21.0	12.1	8.2	10.1
<i>Spokane</i>	58.2	24.5	13.7	2.8	0.5	0.2

It is noteworthy that LA92 has a much more even distribution of time spent in each LOS than do either of the other cities. In spite of differences in their size, location and availability of public transportation, chase car observers assigned similar amounts of driving time to LOS B in all three cities. Perhaps most interesting, however, is the difference in time spent in LOS E and F between Baltimore and LA. The chase car recorded almost 3.5 times the data in LOS E in LA as in Baltimore and approximately six times the data in LOS F. Presumably, these data reflect differences in the traffic congestion levels in each city.

A useful way to assess city to city comparisons of congestion is by using the Roadway Congestion Index (RCI) (TTI 1998). The RCI is an indicator of average congestion over an entire metropolitan region. The RCI is calculated as:

$$RCI = \frac{\frac{FwyVMT}{LnM} \times FwyVMT + \frac{ArtVMT}{LnM} \times ArtVMT}{13,000 \times FwyVMT + 5,000 \times ArtVMT} \quad (1)$$

where,

FwyVMT = Estimated vehicle-miles of travel on the chosen area's freeways

LnM = Estimated lane-miles of roadway

ArtVMT = Estimated vehicle-miles of travel on principal arterial streets

The constants 13,000 and 5,000 indicate the capacity of the facility type.

According to the 1992 RCI, LA has an index score of 1.54, while Baltimore has a score of 1.04 (TTI, 1998). The proportion of seconds the chase car records in congestion should, ideally, be close to the ratio of RCIs to ensure regional representativeness. Hence, the LA92 data should only contain, at most, 1.5 times the number of seconds contained in B92. Other evaluation has also suggested that the visually assigned LOS may not represent the target statistics of the Highway Capacity Manual-assigned LOS (Niemeier *et al*, 1998).

Table 3 further illustrates the variability between LOS measures for three types of facilities. Although the mean speed for LOS F on arterial/collectors is very similar for Baltimore and LA, it differs substantially from that of Spokane. For this facility type and LOS, Baltimore and LA have approximately twice the mean speed as Spokane and about 1.5 times the standard deviation. The ramp facility type shows even more pronounced differences, and across all LOSs. For example, the mean speed in LA's LOS F is

nearly five times that Baltimore's LOS F on this facility type. Furthermore, the standard deviation for LA is almost twice the magnitude of that for Baltimore.

In particular because the EPA facility-based cycle depends on LOS as one of its key variables, it is important to determine if LOS is consistently measured between cities. The RCI and the differences in mean speeds and standard deviations, however, suggest that there may be some unevenness in how LOS between cities was assigned or alternatively that different traffic levels were not appropriately sampled.

Table 3. Descriptive Statistics of 'Composite' Speed by Facility Type and LOS

Fac/LOS	BALTIMORE				LA				SPOKANE			
	Min	Max	Mean	St.Dev	Min	Max	Mean	St.Dev	Min	Max	Mean	St.Dev
ARTERIAL												
All LOSs	0	74.50	25.41	18.04	0	63.10	21.48	15.56	0	74.90	26.53	17.01
LOS A	0	74.50	30.97	17.77	0	61.10	22.65	15.21	0	74.90	29.25	16.92
LOS B	0	65.00	23.60	17.49	0	63.10	22.90	15.85	0	69.50	26.39	16.99
LOS C	0	63.15	20.30	16.60	0	59.10	21.24	15.65	0	56.68	18.95	14.35
LOS D	0	71.29	17.51	15.15	0	53.00	18.35	15.12	0	53.40	15.14	13.13
LOS E	0	56.77	12.15	14.77	0	47.69	13.39	13.74	0	34.50	15.21	11.22
LOS F	0	43.20	11.79	12.02	0	44.20	11.15	12.54	0	36.90	5.51	8.45
RAMP												
All LOSs	0	72.69	40.35	17.06	0	76.00	29.83	20.25	0	79.10	37.23	17.87
LOS A	0	69.80	42.50	15.49	0	61.10	28.88	19.16	0	79.10	37.67	18.79
LOS B	0	71.15	39.62	15.32	0	76.00	35.44	20.17	0	61.80	38.60	13.93
LOS C	0	68.52	42.52	15.61	0	65.70	30.42	20.96	0	63.70	33.28	19.72
LOS D	0	72.69	44.04	19.69	0	65.70	24.31	21.33	-- ^a	--	--	--
LOS E	15.31	47.60	28.50	9.69	0	63.70	38.59	16.05	--	--	--	--
LOS F	0	42.40	4.31	8.69	0	51.50	20.90	15.58	--	--	--	--
FREEWAY												
All LOSs	0	80.91	56.12	13.21	0	80.30	44.75	20.31	0	83.15	59.10	8.85
LOS A	0	80.91	59.39	7.07	29.60	76.36	57.27	8.72	0	83.15	62.06	9.86
LOS B	0	77.30	59.13	8.57	28.00	75.60	62.72	6.14	0	73.83	58.20	7.12
LOS C	0	75.84	59.24	8.34	13.72	80.30	60.85	7.86	0	70.70	57.00	7.19
LOS D	0	75.80	57.13	10.49	6.10	73.97	56.42	8.83	31.57	60.04	54.92	6.79
LOS E	0	71.30	44.37	16.33	0	69.50	38.89	17.42	24.95	55.70	41.72	6.34
LOS F	0	69.47	23.81	16.46	0	66.00	23.03	13.82	--	--	--	--

^aMissing data.

2.3.1.b. Target Data by Facility Type

Continuing with the same three databases, we investigated the relative "lock-on" rates of chase to target vehicles with respect to different facility types. Lock-on rates indicate how much of the data in each database actually comes from target vehicles as opposed to the chase car. When viewed by facility-type, we see that lock-on rates vary between cities, and vary dramatically between facility types. Table 4 displays the percent of the data recorded from target vehicles.

Approximately 47 percent of the data in LA92 come from non-lock chase car records, rather than the target vehicles. Approximately 58 percent of Spokane data are non-lock chase while nearly 63 percent of Baltimore data come from non-lock chase car records as opposed to target vehicles. The implication is that the facility types with low lock-on rates are hugely dependent on the ability of a chase car driver to mimic prevailing traffic conditions and/or the ability of chase car drivers to drive like the "average driver"

if there are no other vehicles around. Since lock-on rates are relatively low on private roads, local roads and to some extent ramps and arterials/collectors the data suggest there may have been very few targets for lock-on. With few target vehicles on the road the chase car driver necessarily has difficulty gauging how to drive with “the general flow of through traffic” (Austin *et al*, 1993, p. 54).

Table 4. Lock-On Rates

	Lock-On Rate (% Data from Target Vehicles)		
	Baltimore	LA	Spokane
Private Road	4.2	0.0	5.0
Local Road	3.7	1.5	5.3
Arterial / Collector	38.3	45.2	41.9
Ramp	23.9	37.8	27.9
Freeway	61.8	76.9	74.9
HOV Lane	66.7	100.0	-- ^b
Overall Rate	37.2 ^a	53.1	42.3

^a1458 seconds of data in the Baltimore database were undefined and therefore were left out of this analysis.

^bMissing data.

Equally important as the lock-on rate for each facility type is the amount of time spent on each roadway type. For example, although on facilities such as High Occupancy Vehicle (HOV) Lanes show 100.0 percent lock-on, when the amount of overall time spent in HOV lanes is examined the limitations of the collected data become apparent. Table 5 shows the percentage of lock-on for the LA92 database according to the share of total time recorded on each facility type.

Table 5. Lock-On Rates and Durations (LA92)

Facility Type	Lock-On Rate (% Data from Target Vehicles)	Time on each Facility Type (% Total Seconds)	Time-weighted Lock-On Rate (%)
Private Road	0.0	0.2	0.0
Local Road	1.5	1.4	0.02
Arterial / Collector	45.2	65.0	29.4
Ramp	37.8	5.4	2.0
Freeway	76.9	28.1	21.6
HOV Lane	100.0	0.0001	0.0001
Overall Rate	53.1	100.0	53.1

From this we see that the largest share of time and lock-on combined comes from arterials/collectors, a high of 29.4 percent. This assessment also shows that target vehicle data on ramps is very limited. Since accelerations necessarily occur at these locations, ramps are important in defining emissions, therefore target car data from these facilities would be preferable to "non-lock" chase car data. By using the “non-

lock” chase car data, we essentially reflect the behavior of one driver instead of many. Since accelerations are crucial to air quality impacts and they can be highly variable, characterizing a facility type based on a single driver does not allow the extent of driver variability to be incorporated. We explore this idea further in Section 2.3.3.a. Note also, it is the chase car driver's responsibility to lock on to target vehicles whenever possible. Because of this, a chase car driver might accelerate or decelerate in a manner very different from that of a target car driver, whose motivations may only be to join the stream of traffic.

2.3.2. Missing Target Car Data

Since, “non-lock” chase car data are used extensively to replace missing target vehicle values, it is useful to use speed-time traces in the LA92, B92 and S92 data to conduct side-by-side comparisons of the driving behavior of chase and target car drivers. Some interesting anomalies emerged from this analysis. Two are illustrated in the speed-time trace constructed from the LA92 data (Figure 3a and 3b).

The thin line represents the “non-lock” chase car’s trace while the bold line indicates target data. At the point marked “A” in Figure 3a, a target car abruptly appears and is abruptly cut off, forming a hook shape. At the point marked “B” in Figure 3b, the chase car accelerates just before acquiring the target and then begins to slow in order to match the target’s speed.

We hypothesized that these peculiarities were caused from a) loss of vehicle lock and/or b) a chase car attempting to catch up to a prospective target. Review of the LA92 videotape revealed some explanations for these anomalous events.

- As hypothesized, suspect points, such as those marked "A" in Figure 3a, were seen on the videotapes to be due to loss of lock on the target.
- Other suspect points, such as those marked "B" in Figure 3b were not due to the chase car accelerating to acquire a target as hypothesized. Instead, they appeared to be primarily due to turning events and lane changes by the target vehicles. In some cases the chase car turned off one facility on to another. In other cases, the anomalies were due to the target vehicle exiting the route on which the chase car was recording.

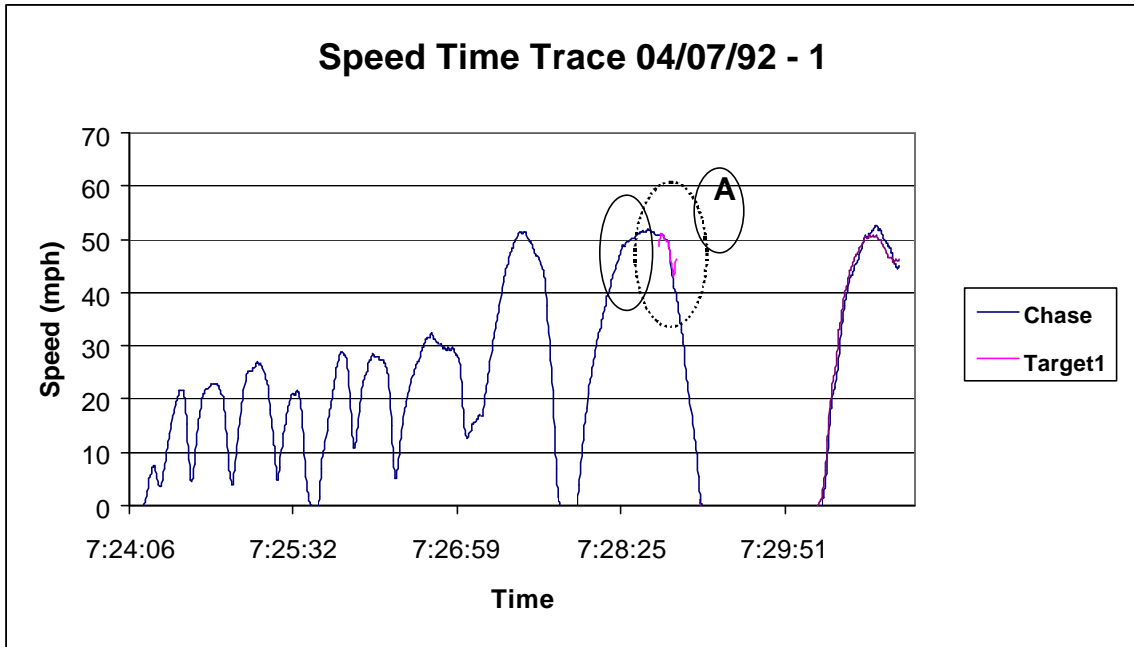


Figure 3a

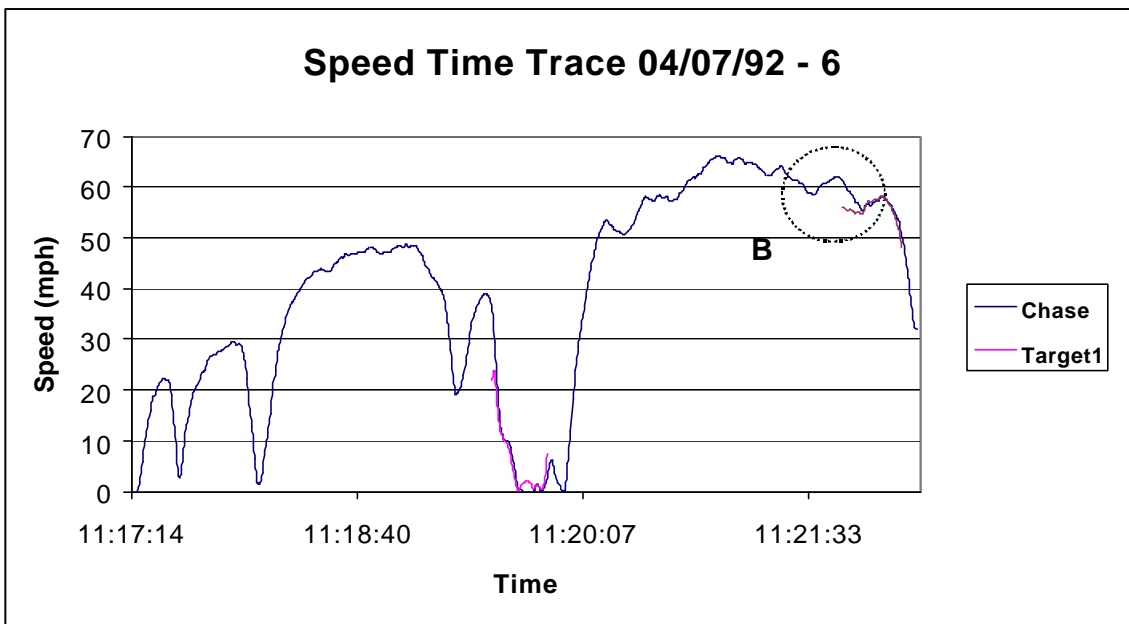


Figure 3b

In addition to the LA92 videotapes, videotapes from the 1997 Highway Performance Monitoring System (HPMS) data collection effort in the Sacramento, CA were reviewed. The HPMS data were collected using the same chase car protocol as was used for LA92 and exhibited similar anomalies. The HPMS

data confirmed our findings concerning point A in Figure 3a. However, they also substantiated our hypothesis concerning point B (Figure 3b), that the chase car accelerates to acquire a target and then slows to match the target's speed. This is a logical course of action, however since the speeds and accelerations of the chase car are often used in lieu of target vehicle data (see Table 4) hard accelerations and/or high speeds will bias the created composite speed-time trace. This indicates that chase car drivers may not drive in a manner similar to the general public since they have different and specific motivation for their behavior.

2.3.3. Driver Variability

For chase car data to be valid in constructing emissions cycles, the variation in speed under “non-lock” conditions must be equal to or less than the target values. That is, on average chase car drivers should not drive any more erratically than target drivers. This ensures a more conservative analysis of driver behavior and also ensures that the chase car driver adequately represents typical driving behavior in the absence of target vehicles. By conservative, we imply that chase car drivers tend toward the mean behavior of target vehicles under similar conditions. “Non-lock” chase car data with higher variability would influence the mean of the overall data set and would not reflect the behavior observed in the population.

To examine this variability, we first determined the standard deviation and mean speed for “non-lock” chase cars and compared them to the standard deviation and mean speed for target vehicles across all three cities. Since the percentages of lock-on varied widely by facility type and LOS, we looked at the speed dimensions according to these two variables. The HOV Lane facility type has been removed from further consideration in this study because none of the databases contain enough data from this road type. Table 6 describes results of an ANOVA analysis as well as displaying the mean speeds and standard deviations described above.

Table 6. Descriptive Statistics and ANOVAs for Non-Lock Chase and Target Car Data

Baltimore	Non-Lock Chase		Target		ANOVA	
	Mean.	Std. Dev.	Mean	Std. Dev.	F-Stat	Sig.
All Roadway Types	28.2	19.7	35.7	22.0	5892.4	.000
Private	11.4	10.9	14.3	12.0	6.1	.014
Local	18.2	13.0	17.1	15.5	5.0	.026
Arterial/Collector	25.5	17.4	26.0	18.8	22.8	.000
Ramp	39.0	17.0	44.8	16.4	157.1	.000
Freeway	57.3	12.3	55.4	13.6	183.8	.000
LA	Non-Lock Chase		Target		ANOVA	
	Mean	Std. Dev.	Mean	Std. Dev.	F-Stat	Sig.
All Roadway Types	26.6	18.5	30.0	21.4	702.9	.000
Private	5.6	4.7	-- ^a	--	--	--
Local	16.4	11.1	16.4	11.8	.000	0.998
Arterial/Collector	22.1	14.9	20.7	16.3	132.1	.000
Ramp	31.1	19.1	27.8	21.7	32.9	.000
Freeway	51.5	16.4	42.7	20.9	965.1	.000
Spokane	Non-Lock Chase		Target		ANOVA	
	Mean	Std. Dev.	Mean	Std. Dev.	F-Stat	Sig.
All Roadway Types	27.7	18.2	32.7	20.8	2915.7	.000
Private	5.3	6.8	1.3	2.6	26.4	.000
Local	21.1	17.1	37.4	15.5	580.6	.000
Arterial/Collector	27.0	16.7	25.9	17.5	134.5	.000
Ramp	35.6	18.7	41.3	14.8	62.957	.000
Freeway	58.7	11.3	59.2	7.8	11.965	.001

^aMissing data.

According to our analysis, the variation between non-lock chase car and target vehicle mean speeds, calculated on a second by second basis, is significant across all three cities and on nearly all facility types at a 95 percent level of confidence. With regard to the aggregate data (no distinction between facility types), B92 shows the highest difference in mean speeds between non-lock and target data while LA92 exhibits the lowest. In comparing mean speeds by facility type, we see that the most pronounced difference in LA is on freeways, in Baltimore on ramps, and in Spokane on local roads. In B92 and S92 we see that the target vehicles have a significantly higher mean speed than the chase vehicles while in LA the chase car has the significantly higher mean speed. It should also be noted that although the mean speeds in some cases appear very similar, since the numbers of cases (seconds) in the databases are so large, a slight difference in mean speed is significant. The only facility type that did not show a significant difference was local roads in LA. We suspect there was too little target data recorded of this type in the database to analyze the difference in a meaningful way.

We then posited that an incremental difference in speed between non-lock chase cars and target vehicles would be more important to identify than a large difference, particularly at higher speeds where coaxing the engine into an enrichment phase is likely to be accomplished with smaller speed changes. In order to examine the speed variation from this perspective, we calculated the coefficient of variation (CV) for speeds recorded for target drivers and for chase drivers while under “non-lock” conditions by facility type and for each LOS represented in the B92, S92 and LA92 data sets.

From Table 7 we see that by facility type, the target vehicle typically exhibits more variation in speed than does the non-lock chase car for LA92. For non-lock chase car data to be a candidate for replacing missing data, this should be the case. As mentioned previously, to keep the estimates of driving behavior conservative, if non-lock chase car data is to be used, it should not contain more variation than exhibited by the target vehicles recorded. The coefficients of variation indicate that the non-lock chase car data tends to maintain the mean speed, (*i.e.*, the behavior of the "average driver") rather than introducing additional variation into the data set. For B92 and S92 the trend is less clear. On some facility types, such as local roads in Spokane or private roads in Baltimore, the chase car variation far outweighs the variation in target vehicle speed.

Table 7. Coefficients of Variation for Speed

Baltimore	Non-Lock Chase CV	Target CV
All Roadway Types	0.70	0.62
Private	0.95	0.84
Local	0.71	0.91
Arterial/Collector	0.68	0.72
Ramp	0.44	0.37
Freeway	0.21	0.24
LA	Non-Lock Chase CV	Target CV
All Roadway Types	0.70	0.71
Private	0.80	No Data
Local	0.68	0.71
Arterial/Collector	0.68	0.79
Ramp	0.62	0.78
Freeway	0.32	0.49
Spokane	Non-Lock Chase CV	Target CV
All Roadway Types	0.66	0.64
Private	1.30	2.05
Local	0.81	0.41
Arterial/Collector	0.62	0.67

Ramp	0.52	0.36
Freeway	0.19	0.13

In Table 8, we further examined the CVs by disaggregating the three predominantly sampled roadway types, arterial/collector, freeway and ramp, by LOS. As Table 8 shows, LA displays slightly more variation between non-lock chase cars and target vehicles on freeways with a LOS of B, C or D and ramps with LOS C. Baltimore, however, has significantly more variability when the CV is considered by LOS in conjunction with facility type. For instance, the CVs for non-lock chase cars on arterial/collectors and freeways are both lower than those for target vehicles. However, when LOS is included, the CVs for non-lock chase cars are lower than those for target vehicles in both Baltimore and Spokane. In fact, for freeways in Baltimore the non-lock chase car CVs are higher than target CVs for every LOS except B. These results indicate that subsets of the data are not as robust as the aggregate. In other words, chase car driving exhibits greater variability under certain LOS conditions than do target vehicles.

Table 8. Coefficients of Variation by Facility Type and LOS

	CV LOS A		CV LOS B		CV LOS C		CV LOS D		CV LOS E		CV LOS F	
	NL ^a	TGT ^b	NL	TGT	NL	TGT	NL	TGT	NL	TGT	NL	TGT
Baltimore												
Arterial	0.57 ^c	0.54	0.75	0.68	0.78	0.81	0.85	0.84	1.08	1.28	1.66	0.74
Ramp	0.38	0.27	0.34	0.48	0.43	0.25	0.51	0.16	0.34	0.23	2.02	--
Freeway	0.13	0.11	0.14	0.14	0.18	0.11	0.27	0.14	0.39	0.36	0.69	0.68
LA												
Arterial	0.66	0.71	0.65	0.73	0.69	0.77	0.81	0.83	0.94	1.06	0.52	1.34
Ramp	0.66	0.70	0.55	0.59	0.74	0.60	0.60	1.24	0.34	0.51	0.60	0.87
Freeway	0.14	0.16	0.11	0.09	0.14	0.13	0.19	0.14	0.39	0.46	0.56	0.60
Spokane												
Arterial	0.58	0.57	0.65	0.64	0.76	0.76	0.77	0.89	1.10	0.69	1.61	1.22
Ramp	0.51	0.44	0.46	0.23	0.66	0.43	-- ^d	--	--	--	--	--
Freeway	0.22	0.13	0.20	0.08	0.12	0.13	0.22	0.12	0.12	0.15	--	--

^aNL = Non-lock Chase Data

^bTGT = Target Data

^cShaded numbers indicate non-lock chase car CVs that are higher than the CVs of corresponding target vehicle data.

^dMissing data.

2.3.3.a. Accelerations

It is commonly known that acceleration events strongly affect emissions. However, Cernuschi *et al* (1995) also demonstrated that differences in relative deceleration rates have an effect on emissions.

According to Cernuschi's methods, although producing lower emissions than at cruise, hard decelerations actually produce more emissions than normal decelerations. To investigate differences in

acceleration/deceleration patterns, we compared acceleration and deceleration rates between non-lock chase car data and target car data in the LA92 data.

We created three categories: cruise ($-0.0340 \leq a \leq 0.0340$ mph/s), normal acceleration ($0.0341 \leq a \leq 3.290$ mph/s) and hard acceleration ($a \geq 3.30$ mph/s), where a is the second by second acceleration of the vehicle recorded. The cruise interval is similar to those used by Holmén and Niemeier (1998) and hard acceleration was defined from previous evaluation of chase car data (Holmén and Niemeier, 1998).

Deceleration rates were classified as mirror images of their acceleration counterparts: cruise ($-0.0340 \leq a \leq 0.0340$ mph/s), normal deceleration ($-0.0341 \leq a \leq -3.290$ mph/s) and hard deceleration ($a \leq -3.30$ mph/s). Results of the shares of seconds in the acceleration and deceleration categories are displayed in Table 9.

Table 9. Accelerations and Decelerations (LA92) [edit as necessary]

Acceleration (%)			Deceleration (%)		
	Chase (non-lock)	Target		Chase (non-lock)	Target
Cruise	27.9	21.4	Cruise	31.0	24.5
Normal	66.3	75.2	Normal	55.7	70.5
Hard	5.9	3.4	Hard	13.3	5.0
Total	100.0	100.0	Total	100.0	100.0

Although the shares of hard accelerations and decelerations are small compared to the normal and cruise categories for both non-lock chase and target vehicles, the analysis shows some substantial differences between hard accelerations and decelerations. The non-lock chase car recorded almost twice as many hard accelerations, proportionally, as did the target vehicles. With regard to hard decelerations, the non-lock chase car recorded over 2.5 times as many events as target vehicles. A relatively large number of hard accelerations and decelerations may be explained by the chase car drivers' need to speed up or slow down in order to quickly acquire a target. However, since the non-lock chase car data is used to replace missing data (*i.e.*, seconds for which there are no target values), their influence must be taken into consideration. By overpredicting the number of hard acceleration or hard deceleration events by such a large proportion, driving cycles will tend to overemphasize the presence of these events in "typical driving behavior" and thus in the driving cycles.

2.4. Difference in Driving Behaviors across Regions

The goal of this section is to investigate potential differences in driving behaviors across regions, as demonstrated in driving data collected from Los Angeles, Spokane and Baltimore. The analysis in this

section relies heavily on speed-acceleration frequency distributions (SAFDs or Watson Plots), and the 'DiffSum'¹ measure. The relevant SAFD matrices and the calculations of 'DiffSum' are provided in Appendix A.

Several agencies and researchers have analyzed the three data sets. Each agency used different methodologies and calculations, so there are now several versions of each data set. To avoid confusion, a summary of the main characteristics of the data used in this section follows:

- All three databases used in this analysis exclude trip end information.
- Speed data used in this analysis refer to 'composite' speed².
- A few records in the B92 and S92 databases had negative speeds. This was likely due to equipment errors. In this analysis, all negative speeds were converted to 0 mph. No records in LA92 were found to be negative.
- Accelerations and decelerations were estimated from composite speeds using the 'midpoint average' method. The formula used is:

$$\mathbf{a}_n = 0.5 \times (\mathbf{V}_{n+1} - \mathbf{V}_{n-1}) \quad (1)$$

where,

\mathbf{a}_n = the estimated 'midpoint average' acceleration/deceleration (mph/s) at the second n,
 \mathbf{V}_{n+1} , \mathbf{V}_{n-1} = the Speeds (mph) at the second n+1, and at the second n-1, respectively.

Figure 4 illustrates the SAFDs of driving data collected in the three cities. The figure shows that the SAFDs for all three data sets generally have similar shapes; each has three peaks at idle (0 mph), at a medium speed (35 mph) and at a high speed (55-60 mph). Percents of frequencies at the peaks, however, are different across the data sets. The SAFD for S92 displays higher percents at the medium-speed peak (8.23%) and the high-speed peak (6.08%) than do the SAFDs of LA92 (4.10 % at the medium-speed peak and 3.82% at the high-speed peak) and B92 (3.86% at the medium-speed peak and 4.0% at the high-speed peak). The frequency percents at idle are approximately the same across the data sets (12–14%).

¹ "DiffSum" is used to gauge the difference between a pair of SAFDs into an absolute value. It is the sum of the absolute value of the differences between the frequencies (in percent) in each cell of joint speed and acceleration.

² Composite speed - "the target vehicle speed-time profile substituted for the chase car speed-time trace when available," (Austin *et al*, 1993.)

Figure 4

The SAFDs for LA92 and B92 look more similar to each other, than either does to the SAFD of S92. The DiffSum measure supports this statement (see Table 10). (See Appendix A for detailed matrices for each SAFD and the estimations of 'DiffSum.')

Table 10: DiffSum

Data set – pair	DiffSum
LA92 vs. S92	30.25
LA92 vs. B92	21.39
B-92 vs. S92	31.82

Previous research (Carlson and Austin, 1997) indicated dramatic differences in time fractions spent on particular facility types and levels of service (LOS) across the three data sets. Time fractions spent by facility type and LOS for each data set are shown in Table 11. Table 11 shows that LA92 has the highest fraction of time on freeways and ramps, while S92 has the highest time fractions on arterials. Percent data collected on private roads and local roads in LA92 is minimal (less than 2 % when combined), while the other two databases have fractions of approximately 10 percent. Table 11 also shows that percents of time in different LOSs on each facility type are dramatically different across the data sets.

Differences in time fractions on facility types motivated analyses of SAFDs by facility type, for instance, whether or not SAFDs are similar across cities, and their similarity to full SAFDs. Figures 5 through 9 show a series of SAFDs by facility type for the three cities. The figures show that the SAFDs are relatively different across facility types, but SAFDs by facility type are relatively similar across the cities. For example, all three SAFDs for freeways have one high peak at 60 mph (see Figure 5) and all three SAFDs for ramps have two peaks, one at idle and one at high speed (55 – 60 mph) (Figure 6). The differences in frequency percents at the peaks change across the cities, which is reasonable since the fractions of time at different traffic densities varied (Table 11). For the freeway facility type, no data in S92 were collected in LOS F, and only 3% were collected in LOSs D and E combined. Often Spokane travelers experienced ‘free flow speeds’ on freeways, resulting in the high frequencies (27.5%) at the high-speed peak. Alternatively, B92 and LA92 experienced 10% and 40% of data collected on freeways, in LOSs E and F, so percent frequencies at the high-speed peaks are much lower (20 % and 13%, respectively). Severe congestion levels in LA also cause low ridges from the peak toward idle in the SAFD.

Table 11

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Similarly, differences in time fractions can be used to explain the difference in SAFD shapes for ramps across cities. Table 11 shows that S92, B92 and LA92 have 0%, 10% and 40% of its data collected on ramp in LOSs D to F, respectively. The SAFDs of S92 and B92 therefore are quite similar to each other, but they notably differ from the SAFD of LA92.

SAFDs for arterials, local streets and private roads showed slight differences across the cities. For private roads (Figure 9), almost all speeds recorded in LA92 are below 25 mph, while they are as high as 40 mph and 50 mph in S92 and B92, respectively. Similarly, speeds recorded on local roads (Figure 8) for LA92 are rarely above 40 mph, but they were as high as 65 and 55 mph in S92 and B92, respectively. S92, in fact, had a third peak at a high speed (50 mph), while the others had only two peaks, one at idle and another a minimum speed. This can be explained by the different characteristics of local streets and private roads available in different regions. This could be due to a difference in the length of local and private roads between cities and possibly different speed limits.

For arterial SAFDs (see Figure 7), both LA92 and B92 have two peaks, one at idle and the other at medium speed (30 mph), while S92 has three peaks with the additional peak at high speed (50 mph). The high-speed peak found in S92 is likely due to large time fractions experiencing LOSs A and B on this road type. Percents of frequencies at the peaks are quite different across the cities.

To further investigate the differences in driving behaviors across regions, a series of SAFDs by facility type and LOS were constructed as shown in Figures 10 through 19. The SAFDs by LOSs on private roads and on local roads as well as those on ramps with LOSs E and F were not constructed due to the limited amount of data collected. For freeways, ramps and arterials, SAFDs for LOSs A, B and C were aggregated because driving data in these three LOSs are all in the region of 'free flow speed,' with only minor interactions from other vehicles driving nearby (HCM, 1994).

The figures indicate that, for freeway travel, LOS A - C driving patterns do not differ greatly from those in LOS D, but do differ from those in LOS E and LOS F. SAFDs on freeways in LOS E and F are also different. Driving patterns on ramps in LOS A - C are not much different from those in LOS D. For arterial travel, driving behaviors in LOS A - C differ slightly from those in LOS D, and they are dramatically different from those in LOS E and LOS F. Note that some figures should be considered exploratory due to limited data (*e.g.*, Figures 11 and 12 for S92 on freeways with LOS D and E and Figure 19 for S92 on arterials with LOS F).

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

These figures reveal two interesting patterns that are worth noting here. First, the SAFDs by LOSs on arterials and freeways of LA92 and B92 are most similar to each other, and quite different from those of S92. The estimated measures of DiffSum, shown in Table 12, also support these comparisons. One explanation might be that residents in congested cities drive differently from those in uncongested cities, even when they were traveling on the same type of facility and encountering the same traffic density (LOS). Both Los Angeles and Baltimore are very large urban areas with high traffic volumes. Recall from Section 2.3.1.a, the TTI 1996 roadway congestion indices (RCIs) show that these two cities were congested, *i.e.*, their RCIs were beyond the acceptable level of 1.0. Consequently, residents in these two areas might be likely to develop different driving habits because of their daily traffic congestion experiences and then behave similarly regardless of traffic density. The SAFDs imply similar developed behaviors in Los Angeles and Baltimore. Spokane, on the other hand, is a moderately large city and has an RCI below the congestion mark, which indicates that Spokane residents do not experience traffic congestion as frequently as in the other two cities.

Table 12. DiffSums

		Facility Type						
		Arterial		Ramp		Freeway		
		LA92	S92	LA92	S92	LA92	S92	
Level of Service	A-C	LA92	-	38.23	-	52.51	-	40.81
		B92	31.58	33.98	63.2	37.46	35.70	43.93
	D	LA92	-	43.26	-	*	-	109.60
		B92	27.43	31.10	109.31	*	38.42	140.63
	E	LA92	-	87.82			-	124.23
		B92	40.19	86.51			58.89	147.48
	F	LA92	-	60.63			-	*
		B92	65.59	79.31			34.60	*

Note: Shading indicates cells for which no analyses were performed due to data limitations.

Asterisks indicate cells for which no analyses were performed because one of the SAFDs needed for the analysis does not exist.

Second, the SAFDs of LOSs A - C on ramps are similar across the cities (Figure 14). In fact, the SAFD for B92 is more similar to that for S92 than to LA92. Ramps are usually short in length, when compared to freeways or arterial street blocks. On-ramps and off-ramps usually require a complete stop immediately before or after their sections (*e.g.*, at traffic signals). Additionally, most ramps joining two freeways have a narrow turning radius. All these factors were hypothesized to mask the difference in driving patterns (on the SAFDs.) Hence, we do not see much difference in the shapes of the SAFDs on ramps across congested and uncongested cities. It should be noted, however, differences in that shape

might also be masked because the majority of ramp data comes from non-lock chase car data rather than from target vehicles.

3. INSTRUMENTED VEHICLES³

The instrumented vehicle (IV) study was conducted in three cities: Spokane, Washington, Baltimore, Maryland, and Atlanta, Georgia. The Radian Corporation conducted both the Spokane and Baltimore studies in 1992. The Atlanta study was conducted as a cooperative effort between Georgia Tech and the EPA. All three studies produced second-by-second data; however, detailed data collection descriptions were only available to us regarding Baltimore and Spokane. It is reasonable that all three studies were performed in generally the same fashion, following a similar protocol. However, there are some known differences between them, for example, Atlanta does not have centralized Inspection/Maintenance (I/M) centers and Centralized I/M stations were a primary consideration for city selection in the Radian study. Because of the possibility of further important discrepancies, we chose to exclude the Atlanta data from our analyses.

Two collection efforts were simultaneously undertaken in both Baltimore and Spokane: collection of 3-parameter (3p) data and 6-parameter (6p) data. The 6p data were collected only for a small population of vehicles with the goal of representing certain distributions of manufacturers, rather than representing the Baltimore or Spokane vehicle populations as a whole. Seven manufacturers participated in the 6p study, which included only vehicles of model years 1989-1991. In total, data were collected from 42 vehicles in the Spokane 6p study and from 37 vehicles in the Baltimore 6p study, compared to 102 and 113 vehicles included in the 3p study for Spokane and Baltimore, respectively. If the 3p and 6p data were combined, the 6p data would represent 25-30 percent of the total, and given the purpose of the 6p study, we felt that including it would introduce a substantial bias to the sample.

Installation of vehicle instrumentation took place from February 2 to February 17, 1992 (17 days) in the Spokane study. Removal occurred from February 10 to March 2, 1992. In Baltimore, installation lasted for a total of 19 days, from March 5 to March 16, 1992 at one station and from March 17 to March 26, 1992 at a second station. Removal of the Baltimore dataloggers occurred between March 12 to April 5, 1992. The 3p data includes approximately 3.4 million seconds of data in Baltimore and about 2.1 million seconds in Spokane.

³ This section references Defries, T.H. and S. Kishan. *Light-Duty Vehicle Driving Behavior: Private Vehicle Instrumentation*. Draft Final Report. Office of Mobile Sources, USEPA, Ann Arbor, MI. August 24, 1992.

3.1. City Selection

The potential sites for instrumented vehicle data collection were evaluated for the following characteristics:

- Classification as a non-attainment area (although Radian does not specify for which NAAQS or combination of NAAQS)
- Employment of a centralized I/M program (for practical purposes of sampling)
- Use of a travel demand model (needed for route generation for chase car studies being conducted simultaneously)
- Relatively flat terrain (to represent the majority of US urban driving conditions)
- Relatively low altitude (since most US vehicles operate at low altitudes)
- Low levels of precipitation
- Minimal sprawl (to ensure urban rather than suburban data would be collected)

Using these criteria, the original candidate pool included 25 cities. Of these, 20 exclusively utilized centralized I/M stations. From these 20, Spokane was chosen to represent city driving on flats and hills and Baltimore was chosen to represent a “variety of city driving conditions” (city streets and highways) (Defries and Kishan, 1992, p. 4-1). Spokane’s I/M program tests vehicle years 1968 and newer while Baltimore’s program tests vehicles 1977 and newer. The biggest flaw in choosing Baltimore, according to Radian, was the city’s proximity to Washington, DC. Because of the location, the data obtained from the Baltimore study could not be considered representative of urban Baltimore alone.

3.2. Data Collection Protocol

In both Spokane and Baltimore, vehicles to be included in the study were selected from a pool of vehicles entering the cities’ I/M stations during the study period. In Baltimore, two sites were chosen, one within the city limits and one in the county, outside the city limits. The county station had the highest volume of vehicles in the Maryland I/M program. To randomize the sample of vehicles as much as possible, times of day were used to define the sampling framework. The driver of a vehicle that entered the designated I/M station during one of the randomly chosen time periods was invited to participate in the study. Upon entering the station, the Radian representative estimated the driver’s age, the vehicle age, the vehicle type, and the vehicle origin (foreign or domestic). (S)he then noted the vehicle’s license number to obtain the vehicle identification number (VIN) for further details of the vehicle and engine. If the vehicle did not participate in the program, the representative could then use this preliminary information to select a

replacement vehicle. The first vehicle to enter the I/M station that was similar to the refusal vehicle, regardless of the defined sampling time frames, was accepted as its replacement.

In both cities, the Radian representative estimated the age of drivers and placed them in one of three categories:

- Young (< 25)
- Middle (26-65)
- Old (> 65)

The representative then placed the vehicle type in one of three general categories:

- Sedan, luxury, station wagon
- Pick-up, utility, van
- Sports car

Drivers in Spokane and Baltimore had to answer “yes” to all of a series of screening questions and the datalogger had to be successfully installed on their vehicles before they could take part in the study. The average 3p installation time was approximately 70 minutes. Once vehicles were instrumented, Radian ran calibration tests such that vehicles’ distance sensors had to agree within 1 percent of the true distance driven and the speedometer had to agree within 5-10 percent. No motorcycles, or diesel or alternative fuel powered vehicles were included in the study.

After data had been collected and the datalogger had been removed, a member of the Radian team interviewed the driver using four specific questions: 1) Was the vehicle driven? 2) Were any long trips taken? 3) Who drove the vehicle? 4) Was the car worked on during the study period? Since both cities have biennial I/M requirements, most vehicles were from even numbered model years. New vehicles in Spokane are exempt from I/M requirements for the first year. Therefore, the newest vehicle included in the Spokane study was model year 1990.

3.3. Technology

Two types of technology were used to measure speeds and accelerations in the IV studies. For all older model (and some late model) vehicles, speedometer cables were used. The late model vehicles with speedometer cables had OEM cruise control. Vehicle models that did not use speedometer cables were equipped with OEM speed sensors. Three distance sensor types were then used. RPM sensors (primary and other) were employed and comments on the vacuum source were noted. It is important to note that when dataloggers would not fit or work on certain vehicles, the vehicles were allowed to leave without

instrumentation. This proved to be a small proportion, approximately 5 percent, of the combined Spokane-Baltimore) sample.

3.4. Number of Vehicles in Study

The target number of vehicles was set at 99 3p vehicles for 8 days of study in each city. Both studies had tremendous success in this regard. Spokane recruited 102 vehicles for their study while Baltimore enlisted 113 vehicles. The rationale for a target of 99 vehicles was not, however, conveyed in the report. There are some potential problems with this sampling technique. First, only drivers whose vehicles needed to be inspected in February or March would be included in the study. It is possible to introduce systematic bias here from associated car sales periods. Second, there was a monetary incentive given to drivers. The offer of money could systematically attract less well off drivers (with older vehicles) rather than middle or upper income drivers (with newer, possibly more powerful vehicles). This might introduce a bias since vehicle type is expected to be a significant explanatory variable for driving behavior. Third, fleet vehicles were not incorporated in the study. Their proportion to the total population of vehicles in each city is unknown. Fourth, the elderly (particularly with luxury vehicles) tended not to participate. Fifth, there was a potential systematic technical bias against distributorless ignition system carburetors because of mechanical difficulties in installation.

3.5. Differences in the Analyses

Different data editing guidelines were used for Spokane and Baltimore (except for the first 11 vehicles in Baltimore) because of problems in recording engine start-up and shut down problem. The technical problem derived from the method used to record vehicle speeds. The Manifold Absolute Pressure (MAP) controlled the activation and deactivation of the datalogger by controlling the RPM, which in turn controls vehicle motion. The delineation of trip ends differed between Spokane 3p data and Baltimore 3p data, which was due primarily to shut-off points of their respective dataloggers. Specifically, in Spokane when the vehicle's RPM fell below 300, the datalogger would shut off, even if the speed of the vehicle was zero, thus recording a non-zero value at the trip end. In Baltimore, the datalogger would shut off when the speed of the vehicle fell below 0.1 meters/second.

Trips are explicitly defined as the time from the engine start to engine shut-off (Defries and Kishan, 1992). The recorded trip ends could differ between Spokane and Baltimore because of a problem with stalls (no percentage is provided for the number of stalls) and the difficulty in separating stalls from trip ends in Spokane. The problem was corrected in Baltimore and stalls could be distinguished from trip ends.

The data produce a range of speeds and accelerations but it is difficult to know how representative these are of typical driving behavior. The average speed over the entire database (combining both Spokane and Baltimore) was 24.7 mph (unweighted was 18.2 mph) with a standard deviation of 20.0 mph. The speed categories containing the highest percentage of data were idle (19.5%) and 30-35 mph (11%). Hard accelerations occurred 2.7% of the time while hard decelerations occurred 3.8% of the recorded time. Other statistics include a median travel time of 7 minutes, 1 minute of which was at idle. The median miles/trip was 2.3 and the average distance weighted by stops equaled 0.83 miles.

3.6. Comparisons of driving data collected by two different protocols

In this section we compare the driving data collected using the two different data collection protocols, the Chase Car (CC) protocol and the Instrument Vehicle (IV) protocol. Both protocols were employed to collect driving behaviors in the same two cities (Baltimore and Spokane) in the same year. As noted earlier, IV driving data was collected in Spokane and Baltimore from February to April of 1992; the two IV data sets will be referred to as 'B-IV' and 'S-IV'. The CC protocol was employed to collect driving data in Baltimore in July and Spokane in November and December.

Because the CC protocol does not capture trip end speed profiles, surveys were conducted in several parking facilities in Sacramento, CA in an attempt to capture trip end data. Using these surveys, "average" profiles of 60-second trip starts and 40-second trip ends were constructed (Austin *et al*, 1993). These profiles were added to the beginning and end of each run in the CC data sets. We also use the CC data sets that included trip end information in our comparisons. The S92 and B92 data sets include trip end profiles we will refer to as S-TE and B-TE, respectively.

The characteristics of the data sets follow. For all the CC data sets, both those excluding and including trip ends, the term "speed data" refers to "composite speeds." Accelerations were estimated from these composite speeds using the "midpoint average" technique (see Section 2.4 for detailed calculations). For analysis of the IV data, accelerations were also estimated using the "midpoint average" technique. However, the IV data sets are missing data (or have gaps) during some runs. In these cases, the accelerations of the first seconds and the last seconds of data stream cannot be estimated. The following scheme was used to attack the problem. For the beginning second and the ending second in each continuous data stream, the accelerations are assumed to be the same as the estimated acceleration of the second immediately following and the second immediately preceding, respectively. Some records in the IV data sets were later discarded from the analysis because the estimated accelerations of the adjacent

seconds were not available, for example, the case of a stream of two recorded seconds bounded by two gaps.

The descriptive statistics for speed and acceleration in the six databases are shown in Table 13. The table indicates that the mean speeds for the CC databases are generally higher than those of their IV database counterpart. There are at least two possible explanations for this. First, the CC protocol does not capture short trips and largely reflects activity on local streets with low speeds. Second, the CC protocol does not directly capture trip end profiles, which include a high percentage of idle and low speeds. Including 'average' trip end information in the CC data (*i.e.*, S-TE & B-TE) brings mean speeds closer to those seen in the IV data (Table 13). The maximum speed collected using the IV protocol is higher than that captured by the CC protocol in Baltimore, but is lower in Spokane.

Table 13. Descriptive statistics of speeds and accelerations in the six data sets.

City	Data Sets	Speed (mph)				Accel (mph/s)	
		Min.	Max.	Mean	Std.Dev.	Max.Decel.	Max.Accel.
Baltimore	B92	0	80.9	30.7	21.0	-12.6	8.0
	B-TE	0	80.9	28.2	21.4	-12.6	8.0
	B-IV	0	94.5	24.5	20.5	-15.5	10.9
Spokane	S92	0	83.2	29.8	19.5	-11.3	9.2
	S-TE	0	83.2	26.9	20.0	-11.3	9.2
	S-IV	0	77.5	23.2	17.7	-13.7	11.1

Table 13 also shows that the maximum accelerations and decelerations collected by the IV protocol are always higher than those collected using the CC protocol. This suggests that the IV protocol captures hard accelerations and decelerations beyond the range of the CC protocol. This is likely a product of the CC protocol: CC drivers are directed by the protocol to avoid those vehicles being driven aggressively.

Figures 20 and 21 depict the SAFDs of these six databases. The SAFDs of all three Spokane data sets have a similar surface (Figure 20); all have three peaks, at idle, at moderate speed (35 mph), and at high speed (55-60 mph). The fraction of time at idle is slightly higher in S-IV (17.7%). The time fractions at the medium-speed peak are similar across data sets, approximately 7.0 to 9.5%, but they are different at the high-speed peak, 5.0 to 6.0% for S92 and S-TE, and 3.0% for S-IV. (See SAFD matrices, Appendix B). Comparing S92 and S-TE implies that including trip end information in the driving data changes the SAFDs surface by slightly increasing the time fractions at idle and some other slow speed cells, while reducing the fractions of time at the other two peaks.

For Baltimore (Figure 21), all three SAFDs have three peaks, similar to those of Spokane. The IV data has the highest time fractions at idle (slightly above 20%) and at the medium-speed peak, while it has the lowest time fraction at the high-speed peak. Including the trip ends in the data set created only minor changes on the SAFD surface, similar to Spokane.

It should be noted that for both cities the SAFDs of the IV data have higher frequencies at idle, and have lower frequencies at high-speed peak. As stated above, these are likely due to the effects of the short trips and trip ends, which can be captured by the IV.

DiffSum is a standard, but non-stochastic measure of the similarities between SAFDs (Table 14, see Appendix B for detailed calculations). The measure indicates that the SAFDs of S92 and S-TE are reasonably similar, as implied by the lowest values of the pair’s DiffSum among the three relevant pairs. The measure also implied that adding trip end information causes the SAFD of the CC data to be more similar to the SAFD of the IV data. This was also found in the Baltimore data sets.

Table 14. Estimated DiffSum

Vs.		Data Sets			
		S-92	S-TE	B-92	B-TE
Data Sets	S-92	-	19.6		
	S-IV	34.3	27.1		
	B-92			-	15.3
	B-IV			28.3	24.2

Figure 20

Figure 21

Next we consider the percents of hard accelerations/decelerations collected by the different protocols using the standard cut point value of 3.3 mph/s. Table 15 shows time fractions of hard accelerations and decelerations.

Table 15 indicates that the IV data sets have the highest fractions of time in hard acceleration in both Spokane and Baltimore. The IV protocol also captured higher time fractions of hard decelerations in Baltimore, but lower time fractions of hard decelerations in Spokane.

Table 15. Percent of time with hard accelerations and decelerations of the six data sets

Data Sets	%hard acceleration	%hard deceleration
S92	2.02	3.48
S-TE	1.89	3.05
S-IV	2.12	2.90
B92	1.80	3.21
B-TE	1.72	2.88
B-IV	2.21	3.63

To further investigate whether or not the IV protocol captured hard accelerations and decelerations that were not captured in the CC protocol, speed-acceleration frequencies⁴ (SAF) of the pairs of the CC data sets and the IV data sets were compared. The results of comparison were shown in Tables 16 for Spokane and 17 for Baltimore. The black-shaded cells represent those speed-acceleration joints that were found in both the CC data and the IV data. The gray-shaded cells with the letter 'C' inside represent those speed-acceleration combinations that were found in the CC data, but not in the IV data. The non-shaded cells with the letter 'I' inside represent speed-accelerations found in the IV data, but not the CC data. The cell numbers represent the number of cases (seconds) found in the database.

For Spokane, the IV protocol seems unlikely to capture the speed-acceleration combinations beyond the range that CC protocols capture (see Table 16). In fact, the CC protocols seem to capture some speed-acceleration combination beyond the IV protocols, especially at the high speed (*e.g.*, there were 12 seconds of data captured in the "85" speed bin by the CC, but not by the IVs). Table 17 reveals a different finding. For Baltimore, Table 17 clearly shows that the IV protocol can capture hard accelerations/decelerations as well as the extremely high speeds beyond the ranges captured by the CC protocol.

⁴ The SAF is similar to the SAFD, but each speed-acceleration cell represents the frequencies (number of seconds recorded).

Table 16

Table 17.

4. THE GPS PROTOCOL

A number of researchers are expressing interest in using Global Positioning System (GPS) units to collect driving data in lieu of the CC and IV methods. To our knowledge, a GPS protocol has never been tested or employed specifically to collect on-road driving data. There are, however, some GPS studies that are closely related. Reviewing these studies yields some insights and suggests possible elements for a future GPS protocol.

In section 4.1 we provide a summary of several topics from a study conducted in Lexington, KY using GPS technology, including descriptions of the data collection equipment, software performance, the map-matching process of the positional data and post-usage attitudinal data. Section 4.2 summarizes findings and suggestions from the Lexington bench test that attempted to identify the types and configurations of GPS units most suitable for the Lexington project. Section 4.3 discusses several concerns raised about the use of GPS units to collect on-road data.

4.1. Review of the Lexington study⁵

Travel data collected from two traditional travel survey methods, telephone interviews and travel diaries, have long been criticized for their limitations. Such limitations include the failure of participants to report short trips and the rounding of reported travel times to 5 or 10 minutes intervals. The Office of Highway Information Management, Federal Highway Administration (FHWA), initiated a new method of personal travel data collection which provides more robust data than do the traditional survey methods. The new method uses automated data collection devices to collect self-reported trip information and information from GPS units. With further support from the Office of Technology Application, FHWA, this new method of travel survey was tested in Fayette and Jessamine counties, in Lexington, Kentucky. Attitudinal surveys were subsequently employed in order to solicit the opinions of participants on several operational aspects of the new method.

The combined GPS/travel diary method was conducted with 100 travelers from September to December of 1996. Two main types of data were collected. First, self-reported trip information, including driver

⁵ This entire section 4.1 is referenced from: *Lexington Area Travel Data Collection Test: Global Positioning Systems for Personal Travel Surveys*, Battelle Transportation Division, a final report to Office of Highway Information Management and Office of Technology Application, FHWA, US DOT, Columbus, September 1997.

and passenger names and trip purposes was used. Travelers reported this information at the beginning of each trip through 'Personal Travel Survey' (PTS) software on a personal computer provided by the researchers. Second, GPS data, including positional fix and travel speed was collected. This data was retrieved by a GPS receiver and recorded on a memory card through the PTS software mentioned above. The complete set of equipment used in the field test was comprised of the following:

- a Sony MagicLink PIC-2000 personal digital assistant (PDA) hand-held computer.
- a Garmin TracPak-30 GPS receiver, equipped with either a magnetic roof mount or a suction cup device for mounting inside the windshield.

(See Appendix C for detailed specifications of the PDA and the GPS receiver),

- Personal Travel Survey (PTS) software,
- SRAM PCMCIA memory card, for installing the PTS software and providing memory up to 2 megabytes for data storage
- a set of connecting cables: a power cable, plugging into the vehicle's accessory port, (power supply for the GPS receiver and the PDA), and a serial cable to connect the GPS receiver to the PDA.

The complete set of instruments was distributed to each participant for self-installation and use during data collection period (approximately one week). Besides the set of equipment, the mailing package also contained a monetary incentive, return shipping instructions, instructions for self-installing the equipment, and instruction material on the PTS software. For each set, the total cost was approximately \$1400 in 1996.

In the first two and a half months of the field test, 15 sets of equipment were deployed. An additional 12 sets were available for field test from mid-November to December. Before sets of equipment were shipped to participating households, each piece of equipment was checked operationally. Each set of equipment contained a new memory card. A hotline was set up for those who had questions or troubles installing and/or using the equipment. Personnel were available to install the equipment upon request.

Table 18 shows an example of a travel data file, in ASCII format, collected from the field test. The upper part contains trip information self-reported by the traveler⁶. The lower portion is information from the GPS receiver unit, starting with the total number of GPS records sampled for that particular trip, followed by a list of the positional data records. Each positional record was organized into five columns. The first two columns were UTC time⁷ and the date, the next two columns are positional data, latitude and longitude, and the last column is speed in units of knots, which is estimated internally by the GPS unit.

4.1.1 Results from Data Retrieval Operation

The performances of the software and hardware used in the project are summarized as follows. Out of 100 samples, researchers retrieved 14 samples that had only self-reported trip information; these samples have no GPS data. Checking GPS receivers found all units functioning properly. The GPS problems were believed to have occurred because the GPS receivers did not receive a proper power supply, due to either a poor connection between the cable and the accessory port or a malfunction of the port.

As PTS software are configured to record data from the GPS unit at a frequency of 1 Hz, the GPS data were actually recorded at irregular intervals, averaging between 20 to 30 records per minute (see Table 18 for an example). The problems were believed to have occurred due to communication problems between the PTS software and the GPS receiver. The GPS receivers were found to consistently produce the positional data once per second. Another factor that affected GPS data continuity was faulty receiver operation. Gaps occurred when the GPS receiver was trying to achieve positional fix at the trip start or loss of positional fix due to signal blocking from structures (*e.g.*, tunnels or parking structures).

⁶ Start time/date and ending time/date were retrieved from the internal clock and calendar of the hand-held computer.

⁷ A satellite clock that is 4 hours ahead of Eastern Standard Time.

Table 18

Table 19 summarizes trip data collected from the field test. Considering only 86 observations that have some GPS records, the retrieved data consisted of 2,919 individual trips. Of those, 456 trips (15.6%) were found to be shorter than 1 minute and were assumed to be either ‘practice’ sessions or those trips that had been incorrectly input (*e.g.*, travelers made a mistake, then canceled the trip, and restarted another with correct information). These 456 trips were excluded from subsequent analyses. The other 2,463 trips (84.4%) were considered actual trips. Out of these, 578 trips (23.5%) had no valid GPS data, 156 trips (6.3%) had fewer than 15 valid GPS data points, and the other 1,729 trips (70.2%) had more than 15 valid GPS data points. Only the trips that had more than 15 valid data points were considered adequate for the map-matching process.

Table 19. Statistics of data collected in the field

No of Obs.	No. of trips retrieved							
	PDA data				GPS Data			
	Total PDA Trips Recorded	Trips shorter than 1 minute	Trips longer than 1 minute	%Good PDA of Total PDA trips	Good PDA trips with no Valid GPS points	Good PDA trips with less than 15 valid GPS points	Good PDA trips with more than 15 valid GPS points	%Good GPS of Good PDA Trips
Summary of statistics for all samples taken during the field test								
100	3254	508	2746	84.4%	861	156	1729	63.0%
Summary of statistics after removal of the 14 samples that recorded no GPS positional data								
86	2919	456	2463	84.4%	578	156	1729	70.2%

Note:

PDA data – Self-reported information.

- ◆ *Total PDA trips - the total number of trips recorded by an individual respondent.*
- ◆ *“Bad” PDA trips - the number of PDA trips with a total duration of less than one minute.*
- ◆ *“Good” PDA trips - the total number of valid trip records. These good PDA trips are also shown as the percentage of the total PDA trips*

GPS data - The GPS positional data collected for the “Good” PDA trips.

- ◆ *“Zero” valid GPS points - the number of trips where no valid GPS positional points were recorded.*
- ◆ *“Bad” GPS points – the number of trips where fewer than 15 valid GPS positional points were collected.*
- ◆ *“Good” GPS points – The number of trips that collected more than 15 valid GPS positional points. “Good” GPS points are shown as a percentage of the total number of good PDA trips.*

Source: Battele, 1997.

The loss rate of good PDA data due to missing GPS data was unexpectedly high since all hardware were found functioning properly. The Lexington researchers did not detect any obvious systematic patterns or

trends in the lost records, and were likely due to shorter trips or difficulty in getting a positional fix with the GPS.

The accuracy of the collected GPS data depended on a number of factors. For example, the status of the Navstar GPS satellites (Selective Availability On Versus Off), the receiver design (Absolute GPS Versus Differential GPS), and the location of travel. With full capabilities (Selective Availability off), the GPS satellites yielded positional locations with an accuracy up to ± 15 meters with 95% probability. However, Department of Defense (DoD) has employed the option of Selective Availability for security purposes, thus reducing the accuracy of the data, to ± 100 meters with 95% probability.

Differential GPS (DGPS) can significantly increase the accuracy of positioning data by performing differential corrections that minimize the effects of the Selective Availability. The Garmin GPS receiver used in the project with differential corrections yields data accurate within ± 10 meters. DGPS were not selected for use in the Lexington study because they were generally more costly, provided unclear advantages to the project objectives, and a ground source of differential correction signal was unavailable. Researchers expected DGPS issues would be mooted in the future for two reasons: 1) the government's intention to reduce use of selective availability and eventually discontinue its use, and 2) the accuracy of the absolute GPS (AGPS) data were expected to be better than they turned out to be.

4.1.2 Base Map and Map Matching Analysis

The Lexington area base map contains information on 10,200 roadway segments covering over 1930 kilometers of road. The street centerline accuracy ranges from 2.1 meters to 4.5 meters. Each segment is classified into six functional classes: freeway, arterial highway, major arterial, minor arterial, collector, and local streets. The base map was detailed enough to recognize overpasses, underpasses, one-way streets, on- and off-ramps. The Lexington area base map, however, covers only the Fayette county area. The TIGER data set for the Jassamine county area supplemented the Lexington area base map to provide full coverage of the entire study area. Created mainly from US Geological Survey (USGS) topographic maps, TIGER data files do not have nearly the accuracy of the Lexington area base map. The USGS

maps allow a maximum positional error of 50 meters⁸. The actual accuracy of the TIGER files cannot be specified, because the TIGER files of some areas have been updated using other sources⁹.

The data map-matching process was performed using software developed by TransCore (formerly JHK associates) and the network database (the Lexington base map combined with TIGER Files). The irregular intervals associated with GPS data recorded in the data file were found to reduce the efficiency of the matching algorithms. To improve the algorithm performance, the researchers performed a 'logical addition of synthetic data' to fill gaps in the GPS data streams, transforming the original data files into the synthetic data files with GPS records for every second. This approach improved performance of the map-matching process significantly.

Out of the 1,984 individual trips subjected to the map-matching analysis, 1,921 (97%) trips were successfully matched in the network. Those that could not be matched had too few valid GPS data points (fewer than 20) or represented very short distances (less than 0.1 miles) based on the available GPS data. Figure 22 shows examples of map-matching GPS data points onto the base map in four different scenarios. In each illustration, the thinner line represents a trace of "raw" positional data, while the thicker line represents the route the vehicle used as revealed from the map-matching process.

4.1.3 Attitudinal Survey

Following the field test an attitudinal survey of participants was conducted to explore several aspects of the new data collection method. The attitudinal data can be categorized into three main areas: installation of data collection equipment (GPS receiver), use of data collection equipment (PTS software) and general concerns and issues. A total of 106¹⁰ individuals responded to the post-study survey. The attitudinal data for each question were summarized and recorded in detail (*e.g.*, descriptive statistics by demographics), in the Lexington report. The following summarizes some of the more interesting results.

- Several drivers suggested new places for installing the GPS receiver unit, including mounting under the windshield instead of on the roof.

⁸ Source: <http://blue.census.gov/cgi-bin/geo/tigerfaq?Q26>

⁹ Source: <http://blue.census.gov/cgi-bin/geo/tigerfaq?Q23>

¹⁰ The survey also allowed and encouraged other household members of the participating samples to drive the car and use the data collection units. All of the 106 travelers using the units on the recall day were participants in the attitudinal surveys.

- Figure 22

One-third of the respondents, mostly in the age group of 18-49 years old, reported that there were some trips on which they did not have enough time to start the PDA and enter the trip information. (Note that neither trip information nor the GPS data of these trips were recorded into the memory cards, because the travelers did not turn on the PDA.)

- Most respondents, more than 93 percent, had no personal concerns about having their vehicles' movement, recorded. Those who expressed concerns were mostly female or drivers in the age group of 25-49, but even only 5 out of 42 female respondents expressed concern. The majority of those concerned were primarily worried about personal privacy issues.
- Less than 5 percent of respondents expressed concerns about the government collecting personal travel data. Males and females expressed concerns at about the same rate, most of them belonging in the 25 – 49 year age group.
- Over a quarter of the respondents expressed concerns about the safety of their vehicle while the equipment was installed. Several concerns were associated with the equipment draining the vehicle's battery, and the possibility of the equipment being stolen (Battele, 1997).

4.2. Review of the Lexington Bench Test¹¹

Before actual data collection took place, a research team (Wagner *et al*, 1996) conducted a bench test aimed at identifying optimal GPS configurations for the project. The bench test for GPS configurations examined two main issues:

1. Can the GPS positional data be collected with the continuity required for the personal travel survey using only a GPS receiver?
2. What type of GPS receiver technology is best suited for this application?

A series of trials were conducted on three relatively high-performance, low-cost, off-the-shelf GPS receivers. The features and properties of the three receivers are shown in Table 20. Seven test configurations of the GPS receivers were tried to identify the optimal configurations for data collection in the field. The seven test configurations are summarized in Table 21.

¹¹ This entire section is referenced from: Wagner D.P., Murakami E. and Neumeister D.M. (1996), *Global Positioning Systems for Personal Travel Surveys*, Paper presented at the National Traffic Data Acquisition Conference (NATDAC) 1996, Albuquerque, New Mexico.

Table 20. Features of the GPS Receivers Used in the Bench Tests

Receiver Feature	GPS Receiver		
	All-in-View Serial Receiver	PCMCIA (Type II) Receiver	Integrated Receiver & Antenna
Horizontal Position Accuracy	30 meters per axis (with SA inactive) 100 meters per axis (with SA active) <3 meters per axis (with differential correction)	50 meters per axis (with SA inactive) 100 meters per axis (with SA active)	50 to 100 meters
Time-to-First-Fix (TIFF)	5 to 10 minutes (almanac initialization) < 60 seconds (with current almanac, position, time) <30 seconds (with current almanac, position, time, ephemeris)	30 seconds to 8 minutes	15 to 30 minutes (almanac initialization) 30 seconds to 2 minutes (power up)
Signal Reacquisition Time (typical)	2 sec (60 sec obscuration) 10 sec (60 min obscuration)	<10 sec (single satellite obscuration of < 15 sec)	Not listed
Number of Tracking Channels	12	5	3
Satellites Tracked	All in view	9	8
Message Frequency	1 per second	1 per second, resettable 1 to 5 second intervals	1 per second, resettable to 5 or 10 seconds
Message Protocols	NMEA 0183 Proprietary Binary	NMEA 0183 Proprietary Binary	NMEA 0183 Proprietary Binary
Unit Size (inches)	4 W x 6 L x 1.5 H	2.2 W x 5.4 L x 0.25 H	3.2 W x 5 L x 1.7 H
Unit Weight (lbs.)	1.3	0.2	0.75

Source: the Lexington report, 1997.

Table 21. Test Configurations for the Bench Tests

Test	GPS Receiver	Antenna Type		Antenna Mount		Differential Correction	
		Active	Passive	Roof	Dash	Yes	No
#1	Integrated Receiver & Antenna				✓		✓
#2	PCMCIA (Type II)		✓	✓			✓
#3	All-in-view Serial	✓		✓			✓
#4	All-in-view Serial	✓		✓			✓
#5	All-in-view Serial	✓			✓		✓
#6	All-in-view Serial		✓	✓			✓
#7	All-in-view Serial	✓		✓		✓	

Source: the Lexington report, 1997.

From Table 21, the first three trials were designed to compare the efficiencies in data collection between the three types of GPS receivers. The other four trials were designed to compare the performances of the same type of receiver under different configurations. The main focuses of configuration testing were the

mounting locations of the antenna (Roof / Dashboard; Trial 4 / Trial 5), the types of antennas (Active / Passive; Trial 4 / Trial 6), and the differential correction of the GPS data (with / without differential correction; Trial 4 / Trial 7). These seven trials were used to collect positional data along the same test route, which was approximately 19 miles long.

The chosen test routes were selected such that they were "as representative as possible of the travel segments and roadway obstructions afforded in the metropolitan Columbus, Ohio area. ... Some obstructions included natural terrain (e.g. hills and trees), manmade structures (e.g. short, tall, and skyscraper-type buildings), and overhead structures (e.g., automobile overpasses, rail trestles, and pedestrian walkway)." (Wagner *et al*, 1996)

The research team indicated some external factors that might prevent the bench trials from being tested under identical conditions. Because the tests were conducted over several days, different traffic conditions, different geometries of the satellites in view, and the uncertainty of the broadcast update rate for differential correction all had effects on the results of the test.

4.2.1 Percents of valid records

The percent of valid records were very important to the success rate of the map-matching process. All trials were configured to record positional data at a frequency of 1 pulse per second (1 Hz). The percents of valid records collected for the seven trials are shown in Table 22.

Table 22. Percent valid records collected for the Test Route (one-second data)

Trial	Percent Valid Records
#1	51.0
#2	99.3
#3	99.7
#4	99.8
#5	99.5
#6	99.9
#7	99.8

Six trials (#2 - #7) showed excellent performance with the percent of valid records ranging from 99.3 to 99.9 percent. Trial 1 (Integrated Receiver with Antenna) showed the poorest performance; with only 51.0% percent of GPS data being collected. This poor performance was due to the fact that the integrated

receiver used in Trial 1 had only 3 tracking channels. “In general, the more channels available to track satellites, the quicker the receiver will recover from a loss-of-fix due to obstructed views and changes in direction of travel” (Wagner *et al*, 1996). Installing the antenna mounted on the roof and using a passive antenna tended to improve the percents of data collected, but only by a small amount (difference between the percent between Trials 4, 5, and 6). Using differential corrections seemed to have no effects on the percentage of positional data collected (compared between Trials 4 and 7). Recall that this is over a 19 mile route and is not necessarily applicable to collecting on-road travel behavior data since this requires data with a much higher resolution.

4.2.2. Positional accuracy

Positional accuracy ensures correctness in the resulting map-matching process, especially in areas with parallel streets lying close to one another. Tests of accuracy were performed by visually-comparing the plots of positioning data obtained from Trial #4 (Absolute GPS) and Trial #7 (DGPS) on the maps. Both absolute GPS data and DGPS data were found to be consistent with published accuracies. DGPS data was twice as accurate as absolute GPS data. “[T]he differentially corrected path plots always appeared to be significantly tighter around roadway bends and roadway changes” (Wagner *et al*, 1996). Using DGPS, therefore, is significant in areas that have dense roads for which using absolute GPS might result in errors in the map-matching process. However, the research team recommended considering the use of appropriate design (absolute GPS / DGPS) together with the accuracy of the base map and the map-matching algorithms. The study also detected that when the tested GPS units were at stationary, *i.e.*, the vehicle was stopped, the retrieved positional data were not focused at a stationary point, and the retrieved speeds were not at zero mile per hour.

4.3. Concerns with the GPS protocol

This section summarizes concerns regarding implementation of a GPS protocol for collecting driving behavior data. The concerns have been raised both through the Lexington project and its bench test project as well as by other professions in the field.

The GPS protocol can be categorized as an instrumented vehicle (IV) protocol, so it has several advantages and disadvantages similar to the conventional IV protocol. Collecting driving data from sampled drivers driving their own vehicles is a clear advantage of the IV groups. Disadvantages include biases that occur due to the presence of the instruments in the vehicle (*i.e.*, the drivers know they are being monitored). This is an important issue that is irresolute. The GPS, however, has some appealing

characteristics that are superior to the use of conventional IVs. First, with map matching capabilities, the GPS can capture facility types on which sampled vehicles were driven. Second, GPS units are popular with the public and easy to install, thus people tend to feel more comfortable with them than with conventional instrumentation.

4.3.1. Potential loss in driving information of short trips

The GPS protocol is likely to lose speed profiles and facility type information for short trips for two reasons. First, on short trips, the GPS receiver is likely to be unable to achieve any positioning fix. Second, if positional fix is achieved, it is likely that the position could not be matched to the network. In the Lexington project, 62% of the 63 trips that could not be matched to the network were trips that had less than 20 valid GPS data point or represented short distances (*i.e.*, less than 0.1 mile). To be able to obtain speed data for these short trips, we might want to collect speed data from vehicle speedometers in addition to the data collected using the GPS receiver. The speed from speedometers could supplement the GPS data whenever the receiver is lost or does not achieve positional fix (Tom Austin, personal). The missing route information could be recovered using certain strategies, for instances, finding the shortest paths for the position gaps between two consecutive retrievable trips.

Bench tests, similar to the one performed in the Lexington study, should be conducted to investigate optimum configurations for on-road driving data collection. The methodologies used in Wagner *et al* (1996) are constructive and suitable to follow. However, Wagner *et al* (1996) conducted their seven trials using a long test route (19 miles). It would also be interesting to see which GPS receiver models, types of antennas (passive vs. active), locations to place antennas (dashboard vs. roof tops) and design modes (absolute GPS vs. differential GPS) would have better performance for retrieving GPS data on shorter trips.

4.3.2. Potential loss in driving information in certain areas and facility types

A GPS receiver requires signals from at least three satellites to achieve positioning fixes. It is likely to lose positioning fixes on certain types of facilities such as ramps, tunnels, overpasses, and streets in urban canyons, because signals from the satellites are blocked (Tom Kear, personal communication). These facilities would, therefore, yield less retrievable data from a sample. A solution would be, similar to the above, supplemented speed data from the speedometer, when the GPS unit loses positioning fixes

4.3.3. Non-Zero Speeds measured while the vehicle is at stationary

A GPS receiver, often times, does not read a zero speed while the vehicle is stationary. This is because the retrieved positioning data are not focused at, but are scattered around, the stationary point. The magnitudes of estimated speed errors depend on the selective availability (on/off) and the accuracy of the individual receiver (Wagner *et al*, 1997). GARMIN III+ readings can be up to 1.5 mph at stops, but Sierra Research, Inc. has not performed any research in this area (Tom Austin, personal communication). CARB has proposed a quick fix by truncating all speeds below 2 mph to 0 mph.

4.3.4. GPS Vs Differential GPS

Differential GPS (DGPS) should definitely be used for any driving behavior data collection effort using a GPS protocol because it provides more accurate speed and acceleration data. Errors in positioning data may cause errors in estimated speed and acceleration, resulting in significant overestimation of emission rates and emission factors.

4.3.5. Accuracy of base maps

“Matching the GPS data to the roadway network can be done sufficiently without a positionally accurate geographic base file” (Battelle, 1997). The publicly available TIGER/Line files were proved to be accurate enough for the map-matching process, resulting in the high matching success rate of 97%, even absolute GPS data were used. However, absolute GPS data potentially caused errors in street matching for the areas that have parallel roads with close proximity. In these locations, a base map with higher geographical accuracy is recommended.

4.3.6. Automatic Collection of GPS data

In the Lexington study, the GPS data from the receiver were recorded only when the travelers activated the PDA and began recording this information. In some instances, travelers failed to turn on the PDA, either deliberately or inadvertently, resulting in position gaps between two consecutive trips. The GPS protocol should be configured such that GPS data are recorded automatically to the memory card whenever the engine is turned on.

4.3.7. Location of GPS receiver installation

From the attitudinal survey, one-third of travelers said they concerned about the safety of their vehicles. The majority of them were afraid that someone might break into their cars to steal the data collection

equipment. Some of them even took measures to counter the concerns (*e.g.*, removing the equipment set out of the car for overnight parking, or hiding the PDA whenever they parked their vehicles). The location of the GPS receiver unit should be carefully reviewed considering the safety of participants' vehicles.

4.3.8. Power Supply

In the Lexington study, travel data collected from 14% of the travelers contained no GPS data, only trip information data. The GPS units were checked and found to function properly. The problems were believed to occur because of a poor connection between the cable and the accessory port or a malfunction of the port. The GPS protocol should employ some measures to guarantee that GPS receivers have a proper power supply and that connections with the storage unit are adequate at all times during operations.

4.3.9. Communication Problems between PTS Software and the GPS receiver

In the Lexington study, although the PTS software was configured to record positional data from the GPS receiver every second, the retrieved data files showed the positioning data were recorded at irregular intervals, average 20 –30 records per minute. The second-by-second speed data is critical to driving cycle construction. The GPS protocol, therefore, must ensure that there are no communication problems between the software used and the GPS receiver, and that the GPS data can be recorded every second as configured.

4.3.10. Potential Protocol Improvement via Intelligent Transportation Systems (ITS)

Beyond the scope of the Lexington project, GPS technology has been well developed in several projects in Intelligent Transportation Systems (ITS). In the Orlando TRAVTEK project and the Chicago ADVANCE project, GPS technology has been used to assist drivers in selecting the fastest route to their final destination, avoiding congestion and accidents. These projects have been implemented using GPS technology, incorporated with a base map and real-time traffic data provided by Transportation Management Center (TMCs). This equipment set, if it were applied with the GPS protocol, could collect certain parameters used to identify LOS from the TMC, which is generally more accurate and less subjective. GPS technology could also be further modified by using a base map that contains information about road classification; the roadway class type could then be recorded in real time in the data file. No map-matching step after the surveys would be required.

5. CONCLUSIONS

The purpose of this study was to evaluate the chase car protocol and to recommend solutions, including new on-road driving data collection methods, for any identified problems. The study focused on four basic analysis tasks: 1) review and evaluation of the current chase car protocol; 2) review and comparison of the instrumented vehicle data to the chase car data; 3) evaluation of the GPS technology; and, 4) recommendations for refining the existing chase car protocol.

Our comparisons of chase car (CC) and instrumented vehicle (IV) data reveal notable and predictable discrepancies between them. It is difficult to say, however, which method produces more representative or accurate data. On the one hand, instrumented vehicles record data directly from the drivers' personal cars, they capture real instead of contrived routes (although these are not recorded), they allow for many more data points to be obtained from each vehicle, and they allow for the possibility of accurate trip ends to be recorded. Chase cars, on the other hand, allow for link level data to be obtained, allow the researcher more control in collecting the data, capture facility information on-route, and avoid the sampling and behavioral biases associated with instrumenting personal vehicles. Although no data were available for this report, the possibility of using a Global Positioning Satellite (GPS) technology instead of standard instrumentation shows potential, although it too has difficulties.

There are several methodological options for future data collection efforts. These include development of a refined protocol for chase car data collection, a potential protocol using GPS technology, and a method that combines GPS with other technologies in order to gather the most accurate and representative data. Recommendations for future data efforts and their associated technology conclude this report.

5.1. Improvements to the Chase Car Method

The chase car protocol was evaluated with respect to variability associated with the measurement and tracking system (*e.g.*, the chase car, the laser, speed and LOS measurement) and the operational procedures (*e.g.*, target vehicle selection, non-lock data collection procedures). While there are clearly several options for collecting on-road data in phase 2 of the project, using an improved chase car protocol currently seems the most feasible. This is especially true given the short timeframe for implementation and the need for additional testing of certain aspects of the GPS technology. We have made a number of recommendations for refining the chase car data collection process. Among the recommendations are improvements in: 1) sampling and route selection procedures; 2) the choice of the lane during data collection; 3) treatment of missing data; 4) selection of the chase vehicle itself; and, 5) the laser tracking

system. It should be noted that even given the proposed protocol changes, extreme driving may not be adequately captured in the chase car data and may continue to introduce some bias.

From our analyses we see that, in general, the use of target car data is more reliable than the use of non-lock chase car data. We would recommend only minimal non-lock data be used in place of missing target data and only when absolutely necessary. There are several reasons for this conclusion:

- Results shown in Sections 2.3.1.b and 2.3.3 illustrate that use of non-lock chase car data to represent the driving population is precarious, particularly on certain facility types and under some LOS conditions where the data is inconsistent with target values.
- Results shown in Section 2.3.3.a reveal the proportion of hard accelerations versus normal accelerations between non-lock chase vehicles and target vehicles can be markedly different.
- The motivation of CC drivers is contrary to the motivations of target drivers, therefore causing their driving behavior to be different from that of the population they are sampling.

The goal of a refined protocol is to gather more and better target vehicle data than was retrieved previously. The theme of a refined chase car protocol needs to be, “Make it simple.” In order to collect better data, the protocol needs to be set up so that it minimizes the functions that the driver and passenger need to perform during actual data collection runs.

5.1.1. Route Choice, Sampling and Trip Ends

There are four primary concerns in choosing CC routes and making sure they are adequately sampled: 1) representing a typical trip, 2) the complexity of the routes chosen, 3) capturing as much as possible the variation in driving behavior that exists in the general population, and 4) capturing trip ends.

5.1.1.a. Method of Route Choice

Routes used in the 1992 data collection efforts relied on travel demand modeling to connect origin and destination pairs and to determine the most “typical” route between them. Without using additional technology, CC route selection can not be directly defined and modeling remains the only option.

Volumes on modeled links could be verified in some areas using traffic counter data, particularly in areas where Travel Management Centers (TMCs) are in operation.

5.1.1.b. Route Design

From videos of the LA92 collection effort, the CC routes appeared to be too complicated for drivers to concentrate on collecting target vehicle data. Several times, we noted the driver and passenger discussing whether or not to obtain a target because they were going to be on a specific facility for a very short distance. Most times, on surface streets at least, the driver did not chose to lock on even if targets were available.

The route design should be simple enough that it does not cause CC drivers to question whether or not to try to obtain a target. Everything that can be done before the driver enters the car should be done. Facility type should be determined and documented before the run commences, from pre-determined route information and maps, or from route information and prior documentation of the facility type.

Specifically, we recommend choosing the top 20-40 origin-destination pairs in a region to identify typical routes. Having chosen routes, divide each into segments by facility type. For instance, if a route contains eight different facility types, the route can be split into eight segments. A CC would then repeatedly collect data on the same segment to characterize each type of facility. The number of repetitions on each route should be a function of the variability in traffic flow by time of day and day of week. If route level information is then required, the data gathered from each of the route segments could then be merged to produce route level (aggregate) data for the origin-destination pair. This would allow CC drivers to choose more target vehicles and potentially stay with them for longer periods of time. It would also remove the CC drivers' disincentive to engage target vehicles, by leaving the chase car on a single facility for a longer period of time.

The identification of facilities on which to actually conduct on-road data gathering can be proposed by the consultant and should be related to VMT. At this time, given that the trip versus link debate is on-going, we suggest that trips be identified using the region's travel demand skim information but with replications by facility types. Thus, 100 different trip routes might be identified (using the skims) that cover a range of facility types. However, rather than driving the entire trip once or twice, the consultant should propose a plan that includes facilities being driven a number of times.

It is also important that LOS information be retained. However, the previous visual method used in the chase car proposal is not suitable for this purpose. The consultant, therefore, should propose an alternative method of recording this information, preferably based more closely on standard traffic density measures.

5.1.1.c. Sampling

An appropriate manner for determining a representative sample of drivers depends on the true or assumed variance in driving behavior. To adequately address this issue, we suggest using the variance from previous chase car data to determine the appropriate sample size or the minimum number of target vehicles needed to characterize the variance on each facility type. Assuming a normal distribution, the minimum necessary sample size can be calculated through Equation 1.

$$n = \frac{(z_{\alpha/2} s)^2}{B} \quad (1)$$

where,

n = sample size.

$z_{\alpha/2}$ = the z value that corresponds to the desired level of confidence.

s = the standard deviation of speeds from 1992 data.

B = the error of estimation around the population mean.

As an illustration, we have calculated a minimum sample size for freeways. From Table 3 we see that the LA92 data show the greatest standard deviation in freeway speeds. Therefore, LA will require the largest minimum sample size of the three cities discussed in this report. If using the sample size calculated for LA, Spokane and Baltimore will not be undersampled. At a 95 percent level of confidence, and accepting an error of estimation equal to 5 mph, we use Equation 1 to see that the minimum number of target vehicles sampled on freeways should be:

$$n = \frac{(1.96 \times 20.31)^2}{5} = 317$$

It is important to note that these are not second-by-second computations and that, although mean speed is employed here to illustrate construction of an appropriate sample size, modal activity could instead be used. Construction of a smaller sample size is also feasible using the same computation. However, it should be noted, that in using a smaller sample size there are tradeoffs such as a reduced level of confidence and/or an error greater than 5 mph. It is also important to note that the sampling scheme presented above does not address the length of the road segment. We therefore recommend sampling the length on any given facility proportional to the average time spent on that facility for the trips in that region.

5.1.1.d. Trip Ends

An inherent limitation of using the chase car method for collecting driving behavior data is that it misses trip ends. To attempt to remedy this, individuals could be solicited to participate in a study in which the participant's vehicle is followed from his/her driveway for 20 minutes at the start of a trip. This method contains some biases because each participant will know that his/her behavior is being recorded. However, capturing trip ends is very difficult and this presents one alternative for creating approximations.

5.1.2. Lane Choice

Although the "white car protocol" described in Section 2.2 provides a random component for choosing the lane in which target vehicle data is collected, the protocol is too complicated to be consistently applied during actual CC runs. The videotapes indicate a lane bias in the LA92 freeway data, a bias toward right hand or slower moving traffic. Occasionally, when the driver and passenger attempted to implement the "white car protocol," there were incidences where they became confused and chose the white car (rather than just the white car's lane) as their target vehicle. Again, lane choice can be predetermined, thus keeping the passenger and driver from additional on-road responsibilities.

To better capture variation in driving behavior, a lane sampling program that includes the different speeds and accelerations can be created. There are two types of variation that need to be captured through the sampling program: 1) within lane variation, and 2) between lane variation. Within lane variation can be captured by sampling many different vehicles in the same lane. Between lane variation demands more extensive pre-run planning, especially on freeways where the bias has appeared most extensively.

We recommend choosing lanes at random from among the available choices, according to pre-determined time increments, and recording the lane number during the data collection procedure. For example, let's assume that a CC will be on a specific three-lane freeway for five minutes. For this example, we will use 20 second time increments for each lane. We can number the lanes 1, 2 and 3 and place them in a random number generator. For each 20-second time increment then, a computer randomly chooses a lane, thus producing a lane program for the driver to follow. Since the lane choice is random and predetermined, this may introduce less confusion for the driver while simultaneously limiting the bias introduced by undersampling certain lanes. Time to transition between lanes would also have to be included in the plan.

5.1.3. Treatment of Missing Data

It must be remembered that, although researchers use data on a second-by-second basis for cycle construction, the real sampling unit is the driver-vehicle combination. Each second represents a data point of the chosen sample. These data points provide a profile of each sample, *i.e.*, the driver-vehicle. The justification for using the non-lock chase car data seems to be that, without it, there is not a big enough sample to build driving cycles. When chase car data is used in place of the missing target data it does not substantially boost the sample size. Instead, it adds only one driver-vehicle profile to the sample (thus raising the sample size by 1).

5.1.4. Vehicle

The current chase car vehicle may not be appropriate for conducting future studies. In an informal survey, college students from the UC Davis campus were shown a picture of the chase vehicle (Austin *et al.*, 1993, p. 24) and asked what it looked like. Invariably they thought it resembled a police car. No formal conclusions can be drawn from this, however, it does indicate that the chase car's appearance may alter target drivers' behaviors.

Additionally, with changes in the overall fleet, the laser mounted in the chase car may no longer be able to target a growing proportion of the population, particularly Sports Utility Vehicles (SUVs). Because SUVs are substantially higher off the ground, the laser may return erroneous readings or may not be able to lock-on to the vehicle at all (it may pass beneath the bumper of an SUV).

Using a powerful light duty truck might provide a viable alternative to the Chevy Caprice. This would give the requisite height, would provide the necessary power for catching and staying with almost any target vehicle, and would not be easily confused with a law enforcement vehicle. However, in recognition of the costs already incurred, alteration of the Caprice's appearance is a practical alternative to purchasing a new vehicle. Specifically, we suggest outfitting the Caprice with a rooftop bicycle rack and bicycles to minimize its resemblance to a police vehicle.

5.1.5. Technology

The most notable deficiency in the laser used in the 1992 chase car studies, as evidenced in the videotapes, is its inability to maintain lock on target vehicles. This is particularly true when the chase car travels over minor bumps, around very slight curves or on changing road grades. This decreases the

amount of target data, particularly on ramps and on changing road grades, both of which are important for collecting acceleration data.

Two suggestions to correct for these shortcomings follow:

- 1) use multiple lasers to maintain lock-on.
- 2) use a single laser that can be aimed with a passenger-controlled joystick to maintain lock-on.

Use of multiple lasers could minimize the data gaps introduced by curves in the road. However, unless the divergence of the laser is increased (consequently, decreasing its range) or the lasers are placed at different angles, missing data would remain a problem on changing road grades. A specific example of new laser positioning would be to use two small lasers, one under each headlight of the chase vehicle. If this is technically infeasible, the two lasers could be placed as far apart as technically possible in order to hold lock around corners for the longest amount of time. It should be clear to the passenger (who is controlling laser lock/non-lock) or in post-processing which laser is locked on to the target vehicle at any given second.

Using a manually adjustable laser presents different difficulties. The additional flexibility of a mobile laser, one with lateral as well as vertical mobility, controlled by a joystick, would allow for the opportunity to gain much more consistent and voluminous target data. However, although ideally the passenger would be able to point, lock and adjust the laser to maintain lock, the cost of such a venture could make it an infeasible option. Furthermore, training the passenger to adjust the laser to the proper position with the proper timing might be untenable.

These suggestions may not solve the problem of obtaining additional target data around major curves or on hills because of the need to maintain a specific angle of incidence in order to preserve accuracy in speed readings. However, the possibility of maintaining laser lock on targets under circumstances of slight change will improve the overall reliability of the chase car data set.

Alternatives to the current chase car laser include the use of radar. Several concerns surface when considering the use of radar: 1) In order to be most effective, the radar must work outside of law enforcement range because many potential target vehicles have radar detectors. Detection of the chase car's radar could potentially influence not only the behavior of the driver with the detector, but the surrounding drivers as well, since drivers respond to each other's behavior; 2) Use of radar could also introduce a systematic bias against obtaining data on higher speed drivers since they presumably are more likely to have radar detectors in their vehicles. The use of conventional radar is also questionable for

technical reasons. Radar, as used by law enforcement, measures the shift in frequency of the signal in order to calculate the target vehicle speed. This radar could not give accurate readings from a chase car, where both vehicles are in motion (Britt Holmén, personal communication). Even if it were possible to obtain accurate readings from a stationary source, it may not be possible to record as fine of data as recorded by the laser. Since radar has a long wavelength, it is doubtful that vehicles could be sampled at a second-by-second rate, thus lowering the fineness of the overall sample data.

Scanning radar or scanning lidar (laser-radar) systems appear to address these concerns to some extent. For instance, a scanning radar system developed by Eaton Vorad has the ability to scan both vertically and horizontally and operates outside the radar frequency used by law enforcement, therefore making it less likely to be detected by the public. However, although expensive, narrow band radar detectors can not detect the scanning radar or lidar, cheaper broad-band detectors can be triggered resulting in the same potential problems as use of conventional radar. In other words, a bias could still be introduced in the target data if broad-band detectors are prevalent in the sample area. Furthermore, both scanning radar and scanning lidar have the ability to obtain speed and acceleration data from target vehicles on a second-by-second basis. They can also simultaneously track multiple targets and can be mounted on any vehicle in place of the license plate (Wei-Bin Zhang, personal communication).

Table 23 summarizes the major pros and cons of employing a chase car methodology, assuming that the above recommendations are followed.

Table 23. Pros and Cons of Chase Car

Pros	Cons
Drivers presumably won't change their behavior due to the presence of a chase car	Targets could get suspicious of being followed
Obtain facility type and link level data	CC in an indirect method of data collection—laser could give erroneous readings due to reflection from target vehicle (color bias)
	No chance to gather demographic data
	No direct trip level data collection is possible
	Routes are modeled (not real)
	Relatively little data is collected from target vehicles
	Biases can be introduced by human error at many points
	Potential biases in applying the protocol

5.1.7. Locations and Timing of the Data Collection

From report evaluations discussed above, it appears that regional and facility differences in on-road driving exist. Recall that this conclusion may be modified when vehicle testing has been completed. However, we suggest the CAMP group consider some variation on the testing plan below.

Table 24. Suggested Testing Plan

Facility Type	Sacramento			Central Valley			Bay Area		
	Urban	Suburb	Rural	Urban	Suburb	Rural	Urban	Suburb	Rural
Highway/Freeway	X			X			X		
Major Arterial	X	X		X			X	X	
Minor Arterial	X	X		X		X	X	X	
Collector		X				X		X	
Local						X			

5.2. Global Positioning Satellites (GPS)

GPS systems seem to offer great advantages in terms of returning data from the best variables included in the chase car and instrumented vehicle studies. From it, real route information, link and trip level data, speeds and accelerations from the sample vehicle itself, and trip end data can be obtained. The most problematic disadvantages to this system are 1) the potential for systematic sampling biases and, 2) the influence of the instruments on driver behavior.

Both the Lexington and Radian reports suggest a protocol for using a GPS technology in this type of data collection effort. However, data of the accuracy needed to describe driving behavior are only available at considerable cost both in terms of money and time. Data of this caliber demand use of a differential GPS unit in order to adequately measure the position of the vehicle. Furthermore, since many obstacles to satellite lock interfere with the data collection process, the GPS unit would need to be integrated with the vehicle's speed sensors to obtain uninterrupted second-by-second data. Systems such as this do exist, however they are, at present prohibitively expensive (Tom Austin, personal communication). An integrated system such as this would also take away one of the great advantages of the GPS system, illustrated through the Lexington study, namely the ease of installing and removing the unit from the sample vehicle. The more difficult and technical instrumentation of an integrated, differential GPS system would discourage potential participants and would introduce a stronger sampling bias than the "do-it-yourself" absolute GPS system.

A protocol could be developed for the integrated GPS system to work, taking elements from both the Lexington and the IV protocols. Although technicians would have to actually install the GPS and

associated units, a mail out notice could be sent to potential participants with a notice of monetary incentive and a telephone number to call if they were interested in participating in the project. From the telephone conversation, a time could be set up for the installation of the instrumentation to take place. In this way, the sample chosen from the population would be more likely random than those chosen from an I/M station would. Furthermore, it would give potential participants some time to consider taking part in the study, and to choose a more convenient time to have their vehicle instrumented. It is likely that most people pulling into an I/M station have not figured an extra two hours into their trip and that instrumentation of their vehicle seems like more of an inconvenience than if they were expecting it.

The inherent problems of using IVs still exist in this scenario. However, using a mail technique may help to minimize the sample bias by reaching a larger and potentially more random pool of people. The instrumentation bias may be minimized by vagueness in conveying what the instruments will be doing while they are in the sample vehicle. Possibly, too, in knowing that the data will be biased, estimating the direction and magnitude of that bias and proposing statistical corrections becomes a possibility.

Table 25 lists the pros and cons of using a GPS system for driving behavior data collection purposes.

Table 25. Pros and Cons of GPS

Pros	Cons
Real data from drivers in their own vehicles	Many places that satellites can't reach (urban canyons, on-ramps near overpasses)
Route selection by drivers	Accuracy of GPS unit depends on expense of technology and on Department of Defense decisions
Can possibly link route data with TMC data for density measurement (in lieu of LOS)	Might affect driving behavior (instrumentation problem)
Facility type information	
Possibility for demographic data	
Possibility of many more data points than chase car	
Trip and link level data possible	

5.3. Technology Combinations

If a chase car protocol is used, in order for enough target data to be collected, the data should be supplemented with data from alternative sources. In other words, the use of hand held or stationary lasers could be used in problem areas to supplement chase car obtained target data. Problem areas would likely include freeway on-ramps and off-ramps, as well as private and local roads. Chase vehicles and stationary range-finder lasers have their own distinct advantages and disadvantages. Advantages include

a lack of sample bias and influence on driver behavior, a broad spectrum of vehicle activity, including a variety of speed and acceleration data (Grant and Roberts, 1998).

Another possible combination would be to use cheap and easy to install GPS units to guide researchers in the definition of typical routes. GPS information could be matched to a map and used to define routes for a chase car to follow. Furthermore, the GPS data could be used as a “check” of the chase car data. This would require a substantial addition of study time, however. It would require that a two-step process be implemented. First, GPS units must be supplied to volunteer drivers, the data must be collected and processed, then the processed data would have to be converted into route segments in order for the chase car to collect repeat data along the same routes. This would avoid the use of data subject to the potential behavioral influences introduced by the presence of instruments in the vehicle. However, the sampling bias could still be present in route selection. In other words, if there were a specific segment of the population that refused instrumentation, their daily routes would not be incorporated into the chase car sampling frame.

Regardless of the technology employed for speed and acceleration data, the use of GPS units, absolute or differential may have a distinct advantage over its competitors. The GPS unit, in conjunction with other technology may be instrumental in estimating Levels of Service (LOS). The LOS variable is crucial to the construction of facility-based/LOS driving cycles developed by the USEPA. Density information can potentially be acquired from other sources such as Transportation Management Centers (TMCs). TMCs provide real-time traffic information on the road networks within their jurisdictions. They collect traffic data using surveillance equipment, (*e.g.*, inductive loops and surveillance cameras) throughout their regional networks. After the data is transmitted to the TMC, it is processed using algorithms to estimate traffic characteristics of individual road segments, such as link flow and link speed. These pieces of information are then distributed to the public in a number of ways, such as through web pages, kiosks and GPS routing units installed in some newer vehicles. Link flow and link speed are the parameters that have conventionally been used to identify LOS. If the real-time link flow and link speed data from TMCs can be associated with GPS data, the real-time LOS experienced by the sample vehicle could be estimated¹².

In addition, the incorporation of software like the PTS (used in the Lexington study) with GPS technology could enable a data collection system to compile details of individual trips. Although these data are not

required for driving cycle construction at present, they may prove significant to future research efforts. Using the conventional IV protocol, only personal information from the driver who happened to bring the vehicle to the I/M station can be collected. It can not be shown that this driver is the sole vehicle operator during the data collection period. The driver information, collected through PTS software could be instrumental in distinguishing driving behavior between travelers of different demographic groups (*e.g.*, age, marital status) and attitude. Driving behaviors of the same traveler for different trip purposes might prove different as well. For example, a person might drive very differently when commuting to work than when driving to church. The presence or absence of passengers might also have effects on the driver's behaviors. Self-reported trip information recorded through PTS software contains data on passengers, including names and trip purposes for each. These data could also prove useful in future research efforts.

Combining GPS technology with software like PTS also yields travel data of samples during the data collection periods. The travel data, which is critical to travel demand modeling, is claimed to be superior to the two more conventional data collection methods, telephone surveys and diaries, in several ways. Simultaneously collecting the driving data and travel data might expand opportunities for funding which could in turn increase the sample size so that it is better representative of the driving population.

Incorporating PTS software into a GPS protocol raises some concerns, however. First, the protocol places more burdens on the sample drivers, possibly changing their normal driving behavior. Second, reporting trip information at the beginning of each trip reminds the sampled travelers regularly that they are being monitored.

¹² If the chase car protocol utilized the LOS data from TMCs instead of comparing traffic with the reference figures currently used by the CC driver and passenger, the LOS data obtained would be more rigorous, more accurate and less subjective than obtained in the past.