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Investigation of Vehicles as Probes Using Global Positioning System and Cellular Phone Tracking: Field Operational Test

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CALIFORNIA PATH PROGRAM
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Investigation of Vehicles as Probes Using Global Positioning System and Cellular Phone Tracking: Field Operational Test

**Y.B Youngbin Yim
Randall Cayford**

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**Investigation of Vehicles as Probes
Using Global Positioning System
and Cellular Phone Tracking**

Field Operational Test

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Randall Cayford

December 2000

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ABSTRACT

This paper reports on the first phase of the location technology evaluation for probe vehicles. Two technologies were evaluated, Global Positioning Systems (GPS) and the cellular phone tracking technology developed by US Wireless. Although GPS has shown great potential for vehicle probes, much of the previous research is theoretical in nature. Very little work has been done in the areas of experimental research, implementation or deployment. Most of the field tests were anecdotal; a systematic approach is highly desired to develop a vehicle probe system that is reliable and efficient for traffic management. If GPS is widely deployed in cellular phones, as GTE in 1998 predicted would happen, GPS technology will become even more attractive and realistic for vehicle probe activities.

A custom software package was developed as part of this project in order to conduct the technology evaluation. The software, the Travel Information Probe System (TIPS) maps positions of probes of arbitrary accuracy to an embedded Geographical Information System (GIS) in order to determine the path the probe took. Once the path has been determined, the software calculates the travel time for each road segment traversed. The preliminary analysis of two Bay Area counties showed that accurate location technologies are capable of producing travel time information for nearly all roads. A technology with 20-meter accuracy can produce data for 99.2% of road segments and 98.9% of the freeway segments in the two counties studied.

Keywords: GPS, Positioning Accuracy, Vehicles as Probes, Field Operational Test, Cellular Phone

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EXECUTIVE SUMMARY

The purpose of the study is to investigate the feasibility of vehicle tracking technologies for vehicles as probes (VAP). Two technologies were evaluated, Global Positioning Systems (GPS) and cellular phone tracking technologies developed by US Wireless. The study consists of three phases of project tasks; Phase I -- program development and initial field test, Phase II -- field operational tests, and Phase III -- a large-scale field implementation. The overall goal of the study is to set up a "Vehicles as Probes" (VAP) system for data collection, fusion, and dissemination at the Institute of Transportation Studies, the University of California at Berkeley. This paper, a part of a broad cellular and GPS technology study, is an interim report on the program development and initial field test.

Vehicle probe information can be complementary to those freeways that have single loops since the single loops are not capable of producing the most accurate traffic speed and density measurements. Probe vehicle data can also be used for rural freeways or minor urban freeways where no instrumentation is planned. Local streets and arterials are also good candidates for collecting data from probe vehicles.

The study addressed the following research questions: 1) what positional technologies are most appropriate for vehicles as probes, 2) what degree of positional accuracy is needed for qualitative versus quantitative vehicle as probes, 3) what technical and institutional systems will it take to pass approximate positional information to the Computer Aided Dispatch center and make it available before a call is even answered, and 4) how many probe vehicles are needed to collect adequate sample data for a reasonable estimate of travel speed?

Generally, the more accurate the vehicle positioning, the less the potential for ambiguity in the ITS (Intelligent Transportation Systems) database. Commonly used GPS technologies provide Accuracies of 10 meters for differential GPS and 15 meters for GPS. Cellular phone tracking technologies must provide the mandated E-911 accuracy of 100 meters, with improved accuracies of 50 meters required in two years. The accuracy required for an effective probe system is dependent on the geography of the road network. In areas of greater density, with roads close

together and many intersections, much greater accuracy is required for the probe to be correctly placed on its road segment. Where roads are far apart with few intersections, a much lower degree of accuracy in position identification can be used and still yield correct road segment matches. To quantify the level of ambiguity and to estimate the degree of accuracy required for generating travel times from probe vehicles, two counties in the San Francisco Bay Area, Alameda and Contra Costa, were examined. Simulated probe vehicles with varying levels of positional accuracy were generated and run through the probe following software developed for this project.

Analysis showed that accurate location technologies are capable of producing travel time information for nearly all roads. A technology with 20-meter accuracy can produce data for 99.2% of the road segments and 98.9 of the freeway segments in the two counties studied. At lower accuracies, the coverage goes down sharply for freeways but stays relatively high for highways and major streets. At 190-meter accuracy, 45% of freeway segments and 76% of major streets can generate unambiguous information. While low accuracy location technologies may not be suitable for freeway surveillance due to difficulties distinguishing between freeways and frontage roads, they may still be very effective for traffic surveillance on major surface streets. As these roads are rarely well instrumented using conventional technology, probe systems have great potential for cost-effective supplements to conventional freeway surveillance systems. In particular, systems meeting the E-911 requirement of 100 meter accuracy for two thirds of all calls are, in theory, capable of producing quantitative travel time information for 87% of major street segments, though only 68% of freeway segments. Location accuracy is only one criterion for building a successful traffic surveillance system, however. The field tests conducted in this study show that variability in the positional accuracy and the total length of the tracking sequence are both important factors in whether or not a technology can be successfully used for a probe system. There is a direct relationship between the positional accuracy and length of time a vehicle must be tracked in order to generate travel times. At an accuracy of 10 meters, tracking the vehicle for twice the average segment length is generally sufficient to yield a travel time for at least one link. At 100 meters positional accuracy, the vehicle may have to be tracked for a mile or more.

Another issue, which is particularly problematic for cell phone tracking, is identifying probes that are traveling in a manner representative of the total traffic flow. A probe tracking system must infer from the location data what the travel behavior of the vehicle is and discard those probes which are either not vehicles at all, or are moving differently from the rest of the vehicle stream.

AVL systems installed in fleets, such as the Freeway Service Patrol (FSP) or delivery vans, could be used as the data source for a probe system. While identification of the probe is not a problem for this kind of vehicle there are behavioral problems such as FSP vehicles may stop by the side of the road for periods of time or travel slower than other vehicles when towing. These unrepresentative behaviors must be identified and the generated travel times must be discarded or the accuracy of the system will be degraded. The problem is much worse when the probes being tracked are handheld, such as cell phones. All these difficulties can be partially compensated for by increasingly sophisticated post-processing of the data stream which can increase the accuracy of the results by discarding problematic data. However, the number of probes must be increased in order to compensate for the lost data and the necessary increase is much greater for handheld systems than it is for vehicle-based systems.

Statistical sampling methods suggest that roughly 4% to 5% of the probe vehicle penetration can provide a good estimate of travel times based on the simulation results. Based on the statistical concept of allowable standard errors, the study showed that approximately 150 – 160 observations per hour would be necessary for reliable speed estimates. As some observations will likely need to be discarded as problematic, a larger number of observations will be needed in a deployed system. These figures however are based on simulation results or theoretical analysis; it is highly desirable to conduct a field test to verify these results.

Off-the-shelf software programs were not available to provide an adequate mobile positioning system for vehicle probes. As a result, the staff of the Computer Systems Unit of the Institute of Transportation Studies, the University of California at Berkeley developed a new custom software package, the Travel Information Probe System (TIPS), as part of this project. TIPS maps positions of probes of arbitrary accuracy to an embedded Geographical Information System in order to determine the path the probe took. Once the path has been determined, the software calculates the

travel time for each road segment traversed. TIPS is used for the initial field test of GPS, differential GPS and US Wireless cellular positioning system.

To assess the effectiveness and adequacy of GPS-cellular technologies for incident detection and tracking speed data, we proposed a series of 4 field tests. The tests were 1) determine the positional adequacy of GPS, 2) determine the positional adequacy of cellular technologies, 3) a small scale test of FSP-like probes and 4) a site specific and large scale probe vehicle test after evaluating GPS technologies. This study performed the first three field tests. The fourth is planned in phase III.

Two GPS technologies, uncorrected GPS and differential GPS technologies were tested. The two are similar except for a roughly 5 meter better accuracy for differential GPS, 10 meters versus 15 meters for 95% of the measurements. Using the TIPS software, field data from Oakland California was analyzed. The analysis found that using an assumed accuracy of 20 meters produced the most effective vehicle tracks for both GPS and differential GPS. For both GPS technologies, 26% of the sequences of 100 points had one or more data points well outside the expected 10 –15 meter accuracy. The field test showed that tracking a GPS equipped vehicle is very effective. The TIPS software correctly identified 92%, for uncorrected GPS, or 93%, for differential GPS, of the total path followed by the test vehicle.

One cellular phone tracking technology was also field-tested. Two sample data sets were provided by US Wireless, one of the companies producing tracking technology for cell phones. Working with this data, the TIPS software found that an assumption of 60-meter accuracy produced the best probe tracks. Many of the phone calls tracked had one or more points that were far outside a 60-meter accuracy range, however. Of 3,756 probe tracks, 66% had one or more points outside of a 200-meter accuracy range.

Assuming 60-meter accuracy, our tests matched 107.4 kilometers of road using 44 hours of cell phone tracking data. In contrast, the GPS field test matched 58.6 kilometers of road using only 3.5 hours of tracking data, nearly 7 times the success rate. Unfortunately, without data showing ground truth for the paths taken by the tracked cell phones, there was no way to determine how much of the 107 kilometers matched were correctly matched. Even qualitative estimates of correctness were

difficult as tracks were generally very short. Of 1200 calls tracked, the median length was 30 seconds. With such short sequences, less than 200 calls out of 3756 appeared to match more than one road segment. As it is quite possible to match a single segment with only 2 or 3 data points, no conclusion about the correctness of road segment matching could be made.

All three technologies evaluated produced individual data points that were very far away from the others. This made tracking more difficult and, for the cell phone data, the problem was severe enough that TIPS could not successfully track almost 60% of the probes. Error detection and correction algorithms need to be developed to filter the bad data points. For GPS, which has a known error rate, correction algorithms could be based on testing the distance between points, or on the additional satellite data which can be output by most GPS units. For cellular phone tracking systems, further examination of the nature of the errors, particularly a comparison of reported positions and actual positions for a sequence of points, is needed before any error correction algorithms could be developed. Additional information available to the carrier, such as signal strength, may provide easy means to separate good and bad data points.

Even for an accurate technology like GPS, ambiguity in the path followed is a problem, particularly for freeway segments. Differentiating between freeways and frontage roads is problematic for 6% of the freeway segments even at 20 meters accuracy. Using the best available road data, there was a 12-meter error in road placement so this corresponds to a technology accurate to 8 meters. Several freeway simulations, such as FREQ, provide spatial shift models that may be adaptable to a probe system. Using these models may allow the tracking software to make reasonable predictions of the route followed where the data alone cannot.

Cellular phone tracking, at least the one implementation we examined, shows promise but needs further study to determine its ability to produce quantifiable travel time data. The data tested had short sequences with a large number of bad positions. In its favor, it promises very large numbers of probes. GPS produces long sequences with high accuracy and a moderate number of bad positions. GPS equipped fleets are likely to have fewer identification and travel behavioral problems. A simple field test of FSP-like vehicles showed that deployable systems can be developed using existing technology.

1. INTRODUCTION

Accurate and reliable traffic information is vital to the success of the TravInfo project, the San Francisco Bay Area traveler information system. Unfortunately, the current freeway surveillance systems in the Bay Area do not adequately support the TravInfo database to timely disseminate traffic information through the Traveler Advisory Telephone System (TATS) or through privately offered ATIS products or services. The traffic surveillance problems are primarily due to the lack of the necessary infrastructure. Inductive loop detectors, closed-circuit television (CCTV) and trunk line communication are essential to infrastructure-based surveillance systems for incident detection and freeway speed information. In the absence of the extensive freeway instrumentation, cellular phone calls have served as primary sources of incident detection in the Bay Area.

The Bay Area is planned to cover 500 miles with loop detectors of the 700 miles of Bay Area freeways. A few years ago, 120 miles of Bay Area freeways were instrumented but the study showed that most of the loop detector monitoring stations were generating inconsistent data (SRI, 1998). To improve the quality of the TravInfo database, RTMS (Remote Traffic Microwave Sensor) units were subsequently installed on Route 17 to collect volume, occupancy, and speed data but the study also found that they were more appropriate for signal control and not sufficient for speed or congestion data. Since 1997, Caltrans' District 4 has been working closely with California PATH of the Institute of Transportation Studies at the University of California at Berkeley to systematically develop both diagnosis and prognosis of mal-functioning loop detectors and detector stations. A significant improvement has been made but field tests and corrections require sufficient time to make the system work for the acceptable level of accuracy. As an alternative to freeway instrumentation, many metropolitan areas are interested in collecting traffic data from probe vehicles. Although the concept of the "vehicles as probes" is widely accepted by many transportation professionals, its efficacy for practical application is yet to be determined.

While a number of vehicle identification methods are available for probe vehicles, the present study concentrates on the Global Positioning System (GPS) and cellular technologies. The study consists of three phases of project tasks; Phase I -- program development and initial field test, Phase II --

field operational tests and Phase III -- a large-scale field implementation. The overall goal of the study is to set up a Vehicles as Probes (VAP) system, both hardware and software, for data collection, fusion, and dissemination at the Institute of Transportation Studies, the University of California at Berkeley. Currently, the Computer Systems Unit of the Institute of Transportation Studies is evaluating and improving the inductive loop detectors for Caltrans District 4 in the San Francisco Bay Area. The VAP system will be tied together with the on-going loop detector station work at the Institute of Transportation Studies. The benefits of having probe vehicle data are that they can argue the insufficient data coming from loop detectors while they also can provide traffic information in areas where instrumentation is not in place.

This paper is an interim report on the Vehicles as Probes project for the Phase I study. In Phase I, the study is devoted to the investigation of GPS and cellular technologies, development of software programs and initial field tests of technologies. The Phase II study focuses on conducting a pilot field test of GPS and cellular technologies and developing necessary algorithms for data reduction and fusion. . The Phase III study is to implement a large scale VAP at selected locations with designated vehicles such as FSP vehicles, delivery trucks, or Car-Share vehicles. The broad objective of the Phase I and Phase II study is to assess the feasibility of collecting freeway speed and incident data from probe vehicles equipped with GPS and cellular phones in the San Francisco Bay Area.

The study objectives are:

Phase I – Program development and initial field test

- Review previous studies done in “vehicles as probes” at PATH and elsewhere.
- Investigate the current application of GPS and cellular technologies to freeway surveillance.
- Evaluate the vehicle probe technology using GPS for vehicle positioning accuracy.
- Experiment with a pilot field test of GPS for vehicle positioning.

Phase II – Field operational tests

- Collect probe vehicle data using GPS and cellular technologies
- Compare data from GPS with data from cellular technologies

- Develop algorithms for data reduction and fusion

Phase III – Large-scale field implementation

- Set up a VAP system
- Identify freeway links for VAP application
- Collect and evaluate VAP data

This working paper is part of the broad evaluation of cellular and GPS technologies to support probe activities for vehicle speed or travel time measurements. As the FCC mandated the E-911 requirements that vehicle position reporting be deployed by October 1991 when 911 calls come in, a number of cellular providers developed vehicle positioning technologies to comply with the FCC standards. For network-based solutions, it required that 67% of vehicles made E-911 calls be verified within 100 meters, 95% of vehicles within 300 meters. For handset-based solutions, 67% of vehicles within 50 meters and 95% within 150 meters. Details of the E-911 requirements and implementation plans are described in the separate reports (Ygnace, et al, 2000).

2. BACKGROUND

Incident data collection methods can be categorized in two ways: qualitative and quantitative measurement techniques. The qualitative data collection method is based on the calls made from cellular phones by motorists to report on freeway incidents. The quantitative data collection method is concerned with mobile positioning to determine vehicle speed or travel time between positional fixes

Qualitative data collection for incident locations

Since the mid 1980's cellular calls have played a significant role in the traffic surveillance system. Several problems are noted with this system at least from the operational point of view. First, the contents of calls must be verified. Second, the consistency of the content of information must be checked among the recipients of cellular calls (i.e., Caltrans, California Highway Patrol, TravInfo, Metro Networks, radio and television stations, etc.). Third, cell call information must be fused to the extent that it is understandable, accurate, and reliable. Finally, the increasing number of calls needs to be screened or rerouted so that the recipients can economize cell call handling. A question is, what mechanisms are available to simplify the process yet are cost-effective for receiving and handling call information for traffic surveillance?

Presently, TravInfo relies heavily on the California Highway Patrol's (CHP) Computer Aided Dispatch (CAD) system for incident reporting. CAD data is based primarily on cellular calls from motorists reporting on incidents. The study showed that, on the average, cellular calls reporting on an incident were 3 minutes sooner than the probe vehicles and 5 minutes sooner than CHP officers detect freeway incidents. The biggest problem with motorists' cellular calls is the over saturation of redundant calls on the CAD (Skabardonis, et al, 1998). E-911 calls are answered in the order the calls are received; thus, if the call volume is high on the first incident, the delay of receiving calls on the second incident can be as long as 5 - 10 minutes. Research questions should include: 1) what technical and institutional systems will it take to pass approximate positional information to the CAD, 2) how would this positional data be most effectively utilized, and 3) would the E-911

call receivers be willing to implement the hardware, software and institutional procedures to adapt a new system to efficiently handle over saturated redundant calls?

Quantitative data collection for speed on incident duration:

Presently, over 50% of the speed and congestion data feeding into the TravInfo database from loop detector monitoring stations are not reliable. The assumption is that probe vehicles can provide freeway speed and travel time between positional fixes using cellular phones with GPS. With the inexpensive GPS (about \$150 per unit) now available in laptops and Personal Digital Assistants (PDA) and cellular phones, it seems plausible that probe vehicles equipped with cellular phones and GPS should be able to adequately measure travel time. GTE Mobilnet announced in 1998 that automatic positioning of cellular phones will be commercially available using the GPS technology and broadly available in the near future. In light of the cellular-GPS market penetration, the present study addresses the following questions: 1) would the mobile vehicle positioning technique with GPS adequately measure travel time, 2) how many probe vehicles are needed to collect freeway speed data, and 3) how should the probe vehicle concept be implemented if it is proven to be technically feasible and cost-effective? The paper attempts to answer some of these questions.

Mobile Positioning Technologies Using GPS and Cellular Phones

To comply with the FCC's mandated E-911 requirements, a number of cellular providers have been and are developing mobile positioning methods with cellular technologies. Among them are: Lucent in Mountain View, U.S Wireless Corporation in San Ramon, Radix Technologies in Mountain View, SnapTrack in San Jose, California, and University of Technology, Sydney (UTS), Australia. Most of the cellular positioning work by private firms is performed in the San Francisco Bay Area. Interestingly, each firm is developing different mobile positioning technologies. *Lucent* has been examining the feasibility of CDMA (IS-95 Code Division Multiple Access) positioning and developing a standard for evaluation of different cellular positioning systems.

U.S. Wireless is using the Radio Camera system to recognize vehicle location. The US Wireless system identifies and "fingerprints" the radio frequency pattern, both multipath phase and

amplitude characteristics of a cellular phone when it is turned on. The callers' vehicle location is identified by matching the fingerprint of the caller with the previously identified radio frequency pattern of fingerprints and to their corresponding geographic locations within the calibrated network. In 1999, US Wireless is commissioned to install their infrastructure to measure highway congestion speed on Capital Beltway in Virginia. The study is undertaken in association with the Universities of Maryland and Virginia, and the Virginia Department of Transportation. The evaluation results of the project are not yet available.

The *Radix Technology* is a network-based geo-location system. It is designed to locate wireless telephones to comply with the current FCC E911 mandate. The company claims that its mobile positioning accuracy far exceeds the FCC requirements. The initial Radix's GeoPhone location system is designed for CDMA wireless networks, but its later versions are adapted for TDMA (IS-136 Time Division Multiple Access) and GSM (Global System Mobile) protocols. The Radix system's infrastructure is a low cost sensor at each cell site. The Radix GeoWorkstation manages the functionality of the system and gathers all data from the sensors and calculates the latitude/longitude position of a vehicle at a given time when a cellular phone is operating. The GeoPhone system delivers mobile position data for E911 emergency location services or other value-added location services. The company claims that its high-speed microprocessors enable a complex advanced signal processing system to develop the location technology and algorithms for the cost-effective GeoPhone system, signal-processing techniques. The system can produce a high precision, network-based geo-location system that eliminates many obstacles often associated with network based location solutions.

The *SnapTrack's* system is based on the Global Positioning System with the handset-supported vehicle positioning technology. When the handset SnapTrack is activated, the wireless network sends an estimated location of the handset to a server and the server informs the handset via GPS satellites. Then the handset takes a "snapshot" of the GPS signal, calculates its distance from all satellites in view and sends this information back to the server. The software of the server corrects errors and calculates the caller's precise latitude, longitude, and altitude. In the case of a E911 call, the server sends the information to the Public Safety Answering Point. For other location-based applications, the server can send the coordinates to a third-party service provider, a dispatcher or

back to the handset. The process takes just a few seconds while conventional GPS receivers can take several minutes.

GPS is one of the most promising techniques for vehicle positional accuracy available to date. Especially with *differential GPS*, a greater accuracy can be achieved by using two ground-based satellite receivers. One of the receivers monitors variations of the GPS signal and communicates them to the other receiver that corrects its positional calculations for a greater accuracy. *Carrier-phase GPS* is another technique to improve the positional accuracy. It can be used for more precise timing measurements since its carrier frequency is much higher than the GPS signal. Another type of GPS is called *Augmented GPS*. This technique is used for the transmission of differential corrections and GPS satellite status information for instrument landing in space.

Among the manufactures of GPS products are *Garmin*, *Magellan Products*, *II Morrow*, and *Trimble*. *Garmin* has multiple products but none is directly related to fleet monitoring. However, it allows data feed into the GPS system directly with low AM band and it produces differential GPS units. *Magellan* produces wireless communication applications (i.e., GSC 100) accessing the ORBCOMM satellite constellation. It offers Vehicle Navigation products (i.e., 750NAV, pathMater, GPS Map N Track). *II Morrow* has only aviation units and its market is directed to commercial and general aviation usage. *Trimble* manufactures Automatic Vehicle Location (AVL) devices. It offers mobile units, communication networks, and base station software.

Other types of navigation systems being used for positioning identification are Dead Reckoning, Landmarks, and OMEGA. Dead Reckoning has been tested in many field operations, but it is quite complicated and its accuracy depends on crude measurement tools, thus errors can accumulate rather quickly. A Landmark is good for local areas and is subject to movement or environmental factors. OMEGA is based on few radio direction beacons and thus its accuracy is subject to radio interference. More recently, cellular technologies are seriously considered for vehicle tracking and are reported in a separate paper (Ygnace, et al, 2000).

The Benefits of Probe Vehicle Data

While major freeways in the Bay Area would be equipped with inductive loop detectors and CCTV cameras in the near future, there is no plan to instrument minor or rural freeways. Many municipal streets in the Bay Area except the City of San Jose are not going to have the infrastructure needed to monitor arterial traffic flow. Various data collection techniques such as loop detectors, CCTVs, cellular phones and GPS units, can be applied to different freeway segments and local arterials. Vehicle probe information can be complementary to those freeways where they have single loops since the single loops are not capable of producing the most accurate traffic speed and density. Probe vehicle data can also be used for rural freeways or minor urban freeways where no instrumentation is planned. Local streets and arterials are also good candidates for collecting data from probe vehicles.

Typically about 50% of loop detectors are producing accurate or reliable traffic data. In the Bay Area the performance rate of the existing loop detectors are much less than the national average for various reasons including hardware, software and communication problems. Since 1998, Caltrans with the help of PATH engineers has been identifying loop detector problems and correcting the problems as fast as they can but the process has been arduous in pinning down problems associated with individual monitoring stations.

The need for alternative methods for traffic data collection is apparent for two important reasons: 1) improvement of surveillance data for Caltrans District 4 traffic management and operations and 2) TravInfo's data dissemination of accurate and reliable traveler information for the Traveler Advisory Telephone System (TATS) and Bay Area Information Service Providers (ISP).

Considering the slow progress of loop detector instrumentation of the Bay Area traffic surveillance system and the extent to which loop systems require maintenance, the GPS or cellular phone probe systems are considered as an alternative means of supporting traffic data coverage, especially in those areas where the existing detectors do not work properly and where instrumentation may not be deployed in the near future. The vehicle probe system can potentially provide cost-effective

wide-area data coverage including both freeways and arterials. No heavy infrastructure investment is necessary for vehicle probes.

The present study focuses primarily on the feasibility of the Global Positioning System although cellular technologies were investigated. Presently, cellular providers determine the approximate position of mobile callers in order to pass-off between transceivers. With the GPS, mobile positioning would be more accurate. Our interest was to compare the US Wireless “finger printing” system against GPS in the field test but we were not able to test this technology because the company was unable to provide us with the necessary data. However, the company did provide us with two previously collected data sets. This data was analyzed with respect to the tracking software developed for this project and some limited results are presented below.

3. PREVIOUS STUDIES

Over the past several years, PATH researchers investigated vehicles as probes and PATH produced about a half dozen research reports about cellular phone and probe vehicle technologies. In 1992, Yim et al, looked into the effects of the cellular technologies on travel behavior. This study focused primarily on how travelers change their travel behavior based on cellular phone calls. It did not address cellular calls for traffic management such as E911 calls and had very little to do with vehicles as probes.

Snawal and Walrand (1995) investigated the possibility of using probe vehicles for estimation and prediction of traffic behavior. Note that travel behavior and traffic behavior are two different behavior properties. The 1992 study by Yim and et al, investigated travel behavior while Snawal and Walrand investigated traffic behavior. Travel behavior deals with motorists' departure time, mode, route, and trip cancellation. Traffic behavior is concerned with vehicle speed, density, volume, and travel time. The study of Snawal and Walrand addressed some of the key issues involving a traffic monitoring system using probe vehicle reports on speeds, locations or travel times. An algorithm could update and estimate traffic conditions and thus could make predictions for the future state of traffic conditions. The results of the evaluation study indicate that vehicle probes are feasible for a traffic data source. The study found that probe vehicle speeds correlate well with those of the speeds obtained by loop detectors. The study also estimated that about 4% of the vehicles on a highway would be required to produce a good estimate of travel times based on the simulation results. The communications bandwidth required for vehicle probes is fairly modest and can be economical. Network simulations performed for the study is limited to the configuration available for loop detector data.

Linnartz, et al, (1994) analyzed the probe vehicle concept, focusing on communication limitations. It addressed a radio communications concept that is simple, inexpensive and spectrum-efficient for the probe vehicle transmissions. The authors developed a computer tool called PROMOT (PRObe vehicle concept for Monitoring road Traffic) to evaluate this concept in a realistic traffic situation on the Bay Area transportation network. The authors believed that radio is an appropriate medium for wireless probe communication; thus, one radio channel could be dedicated to transmit traffic

data from probe vehicles to base stations. A random-access transmission scheme (slotted ALOHA) was found to be an efficient spectrum and it was an inexpensive and flexible method for transferring traffic reports from probe vehicles to base stations.

The study dealt with a method of collecting real-time traffic data from probe vehicles that automatically sends traffic reports to one or more base stations that are connected to a traffic center by a wired communications network. Each probe vehicle keeps track of its own geographic position using dead-reckoning or GPS satellite positioning and transmits its average instantaneous speed and travel time on a radio channel so that a near by base station can receive information. The propagation distance of the traffic messages transmitted by probe vehicles and probe vehicle penetration rate are the two most significant communication parameters affecting the proficiency of the probe vehicle concept for collecting real-time traffic data. The results of the network simulation showed that as the distance between the base station and freeway link (where a probe vehicle is sending messages) increases, the number of messages received in the base stations decreases significantly. This could be due to the volume of messages sending and the capacity of the wireless communication link between probe vehicles and the base station. The authors suggested that it might be necessary to refine the resolution for the analytical computer tool.

Westerman, et al, (1996) developed a method for estimating real-time travel times (or mean speed) using vehicle probe information. The study showed that approximately 3-5 probe reports per period are required in order to obtain 85% accuracy considering that a proper historic database is available. If reports are required to be sent every 10-15 minutes, only the 1% probe vehicle penetration rate is adequate. If reports are to be sent every 1-5 minutes, the 5% penetration rate is necessary. The study found that it is difficult to obtain accurate real-time traffic flows and traffic densities solely from probe vehicles. Probe vehicles are feasible for determining traffic variables for several hours or days where no infrastructure is available. However, the authors learned that fusing probe vehicle data and induction loop data could considerably improve the accuracy of traffic data.

Moore, et al, (1998) investigated the feasibility of using the existing Freeway Service Patrol (FSP) trucks as probe vehicles to measure the level of service on Los Angeles freeways. The study team

conducted an extensive review of literature on FSP and probe vehicles, researched the FSP system its operations, and FSP truck driving characteristics, and explored the feasibility of integrating loop detector and FSP probe data. The study identified operational and institutional constraints that may limit the use of FSP trucks as probe vehicles. The primary reason is that FSP vehicles are dispatched during working hours and thus they cannot be deployed as probe vehicles beyond net patrol hours. The maximum time limit for using them as probes is working hours. Beyond this finding, the results of the study are inconclusive and therefore further analysis is recommended.

Hall et al, (1997, 1999) conducted a field operational test of an automatic-vehicle-location (AVL) system for the OCTA (Orange County Transit Authority) Transit Probe Project in Orange County, California. Its objective is to evaluate the OCTA Transit Probe Project. The OCTA Transit Probe Project is tracking data with GPS equipped buses for multiple purposes including bus schedule adherence and fleet management, information on roadway traffic congestion, and transit data dissemination to patrons. The interviews with project participants covered a range of issues related to project management, project objectives and institutional barriers. One of the research issues was whether the tracking data could be effectively integrated into existing traffic and transit systems.

The authors believed that bus tracking systems provide many potential benefits. The benefits include drivers stay on schedule, dispatchers respond to problems, schedulers allocate appropriate time between schedule checkpoints, and travelers have information on real-time bus arrivals. The study found that reliability is a major problem with Transit Probe. Problems include missing undetected data resulting from inoperable or failed units, lack of complete coverage on routes, and inability to immediately update data at schedule changes. The authors concluded that transit probe clearly has not met reliability expectations for an actual deployment. In order to gain benefits from transit probe, it is necessary to have carefully planning operational procedures, keeping data maintenance, and system interfaces and ensuring the equipment reliable.

Although these studies provide useful information, much of the research effort has been placed on theoretical analysis or on simulation modeling. This present study is aimed at the practical application of the GPS technology deployment through program development, field tests and project implementation.

4. ISSUES ON VEHICLES AS PROBES

GPS and cellular technologies for freeway surveillance in the Bay Area are used with the Freeway Surveillance Patrol (FSP) vehicle reporting system. There are other GPS-cellular applications to private fleet vehicles in the Bay Area, but information about their operations is not readily available.

Presently, 50 FSP vehicles patrol designated freeway segments (beats) regularly to report on freeway speed and incident's nature and location. The speed data are automatically fed into the TravInfo Traveler Information Center (TIC). Only two FSP vehicles patrolling SR 17 are equipped with cellular phones and GPS. Other FSP vehicles use a radio communication system.

The speed data furnished by the FSP vehicles are often unreliable because the primary function of these vehicles is to respond to incidents as quickly as possible. Therefore, FSP vehicle speed may not represent the speed of the freeway traffic. To understand the FSP activities, FSP and TravInfo operators were interviewed in 1998 and 1999. The FSP vehicle operators at the Metropolitan Transportation Commission (MTC) were interviewed in 1999 and it was learned that they were evaluating the FSP activities to determine the need to upgrade equipment for FSP vehicle operation.

As Moore, et al, (1998) found, using FSP vehicles as probes has certain limitations, such as FSP vehicles cannot be deployed beyond their net patrol hours. In addition, the problems with the Bay Area FSP vehicles are that 1) they are not sufficiently equipped with the most current state of the art technologies to send timely information to the TravInfo Traveler Information Center, 2) their primary function is quickly responding to incident reports, therefore, their speed data oftentimes cannot be reliable. However, FSP vehicles can provide useful information when they do not have to respond to incidents. There are other possibilities for collecting probe data using government or private fleet vehicles or public participation. Assuming that various types of vehicles can be used for probes, the question is then what are the technical issues that we need to address for GPS tracking traffic data and what level of data accuracy is acceptable for traffic management?

Two major GPS issues for probe vehicles are positional technique and acceptable level of positional accuracy. In addition, it is necessary to address institutional issues associated with dealing with E911 calls.

Positional Technique Issue

With respect to the quality of probe vehicle data, there is a question of what positional techniques are most appropriate for qualitative vehicle as probes information? The assumption is that the verification of the mobile positions of cellular callers can be done via GPS qualitatively and that this GPS positional technique is sufficient for incident management. However, the further question is whether the GPS - cellular phones can provide reasonable accuracy of travel speed information.

A mobile vehicle's position can be determined by triangulation off cellular transceivers, or triangulation off GPS satellites. GPS is a system specifically deployed and optimized to provide global position. Although initially quite complicated and expensive, market volume has reduced the GPS component size to a two-chip set. Marketing for these chips is being specifically targeted for laptops, PDA, and phones, and one might assume it is only a matter of time before they are available for a wristwatch. Current uncorrected accuracy is 15 meters for 95% of the readings, 10 meters for 50% of the readings. By correcting for variations in atmospheric conditions greater accuracy can be obtained. Reasonably priced units with correction are accurate to 10 meters 95% of the time and 3-5 meters 50% of the time. Accuracy with correction is primarily dependent on the quality of the electronics in the unit and accuracies of less than 1 meter are available but much more expensive. These accuracies are dependent on clear views of the sky and reasonable antennas. The GPS capabilities being built into mobile phones and other small devices are not expected to achieve the same accuracy as current commercial GPS units in the near future.

Cellular phone companies presently determine the approximate position of mobile callers in order to know when to pass-off between transceivers. They will increase this accuracy in the future. Because the transceivers are ground based and rarely in line-of-sight to the phone, the multiple paths for the radio waves inherently make accurate positioning difficult. The question is then is it

cost effective for the cellular carriers to attempt to develop accurate cellular based triangulation positioning when GPS is already so cheap?

Positional Accuracy Issue

There is a question of what degree of positional accuracy is needed for qualitative versus quantitative vehicle as probes. Generally any incident that induces a driver to initiate a 911 CAD call could be significant and de-localized enough that an approximate position might be adequate. Data from the Computer Aided Dispatch system is inherently qualitative; thus, matching a qualitative position via triangulation to the CAD data would seem appropriate.

It is plausible that wide-area quantitative travel time data from probe vehicles may be generated from positions not as precise as small-area travel time data. It may not be necessary to know vehicle position very accurately in order to determine the travel time between Oakland and San Jose. However, significant accuracy is required to determine the street in an urban grid, or to determine if a vehicle is queued on the freeway or on an adjacent off-ramp. Generally, the more accurate the vehicle positioning, the less the potential for ambiguity in the ITS (Intelligent Transportation Systems) database.

The accuracy required for an effective probe system is dependent on the geography of the road network. In areas of greater density, with roads close together and many intersections, much greater accuracy is required for the probe to be correctly placed on its road segment. Where roads are far apart with few intersections, a much lower degree of accuracy in position identification can be used and still yield correct road segment matches. To quantify the level of ambiguity and to estimate the degree of accuracy required for generating travel times from probe vehicles, two counties in the San Francisco Bay Area, Alameda and Contra Costa, were examined. Simulated probe vehicles with varying levels of positional accuracy were generated and run through the probe following software developed for this project.

Alameda and Contra Costa have a total of 29 million meters of directional roadway. The roads are classified into 3 categories, freeways, major arterials and local roads. There are 1.1 million meters

of freeway, 5.7 million meters of highways and major arterials, and 22 million meters of local roads.

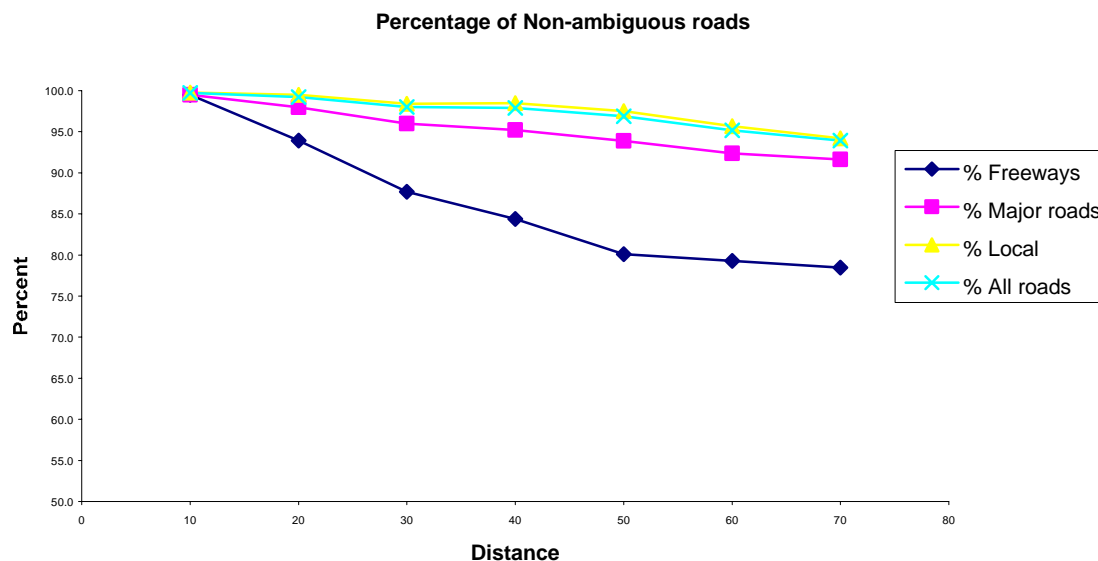
Working with the county data, each road segment was examined to determine whether a vehicle travelling along that segment could be correctly followed as it left the segment using various levels of location accuracy. All possible paths out of the segment were examined. If one of the possible paths was ambiguous, that segment was marked as ambiguous. This is an extremely conservative test of vehicle following and represents a worst-case measure of location ambiguity. Due to very long run times, which increase exponentially as the distance increases, a second test was done with larger values of positional accuracy where only freeways and major arterials were examined and only paths along the major road were generated. This is a reasonable restriction on a probe system where travel times are produced only for the major roads, not for all local roads.

The set of all links was tested using accuracies from 10 meters to 70 meters. Figure 1 shows the percentage of ambiguous links for the 3 classes of road as well as for all roads combined. The first line is for all classes of road, the second line is for highways and major arterials combined, and the third line is for freeway links only. At 10 meters, the percentages for all the classes are quite high, 99.5% for freeways, 99.5% for major roads, and 99.8% for local roads. The percentages decline for all classes as the location error increases but the effect is most marked for freeway links. Freeways tend to cut across links of the other types and tend to have close parallel streets which are uncommon for the other classes. So, while 94.2% of local roads are unambiguous at 70 meters, only 78.5% of freeway links are unambiguous.

Figure 2 shows the percentage of ambiguous links for freeways and for major roads if we restrict the path following to only look at vehicles which travel on those two classes. By 100 meters, only 2/3 of the freeway links are unambiguous, while 87% of the major roads are still unambiguous. By 190 meters, less than 45% of the freeways are unambiguous but more than 75% of the major roads are. This suggests that while technologies with large inaccuracies in position measurement are not suitable for measuring freeway conditions, they may still be very useable for measuring major road and arterial conditions. A combined system using conventional freeway surveillance technologies,

such as loops, supplemented by a relatively inaccurate probe system, such as cell phone tracking, for the arterials may provide good wide-area coverage.

Figure 1. Non-ambiguous road segments as a function of positional accuracy

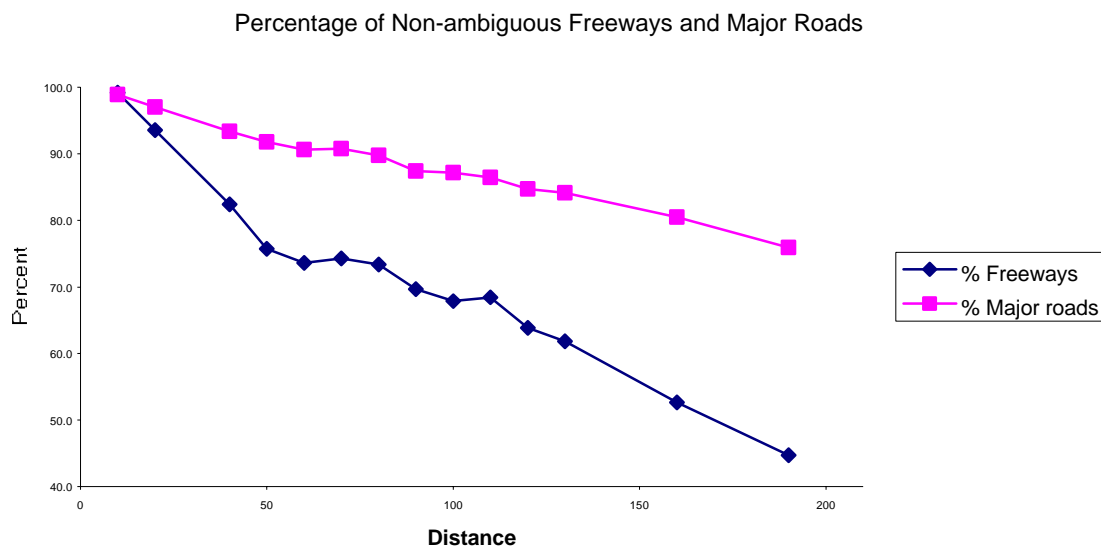


Below 30 meters, the ambiguous paths are of three main types. One is very short sections of divided roads at intersections. In this configuration, the software determines that the vehicle might turn right, proceed a short distance up the road to the end of a divider, make a u turn and come back to the other side of the original intersection. This path can be traveled in a very short time and cannot be distinguished from a vehicle simply proceeding across the intersection. Future enhancements to the software may eliminate this but the effect is minor in any case. The section of road, which is ambiguous, is only the very short section across the intersection. The longer road segments on either side of the intersection are not affected.

A second type of ambiguous path found even with very accurate location technologies is caused by dedicated right turn lanes divided from the main roadway. It cannot be determined whether a vehicle took the right turn lane or proceeded up to the intersection and turned right. Again, future versions of the software may assume that all vehicles take the right turn lane and eliminate the ambiguity. The impact is small, in any case.

The third type of ambiguity is more serious and occurs mostly at freeway ramp interchanges. A vehicle may exit the freeway, proceed straight down an off ramp, cross an intersection at the bottom of the ramp and enter the freeway via an on ramp on the other side. This path is ambiguous relative to simply proceeding along the freeway, even at quite accurate location distances. In some cases, the distance from the right hand lane of the freeway to the off and on ramps is less than the distance to the far left lanes of the freeway.

Figure 2. Non-ambiguous road segments as a function of positional accuracy (major roads only)



There are some additional ambiguities caused by coding errors in the Etak data set used. Some overpasses are not correctly marked. This results in certain paths appearing to be ambiguous which are not, in fact possible. The situation appears as a vehicle exiting the freeway, traveling down an off ramp, turning left at the intersection at the bottom and immediately right onto the freeway again at a non-existent intersection. Further work with Etak on the correct coding and interpretation of overpasses will eliminate these problems.

As the accuracy of position location drops, further ambiguous situations appear. At 50 to 60 meters, some city blocks become ambiguous. Here, a vehicle may turn at an intersection, turn again and follow a parallel street, and turn back onto the original street while never moving more than 50

meters away from the original street. Some freeway arterials are less than 60 meters away at all times between successive on and off ramps. For these, it is impossible to tell if a vehicle exits the freeway, travels for several segments on the arterial and reenters the freeway.

At 100 meters, many more areas of the road network become ambiguous. Many residential areas have all the streets less than 100 meters apart. Surprisingly, restricting the probes used to only those traveling on the major arterials yields a quite reasonable percentage of segments which can be unambiguously identified. This restriction may drastically lower the number of probes which can be used, however. Whether the probe will stay on the major arterial or not cannot be known until after it has been followed. Once the vehicle has left the major road it will be discarded but, in situations such as cell phone tracking, where there is a hard limit to the total number of probes which can be tracked, following an unusable probe prevents the system from following a usable one.

It appears that probe following can be effective for a large percentage of road segments even with fairly inaccurate location technologies. However, the simulated vehicles were tracked for whatever distance was required to identify links. There is a direct relationship between the positional accuracy and length of time a vehicle must be tracked in order to generate travel times. At an accuracy of 10 meters, tracking the vehicle for twice the average segment length is generally sufficient to yield a travel time for at least one link. At 100 meters positional accuracy, the vehicle may have to be tracked for a mile or more.

Probe Identification and Behavioral Issues

Positional accuracy is only one of the difficulties in probe systems. A second issue, which is particularly problematic for cell phone tracking, is identifying probes which are traveling in a manner representative of the total traffic flow. A probe tracking system must infer from the location data what the travel behavior of the vehicle is and discard those probes which are either not vehicles at all, or are moving differently from the rest of the vehicle stream.

It has been suggested that AVL systems installed in fleets, such as the Freeway Service Patrol or delivery vans, could be used as the data source for a probe system. While identification of the probe is not a problem for this kind of vehicle there are behavioral problems. FSP vehicles may or may not be traveling in the regular vehicle stream. They may stop by the side of the road for periods of time. When towing a vehicle, they are likely to be traveling slower than the other vehicles. Delivery vans stop and make deliveries. These unrepresentative behaviors must be identified and the generated travel times must be discarded or the accuracy of the system will be degraded.

The problem is much worse when the probes being tracked are handheld, such as cell phones. In addition to the same travel behavior problems AVL systems have, there is no guarantee that the probe is in a vehicle at all. Even if it is in a vehicle, the range of possible vehicles is greater and there are many more ways in which the probe may not be traveling in a representative manner. A motorcycle may be traveling between lanes on a congested freeway and generating travel times much greater than the mean time. A passenger on a train running down the center of a freeway will appear to be on the freeway but is certainly not valid for determining freeway travel times. For cell phones, earlier research has shown that driver behavior changes when talking on a phone. For a call-based system such as US Wireless, the correction for the behavioral change is problematic. There is no way to tell if a call in a moving vehicle is being made by the driver or a passenger. For carrier based tracking systems, the problem can be dealt with by discarding probes making a call.

All these difficulties can be partially compensated for by increasingly sophisticated post-processing of the data stream which can increase the accuracy of the results by discarding problematic data. However, the number of probes must be increased in order to compensate for the lost data and the necessary increase is much greater for handheld systems than it is for vehicle-based systems.

Institutional Issue

As mentioned earlier, the biggest problem with qualitative data from probe vehicles is the over-saturation of redundant calls on the California Highway Patrol Computer Aided Dispatch system. Currently, calls are answered in the order they are received, so that if two accidents a minute apart generate 50 calls each, the CHP may not get down low enough in the queue to learn of the second

one for 5 or 10 minutes. If a data structure representing the callers initial position is passed to the CAD center, it may be possible to do such things as answer redundant calls from the accident location with a message indicating the CHP already knows about the accident, or prioritize calls by location rather than queuing time alone.

What technical and institutional systems will it take to pass approximate positional information to the CAD center and make it available before the call is even answered? How would this positional data be most effectively utilized? Would the CHP operationally implement the hardware, software, and institutional procedure to do this? Although these issues are necessary to address, they are not covered in the report because inter-agency cooperation is required and historically such cooperation was not easily obtainable.

Probe Vehicle Sample Size Issue

With the given level of GPS accuracy for vehicle positioning, the question is how many probe vehicles are needed to collect an adequate sample data for a reasonable estimate of travel speed? The sample size of probe vehicles is closely associated with both the positional techniques used and the positional accuracy obtained. Although the sample size cannot be determined without an understanding of the GPS technical limitations or capabilities, a statistical concept may commonly be applied to sample size estimate. A number of methods for estimating the sampling size of probe vehicles are reported in previous PATH reports. Three sampling methods are presented in the following section.

5. SAMPLE SIZE OF PROBE VEHICLES

The sample size of probe vehicles is one of the critical issues to be addressed for the vehicles as probes project. In general, frequently addressed questions were:

- How many reports (sample observations) should be received to obtain the acceptable level of speed information or how often should the probes send their reports?
- What is the acceptable level of standard errors and standard deviation for mean speed calculation?
- What percent of probe vehicle saturation is necessary for a given time interval in order to obtain accurate and reliable information or how many probe vehicles are necessary to provide the minimal reports?

Three sampling methods are presented. The first method deals with when standard error is known or can be obtained; second deals with an algorithm developed for speed estimate of probe vehicles; and third deals with mean speed estimate in a network.

Sampling Method 1: Standard Error is Known

When thinking about the number of required reports that can adequately represent the speed of the vehicle population passing a given link at a given time, we need to establish an acceptable sampling error. The commonly accepted sampling technique is to use the sample mean, standard deviation and standard error of the sample. If we know the standard error from the previous sampling results or historical data, they can be applied to this study. However, data on probe vehicles with GPS are not readily available.

One of the Field Operational Test objectives is to determine the sample size of probe vehicle reports using the standard error for speed studies. The goal is to select the smallest sample size

possible while providing a limit on a pre-specified error. Standard deviation is a measure of dispersion of individually observed speeds. The standard deviation can be obtained from field tests. Note that if “the speed parameter of individual vehicles, s , is constant, and remains constant, it is the interval estimate that is a random variable, because its center, \bar{X} , is a random variable. The deviation of \bar{X} from its target s must be considered an error. So the standard deviation of \bar{X} is called the standard error of the mean (Wannacott & Wannacott, 1977).”

For obtaining a sample size, we can pose a question, what should the allowable sampling error be? The allowable sampling error depends on the level of fluctuation on the sampling distribution of \bar{X} . If we are looking for the confidence level of 95%, its probability is:

$$\Pr(\mu - 1.96\sigma_{\bar{x}} < \bar{X} < (\mu + 1.96\sigma_{\bar{x}})) = 95\% \quad (1)$$

Where μ = population mean
 σ = standard deviation of the population
 $\sigma_{\bar{x}}$ = standard error of the sample mean
 \bar{X} = sample mean

If the confidence level is 85%, its probability is:

$$\Pr(\mu - 1.47\sigma_{\bar{x}} < \bar{X} < (\mu + 1.47\sigma_{\bar{x}})) = 85\% \quad (2)$$

Therefore, the 95% confidence interval of the population mean is:

$$\mu = \bar{X} \pm 1.96\sigma_{\bar{x}} \quad (3)$$

The 85% confidence interval of the population mean is:

$$\mu = \bar{X} \pm 1.47\sigma_{\bar{x}} \quad (4)$$

The standard error of the mean (or the standard deviation of \bar{X}) is:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \quad (5)$$

Using the above concept, the standard error of the mean speed can be written as (May, 1998):

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \quad (6)$$

$s_{\bar{x}}$ = standard error of the sample mean (miles/hour)

s = standard deviation of the sample of individual speeds

n = Number of observed individual speeds

Thus, the sample size, n , can be derived from:

$$n = \left(\frac{s}{s_{\bar{x}}} \right)^2 \quad (7)$$

Or it can be rewritten as (May, 1992):

$$n = \left(\frac{ts}{\mathcal{E}} \right)^2 \quad (8)$$

n = sample size required by probe vehicles

s = standard deviation of the probe vehicle sample

\mathcal{E} = specified allowable error

t = coefficient of the standard error of the mean for the specified probability level

t

“In most speed studies, probabilities or confidence levels closer to 0.95 or 0.99 are selected. In these cases, a coefficient on the order of 2 to 3 is used for the standard error of the mean (May, 1992).” Based on the Figure 1, if we want to estimate the population mean within ± 1 mile per hour with a 95% confidence level and based on previous speed studies, the standard deviation is expected to be 5.2 miles per hour. A minimum sample size of 152 observations.

Sampling Method 2: Speed Estimate Algorithm

Sanwal, et al, raised the following questions: how many vehicles need to serve as probes in such a system; how often should the probes send their reports; what are the measurement/data that the probes should report? Sanwal, et al, argued that the accuracy of the speed estimates obtained from probe data depends on the number of probes operating in the system, frequency of reports (f_R), the contents of the reports, and the algorithm used to obtain the estimates. To get this information, Sanwal, et al, simulated a highway segment with probe vehicles traveling on it and used the reports to predict future travel times.

The issue was estimating the link speeds from the probe data. If actual speeds of the traffic in link j is a function of time t , then let $v(j,t)$, where $j = 1,2,\dots,n$ and the interval of interest is $[0, T_f]$. If the speeds and positions of the i^{th} probe vehicle on this highway is a function of time be $[v_p^i(t), x_p^i(t)]$. The probe speeds are related to the average speeds as:

$$v_p^i(t) = v\{l[x_p^i(t)], t\} + z_i(t) \quad (9)$$

If the function $l: R \rightarrow \{1,2,\dots,n\}$ maps the position of the probe vehicle to the link

$z_i(t)$ is a random process representing the deviation of the speed of vehicle l at time t from the collective flow at time t .

The number of probes required for a good estimate of travel times is about 4% of the vehicles on the highway, based on the simulation results. It is assumed that vehicles in a particular link report their speeds only if the speeds are off by more than a certain fraction from the speeds estimated for that link. Sanwal, et al, reported that if the speeds on the highway were very close to the estimated speeds then the probe reports would not contain much useful information. The fraction of probe vehicles in actual highway traffic is likely to be a variable and the precision errors for various values of the exception range (ER) for frequency is 1 per minute.

Sanwal, et al, said that, to estimate the density k , they assumed a Poisson distribution for the total number of vehicles on a link during a certain time period. Their study determined that the number of probe vehicles on a link during a time period is Poisson distribution with a parameter equal to the number of observed probe vehicles N_p .

If the traffic density, k , on a link (say 5 to 10 Km) during a certain time period (say 5 to 15 minutes) is defined as the total number of vehicles that occupied that link during that time period and if the traffic flow, q , is defined as the total number of vehicles that passed a particular crosscut of a link during a certain time period, then the traffic density, k , depends on the inflow, q , and on the link travel time, t , during a particular time period. Suppose we consider 2,000 vehicles per lane per hour under free flowing, 4% of 2,000 vehicles per hour are 80 probe vehicles per hour.

Sampling Method 3: Mean Speed Estimate in a Network

Drain, et al, developed a model to measure travel time. In their model, the mean speed was calculated by a least squares fit of a series of position measurements. This process would be necessary in systems such as cellular triangulation where measuring the instantaneous speed is not possible. The variance of the speed estimate was found to be proportional to the variance of the position measurement variance and inversely proportional to the cube of the number of measurement points and the square of the time interval between measurements. This means that only a relatively small number of measurements are needed, particularly if they are widely spaced in time. A formula was also developed for estimating the travel time from the mean speed.

Drain, et al's model looked at the overall problem of how many travel time measurements were needed to characterize a network (Drain, et al, 2000). They said, "if too few measurements are made then only a small number of links can be characterized; thus, the overall information is not greatly improved over the historical travel time averages. This derivation assumed a worst-case scenario that the probes were randomly chosen. The model was developed in terms of coverage, i.e. fraction of links for which the links have been measured in the time frame of interest. The result was a surprisingly simple approximation:"

$$E = 1 - \exp(-\alpha\rho L) \quad (10)$$

Where α = fraction of vehicles sampled
 ρ = density of traffic per unit length
 L = average link length
 E = coverage.

According to Drain, et al, this formula suggests that, to improve the coverage, it is necessary to increase the fraction of vehicles sampled or increase the average link length. The latter arises because the larger the link length the more likely it is that a randomly chosen vehicle will be on that link. The heavier the traffic density, the greater the coverage because the total number of sampled vehicles becomes larger. “The exponential nature of the formula indicates why only a relatively small fraction of vehicles is needed to characterize a network, once $\alpha\rho L$ is greater than one, the coverage rapidly approaches 100% (Drain, et al, 2000). A careful interpretation is necessary when using this formula. The study suggested that even though longer links may cover greater information, they may not provide useful information for a particular area if links are too long. Drain, et al’s simulation study showed that 5% of the probe vehicle penetration rate is sufficient enough to give useful information.

The sampling methods described in this section suggest that roughly 4% to 5% of the probe vehicle penetration can provide a good estimate of travel times based on the simulation results. Based on the statistical concept of allowable standard errors, the study showed that approximately 150 – 160 observations per hour would be necessary for reliable speed estimates. These figures however are based on the simulation results or theoretical analysis; it is highly desirable to conduct a field test to verify these results. The field test is intended to verify these results.

6. TRAVEL INFORMATION PROBE SYSTEM

Considering the current state of GPS and its capabilities, the initial focus of this project was concentrated on the application of GPS. The early stages of the project were:

- Investigation of the current state of the GPS technologies and commercially available GPS.
- Evaluation of the off-the-shelf GPS programs for their usefulness in working with vehicle probes.
- Development of additional software programs.
- Identification of problem areas and further research.

In evaluating GPS for vehicle probes, our interest was to examine both GPS and differential GPS for detecting nodes on roads and sending information gathered on position and time of vehicles to a centralized database over the internet via wireless modem. To assess the effectiveness and adequacy of GPS technology for incident detection and vehicle speed information, we first investigated the current state of the technologies and commercially available GPS units and software packages.

For the early testing, a Garmin 12 CX GPS unit and a differential GPS unit were purchased along with other necessary hardware items (i.e., a Mac laptop, Ricochet) with data cable and antenna and software programs (i.e., GPSY software).

We searched for GPS programs that might serve our needs and explored several possibilities. One was from Teletype GPS that is a locator software to record position and trip data to a laptop for \$95; our own GPS NMEA receiver must be supplied. Moor Associate Inc. had a DOS-based utility called Capture for \$49. Gnostech has a program called the Generic Test Station but it provides additional functionality. A program called RECSIM III – NMEA Simulator could be downloaded. It enables a PC to generate NMEA sentences.

Most of the software purchased or downloaded was not able to produce the desired outcome. The questions for commercially available GPS software were:

- Could the software read latitudinal, longitudinal, speed or time information and bearing make it available to other programs?
- Could the software be easily integrated with other commercial or custom software packages to produce travel times.

The initial plan was to carry out the GPS vehicle location project already underway by Caltrans' engineers. The tasks early in the process involved evaluation and modification of a single or combination of commercially available software packages to meet the needs of probe vehicle activities. A couple of engineering students at the University of California at Berkeley worked on the project during the summer months and part of the fall semester in 1999. The initial development goals were:

- Using a GPS unit attached to the serial port of a laptop, read the positional data into a commercial software package (GPSY).
- Pass the data to a custom Real Basic program running on a Mac laptop to calculate when nodes are passed and when events should be sent to the central database.
- The software will determine when GPS unit passes the node by creating a line perpendicular to the direction of travel and recording the positive distance between the two.
- Determine if the person has pulled over for legitimate reasons, or has wandered off the highway for other reasons.
- Send the data to a central database
- Additional software should eventually let people access the database (which at that point should have an algorithm for determining the best route) to use in travel.

The students had difficulty in modifying the existing programs. The off-the-shelf software programs were not easily adaptable to the mobile positioning system for vehicle probes and the custom programming was much more difficult than anticipated. Further, the planned software would be usable in only limited circumstances and unusable at all for evaluation of other location technologies such as cellular phone location systems.

It was decided that a more general and extensive software tool was needed. The staff of the Computer Systems Unit of the Institute of Transportation Studies, the University of California at Berkeley developed an entirely new program, the Travel Information Probe System (TIPS). Among the design goals for TIPS were:

- Usable with any location technology
- Usable with arbitrary positional accuracy
- Applicable to any road network with minimal network coding
- Allow a mixture of probe technologies to be used simultaneously
- Component architecture to easily allow the addition of pre- and post-processing routines such as spatial shift models, error correction modules and alternative path following procedures.
- Designed for future deployment on an area wide scale

The primary objective of this investigation was to determine link travel times given a sequence of times and positions generated by a probe vehicle traveling down a road. Any individual point is insufficient to determine where the probe vehicle is located. For instance the vehicle may be sitting on an overpass above the freeway or be sitting below on the freeway. A single data point is insufficient to differentiate between these two situations. A series of data points, however, can show that the vehicle exited the freeway and turned onto the overpass. By following the vehicle through a series of positions it is possible to determine the track that the vehicle took and, if the accuracy is sufficient, to determine unambiguously which links the vehicle traversed.

The approach taken for the TIPS software was to implement a path following algorithm operating on an embedded Geographical Information System (GIS). Data points are matched to an underlying network map and a set of possible paths through the matching network links is built. For each data point the software identifies all possible links located within a specified accuracy distance. This set of links represents the possible current positions of the probe vehicle. The set of links is added to the sets of links generated by earlier data points and each of the new links is examined to determine whether it can be reached from any of the previous possible positions. As successive data points are added, the number of possible paths changes until eventually the set of possible paths is reduced to

zero or one. If the set of paths is reduced to one, the actual path travel has been determined and the travel time across the links which comprise that path can be calculated.

Other approaches to a probe system are possible, using statistical sampling between successive points, for instance, but a path following approach provides two great advantages. The first advantage is that successful matching of the points to an unambiguous path consisting of multiple links yields a very high certainty that that is the actual path the vehicle followed. The second advantage is that link travel time is easily determined as a by-product of the path-matching algorithm. Other approaches usually require a conversion from other data such as spot speeds and bearing to travel time. The primary disadvantage of using a path following approach is that success in matching points to links is highly dependent on having a relatively small time interval between points. The number of points required to successfully identify the path followed is directly related to the positional accuracy of the points so technologies with relatively inaccurate positioning may require a very large number of data points in order to determine the path followed.

Map data providing road locations is sold by a number of vendors. Most data is based on the Tiger data generated by U.S. Census Bureau, enhanced for greater accuracy. The typical data consists of a series of line segments marking the centerline of the road together with supplemental information indicating the type of road, direction of travel, numbers of lanes and the length of the segment. The Tiger data is accurate only to within 160 meters. The relative distances between links are somewhat better. Commercial vendors of map data typically supplement the Tiger data by correcting positions based on satellite photographs. Etak is recognized as one of leading vendors of highly accurate map and is used by TIPS as the data source for the underlying road network. Within urban areas of the United States their data provides an absolute accuracy of 40 feet (12 meters) and a relative accuracy of 16 feet (5 meters).

Road segments begin and end whenever one road crosses or touches another. Segments are not topologically connected and segment intersections do not imply any physical connection between the crossing roads. A network topology was generating by combining the road geometry with supplementary data of various types. The primary supplementary data used in this investigation were overpass specifications which indicate which line segments are connected, road class and

directional information. Additional information about barriers and turn restrictions was available and could be used in an enhanced version of the software.

The primary components of the Travel information Probe System software are:

- An embedded road network with topologically connected links
- A set of input modules, one for each position generating technology, including serial attached GPS units generating NEMEA sentences, ASCII strings or Trimble packets, an IP packet based network interface, a file based interface, and a simulated probe generator
- A link matching module
- A path finding module
- An ambiguous path resolution module
- A travel time calculation module
- A database interface module

Currently, the TIPS software exists in several versions supporting various research needs. Planned future developments will combine features from the different versions and enhance the software to a level where it will support an extended field test of real-time data collection from a large number of probes.

7. FIELD OPERATIONAL TEST

To assess the effectiveness and adequacy of GPS-cellular technologies for incident detection and tracking speed data, we proposed a series of field tests for a number of experiments. Among them are testing:

- The positional adequacy of GPS
- The positional adequacy of cellular technologies
- A small scale test of FSP-like probes
- A site specific and large scale probe vehicle test after evaluating GPS technologies

The initial field test regarding the positional techniques and positional adequacy of GPS was conducted in June 2000 and the preliminary findings of the GPS field test are reported in this section. Only limited testing of cellular technologies was possible due to the problems obtaining sufficient data. Some tentative findings on cellular technologies are reported in the cellular phone field test section below. Site specific and large scale field operational tests are planned to be conducted later after the GPS technologies are fully tested and further development is done on TIPS.

GPS Field Test for Vehicle Probes

On June 26, 2000, a two-person team was dispatched to collect data in Oakland where the US Wireless infrastructure was in place. The team-collected data from 11AM to 4PM on I-580 east bound, I-580 west bound, and Broadway, a major arterial in Oakland. The team drove I-580 East bound five times, I-580 West bound four, and Broadway four times. A total of 38.4 miles (62.4 kilometers) was traveled. The team recorded the time pass through each node. The freeway nodes are defined by freeway overheads. Arterial nodes are defined by intersections. Two cellular phones were turned on to collect US wireless data. Both Differential GPS and GPS were tested.

I-580 East 13 nodes 5 runs between Fruitvale and 27th (Appendix A)

I-580 West 12 nodes 4 runs between Fruitvale and 27th (Appendix B)

Broadway 35 nodes 4 runs between Embarcadero and MacArthur (Appendix C)

The primary purpose of the initial field test was to test the mobile positioning accuracy and suitability of GPS for probe vehicle activities. The subsequent phase of the field test was planned to compare the GPS data with US Wireless data and to determine standard deviation of the sample mean to verify the required sample size.

Analysis of the GPS Field Test Data

The TIPS software was developed to map probe locations of arbitrary accuracy to the actual street network and determine travel times across links. It also has an analysis mode where a range of possible accuracies is applied to the same data set, probe tracking performed and statistical information generated. The field data from the GPS collection efforts were analyzed by TIPS to determine what the actual accuracy of the GPS to road mapping was and to determine the success rate for mapping GPS locations to actual links traveled.

There were two GPS data sets collected over the same route, one with differential corrections (the DGPS data) and one without (the GPS data). For analytical purposes the data points were divided into sequences of 100 seconds. Sequences were also ended if there was a break of more than 5 seconds between successive points. This gave us a reasonable number of virtual probes to test. It should be pointed out that the results are worse than a production system operating continuously on the same data would achieve. The breaks result in at least two links lost, the last one in the old sequence and the first one located in the new sequence.

The DGPS data set had 12,620 data points divided into 132 sequences. Each sequence was analyzed using positional accuracies ranging from 10 meters to 100 meters. At each accuracy, the links traveled over were identified and the total length of unambiguously identified links was calculated.

The first test was of positional accuracy. The road-mapping algorithm identifies all links which are within the specified distance of the data point being processed. These form the set of possible links on which the probe vehicle may be travelling. Each of the possible links is examined to determine

if the probe vehicle could have reached this link from the last known position of the vehicle within the time determined by the difference in clock time between the current data point and the last data point. Unreachable links are discarded. If the inaccuracy in the location measurement is greater than the test distance being used, the set of reachable links will often be empty. For instance, if the actual accuracy is 30 meters but the test accuracy is 10 meters, a data point from a vehicle travelling along the freeway may only be matched to a neighboring frontage road and not the next freeway link. If the frontage road is not reachable from the freeway within 1 second of travel time, the algorithm will find that there are no reachable links and the current position of the probe becomes unknown. By testing a range of accuracy distances, TIPS will find the minimum accuracy which encompasses all the data points in the sequence.

For the DGPS data set, the median accuracy for all sequences was 30 meters. Thirty-six sequences (26%) required an accuracy of 100 meters or more. This is not unexpected, as accurate GPS positioning requires receiving signals from 3 or more satellites. Passing under overpasses or past skyscrapers can cause readings with large inaccuracies even though the usual accuracy is quite high. Thirty-seven sequences (27%) only required an accuracy of 10 meters, the smallest distance tested. The expected accuracy for DGPS was 22 meters on average for 95% of the data and 17 meters for 50% of the data. This is based on the sum of the 12 meters inaccuracy in road location in the Etak data set and the 10 meters inaccuracy in the DGPS unit (5 meters, 50% of the time). If we assume the highly inaccurate positions are due to difficulties seeing the satellites and those points are eliminated, the median accuracy drops to 20 meters.

The second test was to determine what percentage of the path traveled could be successfully identified at each accuracy level. Each point in the sequence was mapped to its possible links and if the position could be unambiguously identified, the link length was added to the total distance mapped. If the test accuracy is higher than the actual accuracy, the algorithm will fail to identify links due to too great a reduction in the set of possible links found for each data point. If the test accuracy is lower than the actual accuracy, the total distance will decrease, as the number of ambiguous paths will increase. This test provides two important results. First it gives an indication of the actual field accuracy of the positional technology used. Second it suggests an optimal value for the accuracy parameter to be used by the TIPS software in a deployed probe tracking system.

For the DGPS data set, an accuracy level of 20 meters identified the greatest number of links. For 20 meters, TIPS successfully identified 58.3 kilometers of road traveled. The total distance traveled during the field collection was 62.4 kilometers so the TIPS software identified 93% of the path followed by the probe vehicle. The version of the software used in this test makes no allowances for one or a small number of bad data points. A planned enhancement to the software is to add an error correction module which will compensate for individual bad data points in the middle of sequences of good data points. This should bring the success rate of the TIPS software close to the 99.2% limit suggested by the simulation results described above for a technology capable of 20-meter accuracy.

The second data set was produced by a GPS unit without differential correction. The unit used, a Garmin Emap, claims an accuracy of less than 15 meters. Combined with the 12-meter inaccuracy of the Etak road data, the expected system accuracy was 27 meters for 95% of the data. The GPS data set was analyzed by the TIPS software using the same tests as for the DGPS data set.

The GPS data set had 10,775 data points divided into 106 sequences. This is fewer points than in the DGPS data set due to problems with the logging computer used for the GPS unit. The median accuracy for all sequences was 30 meters. Of the 106 sequences, 28 (26%) required an accuracy of 100 meters or greater while 28 required an accuracy of only 10 meters. These numbers are very similar to the DGPS data set. Eliminating the highly inaccurate points due to satellite reception problems, however, leaves the median accuracy unchanged at 30 meters. This reflects the difference in system accuracy of DGPS at 22 meters versus GPS at 27 meters.

For the mapping test, the greatest number of links was identified using an accuracy of 20 meters. At this accuracy, TIPS identified 53.6 kilometers of links traveled. Based on the 62.4 kilometers of actual distance traveled, this represents a success rate of 86%. But the problems with the logging computer meant that the GPS unit was not recording data during portions of the travel time and the base distance should be less for the GPS unit than for the DGPS unit. Of the 12,260 seconds recorded for the DGPS unit, the data suggests that 9,329 were actually spent moving. Of the 10,775 seconds in the GPS data set, the data suggests 8,676 were spent moving. Based on the ratio between

the two data sets, the distance traveled while the GPS unit was operating was estimated to be 58.0 kilometers. Using this as the base distance, the success rate for TIPS working with the GPS data set was 92%. While not conclusive, as the distance calculation is not very precise, this suggests that the slightly greater accuracy when using differential GPS does not significantly improve the road matching performed by TIPS. Further testing needs to be performed to determine if differential corrections yield significant enough practical benefits to justify its greater expense and complexity over uncorrected GPS.

Cellular Phone Field Test for Vehicle Probes

The initial plan for this study was to collect cellular phone positions from a test vehicle equipped with GPS logging. This would provide data to test both the positional accuracy of the cell phone location technology and the suitability of cell phone tracking for a travel time probe system. Unfortunately the company providing the cell phone tracking data, US Wireless, was unable to provide us with any tracking data for the PATH data collection vehicle. They were, however, able to provide us with two sets of cell phone tracking data from Oakland, California.

The data were collected on May 18, 1999 and on December 20, 1999. The data consisted of X and Y locations and times at 1 to 3 second intervals for 1200 individual calls. Combined, there were 72,300 data points providing 44 hours of probe tracks. The calls varied in length from 2 seconds to 2,300 seconds with an average length of 42 seconds and a median length of 30 seconds. The data were analyzed using a similar technique to that used for the GPS data except sequences of less than 5 points were discarded and sequences were allowed to be whatever length was collected. The location accuracy was tested from 10 meters to 200 meters. There were 3,756 sequences in the combined data set containing 69,283 data points. The remaining 3,000 points were discarded.

Analysis of the Cellular Phone Field Test Data

Without a separate source of information about where the callers were located it was impossible to determine the actual location accuracy of US Wireless' technology. It was possible, however, to

make some estimates of the variability of the location data between points and of the average accuracy.

The first test of the data was to determine the level of accuracy required to provide a consistent probe track. The data was analyzed by the TIPS software using accuracies ranging from 10 to 200 meters. Of the 3,756 probe tracks tested, 2,537 (66%) required an accuracy level of 200 meters or more. Another 382 (10%) required 100 meters but less than 200 meters.

The second test applied was to attempt to map the sequences to actual road links. The mapping was also done using distances ranging from 10 meters to 200 meters. Of the 3,756 sequences, 2,113 (59%) failed to match any links at all at any of the distances. Of the remaining sequences, the greatest distance matched was a total of 107.4 kilometers at accuracy of 60 meters. This does not show that the positional accuracy of some sequences of the US Wireless data points is 60 meters, however. It only shows that the accuracy is unlikely to be better than 60 meters. Unfortunately, it may be the case that the accuracy is much less and that neighboring points in the sequence simply have the same relative spatial shift from their true position. Conclusions about the accuracy are particularly difficult as the average length of path found for the sequences which successfully matched any links was only 65 meters. It is quite possible to match a path this short with only 2 or 3 points as 65 meters is close to the length of a typical road link. Several points clustered together in an otherwise chaotic sequence are sufficient to account for such short matches. Of the 3,756 probe tracks examined, less than 200 were likely to have matched 2 or more links. Unfortunately, only the total length of identified links was reported. Calculating the length of connected links would help determine if sequences which matched several links were matching a connected path or were matching several scattered links.

There was no way to determine the actual distance traveled by the cell phones tracked in the data set. However, if we compare the cell phone data set with the GPS data sets examined earlier, we can get some sense of the relative effectiveness of the two technologies for probe tracking. Using GPS technology 3.5 hours of tracking data generated travel information for 58.6 kilometers of road. The 44 hours of cell phone tracking data generated travel information for 107.4 kilometers of road. The GPS data produced almost seven times as much travel information per unit tracking time.

The TIPS software provides a visual map interface where its operations while testing and finding links can be displayed. With the GPS field data, it was possible by visual inspection to determine that the road links the TIPS software matched were, in fact, the road links traveled over. With the cell phone data this was not possible, as the actual locations were not known. Hence, though the software matched 107 kilometers of road, we have no assurance that the roads matched are correct, particularly as most matches were of single links. If the cell phones positions were consistently 100 meters Eastward of their true positions, for instance, many links would probably be matched as most of Oakland's streets form a grid. But they would be the wrong links. Only by using cell phone data generated by tracking a known vehicle can it be determined if the matched links are valid or not.

GPS is a relatively mature technology. Its characteristics, accuracy and limitations are well known. This is not the case for cell phone tracking systems, which are in their infancy. We tested sample data from just one of the tracking technologies being developed, collected at just one stage of the technology's evolution and using just a minimal amount of the possible information available. So the results presented here are merely suggestive of the potentials and problems of cell phone tracking technology. Continual improvements as the technology changes are likely to have very large effects on the quality of the data which can be generated.

The two primary problems we found were: short sequences and large variations in positioning. For carrier based tracking, the sequences are likely to be longer as all phones, calling or not, are tracked. Even for call based tracking, the sequences may be long enough if the system can generate enough of them and the positional variability can be reduced. We used only the minimum information available for our testing. A cell phone tracking company will have a great deal more information which can be used to improve the data set. For instance, the data set provided by US Wireless contained measurements of signal strength for all the positional readings. It is extremely likely that using additional data, such as signal strength, would allow the location technology to weed out many of the bad data points and dramatically improve the effectiveness of our probe tracking system.

FSP Field Test for Vehicle Probes

Having demonstrated the practicality of using GPS equipped vehicles to generate travel times, the next phase of the field test was a demonstration of how a deployed system might operate. Any probe system depends on having probes and for GPS tracking, a service vehicle fleet is the likeliest data source. This study chose the Freeway Service Patrol as an example of service fleet which could be easily equipped to provide travel information. A sample collection system was set up and a test vehicle was driven over several miles of freeway as a simulation of an FSP vehicle driving its patrol beat.

The field demonstration used a Sierra Wireless MP 200 installed in the vehicle as the only in-vehicle equipment. The MP 200 is a combined GPS receiver and cellular packet radio device. It is frequently used by police departments for vehicle to station communications. The embedded controller on the MP 200 automatically reports the unit's position at specified intervals to a base station using IP packets sent over a CDPD Internet connection. The Verizon CDPD network was used but the MP 200 can be configured to use a second telecommunications carrier when necessary to improve the reliability of communications. The total cost of the in-vehicle equipment was approximately \$1300. This setup provides an extremely reliable AVL system which is very easy to deploy and maintain. The GPS unit in the MP 200 by default provides uncorrected GPS positions. It can be configured, however, to support a technology called inverse differential GPS. Inverse differential GPS uses additional data returned by the unit to apply differential corrections at the base station. For this test, uncorrected GPS was used. Inverse differential adds a great deal of complexity to the system and, based on the accuracy needs determined by our analysis above, yields very little additional benefit.

The base station consisted of a computer running a version of TIPS configured to listen for vehicle position packets on a specified datagram port. The vehicle packets contain an ID and any number of vehicles can send to the base station at the same time. The base station software tracked the vehicles, mapped the positions to the paths traveled and generated travel times.

Due to time constraints, only very limited field-testing was performed. The test vehicle drove back and forth along a roughly 5-mile section of I-680 between Walnut Creek and Concord. The system had no difficulty in following the vehicle using an accuracy level of 30 meters. The vehicle was successfully followed on both the freeway sections and on the ramps where it turned around. The test section had one intersection which generated an ambiguous path where the vehicle could have exited and reentered the freeway on the other side of the intersection. Several improvements to the software could have been made to eliminate this ambiguity and will be implemented in future versions.

The travel times generated were approximately correct but an exact comparison of generated travel times to actual travel times was not done. Additional work on the travel time generation module would need to be done before the system could use real FSP vehicles, in any case. Error correction to differentiate between stops in traffic and stops to aid vehicles needs to be developed. This is planned as part of the phase III of the Vehicles as Probes project.

Though only FSP vehicles are discussed above, the prototype system could be used with most AVL systems currently in use. The Carlink project at PATH uses a similar setup as does Fed-Ex for tracking its long haul trucks. For any fleet the behavioral characteristics of the vehicles must be taken into account. The TIPS software is modularized in a way that allows easy adaptation to different fleets with different characteristics.

Techniques to Improve Probe Vehicle Tracking

Analysis of the field test data suggested several areas where further work would improve the ability of a probe tracking system to generate travel information. For both technologies studied, GPS and cell phone tracking, bad data points represented a problem. Route ambiguity is a minor problem for a GPS system but a major issue that must be addressed for cell phone tracking where the accuracy is poor enough that significant portion of the road network, particularly freeways, cannot be covered. Finally, software enhancements to the TIPS software are needed in a number of areas, including the travel time calculations and error detection, before it can be considered for production use.

Tracking depends on following a sequence of positions. When one data point is wrong, the vehicle appears to leap off one road onto another and back again. If too many data points are wrong, tracking becomes impossible. With a technology such as GPS where most of the points are within a known accuracy, with only occasional positions outside that accuracy, it is fairly easy to determine which are the good points and which are the bad points. Tests of relative distance can determine if a point is too far away from the last position to be possible. With most GPS units, information is available from the unit which indicates how accurate the positional data is likely to be. Conditional tracking, where the algorithm backtracks to known good positions when a bad data point is encountered would be relatively easy to implement. Any or all of these techniques would greatly improve the effectiveness of our probe tracking.

The data indicated that bad data points are even more of a problem for the cell phone tracking technology we tested. Over 2/3 of the sequences had data points that were unreasonably distant from the others. Whether the same error detection techniques which could be used to clean up GPS data are applicable to cell phone tracking is unknown. More complete data about the tracked cell phones is necessary before any error detection and recovery techniques can be developed.

As mentioned earlier, spatial ambiguity is one of the shortcomings of GPS or any other location technology. Our tests showed that a system with 20-meter accuracy, in the two Bay Area counties studied, can not identify spatial shifts from a freeway to a frontage road for 7% of the freeway links. A system with 60-meter accuracy cannot identify spatial shifts off the freeway for 21% of the links. Where the accuracy alone is insufficient to determine the route taken in these ambiguous situations, it is possible to partially compensate by including a behavioral model to help determine which route the driver likely chose. Several freeway simulations, such as FREQ, provide spatial shift models which may be adaptable to a probe system.

Enhancements to the TIPS software should improve the effectiveness of our probe tracking system. Path finding is dependent on building a correct network topology. The initial network topology used only road directionality and overpass information. The source Etak data set contains additional information, such as road barriers, turn restrictions and additional road type information.

Incorporating this additional information will decrease the number of possible paths at any accuracy and reduce the percentage of ambiguous links by eliminating connections that appear in the network topology but do not, in fact, exist.

Further testing of the TIPS software will discover further areas needing improvement. Twenty-six Honda vehicles equipped with a GPS based Automatic Vehicle Location system are scheduled to be deployed soon for the CarLink project. Although the CarLink project deals with local transportation, we hope to use its vehicles for further testing and validation of probe tracking using GPS technology. FSP, CarLink, and TravInfo vehicles would be good candidates for probe vehicle field tests and possible field tests with these vehicles are being investigated.

8. CONCLUSIONS

This paper reports on the first phase of the location technology evaluation for probe vehicles. Two technologies were evaluated, GPS and the cellular phone tracking technology developed by US Wireless. Although GPS has shown great potential for vehicle probes, much of the previous research is theoretical in nature. Very little work has been done in the areas of experimental research, implementation or deployment. Most of the field tests were anecdotal; a systematic approach is highly desired to develop a vehicle probe system that is reliable and efficient for traffic management. If GPS is widely deployed in cellular phones, as GTE in 1998 predicted would happen, GPS technology will become even more attractive and realistic for vehicle probe activities.

A custom software package was developed as part of this project in order to conduct the technology evaluation. The software, the Travel Information Probe System (TIPS) maps positions of probes of arbitrary accuracy to an embedded Geographical Information System in order to determine the path the probe took. Once the path has been determined, the software calculates the travel time for each road segment traversed.

Our analysis of two Bay Area counties showed that accurate location technologies are capable of producing travel time information for nearly all roads. A technology with 20-meter accuracy can produce data for 99.2% of the road segments and 98.9% of the freeway segments in the two counties studied. At lower accuracies, the coverage goes down sharply for freeways but stays relatively high for highways and major streets. At 190-meter accuracy, 45% of freeway segments and 76% of major streets can generate unambiguous information. While low accuracy location technologies may not be suitable for freeway surveillance due to difficulties distinguishing between freeways and frontage roads, they may still be very effective for traffic surveillance on major surface streets. As these roads are rarely well instrumented using conventional technology, probe systems have great potential for cost-effective supplements to conventional freeway surveillance systems. In particular, systems meeting the E-911 requirement of 100 meter accuracy for 2/3 of all calls are, in theory, capable of producing quantitative travel time information for 87% of major street segments, though only 68% of freeway segments. Location accuracy is only one criterion for building a successful traffic surveillance system, however. The field tests conducted in this study show that

variability in the positional accuracy and the total length of the tracking sequence are both important factors in whether or not a technology can be successfully used for a probe system.

Two GPS technologies, uncorrected GPS and differential GPS, were field-tested. The two GPS technologies are fundamentally the same except for a roughly 5 meter better accuracy for differential GPS, 10 meters versus 15 meters for 95% of the measurements. Using the TIPS software, field data from Oakland California was analyzed. The analysis found that using an assumed accuracy of 20 meters produced the most effective vehicle tracks for both GPS and differential GPS. For both GPS technologies, 26% of the sequences of 100 points had one or more data points well outside the expected 10 –15 meter accuracy. The field test showed that tracking a GPS equipped vehicle is very effective. The TIPS software correctly identified 92%, for uncorrected GPS, or 93%, for differential GPS, of the total path followed by the test vehicle.

One cellular phone tracking technology was also field-tested. Two sample data sets were provided by US Wireless, one of the companies producing tracking technology for cell phones. Working with this data, the TIPS software found that an assumption of 60-meter accuracy produced the best probe tracks. Many of the phone calls tracked had one or more points that were far outside a 60-meter accuracy range, however. Of 3,756 probe tracks, 66% had one or more points outside of a 200-meter accuracy range.

Assuming 60-meter accuracy, our tests matched 107.4 kilometers of road using 44 hours of cell phone tracking data. In contrast, the GPS field test matched 58.6 kilometers of road using only 3.5 hours of tracking data, nearly 7 times the success rate. Unfortunately, without data showing ground truth for the paths taken by the tracked cell phones, there was no way to determine how much of the 107 kilometers matched were correctly matched. Even qualitative estimates of correctness were difficult as tracks were generally very short. Of 1200 calls tracked, the median length was 30 seconds. With such short sequences, less than 200 calls out of 3756 appeared to match more than one road segment. As it is quite possible to match a single segment with only 2 or 3 data points, no conclusion about the correctness of road segment matching could be made.

All three technologies evaluated produced individual data points which were very far away from the others. This made tracking more difficult and, for the cell phone data, the problem was severe enough that TIPS could not successfully track almost 60% of the probes. Error detection and correction algorithms need to be developed to filter the bad data points. For GPS, which has a known error rate, correction algorithms could be based on testing the distance between points, or on the additional satellite data which can be output by most GPS units. For cellular phone tracking systems, further examination of the nature of the errors, particularly a comparison of reported positions and actual positions for a sequence of points, is needed before any error correction algorithms could be developed. Additional information available to the carrier, such as signal strength, may provide easy means to separate good and bad data points.

Even for an accurate technology like GPS, ambiguity in the path followed is a problem, particularly for freeway segments. Differentiating between freeways and frontage roads is problematic for 6% of the freeway segments even at 20 meters accuracy. Given the 12-meter error in road placement this corresponds to a technology accurate to 8 meters. Several freeway simulations, such as FREQ, provide spatial shift models which may be adaptable to a probe system. Using these models may allow the tracking software to make reasonable predictions of the route followed where the data alone cannot.

Cellular phone tracking, at least the one implementation we examined, shows promise but needs further study to determine its ability to produce quantifiable travel time data. The data tested had short sequences with a large number of bad positions. In its favor, it promises very large numbers of probes. GPS produces long sequences with high accuracy and a moderate number of bad positions. GPS equipped fleets are likely to have fewer identification and travel behavioral problems. A simple field test of FSP-like vehicles showed that deployable systems can be developed using existing technology.

REFERENCES

Hall, Randolph, "Orange County transit probe evaluation: Phase I institutional findings," PATH Working Paper, UCB-ITS-PWP-97-12, March 1997.

Hall, Randolph, Nilesh Vyas, Chintan Shyani, Vikas Sabnani, Simit Khetani, "Evaluation of the OCTA transit probe system," PATH Research Report, UCB-ITS-PRR-99-39, November 1999.

Kumud K. Sanwal, Jean Walrand, "Vehicles as probes," PATH Working Paper, UCB-ITS-PWP-95-11, August 1995.

Linnartz, Jean-Paul, Marcel Westerman, Rudi Hamerslag, "Monitoring the San Francisco Bay Area Freeway Network using Probe Vehicles and Random Access Radio Channel," PATH Research Report, UCB-ITS-PRR-94-23

May, Adolf, Traffic Flow Fundamentals, Prentice Hall, 1990.

Moore, James, Seongkil Cho, Arup Basu, "use of Los Angeles freeway service patrol vehicles as probe vehicles," PATH Report to Caltrans 98-C11, July 1998.

Skabardonis, Alexander, Ted Chira-Chavala, Daniel Rydzewski, "The I-880 Field Experiment: Effectiveness of Incident Detection Using Cellular Phones," PATH Research Report, UCB-ITS-PRR-98-1

Stanford International Research, memorandum on Bay Area loop detector performance, unpublished, 1998.

Wannacott & Wannacott, Introductory Statistics for Business and Economics, Second Edition, John Wiley & Sons, New York, 1977

Weserman, Marcel, Remco Litjens, Jean-Paul Linnartz, "Integration of probe vehicle and induction loop data – estimation of travel times and automatic incident detection," PATH Research Report, UCB-ITS-PRR-96-13, June 1996.

Ygnace, Jean-Luc, Chris Drain, Youngbin Yim, Renaud de Lacvivier, "Travel Time Estimates on the Bay Area Network by Using Cellular Phones as Probes," PATH unpublished paper, June 2000.

Yim, Youngbin, Adib Kanafani, Jean-Luc Ygnace, "expanding usage of cellular phones: user profile and transportation issues," PATH Research Report, UCB-IS-PRR-91-19, December 1991.

Appendix A. DGPS Field Test on I-580 Eastbound

The field test was conducted on June 26, 2000

I-580 Eastbound Oakland, CA

Run:	1	2	3	4	5	6	7	8	9
Start of Run:	1:43:00 PM		1:53:20 PM						
Location		Time at node	Time at node	Time at node	Time at node	Time at node	Time at node	Time at node	Time at node
27th Ave on			1:53:43 PM	2:23:58 PM	2:44:18 PM				3:07:41 PM
580 split			1:53:49 PM	2:24:10 PM	2:44:44 PM				3:07:53 PM
980 on			1:54:07 PM	2:24:30 PM	2:45:05 PM				3:08:18 PM
24 on			1:54:17 PM	2:24:43 PM	2:45:14 PM				3:08:20 PM
Harrison off	1:42:56 PM		1:54:32 PM	2:24:56 PM	2:45:27 PM				3:08:32 PM
Oakland overpass	1:43:12 PM		1:54:32 PM	2:25:13 PM	2:45:43 PM				3:08:46 PM
Harrison on	1:43:29 PM		1:54:48 PM	2:25:30 PM	2:46:00 PM				3:09:02 PM
Grand off	1:43:41 PM		1:55:18 PM	2:25:43 PM	2:46:13 PM				3:09:14 PM
Grand on	1:44:10 PM		1:55:47 PM	2:26:11 PM	2:46:44 PM				3:09:43 PM
Park off	1:44:33 PM		1:56:09 PM	2:26:31 PM	2:47:07 PM				3:10:04 PM
Park overpass	1:44:59 PM		1:56:57 PM	2:26:57 PM	2:47:30 PM				3:10:28 PM
Park on (maybe 14th)	1:45:25 PM		1:56:57 PM	2:27:24 PM	2:47:56 PM				3:10:53 PM
Fruitvale exit	1:45:40 PM		1:57:12 PM	2:27:40 PM	2:48:12 PM				3:11:11 PM

Appendix B. DGPS Field Test on I-580 Westbound

The field test was conducted on June 26, 2000

I-580 Westbound in Oakland, CA

Run:	1	2	3	4	5	6	7
Start of Run:		1:47:10 PM		2:05:29 PM		2:33:45 PM	

Location	Time at node	Time at node	Time at node
Fruitvale on	1:47:34 PM		2:34:10 PM
14th off	1:47:47 PM	2:05:44 PM	2:34:22 PM
Overpass	1:48:09 PM	2:06:05 PM	2:34:45 PM
Lakeshore on	1:48:35 PM	2:06:34 PM	2:35:11 PM
Lakeshore off	1:48:57 PM	2:06:54 PM	2:35:33 PM
Grand off	1:49:24 PM	2:07:21 PM	2:36:01 PM
Grand on	1:49:38 PM	2:07:36 PM	2:36:18 PM
Oakland off	1:49:51 PM	2:07:47 PM	2:36:29 PM
Oakland overpass		2:08:07 PM	2:36:45 PM
Oakland on	1:50:18 PM	2:08:17 PM	2:36:53 PM
980 exit	1:50:39 PM	2:08:35 PM	2:37:10 PM
27th off	1:51:29 PM	2:09:24 PM	2:38:58 PM

Appendix C. DGPS Field Test on Broadway

Broadway in Oakland

Run:	1	2	3	4
Start of Run:	11:30 AM	11:41:09 AM	11:56:40 AM	1:17:25 PM

Location	Time at intersection	Time at intersection	Time at intersection	Time at intersection
Embarcadero	11:39:16 AM	11:41:12 AM	12:06:21 PM	1:17:31 PM
2nd	11:38:46 AM	11:41:26 AM	12:06:13 PM	1:17:42 PM
3rd	11:38:36 AM	11:41:34 AM	12:06:04 PM	1:17:50 PM
4th	11:38:15 AM	11:41:41 AM	12:06:53 PM	1:17:59 PM
5th	11:38:07 AM	11:42:38 AM	12:05:44 PM	1:18:55 PM
88 overpass	11:37:59 AM	11:42:42 AM	12:05:39 PM	1:19:00 PM
6th	11:37:53 AM	11:42:46 AM	12:05:35 PM	1:19:05 PM
7th	11:37:42 AM	11:43:54 AM	12:05:19 PM	1:19:14 PM
8th	11:37:27 AM	11:43:25 AM	12:04:34 PM	1:19:32 PM
9th	11:37:16 AM	11:43:57 AM	12:04:24 PM	1:20:05 PM
10th	11:37:07 AM	11:44:17 AM	12:03:55 PM	1:20:15 PM
11th	11:37:00 AM	11:44:28 AM	12:03:20 PM	1:20:30 PM
12th	11:36:51 AM	11:45:03 AM	12:03:05 PM	1:21:08 PM
13th	11:36:36 AM	11:45:29 AM	12:02:53 PM	1:21:12 PM
14th	11:36:18 AM	11:46:12 AM	12:02:38 PM	1:22:48 PM
15th	11:35:47 AM	11:46:29 AM	12:02:16 PM	1:23:06 PM
17th	11:35:04 AM	11:47:09 AM	12:02:01 PM	1:23:43 PM
19th	11:34:30 AM	11:47:23 AM	12:01:29 PM	1:23:58 PM
20th	11:33:27 AM	11:48:03 AM	12:01:01 PM	1:24:12 PM
21st		11:48:38 AM	12:00:52 PM	1:24:37 PM
22nd		11:49:12 AM	12:00:41 PM	1:25:12 PM
Grand	11:33:20 AM	11:49:22 AM	12:00:35 PM	1:25:22 PM
23rd	11:32:36 AM	11:49:32 AM	12:00:29 PM	1:25:43 PM
24th	11:32:21 AM	11:49:44 AM	12:00:14 PM	
25th	11:32:12 AM	11:49:52 AM	11:59:52 AM	1:25:51 PM
26th	11:32:03 AM	11:50:00 AM	11:59:46 AM	1:25:58 PM
27th	11:31:54 AM	11:50:44 AM		1:26:08 PM
Webster				
28th East	11:31:42 AM	11:50:54 AM		1:26:14 PM
29th	11:31:30 AM	11:51:16 AM	11:59:26 AM	1:26:31 PM
30th	11:31:17 AM	11:51:29 AM	11:59:13 AM	1:26:42 PM
Brook East /Hawthorne		11:52:06 AM	11:58:31 AM	1:27:26 PM
Piedmont	11:30:50 AM		11:58:25 AM	1:27:39 PM
34th	11:30:43 AM	11:52:26 AM	11:57:47 AM	1:27:45 PM
580 overpass	11:30:35 AM	11:52:32 AM	11:57:40 AM	1:27:52 PM
MacArthur	11:30:12 AM	11:53:54 AM	11:57:16 AM	1:28:55 PM