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Travel Time Estimation on the San Francisco Bay Area Network Using Cellular Phones as Probes

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### Publication Date

2000-09-01

CALIFORNIA PATH PROGRAM  
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UNIVERSITY OF CALIFORNIA, BERKELEY

## **Travel Time Estimation on the San Francisco Bay Area Network Using Cellular Phones as Probes**

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**California PATH Working Paper  
UCB-ITS-PWP-2000-18**

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department Transportation, Federal Highway Administration.

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Report for MOU 378

September 2000

ISSN 1055-1417

# **Travel Time Estimation on the San Francisco Bay Area Network Using Cellular Phones as Probes**

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## ACKNOWLEDGEMENTS

The authors wish to thank California Department of Transportation (CALTRANS) for sponsoring this phase of this research project.

Authors would like to thanks CALTRANS Newtech namely Joe Paelen for his participation to the definition of this work.

## **ABSTRACT**

Current traffic travel time estimates are largely based on road sensors embedded in the pavement. Today technical developments in cellular positioning and the spread of wireless phones provides the opportunity to track cell phone equipped drivers as traffic probes. The Federal Communication Commission Phase II mandate for Enhanced-911 (E-911) requires that wireless carriers must provide the location of a 911 wireless call by October 1, 2001 to the Public Safety Answering Point (PSAP), within approximately 125 meters, or under one-tenth of a mile in the majority of situations.

The motivation of this research is to evaluate the feasibility of using cell phones as traffic probes for the Bay Area network. A review of cellular positioning techniques, an analytical model, as well as a simulation model show that accurate travel times estimates can be obtained. Assuming that at least 5% of freeways travelers are equipped with a cell phone, one can predict a 95% accuracy in freeway link travel time estimates.

The E-911 mandate will be the driving force to implement such cellular positioning. However, the production, or adaptation, and warehousing of traffic information from the cell-phones-as-probes can be tailored for the requirements of traffic authorities and information service providers and may become an important business opportunity.

The report also advocates the joint field evaluation of GPS, cellular and conventional systems, to allow the identification of the best mix of technology for future implementations. The possible institutional role of the PATH organization to foster a quicker deployment of these technologies in California is also presented in this report.

## Executive Summary

Travel time estimates can be used to improve the management of the road network as well as providing useful information to travelers, or those considering using the road network. Traditionally travel time estimates have been gathered using expensive roadside infrastructure. This report explores the possibility of gathering travel time data using cellular positioning systems.

Many of the vehicles in the Bay Area already make their trips equipped with cellular telephone. A number of different organizations are developing the technology to allow the measurement of cellular telephones to an accuracy of approximately 100 meters. By carefully processing such measurements from many vehicles, we hypothesize that it will be possible to accurately estimate travel time on the road network.

In order to analyze the feasibility of using cellular telephones to measure location, this discussion paper first discusses the institutional environment. We conclude that there are a number of developments that are likely to facilitate the usage of cellular telephones as traffic probes. The foremost of these is the Federal Communications Commission E-911 (Phase II) mandate. This requires that all cellular telephones be located to an accuracy of about 125 meters by October, 2001. This means that cellular positioning systems are very likely to be implemented in most areas of the United States within the next few years.

Our paper then provides an overview of cellular positioning, explaining some of the basic concepts. We then discuss the actual developments that are taking place. We conclude that this is a very active area of research and development with a number of different solutions being developed. The prospects appear to be strong that a solution offering an accuracy of about 100 meters will be developed in close to the time frame demanded by the FCC.

We then present the results of a number of analytical and simulation models. The analytical model allow insight into the various parameters that will affect the performance of cellular positioning systems whilst the simulation model allow a more precise evaluation. Our general conclusion is that accurate travel time estimates will be possible provided around 5% of the vehicles are equipped with live (i.e. switched on) cellular telephones. We present evidence that suggest that at least this proportion of vehicles on the Bay Area network will be equipped with live cellular telephones.

We next consider the business issues to provide an indication of the reasoning that will need to be made when deciding between some different alternatives. This analysis provides some suggestive evidence that cellular telephone positioning could be a cost-effective approach.

The final aspect that we considered was how a field trial could be carried out. This trial would be used to go beyond the tentative conclusions of this paper in order to establish the feasibility of using cellular telephone technology to measure travel time. This trial would consist of making actual travel time measurements using one or more cellular telephone systems, making ground

truth measurements using existing technology, and as well comparing the results with a GPS vehicle probe solution.

## TABLE OF CONTENTS

<b><u>ABSTRACT</u></b> .....	<b>III</b>
<b><u>EXECUTIVE SUMMARY</u></b> .....	<b>IV</b>
<b><u>1. INTRODUCTION</u></b> .....	<b>1</b>
<b><u>2. INSTITUTIONAL ENVIRONMENT</u></b> .....	<b>2</b>
<u>THE MAJOR TRENDS IN THE CELLULAR PHONE MARKETS AND ITS RELATED OPTIONS</u> .....	2
<u>THE CELLULAR MARKET AND DIGITAL TECHNOLOGY TRENDS</u> .....	2
<u>THE TELEMATICS ASPECTS - DRIVING FORCES</u> .....	3
<u>SAFETY ASPECTS DRIVING FORCES; THE E911 MANDATE LEADS THE WAY TO</u> <u>POSITIONING CAPABILITIES</u> .....	4
<u>BACKGROUND ON E911:</u> .....	4
<u>SPECIFICS OF THE 1999 ACTION:</u> .....	5
<b><u>3. CELL PHONE POSITIONING THEORY</u></b> .....	<b>6</b>
<u>PROSPECTS FOR DIFFERENT MOBILE TELEPHONE STANDARDS</u> .....	11
<u>GSM</u> .....	11
<u>CDMA</u> .....	12
<u>Analog</u> .....	12
<u>Third Generation Mobile Standards</u> .....	13
<b><u>4. CURRENT WORK IN CELLULAR POSITIONS AND ITS POTENTIAL FOR</u></b> <b><u>TRAVEL TIME DATA</u></b> .....	<b>13</b>
<u>CURRENT WORK IN CELLULAR POSITIONING</u> .....	13
<u>Lucent:</u> .....	13
<u>University of Technology, Sydney (UTS) :</u> .....	13
<u>U.S Wireless Corporation, San Ramon, California :</u> .....	13
<u>Radix Technologies, Mountain View, California:</u> .....	14
<u>SnapTrack , San Jose, California:</u> .....	14
<b><u>5. HOW THE CELL PHONE PROBE CONCEPT APPLIES TO THE BAY AREA ROAD</u></b> <b><u>NETWORK NEEDS FOR TRAFFIC INFORMATION</u></b> .....	<b>15</b>
<u>OVERVIEW ON THEORETICAL PROBE MODELS</u> .....	16
<u>Placing the vehicle on the road</u> .....	16
<u>Estimating the mean speed</u> .....	17
<u>Number of Measurements needed to characterize a network</u> .....	17



<u>Effect of differing densities</u> .....	17
<u>Directional Errors</u> .....	18
<u>Effect of wrong road placement</u> .....	18
<u>Overall Model</u> .....	18
<u>Utilization of Positioning Receivers</u> .....	18
<u>Overall Results</u> .....	18
<u>RESULTS FROM THE USE OF A SIMPLE SIMULATION MODEL</u> .....	19
<u>Filtering</u> .....	20
<u>Case studies and probe travel time estimates</u> .....	21
<u>Synthesis</u> .....	29
<u>ESTIMATES OF THE CELL PHONE DISTRIBUTION ON THE BAY AREA ROAD NETWORK LINKS</u> .....	29
<u>The road network</u> .....	29
<u>The cellular phone distribution</u> .....	31
<u>BUSINESS ISSUES</u> .....	32
<b><u>6. FIELD OPERATIONAL TESTS</u></b> .....	<b>33</b>
<u>INTRODUCTION</u> .....	33
<u>OBJECTIVES</u> .....	34
<u>INVESTIGATION OF THE GLOBAL POSITIONING SYSTEM</u> .....	34
<u>DEVELOPMENT OF MODELS FOR VEHICLE POSITIONING USING CELLULAR TECHNOLOGIES</u> .....	34
<u>The GPS surveillance technology</u> .....	35
<u>Cellular positioning technology</u> .....	35
<u>Methodology</u> .....	36
<u>Field Test Plan for Phase 2 Study</u> .....	36
<b><u>7. DISCUSSION</u></b> .....	<b>37</b>
<b><u>REFERENCES</u></b> .....	<b>38</b>
<b><u>APPENDIX A: ANALYTICAL MODELS</u></b> .....	<b>39</b>
<u>Utilisation of Positioning Receivers</u> .....	42
<b><u>APPENDIX B: RESULTS FROM ANALYTICAL MODELS</u></b> .....	<b>44</b>
<b><u>APPENDIX C: NOTES ON AN EXPERIMENTAL DESIGN FOR A POSSIBLE TEST OF CELL-PHONES-AS-PROBES ON I-80</u></b> .....	<b>45</b>
<b><u>APPENDIX D: LONG TERM VISION PLAN FOR CELL PHONE TECHNOLOGY APPLIED TO TRAVEL TIME ESTIMATES</u></b> .....	<b>48</b>

# 1. INTRODUCTION

As part of the information age the transportation sector is motivated to obtain reliable information in order to observe and control traffic flow. Providing traffic information and travel time estimates between any two points is becoming a major challenge for the public institutions and private companies targeting the mobility services that can be offered to the driving population. The ways of providing such information may vary from country to country and involve a wide range of possibilities; changeable Messages Signs installed at strategic highway intersections, dedicated in-car devices or even simple radio or internet messages.

Travel time estimates are becoming an important part of a nation's Intelligent Transportation Systems regardless of the distribution channel. Basic traffic data are usually collected by road-side systems. Such systems mostly use inductive loop detectors. The detectors help to define the traffic density, the traffic flow and speed. These are the basic parameters needed by the operational traffic engineers.

These stationary sensors are very useful but the cost of implementing and maintaining such sensors to attain significant coverage of the roadway network is becoming prohibitive. There are other ways to estimate travel time, particularly using equipped vehicles as sensors (probe vehicles). Use of probe vehicles is likely to lead the way for more efficient and more cost effective techniques.

In a recent statement Mercedes Benz points out that:

”Most experts agree that the idea of highways with costly imbedded sensors that monitor and even control traffic flow, or provide re-routing around traffic jams, would be too expensive and impractical for universal use. However, imagine that every car on the road might actually double as a moving sensor, continuously feeding information about weather, traffic flow, and road surface conditions to a central mainframe computer. This vast traffic database would then be bundled into a useful, up-to-date route guidance package beamed back to all its subscribers.

The most promising research vehicles for the 'car as sensor' concept are Mercedes-Benz models equipped with special radio systems which gather and transmit data from the car's existing rain and light sensors, its satellite navigation system, and the sensors for the Electronic Stability Program of stability control. The more cars that serve as traffic and road sensors, the more accurate and comprehensive this concept could be. Without the need for expensive sensors in the road or cameras at intersections, the coverage could extend beyond just high-travel highways to all country roads, city streets and bridges.”

The above statement is concerned only with large numbers of vehicles equipped with special purpose positioning devices. This will only happen in the longer-term timeframe. In the short

term there are other means of considering vehicle as probes, particularly leveraging upon the installed base of cellular telephones.

The rapid penetration of cellular phones means that many vehicles on the road network are equipped with a cellular telephone. If these telephones can be accurately located then this offers the opportunity to use every mobile telephone equipped vehicle as a probe.

The present study is aimed at: 1) providing an overview of the technology and the potential benefits arising from the technology, 2) identifying important issues related to vehicle probes with the cellular technologies, 3) outline the assumptions being made in our study, 4) sketching the approach we are following, and 4) providing an early indication of the feasibility of the cellular technology for vehicle probes.

## **2. INSTITUTIONAL ENVIRONMENT**

### **The major trends in the cellular phone markets and ITS related options**

The Stanford Research Institute (SRI) consulting firm predicts that cellular telephone will be by far the dominant communications network for ITS products and services in consumer markets. This prediction is based on the preference for voice, cellular's declining price and growing consumer base, and its ability to support short messaging for transmitting vehicle location data. In addition, future new data services such as packet and high-speed circuit-switched communications and mobile originated short messaging are adding to network functionality and will future-proof technology as ITS services expand.

There are today more than 60 million of cellular subscribers in the U.S., spending an average \$46 a month. Almost one third of these phones are digital and this proportion is growing everyday, due to the strong involvement of cellular carriers who want to increase their capacity by using digital networks. The cell phone suppliers are also participating to this trend, by developing a broad range of new digital handsets with web-phone capabilities. In the San Francisco Bay Area, new analog phones are no longer available.

### **The cellular market and digital technology trends**

There are a number of competing cellular protocols, including IS-95 Code Division Multiple Access (CDMA), IS-136 Time Division Multiple Access (TDMA) and Global System Mobile (GSM). Little more than a year ago, critics wondered if CDMA would make it to the starting line in the wireless industry. Now, CDMA is positioned to catch market-leading GSM by early 2003, according to a new report<sup>4</sup>, "IS-95 CDMA is well positioned in North America, Asia, and other areas of the globe," says Ira Brodsky, president of Datacomm. "It is no coincidence virtually all leading vendors agree the next generation wireless technology will be based on CDMA."

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<sup>4</sup> "CDMA Wireless Business Opportunities", February, 1998 from Datacomm Research

In its report, Datacomm says that GSM does enjoy a comfortable subscriber lead at this point. But, the agency says that growth will slow in this region. Therefore, by having a stronger position in North America, Asia, and Latin America, the research agency expects stronger growth in CDMA technology over the next several years, with CDMA passing GSM in 2003.

As stated in the report, though the demand for CDMA telephones continues to grow more rapidly than the demand for GSM phones, GSM's early lead nearly guarantees that it will remain the most popular digital standard until 2003.

According to a new study written by Micrologic Research and published by Forward Concepts<sup>5</sup>, the market for GSM cellular telephones will grow from \$15.5 billion in 1999 to \$24.5 billion in 2003, a compound annual growth rate (CAGR) of 12.1%. During the same period, the study forecasts the worldwide CDMA cellular market will grow from \$3.5 billion to \$20.4 billion, a compound growth rate of 55.9%. The IS-136 TDMA digital cellular standard is forecasted to have a more modest effect on the market with worldwide handset sales of \$1.4 billion in 1999 growing to only \$3.5 billion in 2003. The report indicates that there will be limited third-generation (3G) cellular service available in Europe and Japan by 2001 and in North America by 2002. The number of 3G cellular subscribers is predicted to reach 16.9 million in Europe, 12.5 million in Japan, and 10.6 million in the Americas by the end of 2005

The study predicts that there will be at least two 3G standards. Europe will use W-CDMA/TD-CDMA and Latin America will use CDMA 2000. North America and parts of Asia, including Japan, will use both standards.

## **The Telematics Aspects - Driving Forces**

Telematics is a recent term used to describe the integration of vehicle control and monitoring systems with location tracking devices and wireless communications. Because of the need of wide geographic coverage, virtually all telematics devices are likely to use cellular cell phones. Telematics devices can be used for many purposes including :

- automatically notify authorities of an accident, and guide them to the car;
- track stolen vehicles;
- provide navigation assistance to lost drivers;
- call emergency roadside assistance;
- perform remote diagnostics of engine functions

The Strategis Group has identified strong interest in telematics particularly among cellular phone users. A significant number of cellular users (78%) are interested in having emergency roadside assistance, compared with just over half of non users; half of cellular user express interest in stolen vehicles recovery, compared with more than one-third for non-users.

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<sup>5</sup> 3G Cellular Market Opportunities. A report on the progress toward 3G cellular technologies with infrastructure and terminal forecasts for Japan, Europe, and North America. A Micrologic report brought by Forward Concepts. Report No. 920, 1998.

On the commercial side, the Automatic Vehicle Location (AVL) systems become a major market for both wireless location and mobile data services. AVL is making the breakthrough from being a niche product for long haul trucking fleets to becoming an essential communications device for business fleets of all types. For tracking fleets the leading communication mode is satellite based and used by half of the users; the cellular carriers only provide 24% of the communication needs. By 2003, the position of cellular and satellite should be reversed, with cellular accounting for two-thirds of all communication needs.

## **Safety aspects driving forces; the E911 mandate leads the way to positioning capabilities**

The safety concerns are the leading market forces driving the new cell phones buyers. Every day there are about 100,000 emergency calls in the United States; 30% of them are from cell phones. The Federal Communications Commission has taken a step to facilitate the emergency response action by asking the cellular carriers to report the location of the 911 calls. This decision came in 1996 through the so-called E-911 mandate. More recently the FCC has revised its rules aimed at providing consumers with enhanced 911 emergency services when using wireless phones. The new requirements promote public safety, competition among wireless 911 equipment manufacturers and the continued improvement in the quality of 911 services. These new rules will enable handset-based methods of providing location information for 911 calls to compete in a reasonable way with network-based solutions in meeting the FCC's Enhanced 911 (E911) Phase II requirements. The FCC also modified implementation requirements for carriers and revised the accuracy/reliability rules applicable to all Automatic Location Identification (ALI) technologies. These new rules will benefit both callers and public safety entities by providing accurate and efficient automatic location information in emergencies.

## **Background on E911:**

The FCC's wireless 911 rules seek both to improve the reliability of wireless 911 services and to provide the enhanced features generally available for wireline calls. To further these goals, the agency has required wireless carriers to implement E911 service, subject to certain conditions and schedules, including a request from a Public Safety Answering Point (PSAP). Phase I of the FCC's E911 rules requires that a dialable number accompany each 911 call, which allows the PSAP dispatcher to call back if the call is disconnected or to obtain additional information. It also gives the dispatcher the location at the cell site that received the call as a rough indication of the caller's location. Phase II of the FCC's wireless 911 rules allows the dispatcher to know more precisely where the caller is located, a capability called Automatic Location Identification or ALI. The original FCC E911 rules were adopted in 1996, and reflected then current expectations about technological development. At that time, it was anticipated that only network-based approaches would be employed to provide ALI. Since then advances in technologies that employ new or upgraded handsets have demonstrated significant progress. However, as a practical matter, the original FCC rules only permit network-based solutions to meet the Phase II requirements in the short term because they require that ALI be provided for all 911 calls in a PSAP's area as of a fixed date (October 1, 2001). As a result, the original rule effectively

precluded use of a handset-based approach, which requires the gradual replacement or upgrade of current handsets. In 1999 the FCC revised its rules to permit the phase-in of new or upgraded handsets in order for handset-based solutions to be a viable competitor for initial ALI deployment under Phase II, while making other revisions aimed at promoting wireless E911 and improving public safety.

### **Specifics of the 1999 Action:**

The FCC adopted the following revisions to its wireless E911 rules in September 1999<sup>6</sup>; the major statements are as follows:

- Wireless carriers who employ a Phase II location technology that requires new, modified or upgraded handsets (such as GPS-based technologies) may phase-in deployment of Phase II subject to the following requirements:
- Without respect to any PSAP request for Phase deployment, the carrier shall:
  - a) Begin selling and activating ALI-capable handsets no later than March 1, 2001;
  - b) Ensure that at least 50 percent of all new handsets activated are ALI- capable no later than October 1, 2001; and
  - c) Ensure that at least 95 percent of all new digital handsets activated are ALI- capable no later than October 1, 2002.
- Once a PSAP request is received, the carrier shall, in the area served by the PSAP: Within six months or by October 1, 2001, whichever is later:
  - a) Ensure that 100 percent of all new handsets activated are ALI-capable;
  - b) Implement any network upgrades or other steps necessary to locate handsets; and
  - c) Begin delivering to the PSAP location information that satisfies Phase II requirements. Within two years or by December 31, 2004, whichever is later, undertake reasonable efforts to achieve 100 percent penetration of ALI-capable handsets in its total subscriber base.
- For roamers and other callers without ALI-capable handsets, carriers shall support Phase I ALI and other available best practice methods of providing the location the handset to the PSAP.
- To be allowable under the FCC rules, an ALI technology that requires new, modified, or upgraded handsets shall conform to general standards and be interoperable, allowing roaming among different carriers employing handset-based location technologies.
- For carriers employing network-based location technologies, the FCC replaces its current plan, which requires that implementation be fully accomplished within 6 months of a PSAP request, with a revised rule requiring the carrier to deploy Phase II to 50 percent of callers

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<sup>6</sup> (Before the Federal Communications Commission Washington, D.C. In the Matter of Revision of the Commission's Rules) CC Docket No. 94-102 To Ensure Compatibility with RM-8143 Enhanced 911 Emergency Calling Systems) Third Report and Order Adopted: September 15, 1999

within 6 months of a PSAP request and to 100 percent of callers within 18 months of such a request.

- The FCC adopts the following revised standards for Phase II location accuracy and reliability:
  - a) For network-based solutions: 100 meters for 67 % of calls, 300 meters for 95 % of calls;
  - b) For handset-based solutions: 50 meters for 67 % of calls, 150 meters for 95 % of calls.
- The FCC directs wireless carriers to report their plans for implementing E911 Phase II, including the technology they plan to use to provide caller location, by October 1, 2000. This report provides information to permit planning for Phase II implementation by public safety organizations, equipment manufacturers, local exchange carriers, and the FCC, in order to support Phase II deployment by October 1, 2001.
- The FCC directs that the Office of Engineering and Technology and the Wireless Telecommunications Bureau, working with interested parties, proceed expeditiously to address issues of verifying compliance with the Phase II accuracy and reliability standards.

### **3. CELL PHONE POSITIONING THEORY**

Cellular telephone systems are radio-based mobile communications systems. In this case cellular means that the systems use many basestations to transmit or receive the signals from the mobile telephones. These base stations are distributed over the service area, nominally in a hexagonal pattern. The area in the closest vicinity of a base station is known as a *cell*.

The mobile's power level is adjusted so that the signal from a mobile is unlikely to be received by base stations that are not in the immediate vicinity of the mobile. This means that frequencies can be reused in different parts of the service area, allowing many more telephones to operate for the same frequency allocation. A further advantage of using a cellular structure is that the mobile will always be relatively close to the base station with which it is communicating. This reduces the power requirements for transmission, so increasing the time between charges for the mobile's battery. The cell size varies depending on the propagation characteristics of the area and the density of users, for example in rural areas the cell radius might be 30 km, in suburban areas five km, and in the central business district of a large city, the cell size might be considerably less than a kilometer.

For some time it has been realized that it is possible to carry out positioning using a cellular telephone system [1]. A number of factors, especially the FCC E911 ruling, has meant that recently cellular positioning has become an active area of research and development [2]. There are a number of advantages to a cellular telephone positioning system:

- It makes use of the installed infrastructure of the cellular telephone system, so greatly reducing establishment costs.
- Cellular systems already have a spectrum allocation.

- In areas of the worst propagation, cellular systems tend to have the greatest number of cells.
- There is already a very large installed user base.
- The cellular system provides a two-way communications link.

The principal disadvantage of cellular telephone positioning technology is that the system has not been designed without regard to positioning, so the engineer has to work around certain characteristics of the cellular system. In particular:

- Cellular systems tend to be designed so that it is only necessary for one base station to pick up the signal from a mobile.
- The bandwidths tend to be narrower than is optimal.

There are several ways that position can be derived in a cellular positioning system. These include :

The **Signal Profiling** involves measuring the characteristics of the received signal and comparing it with a database of previous measurements. A search is made historically measured signal profile that is close to the received signal. The estimated position is taken to be the same as the position of the closest historical profile.

The **Angle-of-Arrival** technique uses a large antenna in order to estimate the angle-of-arrival of the received signal. The antenna could be a large dish, or more likely, it can be an array, synthesized from individual antenna elements. Such arrays are unlikely to be cost effective or environmentally acceptable in metropolitan areas. However, for micro-cellular systems, where the baselines are very short, it might be possible to make accurate measurements with relatively small antenna arrays.

The **Timing Measurement** technique, in its simplest form, requires a receiver to make an accurate determination of the time-of-arrival of received signals. The arrival time of the signal is a function only of distance traveled, so it is possible to combine measurements from different basestations in order to make a position determination.

In cellular systems, timing measurements can be done in two ways. The first is propagation time measurements, which involves a measurement of the round trip time between a mobile and a basestation. This results in circular loci for the possible location of the mobile. Two measurements result in an ambiguous position fix (see figure 1a), a third measurement resolves the ambiguity. The second way is Time Difference of Arrival (TDOA) where the arrival of a signal is measured at a number of different basestations. The TDOA measurements result in hyperbolic loci (see figure 1b).



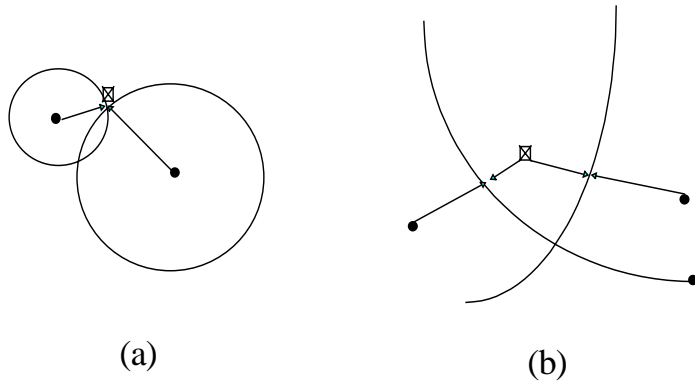


Figure 1. Examples of generic positioning techniques: (a) propagation time measurements (range), (b) TDOA measurements. The black dots indicate the location of the basestation. The mobile is at the spot marked 'X'.

Although two angle of arrival measurements from two basestations can also be combined to make a position measurement (see Figure 2(a)), it is possible to combine a propagation time measurement and an angle of arrival measurement to make a position measurement from a single basestation (see figure 2(b)). The signal profiling does not yield a locus, it corresponds more to pattern matching than conventional positioning methods.

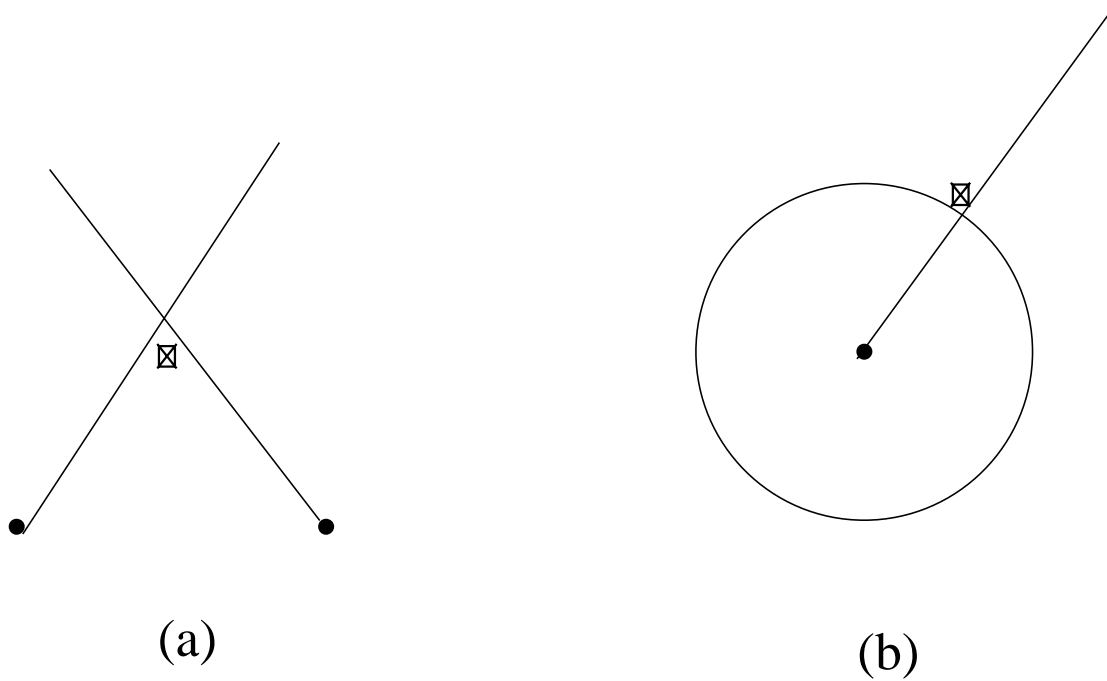


Figure 2: Further examples of generic positioning techniques : (a) angle of arrival measurements, (b) combination of range and angle measurements. The block dots indicate the location of the basestation. The spot mobile is at the spot marked 'X'.

There are two broad categories of positioning systems: self-positioning or remote-positioning. In self-positioning, the mobile telephone works out its location based on the reception of signals from the base stations. In remote-positioning, the system works out the location of the mobile by causing the base stations to operate in a co-operative manner to process the signal received from mobile. Self-positioning has a number of advantages including greater privacy and less changes to the overall cellular network. Remote-positioning has the advantage that certain implementations require no changes to the mobile telephone, allowing the large installed user base of mobile telephones to be used immediately for positioning. For cellular positioning systems, remote-positioning is also referred to as network based positioning and self-positioning can be referred to as handset based positioning.

The architecture of a self-positioning system is shown in figure 3. This architecture is drawn for TDOA systems. The diagram applies to other methods (such as propagation time, profiling) differing only in that there is no need for synchronization and the number of basestations

involved in the measurement). The main elements are the mobile and the basestations. For TDOA systems, there is a need for some means of synchronizing the basestations. The basic operation of the self-positioning system is that the mobile listens to the signals from the basestations and then makes a measurement of position based on those signals. Conceptually, all the positioning methods described above could be implemented as self-positioning, however signal-profiling would be more difficult than the others because of the need to carry a large database onboard the mobile and the need to regularly update the database. From the viewpoint of cellular probes application, the fatal inadequacy of pure self-positioning, as depicted in Figure 2(a) is that only the mobile “knows” its location. For the cellular probe application there needs to be a method of relaying back the data to a central site, known as a Location Service Center (LSC). This could be done using standard cellular packet protocols, such as GSM’s Short Messaging Service (SMS). A combination of self-positioning together with a data link from the mobile to a LSC provides a handset-based solution for travel time estimation.

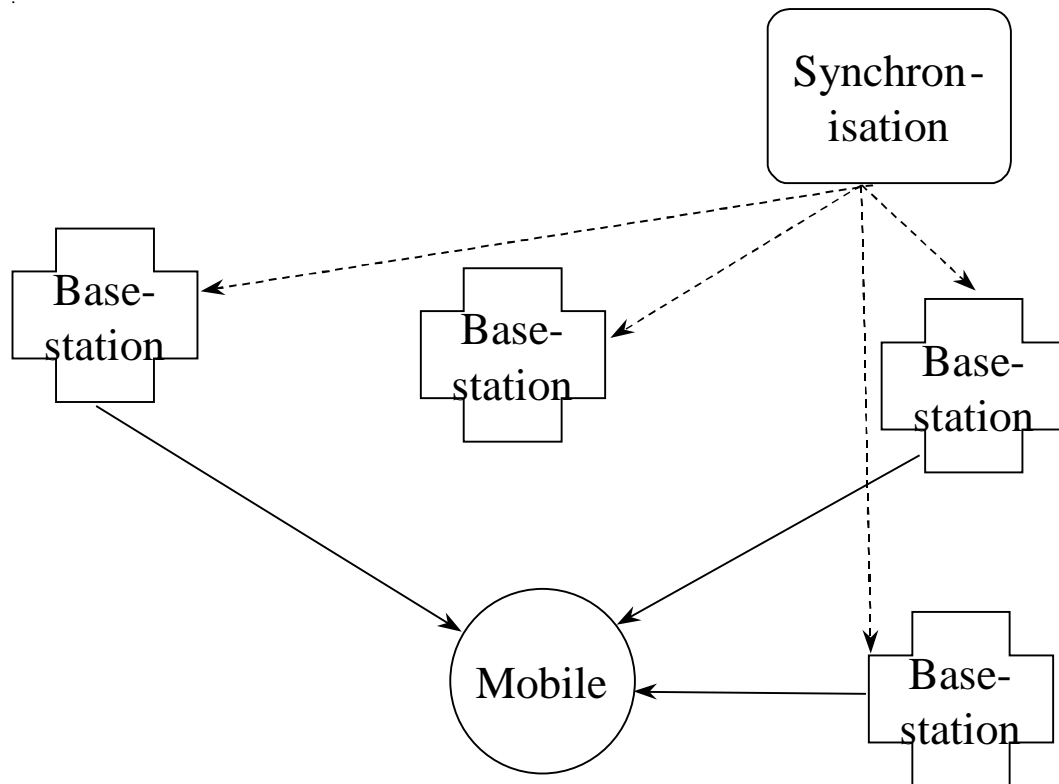


Figure 3: Architecture of a self-positioning system

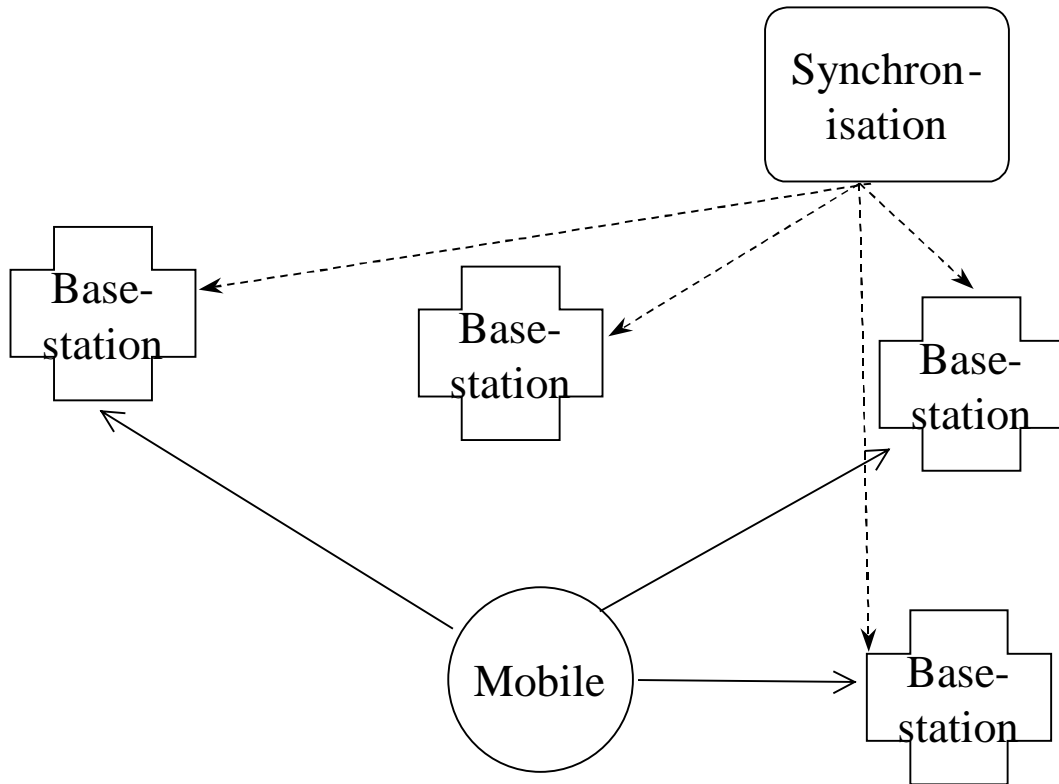


Figure 4: Architecture of a network-based positioning system.

The architecture for a network-based positioning system is shown in Figure 4. Here the signal from the mobile is received at the basestations. The measurements at the basestations are then sent back to the LSC where the position can be calculated and distributed to other parties.

### Prospects for Different Mobile Telephone Standards

Different mobile telephone standards include GSM, CDMA, Analog, and the third Generation Mobile Standards and each has its own characteristics.

#### GSM

GSM was developed as a European digital telephone standard. It was first deployed in 1992 and is now widely used around the world. In the 900 MHz band (GSM 900) there are services operating in at least 53 countries covering Europe, Australia, South Africa, and parts of the Middle East and Asia. In the United States, GSM, implemented at 1900MHz, is referred to as GSM/Personal Communications Services 1900 (GSM/PCS 1900) or GSM North America. In Europe and Asia, GSM is also available at 1800 MHz; the standard being referred to as Digital Communication System (DCS 1800). From a positioning system viewpoint these systems have

similar characteristics; the only significant difference being the propagation characteristics of the higher frequency implementations.

From a positioning viewpoint, the most important signal parameter of a cellular system is the bandwidth. The wider the bandwidth, the easier it is to do time of arrival measurements. Accordingly, systems with a wider bandwidths are more likely to support TDOA and propagation time type positioning technologies.

The bandwidth of GSM is about 250 KHz. This is smaller than would be used for a custom-designed positioning system (GPS uses signals of approximately 1 MHz and 10 MHz). However, the 250KHz of GSM does provide some opportunity for a TDOA or propagation time technology. Measurements have already been carried out [3] indicating that GSM positioning systems are likely to satisfy the FCC mandate for network-based positioning.

It appears that some GSM networks are operated in such a fashion that there is very strong co-channel and adjacent channel interference [4]. This interference can severely limit the accuracy of positioning system measurements.

## **CDMA**

CDMA is considered likely to be the most successful digital telephony standard in the United States. It uses a spread spectrum transmission system and is being assessed for positioning applications [5]. This has the advantage of a relatively graceful degradation in the presence of interference. As well the bandwidth of CDMA is about 1.25MHz, so that it is closer to the optimal bandwidth needed for time of arrival measurements. A further advantage of CDMA compared to GSM and Analog is that all basestations are synchronized, so facilitating the implementation of TDOA solutions. One disadvantage of CMDA is that it uses very tight power control, meaning that in some cases it will only be possible to process a signal from a single basestation. Nevertheless, the prospects for CDMA cellular positioning seem reasonably bright.

From the viewpoint of the cellular probe application, the synchronization of CDMA means it is practicable, using Doppler measurements, to make instantaneous velocity measurements. Without Doppler measurements, a cellular positioning system can only estimate velocity by tracking the progress of the mobile over a period of time.

## **Analog**

Analog is the oldest type of mobile telephony standard. It has a number of disadvantages with respect to mobile positioning, including a very small bandwidth (25KHz) and susceptibility to interference. However most mobile telephones in use in the United States are analog, and the original FCC mandate insisted that these existing telephones should be able to be located. Accordingly there has been more research and development into the problem of network-based location of analog mobile telephones than any other system. Some of this work is innovative and might provide methods of overcoming the severe limitations of analog technology.

In the longer term, analog telephones are likely to be phased out. The reason for this is that the digital standards (CDMA and GSM) allow a greater capacity (i.e. more users for a given frequency allocation) so there are strong economic reasons for cellular operators to encourage customers to adopt digital technology.

### **Third Generation Mobile Standards**

This is the standard that deals with the type of mobile systems that will be deployed after GSM and CDMA. Indications are that the successor to GSM and CDMA is likely to use an even wider bandwidth. This means that successor systems are likely to be even better suited to positioning than the current digital standards. From the viewpoint of the cellular probe application, this provides a strong indication that future developments in cellular standards are unlikely to invalidate the concept.

## **4. CURRENT WORK IN CELLULAR POSITIONS AND ITS POTENTIAL FOR TRAVEL TIME DATA**

### **Current work in cellular positioning**

As stated before this is an area of very active work. Although some information has been published (for example [1]), much of the work is being undertaken in conditions of industrial secrecy. Many claims are made, but there have been few independent trials.

This is a very rapidly evolving field, so at this point we have not attempted to fully survey or evaluate the differing technologies. However, in order to ascertain that positioning technologies are likely to be available we spoke to a small sample of the organizations involved in this area:

#### **Lucent:**

Lucent is actively involved in the positioning area and has been examining the feasibility of CDMA positioning. Lucent also indicated that the CDMA development Group is trying to evolve a standard for evaluating different cellular positioning systems.

#### **University of Technology, Sydney (UTS) :**

The research group has tested a first prototype of a GSM cellular positioning system and has carried out field trials on a second prototype. The technology has been sold to Cambridge Positioning Systems, a United Kingdom based company.

#### **U.S Wireless Corporation, San Ramon, California :**

U.S. Wireless is building a nationwide location information network to provide instant, accurate, and reliable location data to wireless carriers and other service providers. An independent,

shared network operating as a service bureau, the U.S. Wireless network will offer multiple carriers, Internet Portals, call centers, and other service providers a reliable and cost-effective means for gathering location data. The technology can pinpoint the location of any mobile telephone subscriber anywhere, anytime, with close precision. Using proprietary Location Fingerprinting™ technology, the RadioCamera™ system determines a wireless subscriber's location signal profiling. The RadioCamera™ identifies the unique radio signature, or "fingerprint," of the call and matches it to a similar fingerprint stored in its central database. In cooperation with the University of Maryland, the University of Virginia and Maryland and Virginia DoTs, U.S Wireless is measuring highway congestion by tracking motorists talking on cellular telephones as they drive the Capital Beltway [6].

### **Radix Technologies, Mountain View, California:-**

Radix Technologies, Inc. has developed a network-based geo-location system designed to locate wireless phones to an accuracy far exceeding the current FCC E911 mandate. The initial version of Radix's GeoPhone TDOA/AOA location system is designed for CDMA wireless networks, with later versions being adapted for AMPs, TDMA, and GSM protocols. The system co-locates a low cost sensor at each cell site to gather timing data on the cell phone to be located. The GeoWorkstation, co-located with the MSC, manages the system functionality, gathers all data from the sensors, and calculates the latitude/longitude position data. The GeoPhone system can be used to deliver the position data for E911 emergency location services or other value-added location services that may be offered by wireless carriers in the near future. Through the implementation of a highly integrated design, and by using the existing antenna array and network communication resources, the GeoPhone system offers a low cost solution for adding geo-location capability for all existing and future subscribers. Radix has applied its expertise in advanced signal processing to develop the location technology and algorithms used in the GeoPhone system. The development of high-speed microprocessors has enable the cost effective implementation of very complex signal processing techniques. The result is a high precision, network-based geo-location system that eliminates many obstacles which have plagued network based location solutions.

### **SnapTrack , San Jose, California:-**

The company is developing hand set supported positioning applications, instead of network solutions. When SnapTrack is activated, the wireless network sends an estimate of the location of the handset to a server. The server informs the handset which GPS satellites are in its area, and 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 server software performs complex error correction and calculates the caller's precise latitude longitude and altitude. In the case of a 9-1-1 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, whereas conventional GPS receivers can take several minutes.

## **5. HOW THE CELL PHONE PROBE CONCEPT APPLIES TO THE BAY AREA ROAD NETWORK NEEDS FOR TRAFFIC INFORMATION**

Although most of the major freeways in the Bay Area are planned to be instrumented, minor freeways and the majority of arterials have no plans to be instrumented in the near future. We believe that cellular technology, loop detectors and other sensor or detector technologies can coexist and complimentary. For example, the cellular technology can supplement the inductive single loops by providing speed calculation and can also be used in areas where loops and other sensor technologies are not deployed.

Presently, 100 miles of Bay Area freeways are instrumented with inductive loop detectors. Caltrans has planned additional 500 miles of freeways to be instrumented with inductive loop detectors over several years. However, over 70% of the existing loop detectors have not produced accurate or reliable traffic data for various reasons, including hardware, software and communication problems. Caltrans is currently identifying problems and enhancing the existing loop detector performances, but there has been slow progress on identifying problems associated with individual monitoring stations that are already deployed.

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 cellular phone probe system has been recommended 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 SRI study speculated that the cellular phone probe system can potentially provide cost-effective wide-area data coverage including both freeways and arterials. No heavy infrastructure investment is necessary for cellular probes. With the growing number of cellular phone subscribers, it is reasonable to assume that there will be a sufficient number of vehicles equipped with cellular phones to provide accurate and reliable information of traffic conditions at a given link during peak hours. In the Bay Area, over half of vehicles traveling freeways have cellular phones according to the 1998 Bay Area household survey conducted by PATH.

Approximately 100,000 cellular calls report traffic incidents daily in the US which amount to 25% of the total 911 calls annually. In many cases, 911 callers did not know the exact location of where they were calling from or where the incident had occurred. As a result, the federal government mandated that cellular carriers meet the E911 requirement that a specifies caller's location within 50 meter radios by 2001. About a dozen companies have developed or are currently developing various technologies to provide their services to cellular carriers to meet this requirements. The E911 requirements provide new opportunities to utilize cellular technologies for measuring vehicle speed and travel direction. However, the viability of these technologies for monitoring vehicle speed and measuring travel time has not been determined.



## Overview on theoretical probe models

The concept of using a probe vehicle for estimating travel time has been investigated for some time, [7], [8], [9], [10], [11]. These studies have all shown the concept is technically feasible. The results show that in general, roughly 5% need to be instrumented in order to achieve reasonable estimates of the travel time. These studies have assumed that the probe reports represent an independent random sample from the traffic stream and that the vehicle probes are able to estimate their location with a very high order of accuracy. There is no reason to think that the cars traveling with a cell phone are not a random sample of the total vehicle population but the second assumption is not valid in the case of cellular telephone positioning systems. Such systems are likely to have an error of the order of 100 meters RMS. This error can cause the following problems :

- Assignment of a vehicle to the wrong road.
- Mistakes in the direction of travel.

As well, in order to make a position measurement the mobile has to be turned on. Users might turn a phone on for a brief period then turn it off again, so that cellular probes will operate in an intermittent, more random fashion than dedicated probe technologies.

In addition to the issue of accurately tracking mobile telephones, there is a further technical issue of the system capacity needed in order to actually make the measurements. Given the probe application is likely to be a secondary application to the FCC E9111 requirement, it is important the cellular probe application does not use too much of the capacity of the cellular positioning system. If the usage by the cellular probe application is too high, this could jeopardize the primary application, or necessitate the installation of many additional positioning receivers.

Accordingly, our analysis has focused on these differences, rather than completely duplicating earlier work. We have taken two complementary approaches. The first was to construct a series of analytical models that addressed different issues. The second was to develop a simple discrete event simulation.

A brief description of each of the analytical models is presented below, together with the overall results. These models are still under development and require verification and validation. Details of some of the more important models are presented in Appendix A.

### Placing the vehicle on the road

This looked at using a process of map matching to place a probe vehicle on a particular road. We estimated the probability of incorrectly placing the vehicle on a road that was to parallel to the road on which the probe was actually traveling. The probability was found to be a simple function of the ratio standard deviation of the position measurement noise divided by the distance the roads were apart. Further work would look like at the probability of error for other geometries such as two roads crossing perpendicularly.

### **Estimating the mean speed**

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 GSM where it is not possible to measure the instantaneous speed. 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. We are also examining the errors involved in a more direct measurement of the travel time.

### **Number of Measurements needed to characterize a network**

This model looked at the overall problem of how many travel time measurements were needed to characterize a network. If too few measurements are made then only a small number of links will have been characterized, so that the overall information is not greatly improved over the historical travel time averages. This derivation assumed a worst case 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 :

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

Where  $\alpha$  = fraction of vehicles sampled  
 $\rho$  = density of traffic per unit length  
 $L$  = average link length  
 $E$  = coverage.

This formula says that to improve the coverage you need 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 you are 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 there can be rapidly diminishing returns associated with increasing  $\alpha$ , because once  $\alpha\rho L$  is greater than one, the coverage rapidly approaches 100%. Of course care is needed when interpreting this formula. For example, although longer link lengths translate to increased coverage, if the link lengths are too long then they do not provide useful information about travel times in a particular area.

### **Effect of differing densities**

This model looked at the fact that on a road network you have roadways of markedly differing density e.g. Surface network and Freeways. The analysis showed an exponential relationship with density, meaning that those parts of the network with the highest densities will have the greatest coverage. This is a nice property, because much of the interest in travel time measurements occurs when there is congestion, i.e. high density. This result indicates that a cellular based probe system will automatically give more reliable results in such areas.

## **Directional Errors**

One problem with a cellular based travel time estimation system is that it is possible to make an error and consider that the vehicle is going in the wrong direction. A model was developed to estimate the probability of making such an error. It was found the error was inversely related to the ratio of vehicle speed to the standard deviation of the speed measurement. In other words, directional errors are only likely to occur when there is a very low traffic speed. However this source of error can still impact on the performance, because very low traffic speeds are often associated with a serious incident, making the determination of direction of flow quite important.

## **Effect of wrong road placement**

This examines the error introduced by placing a vehicle on the wrong road. It assumed a worst case that travel times on different roads are independent of each other. In this case the effect of wrong placement is quite severe, resulting in an error worse than simply assuming the historical average travel time. However in many cases the travel times of nearby roads are related to each other so the effect is probably not as severe as indicated by this analysis. Aspects of this analysis need to be improved.

## **Overall Model**

This integrates most of the previous models to provide an estimate of the standard deviation of the travel time measurements.

## **Utilization of Positioning Receivers.**

This analysis examines the utilization of positioning receivers in terms of the number of position measurements that need to be made in a network, the number of receivers needed to make a position measurement, and the interval between measurements. A final parameter is the number of positioning receivers that are scattered around the network. This analysis also looks at the communication load involve in making the position measurements.

## **Overall Results**

Most of the above models were linked together to provide an overall estimate of the accuracy of the travel time measurements and the utilization of the positioning receivers. A printout of the model, including all value of all the parameters is shown in Appendix B. These parameters are only tentative, we are currently carrying out an investigation to find more reliable estimates of the parameters. Any suggestions or data are welcome.

Highlights of this analysis are as follows. For just 5% of the vehicles samples, the coverage was very high, i.e. in a 15 minute time window and a link length of 1.5 km (which is relevant to the Bay Area network), most links in the network would be sampled. The model also indicated that for a spacing of 250 meters between roads, the probability of assigning a vehicle to the wrong road was very small, less than .001. It was found that the raw standard deviation of the travel

time was about 10 seconds (about 10% of the travel time for the link) and was only degraded slightly by wrong road assignment and non-sampled links. The effect of directional errors was not included in the model, but it is considered likely that it will be small.

Assuming that 400 positioning receivers were used to make the position measurements, it was found the average utilization of each positioning receiver would be less than 1%. This low value is due the large number of basestations, the small amount of time needed to make a measurement (100 ms), and the relatively long time interval between measurements (ten seconds or more).

## **Results from the use of a simple simulation model**

The simple analytical models do not capture the complexity of vehicle movement along a freeway . Accordingly, we prepared a complementary analysis to the analytical models presented above by building a discrete event simulation of travel along a section of a freeway (see figure5).

The aim of this simulation was to compare average link travel time for a simulated traffic flow situation with different size samples of vehicle probes (5% to 50%, at 5% intervals) drawn from the total population. The position accuracy of the probes is given at random in a 150 meters range, which is what we can expect from cellular positioning methods. We studied different road network configuration to test the robustness of the estimates in travel times.

We simulated vehicles entering the network at constant speed, with a Gaussian speed distribution. We used distributions with different means corresponding to the different network and lane situations, and we were able to input different volume and speed parameters for two lanes of freeway, plus an adjacent road. The network was divided in links of 1.5 km,. The model counts the number of cars per link and their speed on a 3 minutes cycle with a refreshment period of 15 minutes. The results are average (harmonic mean) link travel time estimates over an hour (simulated time).

- Method

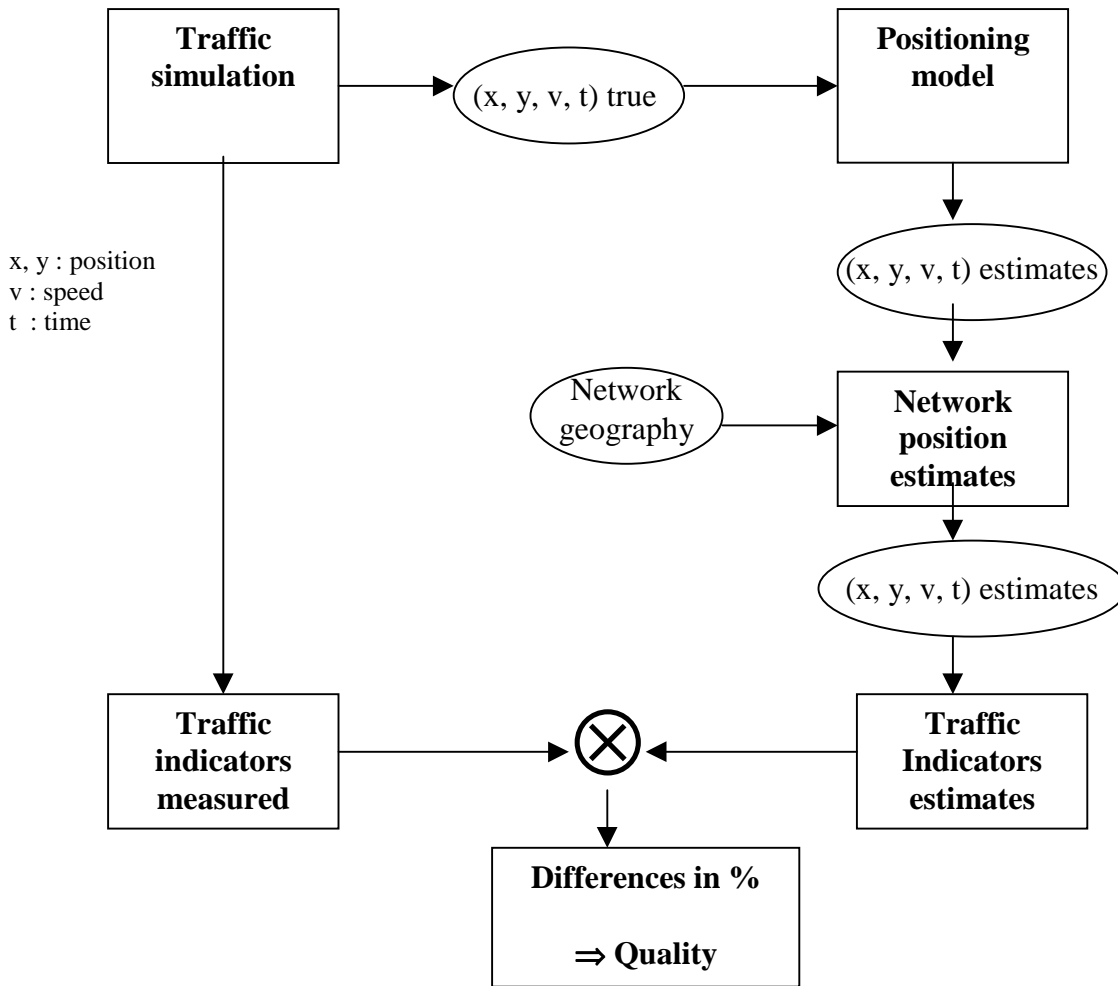


Figure 5: Simulation model of travel time estimates from probe vehicles

## Filtering

The output aims at classifying (class of 5 km/hour interval for example) all the speeds of the probes who have been recorded on the different links. The classification allows us to calculate the travel times for the link and also for each lane if we can observe a multi-distribution of the speeds. The filtering process to adjust the probe sample for positioning error is based on three main actions :

- the probes with a speed greater than 160 km/h are eliminated from the sample

- the probes with a zero speed during a 15 minute measuring period are also eliminated, they can correspond to phones who are not in cars; this is not done if all the probes have zero speed (i.e. traffic stopped)
- the probes whose location has been spotted at least once out of an envelope of 300 meters on each side of the road are also eliminated

The observed distribution of speeds allows us to use link travel time for the network link, if the speeds are the same on each lane, or by lane/link if the distribution shows a two-peak distribution. The figure 6 shows the result of the positioning model applied to the traffic flow distribution of the simulation showing how the positional errors obfuscate the known vehicle positions:

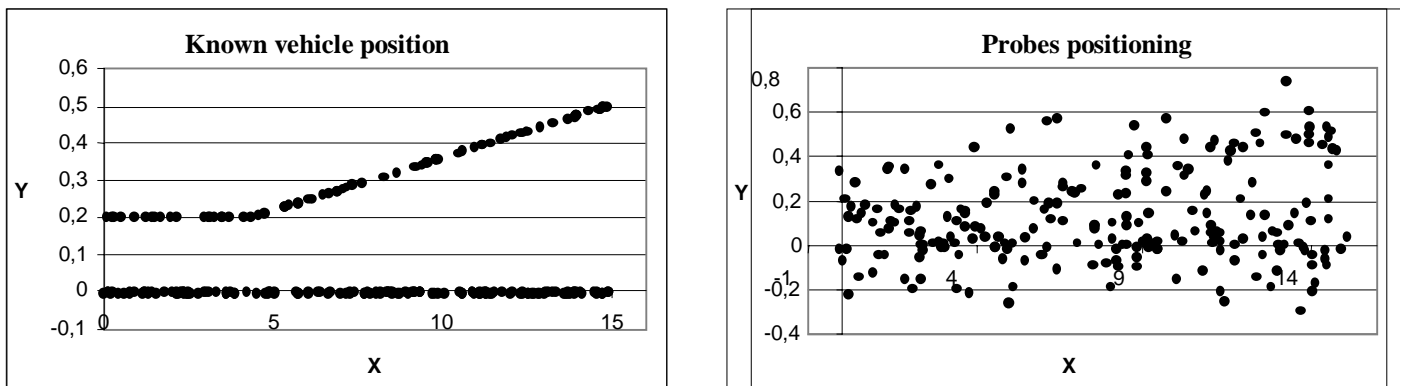


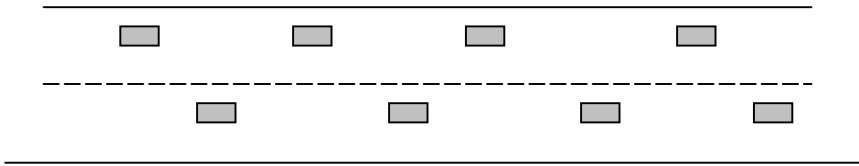
Figure 6: Positioning model of the simulation

### Case studies and probe travel time estimates

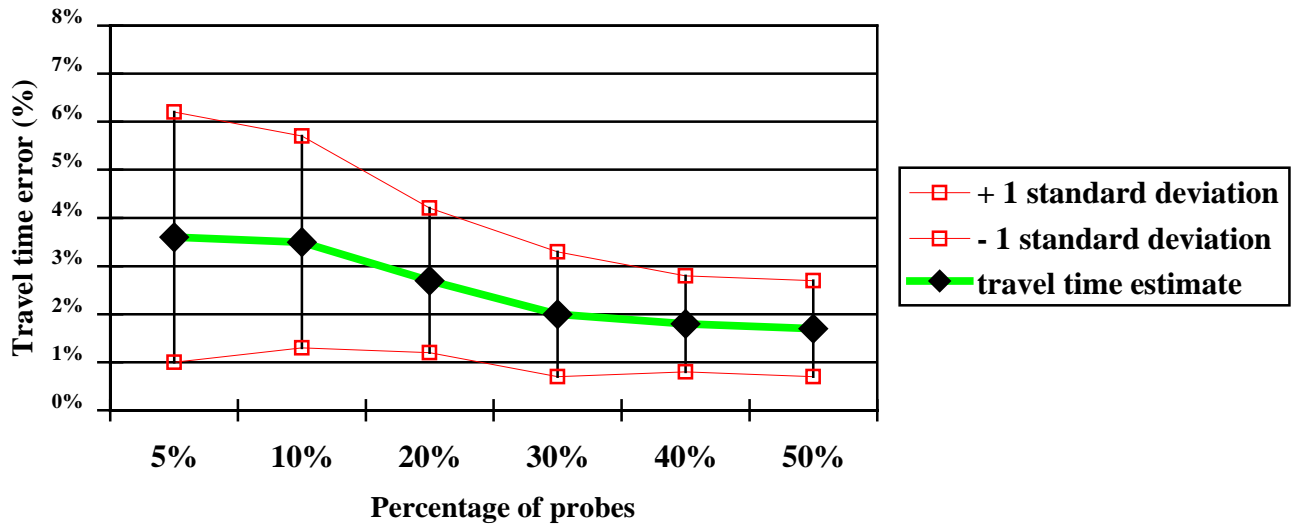
We consider six different cases, in order to assess the effect of different traffic conditions and network geography on the accuracy of the travel times estimates of the probes. The configuration for each case and the results for each case are set out below :

**Case 1 : free flowing conditions on both lanes :**

	average speed	Density
lane 1	100 km/h	1600 v/h
lane 2	80 km/h	2400 v/h



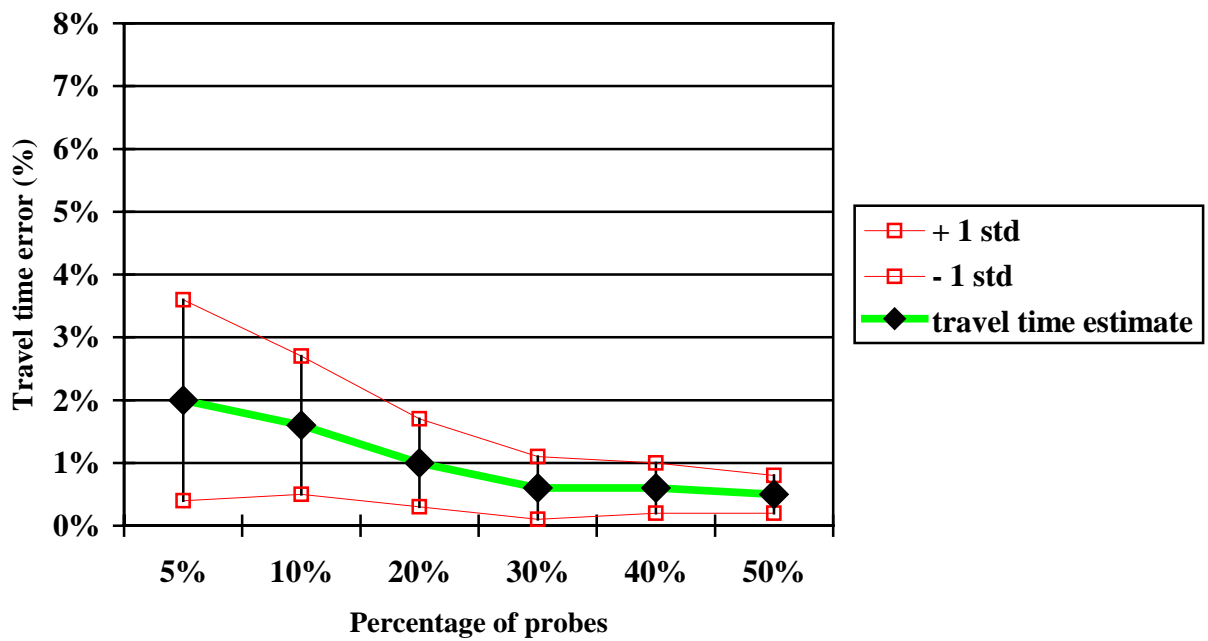
**Differences in travel time estimates  
free flowing condition on both lanes (60 MPH)**



**Case 2 : slow flowing condition on both lanes**

	average speed	Density
lane 1	30 km/h	1000 v/h
lane 2	30 km/h	1000 v/h

**Differences in travel time estimates  
heavy traffic condition on both lanes (20 MPH)**

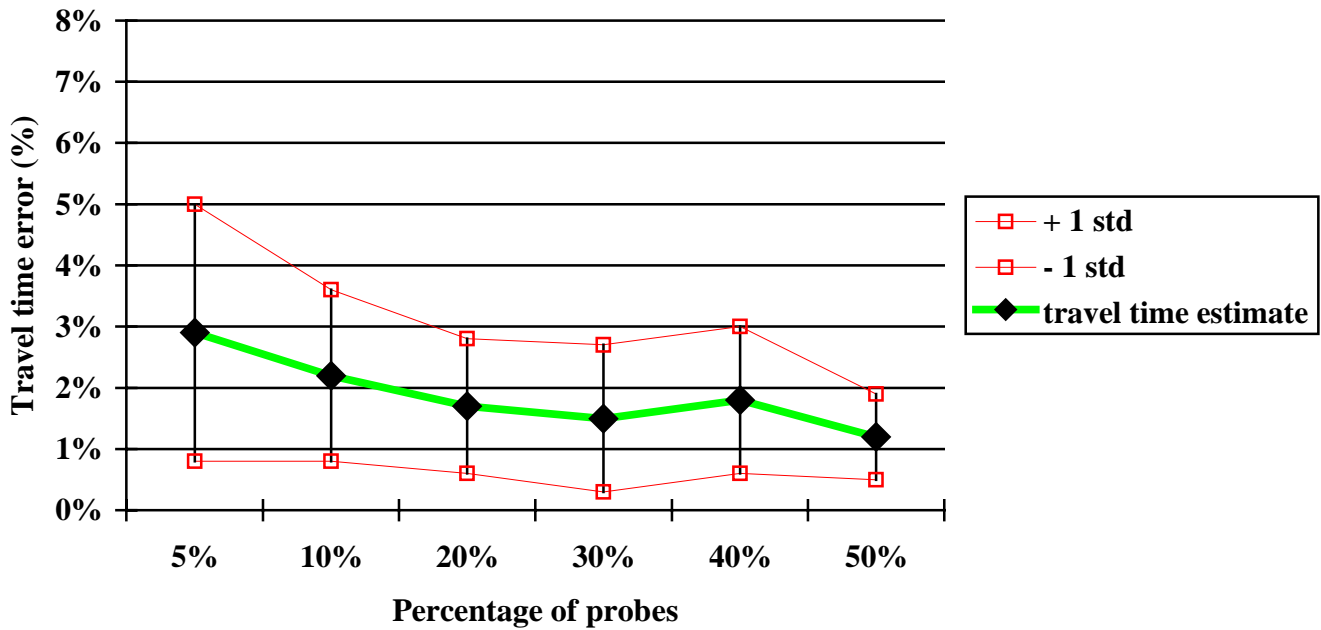




**Case 3 : free flowing condition on one lane and slow flowing condition on the other – differences in travel time estimates for the slow lane**

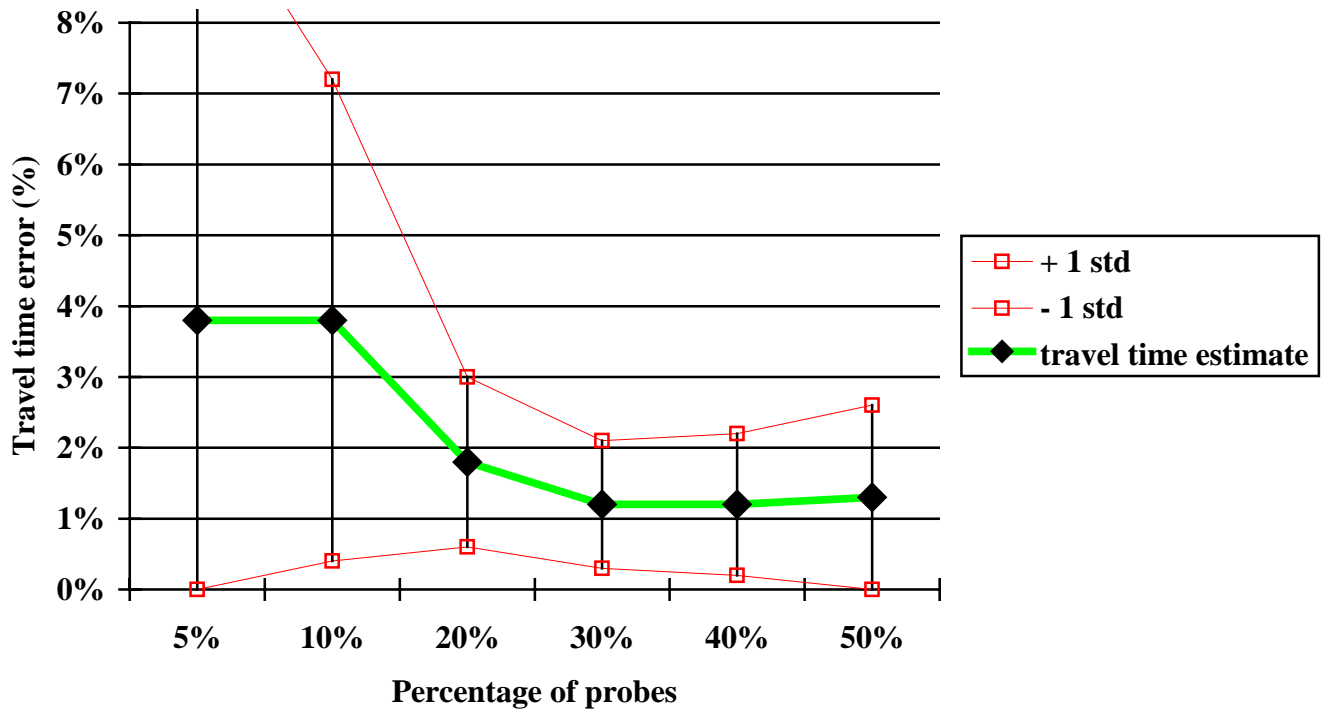
	average speed	Density
lane 1	30 km/h	1000 v/h
lane 2	80 km/h	1500 v/h

**Differences in travel time estimates  
for the slow lane (20 MPH)**



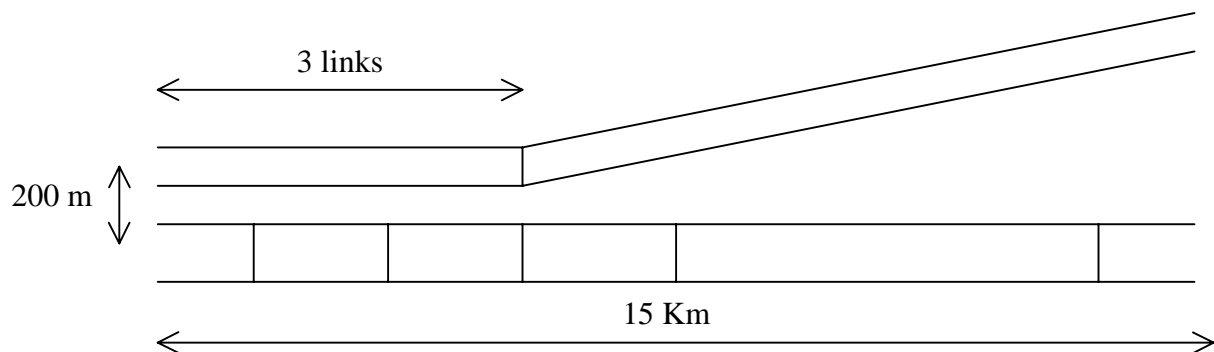
**Case 4 : free flowing condition on one lane and slow flowing condition on the other – differences in travel time estimates for the fast lane**

**Differences in travel time estimates for the fast lane (50 MPH)**

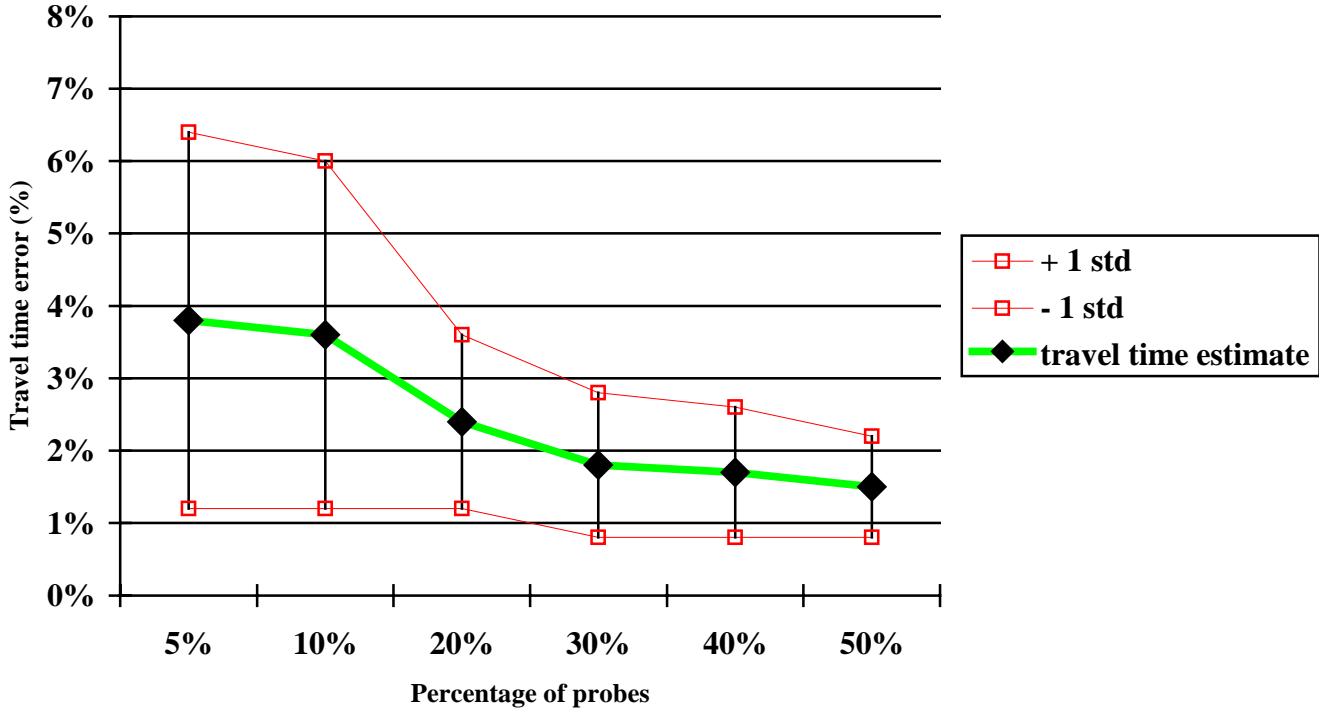


**Case 5 : two fast lanes and a frontage road (we assume for the filtering of the probes that a frontage road is not 200 meters closer from a freeway during more than 3 links, e.g. 4.5 km); free flowing condition on both lanes and slow on the frontage road.**

	average speed	Density
lane 1	90 km/h	1500 v/h
lane 2	70 km/h	2000 v/h
frontage	50 km/h	1000 v/h

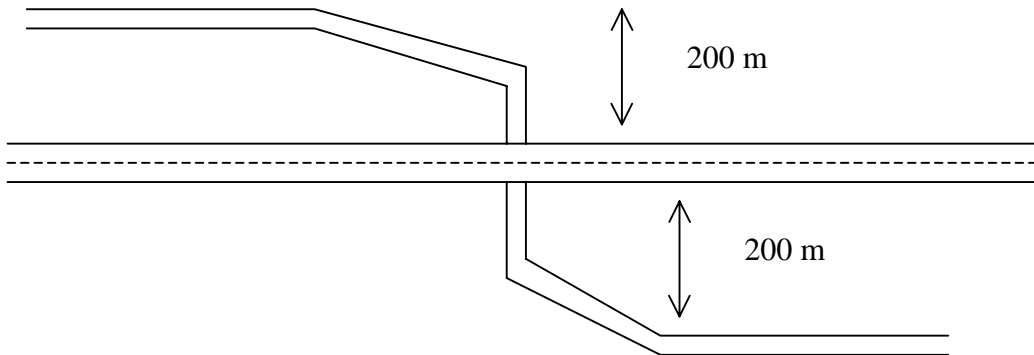


Differences in travel time estimates  
two fast lanes plus a slow parallel lane (30 MPH)

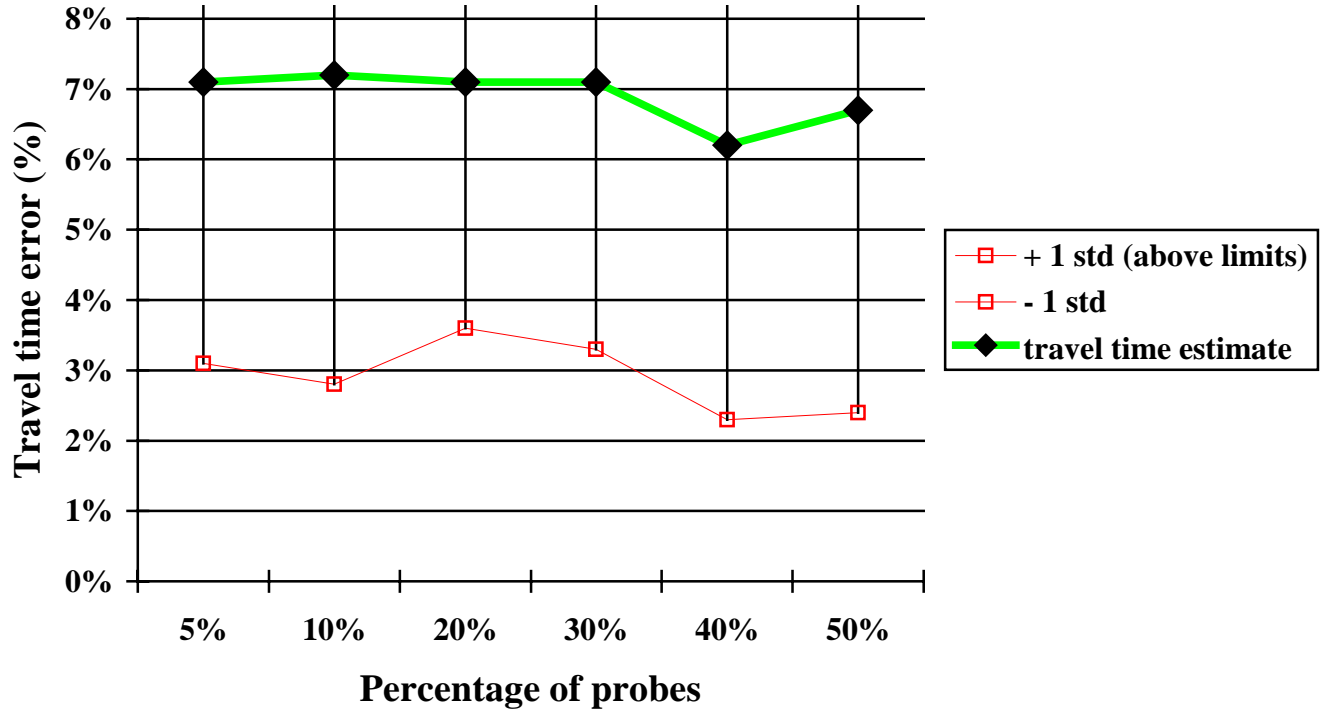


**Case 6 : differences in travel time estimates for a more complex network**

	average speed	density
lane 1	80 km/h	1500 v/h
lane 2	60 km/h	2000 v/h
road	60 km/h	1000 v/h



### Differences in travel time estimates in a more complex network



### Synthesis

The results show a very acceptable accuracy of the cell-phones-as-probes concept, even with as low as 5% of probes. This result is also consistent with the analytical models describe earlier. The use of the cell phone model must be adapted to the road network where it applies. In other words, we will have to calibrate with existing traffic data from other sources. The probe model will also become more and more accurate as the number of digital phones increases, which is almost certainly the actual trend.

### Estimates of the cell phone distribution on the Bay Area road network links

First we gathered data on the distribution of links in the Bay Area. This data is shown below in tables 1 and 2

### The road network<sup>7</sup>

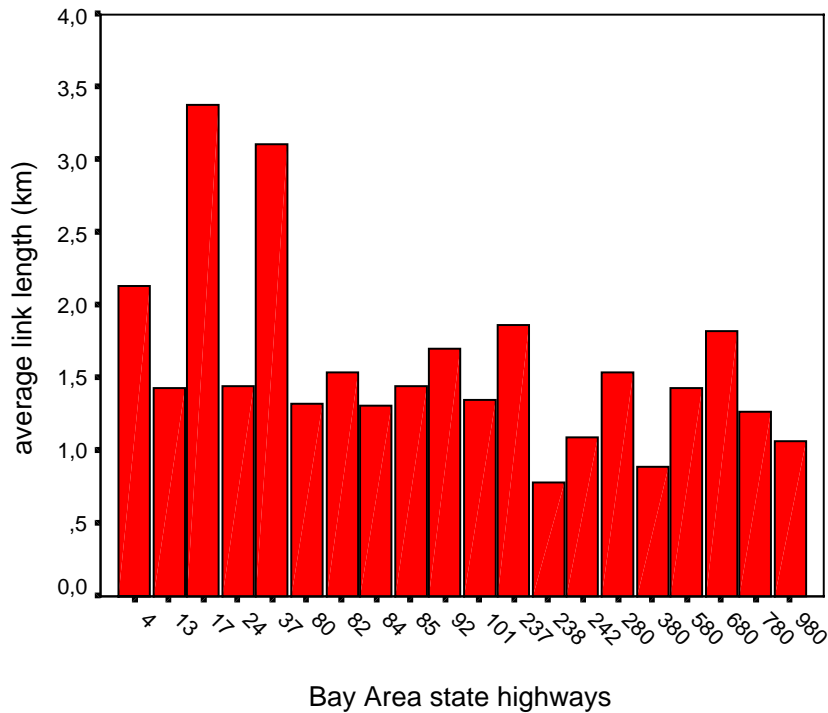
<sup>7</sup> We are considering here the state highway network. The network includes freeways and also major arterials. We would only consider the freeway network for a first deployment phase although the technology could be extended to the arterials after improvement of the cell phone signal positioning/filtering process.

The traffic density is given for both directions<sup>8</sup>, table 1.

Name	exits (nb of links =nb of exits-1)	mileage	average/month	average/peak hour
4	21 exits	26.53 miles	72000Vehic/mth	5875/hour
13	7	5.36	45000	4400
17	12	23.06	77000	7300
24	16	13.54	152000	10500
37	12	21.26	34700	3100
80	50	40.17	147000	12600
82	40	37.47	37000	3500
84	18	13.88	31000	3000
85	9	7.17	87000	7050
92	21	21.14	70000	6500
101	99	82.17	180000	15000
237	12	12.72	70000	6900
238	6	2.43	104000	6000
280	54	50.94	150000	13000
380	4	1.67	130000	12500
580	61	53.19	140000	12500
680	67	74.61	135000	11500
780	9	6.33	53000	5000
980	3	1.33	180000	13000
<b>total</b>				
<b>mileage</b>		<b>498.97</b>		

**table 1 : Bay Area state highway network characteristics**

<sup>8</sup> "1997 traffic volumes on California state highways, Division of traffic operations, June 1998.



**Table 2 : distribution of link mean lengths for the Bay Area freeway network**

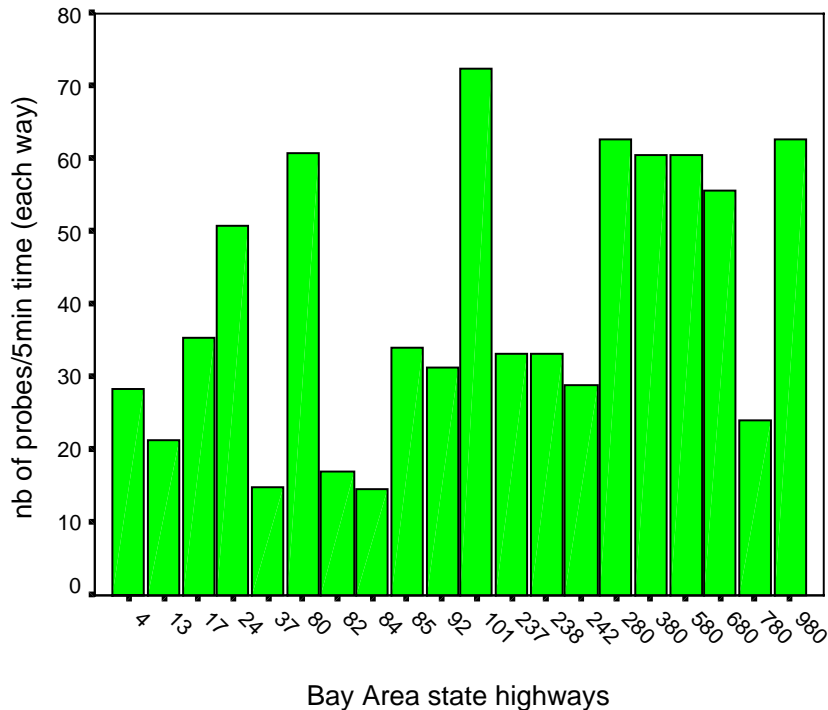
On the network there are some links which have a low traffic density, and are not critical for the travel time variations, unless an accident is reported. A system design consideration will be to balance the links where we absolutely need traffic information, e.g. the ones with high traffic and with poor traffic detection capabilities on the road infrastructure with the links where historical data could be enough.

### **The cellular phone distribution**

PATH conducted a household survey of Bay Area residents in November 1998. The survey suggests that 37.7 % of the Bay Area commuters are expected to travel with a cell phone. The distribution of cell phones equipped travelers is not the same when considering freeway users versus arterial users. When the correction factor of 1.3 (from the cross tabs observation) is applied one can estimate that approximately 50% of freeway users are traveling with a cell phone. Roughly 1/3 of these phones are digital, and 70% of them are always “on” while traveling. This brings our target population to 11.6%. A major carrier can get almost 1/3 of the subscribers. Depending on the potential interest of carriers for entering the DOT market for travel times and the exclusivity issues which have to be evaluated in the future, we estimate between 5% to 12% of probes will be available to deliver the information which is well within the accuracy boundaries that we have evaluated in our simulation work.



A close analysis of the Bay Area network shows the absolute number of probes we can expect by link over a five minute period, table 3.



**Table 3 :distribution of the number of probes by freeway link over a 5 minute period**

We assume that the distribution of probes on the freeway network is the same that the distribution of all the cars on the same network. This can be slightly calibrated during a field test evaluation.

### **Business Issues**

The transportation and the wireless telecommunication sectors have been ignoring each other for a long time. Each one of these sectors is making investment decisions without considering that in many cases they are dealing with the same issues; the end user of the road network is at the same time the end user of a cell phone. However the value of the services are not considered in the same manner. From the telecommunication standpoint, the cell phone user is paying for an individual and personalized service ; the transportation sector is considering the road user as a statistical element of a global stream. The cell phone as a probe concept, links the telecommunication network capabilities to the global transportation needs in the data collection and information domain. These issues have to be evaluated through viable business models with a shared vision of the step by step implementation.

We know that at least, 12 U.S. companies are targeting the E-911 market and further applications for positioning services for the mobile. The probe concept and the DoT travel time market can be the next opportunity for these companies. Organizations wishing to take advantage of this concept will need to address the privacy issues which could arise from the deployment of the positioning technologies on a large scale.

When considering the Bay Area investments necessary for E-911 mandate, one might evaluate the infrastructure costs, if this solution is followed by the carriers, to be \$20,000 a cell site, which brings a total of about 20 millions dollars for the good coverage of the network.. Assuming that the carrier is allowed to charge the subscriber 65 cents a month, this brings the gross income to comply with E-911 mandate to \$23 Millions.

On the other hand the California statewide, transportation investment in detection has been on the order of \$166 million. The annualized cost is estimated to be approximately \$34 million, assuming maintenance & operation costs of 10% and a straight-line ten year life for depreciation. In addition, approximately \$61 million has been programmed for construction. "Programmed" means that there has been a financial commitment to construct the systems. Assuming that one half of the programmed projects are in operation during the next two years the annual statewide cost of detection is of the order of \$49 million.

The equivalent estimate for District 4 (essentially the Bay Area) is approximately 12.4 million annually. The main strategic issue is to evaluate how much a deployment of a Bay Area cell-phone-as-probe-concept would save from the Caltrans operating funds, and how the funding transfer from the transportation infrastructure and maintenance to the wireless operating costs would benefit to the wireless companies involved in this new business.

## **6. FIELD OPERATIONAL TESTS**

### **Introduction**

The field test work assumes that the PATH group can access to cell phone positioning technologies implemented on at least selected links of the Bay Area network. The probes data will have to be compared to “ground truth” data obtained from the road network. There are few places that are instrumented to provide a good estimate of travel times on the Bay Area network. A stretch on I80, between Albany and Emeryville exits, is well instrumented and can provide fairly accurate travel time information. The accuracy of the data is validated by the Berkeley Highway Laboratory. The ideas developed hereafter are 100% dependant on the possibility of implementing telecom technologies to obtain accurate positions of the phones. Many vendors and developers of relevant technologies have been contacted and we are still waiting to know their keenness to participate. The “ground truth” data can also be obtained from GPS measurements of cars traveling on the freeway.

## **Objectives**

Simulations and analytical modeling can only go so far. In order to make a full assessment, a field operation test is required. The objective of the field test is to further investigate the feasibility of cellular technologies for traffic surveillance and management. The accuracy of vehicle speed or travel time data will be tested against data generated from using GPS and Differential GPS. The Field Operational Test (FOT) will demonstrate two scenarios: 1) the Global Positioning System and 2) cellular technology using the cellular analog system. These demonstration scenarios have a common goal that is to measure the accuracy and reliability of vehicle speed or travel time on the Bay Area freeway network.

The first field test was conducted in June 2000. Two field engineers drove a vehicle equipped with two analog phones and a GPS and Differential GPS for five hours between 11 AM – 4PM. The purpose of this field work was to collect data and test the data using the PATH developed algorithm for data reduction.

## **Investigation of the Global Positioning System**

To assess the effectiveness and adequacy of cellular and GPS technologies for incident detection and speed information, the current state of the technologies and commercially available GPS units was investigated. The GPS and DGPS units are used to detect nodes in the roads and send IP packets through a wireless modem containing information on the position and time of the vehicles to a centralized database at PATH. The nodes are placed on critical points on highway overhead bridges and using the TravInfo link definition. The GPS units send continuous amounts of data to a laptop computer where software takes in the information and determine if a node point has been passed. Differential GPS was used to eliminate the inaccuracy inherent in the signals being sent to the GPS unit due to selective availability.

## **Development of Models for Vehicle Positioning Using Cellular Technologies**

At this stage, several simple analytical models of the measurement process have been developed as documented in this discussion paper. There were a number of reasons for constructing these models; identify important parameters, gain a deeper conceptual understanding, and provide ballpark estimates of system performance.

As a result of the modeling process, a clearer idea of the parameters that need to be estimated was gained. Examples of such parameters include; the distribution of cellular users on the Bay Area Network (BAN), statistical distribution of traffic on the BAN, the distribution of cellular base stations in the Bay Area, size of links, acceptable window time, maximum sampling frequency, measurement accuracy's, and other parameters associated with the road network and the cellular systems. At this state, first cut estimates for all the important parameters have been established. The analytical model are now ready to be tested for its technical viability. The first phase of the operational test will be done using the existing simulation models such as PARAMICS. The second phase of the field test will be performed on selected links, if the simulation models were technically proved to be workable.

For the Field Operational Test, we intend to carry out the following tasks:

### **The GPS surveillance technology**

- a) Test and validate the GPS computer programs developed by PATH. The initial work will be done walking around local streets with arbitrarily designated nodes.
- b) Revise the programs if necessary and test them again until they produce desired information and send data to the central databank.
- c) Test and validate the system by driving along I-80 between Albany and Emeryville back and forth to produce data. Analyze the data to validate the robustness of the system.
- d) Install the system in four to six FSP vehicles, transit buses or delivery vehicles to test the system.
- e) Analyze data to determine whether the system can produce accurate and reliable speed data on major freeway links.
- f) Prepare a working paper to report on the FOT results.

### **Cellular positioning technology**

- a) Verify and document the analytical models and simulation models.
- b) Complete the parameter estimation.
- c) Calibrate simulation models to validate different cell technologies
- d) Complete a simulation of performance assuming a system working on three links of the Bay Area Network.
- e) Determine the accuracy of travel time data .

For the second phase of the study, we plan to evaluate cellular technologies further for their vehicle positioning ability against different traffic surveillance technologies. The proposed field test site will be on a 3 mile I-80 corridor defined by the Berkeley Highway Lab between the cities of Emeryville and Albany. We will evaluate cell-GPS vehicle positioning technologies with respect to other technologies such as inductive loop detectors, CCTV camera, and Electronic Toll Collection tags. The proposed field test site is instrumented with inductive loop detectors and CCTV.

The objectives of the second phase field test are to:

- 1) Determine the technical viability of cellular-GPS data collection techniques for freeway and surface street traffic information.
- 2) Compare data generated from using these technologies with data generated from data collected using loop detectors, a CCTV camera in Emeryville, and ETC tags.
- 3) Recommend future course of actions to Caltrans District 4 and the TravInfo Management Board for deployment of cell-GPS technologies for traffic data collection.

## Methodology

The second phase study will be conducted in three phases: 1) data collection using cell-GPS technologies on the Berkeley Highway Lab link, 2) comparison of the data generated from using these technologies with loop, CCTV, and ETC data on this corridor, 3) identification of links most suitable for cell-GPS technology deployment in the Bay Area. The central function of the cellular and GPS field tests will be housed in the newly created Traveler Information Center in Berkeley. Data comparison and analysis will be done at the Richmond Field Test.

## Field Test Plan for Phase 2 Study

The proposed field test will be done over a period of 12 months. The specific tasks are described as follows.

### Data Collection

The purpose of the initial field test will be to investigate the feasibility of cellular-GPS technologies for vehicle probes. The second phase will evaluate several cellular-vehicle positioning technologies on the Berkeley Highway Lab corridor.

#### ***Data collection tasks***

- 1) Coordinate the Berkeley Highway Lab's loop detector activities and CCTV-ETC activities currently underway at PATH.
- 2) Develop a master plan for the field test effort on the PATH research effort on data collection technologies including loop improvement, CCTV and ETC through initial meetings.
- 3) Collect traffic data using GPS and cellular phones, CCTV, and ETC tags.
- 4) Establish a common time frame for data collection tasks.

### Data Comparison

The goal of the field test is to determine the viability of different vehicle probe technologies for generating accurate and reliable travel time information. Therefore, the proposed research is to compare data generated from these technologies for accuracy.

It is hoped that CCTV and ETC projects are developed to a sufficient level to generate data for comparison. It is also expected that US Wireless and RADIX-Sprint will complete their infrastructure deployment on the corridor of the Berkeley Highway Lab. Discussions on the proposed field tests are in Appendix C. The long-term vision plan is shown in Appendix D.

#### ***Data comparison tasks***

- 1) Examine the characteristics of data generated using different technologies.

- 2) Develop data fusion methods for different probe vehicle technologies.
- 3) Compare the data sets generated from different technologies using statistical tools including ANOVA, MANOVA and regression procedures in the SPSS environment.
- 4) Determine the statistical significance of data analysis and acceptable level of accuracy.
- 5) Prepare a report on the results of the comparison.

### ***Link identification tasks***

Based on the results of the Phase 2 study, we will identify freeway network links most suitable for immediate deployment of the cell-GPS technologies in the Bay Area. One of the purposes of the proposed research is to assist Caltrans District 4 and the TravInfo project through multi-level data collection system.

- 1) Review the Bay Area-wide link definition established by the TravInfo project.
- 2) Identify links that are important to traffic management system, however, data on these are not currently available.
- 3) Determine the suitability of deploying the cell-GPS probe vehicle technology on various links throughout the Bay Area.
- 4) Recommend the cell-GPS technologies for immediate deployment on selected links.

## **7. DISCUSSION**

The preliminary indications are that despite the low accuracy of cellular positioning, a probe based travel time measurement system would be able to give reasonable estimates of travel time with the proportion of probes likely to be available in the near future. Furthermore the system load needed to make the measurements is only a small proportion of the total capacity, so that it is quite possible that cellular operators might be interested in implementing the probe vehicle travel time estimation system as a secondary application, see appendix C and D.

In summary, there are strong indications of the feasibility of estimating travel time using cellular positioning systems but a field operational test, as described in section 6, is needed before a firm conclusion can be reached.

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## Appendix A: Analytical Models

### Definitions

Let  $T_i(t)$  be the actual travel time for a vehicle entering the  $i^{th}$  link at time  $t$ .

Let  $\bar{T}_i(t)$  be the historical average travel time for a vehicle entering the  $i^{th}$  link at time  $t$ .

Let  $\bar{\sigma}_i^2(t)$  be the historical variance of the travel time for a vehicle entering the  $i^{th}$  link at time  $t$ .

Let  $\hat{T}_i(t)$  be the predicted travel time based on cellular telephone position for a vehicle entering the  $i^{th}$  link at time  $t$ .

Let  $\hat{\sigma}_i^2(t)$  be the variance of  $\hat{T}_i(t)$ .

Let  $\tilde{T}_i(t)$  be the prediction for the  $i^{th}$  link at time  $t$  such that:

$$\tilde{T}_i(t) = \left\{ \begin{array}{l} \hat{T}_i(t) \text{ is the cellular information available for} \\ \text{that link at that time (or in recent times)} \\ \bar{T}_i(t) \text{ if not available.} \end{array} \right\}$$

A more sophisticated approach would blend the two estimates, perhaps based on a knowledge of the temporal correlation function.

### Efficiency of the Sampling Process

Suppose within the network there are roadway types with markedly different traffic densities (e.g. arterial, freeway, minor...). Let  $N_R$  be number of such types and  $\rho_i'$  ( $i=1, \dots, N_R$ ) be the density on the  $i^{th}$  road type. Let  $M_i$  be the number of links of each type. Let  $M$  be the total number of links,

$$M = \sum_{i=1}^{N_R} M_i$$

We assume that each link of type  $i$  has the same density,  $\rho_i'$ , so the density of the  $k^{th}$  link is given by

$$\rho_k = \rho_i' \text{ where } i \text{ is the road type of the } k^{th} \text{ link.}$$

If we take one sample, the probability of sampling the  $k^{th}$  link,  $q_k$ , is given by

$$q_k = \frac{\rho_k L}{\sum_{i=1}^{N_R} L M_i \rho_i'}$$

where  $L$  is the length of the link.



This is because  $\rho_k L$  is the expected number of vehicles on the  $k^{\text{th}}$  link and  $LM_i \rho_i$  is total number of vehicles on the  $i^{\text{th}}$  type of link. The probability of  $Q$  samples not selecting the  $k^{\text{th}}$  link is  $P_k(Q) = (1 - q_k)^Q$ .

The expected number of links not covered will be

$$F(Q) = \sum_{k=1}^M (1 - q_k)^Q$$

or  $F(Q) = M(1 - q)^Q$  if only one road type

Dividing the sum into the different types gives

$$F(Q) = \sum_{i=1}^{N_R} M_i (1 - q_i)^Q$$

where  $q_i = \frac{\rho_i L}{\sum_{i=1}^{N_R} LM_i \rho_i}$

$\bar{E}$ , the expected efficiency, i.e., the fraction of links for which there is a measurement, is given by

$$\bar{E} = \frac{M - F(Q)}{M} = 1 - \frac{F(Q)}{M}$$

Now consider  $F(Q)$  for large  $Q$ ,

$$F(Q) = \sum_{i=1}^{N_R} M_i e^{-q_i Q}$$

So, let  $N$  be total number of vehicles on the network and  $\alpha$  be fraction of vehicles that are being sampled,

$$Q = \alpha N = \alpha \left( \sum_{i=1}^{N_R} \rho_i M_i L \right), \text{ but with } q_i = \frac{\rho_i L}{\sum_{i=1}^{N_R} \rho_i M_i L}, \text{ we have } F(Q) = \sum_{i=1}^{N_R} M_i e^{-\alpha \rho_i L} \text{ and thus}$$

$$\bar{E} = 1 - \frac{\sum_{i=1}^{N_R} M_i e^{-\alpha \rho_i L}}{M} = \frac{\sum_{i=1}^{N_R} M_i}{M} - \frac{\sum_{i=1}^{N_R} M_i e^{-\alpha \rho_i L}}{M}$$

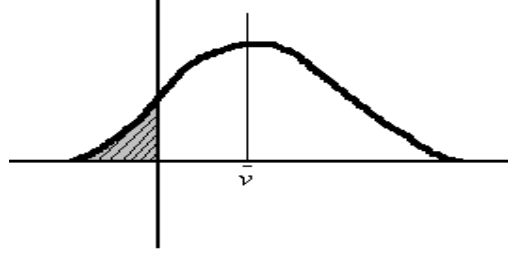
$$\bar{E} = \frac{\sum_{i=1}^{N_R} M_i (1 - e^{-\alpha \rho_i L})}{M}$$

This has the nice property that the denser the road types make an exponentially faster contribution (as a function of  $\alpha$ ). If there is just one road type,  $\rho = \rho_1 = \rho_i$ , and

$$\bar{E} = 1 - e^{-\alpha \rho L}$$

### Directional Errors

Suppose we measure velocity using  $n$  samples and calculate a mean  $\bar{v}$  and a standard deviation  $s_v$ . If the error in measuring velocity is gaussian then we can use standard sampling statistics in order to work out the probability of making a measurement that is in the wrong direction (ie of a different sign to the true mean). In this case the appropriate test is a t-test.



From the above diagram that the probability of choosing the wrong direction is given by the probability that  $t < 0$  where  $t = \frac{\bar{v}}{s_v}$  with  $n-1$  degrees of freedom.

### Effect of Wrong Calculation

Consider the standard deviation of  $\hat{T}_i(t)$  i.e. the erroneous predicted travel time for the  $i^{th}$  link, erroneous because it is actually for the  $i'$  link, i.e. the cell phone has been projected onto the wrong road and the travel time calculation is based on the data for that road. Dropping the function of time, we have

$$\sigma_i^2 = \iint p(\hat{T}_i, T_i) (\hat{T}_i - T_i)^2 d\hat{T}_i dT_i$$

Assuming the links are independent (this assumption needs further discussion) we have

$$p(\hat{T}_i, T_i) = p(\hat{T}_i) p(T_i)$$

Now we consider  $p(\hat{T}_i)$ , assuming  $\hat{T}_i = T_i + n_i$  where  $n_i$  is zero mean estimation noise on the  $i'$  link. The variance of  $n_i$  is  $\sigma_i'$ . Let

$$\begin{aligned} \sigma_i^2 &= \iint p(\hat{T}_i) \rho(T_i) (\hat{T}_i^2 - 2\hat{T}_i T_i + T_i^2) d\hat{T}_i dT_i \\ \sigma_i^2 &= \iint p(\hat{T}_i) \rho(T_i) \hat{T}_i^2 d\hat{T}_i dT_i - \iint p(\hat{T}_i) \rho(T_i) \hat{T}_i T_i d\hat{T}_i dT_i \\ &\quad + \iint p(\hat{T}_i) \rho(T_i) T_i^2 d\hat{T}_i dT_i - \iint p(\hat{T}_i) \rho(T_i) \hat{T}_i T_i d\hat{T}_i dT_i \end{aligned}$$

$$\sigma'_i =$$

$$\int p(\hat{T}_i) \hat{T}_i^2 d\hat{T}_i - \bar{T}_i \int p(\hat{T}_i) \hat{T}_i d\hat{T}_i + \int p(T_i) T_i^2 dT_i - \bar{T}_i \int p(T_i) T_i dT_i$$

Now at any one instant  $\int p(\hat{T}_i) \hat{T}_i d\hat{T}_i = T_i$  but averaged over time as well,  $\int p(\hat{T}_i) T_i d\hat{T}_i = \bar{T}_i$

Let us further assume that each link has the same mean, so  $\bar{T}_i = \bar{T}_i = \bar{T}$  then

$$\begin{aligned} \sigma'_i &= \int p(\hat{T}_i) \hat{T}_i^2 d\hat{T}_i - \bar{T}^2 + \int p(T_i) T_i^2 dT_i - \bar{T}^2 \\ &= \int p(\hat{T}_i) (\hat{T}_i - \bar{T})^2 d\hat{T}_i + \int p(T_i) (T_i - \bar{T})^2 dT_i \\ &= \bar{\sigma}^2 + \hat{\sigma}^2 + \bar{\sigma}^2 = 2\bar{\sigma}^2 + \hat{\sigma}^2 \end{aligned}$$

Provided averages are taken over time as well (This argument needs further rigorous development).

## Overall Model

Consider the Mean Square Error (MSE) of  $\tilde{T} = \tilde{\sigma}_T^2$

$$\tilde{\sigma}^2 = \mathcal{E} \left( \frac{\sum_{i=1}^M (T_i - \tilde{T}_i)^2}{M} \right) = \sum_{i=1}^{\bar{E}M} \frac{\mathcal{E} (T_i - \hat{T}_i)^2}{M} + \sum_{E=\bar{E}M}^M \frac{\mathcal{E} (T_i - \bar{T}_i)^2}{M}$$

Where M = number of links,  $\forall \bar{E} =$  Expected efficiency

$$\tilde{\sigma}^2 = \bar{E} \hat{\sigma}^2 + (1 - \bar{E}) \bar{\sigma}^2$$

If  $P$  is the probability of assigning to the wrong road then:

$$\boxed{\tilde{\sigma}_t^2 = \bar{E} \hat{\sigma}^2 (1 - P) + \bar{E} (\hat{\sigma}^2 + 2\bar{\sigma}^2) P + (1 - \bar{E}) \bar{\sigma}^2}$$

## Utilisation of Positioning Receivers

Let us make the following definitions:

$T_u =$  period of observation (s).

$Q$  = number of vehicles measured in  $T_u$  seconds.  
 $T_L$  = time to follow one vehicle along a link (s).  
 $\delta t$  = time interval between samples of vehicle position (s).  
 $N_L$  = number of bits to send a locus measurement.  
 $T_m$  = time to make a locus measurement.  
 $N_B$  = average number of basestations to make a position measurement.  
 $N_P$  = number of positioning receivers.

From these definitions we can establish the following relationships:

$$\text{Number of position measurements per second} = \frac{QT_L}{T_u \delta t}$$

$$\text{Number of locus measurements per second} = \frac{QT_L N_B}{T_u \delta t}$$

$$\text{System load} = \frac{QT_L N_B T_m}{T_u \delta t}$$

$$\text{Average Utilisation} = \frac{QT_L N_B T_m}{T_u \delta t N_P}$$

$$\text{Average Communications Load} = \frac{QT_L N_B N_L}{T_u \delta t N_P}$$

## Appendix B: Results from Analytical Models

Average link length	1.5	km	L
density of traffic per unit length	100	km <sup>(-1)</sup>	rho
Fraction of vehicles sampled	0.05		alpha
Total road length	1000	km	R
<b>Efficiency</b>	<b>0.9994</b>		
Average speed	50	km/hr	
Average travel time on link	108	s	T_l
Time between samples	10	s	delta t
number of samples	10		n
standard deviation of position measure	125	m	sigma
<b>volume</b>	<b>5000</b>	<b>vehicle/hr</b>	
<b>standard deviation of speed</b>	<b>4.9295</b>	<b>km/hr</b>	<b>sigma_v</b>
<b>standard deviation of travel time</b>	<b>10.648</b>	<b>s</b>	<b>sigma_h at</b>
standard deviation of mean travel time	108	s	sigma_bar r
Distance between roads	0.25	km	a
<b>variate</b>	<b>-3.162</b>		
<b>probability of assignment to wrong road</b>	<b>0.0008</b>		<b>beta</b>
<b>Overall Standard Deviation of travel time</b>	<b>11.748</b>	<b>s</b>	<b>sigma_T</b>
<b>Improvement</b>	<b>9.1931</b>		
Time between updates	900	s	T_u
<b>Number of vehicles monitored in T_u secs</b>	<b>5000</b>		<b>Q</b>
<b>No of position measurements per sec</b>	<b>60</b>	<b>s<sup>(-1)</sup></b>	
No of basestations per position measurement	3		N_B
<b>No of locus measurements per sec</b>	<b>180</b>	<b>s<sup>(-1)</sup></b>	
Time to make a locus measurement	0.1	s	T_m
Load to make locus measurements	18		
No of positioning receivers in area of interest	400		
Average Utilization of basestations	0.045		U_B
Bits per measurement	500	bits	B_m
Average comms traffic per basestation	225	bits/s	

## Appendix C: Notes on an experimental design for a possible test of cell-phones-as-probes on I-80

### Freeway network

#### **Loops vs. probes**

Following a discussion with Ben Coifman and with Randall Cayford it seems that the Berkeley Highway Lab could provide ground true data of average speed and travel time on the piece of instrumented highway between Powell St and Gilman street ((2.7 miles). Some data will be missing between Ashby Av and Powell st because the station at Powell is not wired . We would have to get an approximation for the remaining 600 feet, deducted from the rest of the link. Randall thinks it is reasonable.

It is proposed to get data for a series of 12 consecutive minutes periods divided in 4 subperiods of 3 minutes. Roughly, a 3 minute period corresponds to the time necessary to cross the link in a free flowing condition (55 miles an hour).

The data could be collected from 6 am to 9 pm during 3 weeks, e.g. 21 days

The travel times will be given over a 12 minute time frame. This is our refreshment period, e.g. "the average travel time on the I80 link between Powel and Gilman is let's say 4 minutes and 20 seconds on Monday March 3 between 8 and 8:12 am".....

We will also consider the average speed between 8:00 and 8:03, 8:03 and 8:06, 8:06 and 8:09, 8:09 and 8:12. We will compare average speed from loops and cell phones over the same periods (paired matched periods)

6 ↔ 7 am → 12 minutes, 4 subperiods to test  
7 ↔ 8 am → 12 minutes, 4 subperiods to test  
8 ↔ 9 am → 12 minutes, 4 subperiods to test  
9 ↔ 10 am → 12 minutes, 4 subperiods to test  
10↔ 11 am → 12 minutes, 4 subperiods to test  
11↔ 12 am → 12 minutes, 4 subperiods to test  
12↔ 1 pm → 12 minutes, 4 subperiods to test  
1 ↔ 2 pm → 12 minutes, 4 subperiods to test  
2 ↔ 3 pm → 12 minutes, 4 subperiods to test  
3 ↔ 4 pm → 12 minutes, 4 subperiods to test  
4 ↔ 5 pm → 12 minutes, 4 subperiods to test  
5 ↔ 6 pm → 12 minutes, 4 subperiods to test  
6 ↔ 7 pm → 12 minutes, 4 subperiods to test  
7 ↔ 8 pm → 12 minutes, 4 subperiods to test  
8 ↔ 9 pm → 12 minutes, 4 subperiods to test

We will rotate the 12 minutes period each day within the hour considered e.g.; 6 to 6:12 am on the first day, then 7:12 to 7:24 and so on for the first day of the experiment ; we will start at 6:12 for the second day and so on; 6:24 am the third day and so on....

This method will allow us to obtain an optimized number of observations for each period of 12 minutes (and related subperiods of 3 minutes) on a continuum from 6 am to 9 pm for the 21 consecutive days of experiment.

The experiment represents 315 periods of 12 minutes representing 1260 subperiods of 3 minutes. Assuming a normal distribution of measured speeds during the 21 days, 1260 tests will allow us to obtain a roughly 5 % interval of confidence of the average speed for the sample of measurements representing the total flow on I 80. (under the assumptions of a average speed of 30 mph and standard deviation of 25 mph).

The measurements of travel time by the observed loops on the 2.7 miles I 80 stretch and the 3 associated freeway links ( 4 exits) will be compared by pair of observations to the observed probe travel times over the same periods and subperiods of time. The output would be the comparisons of means for the two methods of measurements and their statistically significant correlation. The method allows to measure the association over 1260 paired-matches measurements. The calculation would concern East bound and Westbound traffic.

#### **cameras**

It is possible to control at random or over the entire period of the experiment the accuracy of the speed data observed from loop data by using the already installed cameras. The entire three weeks of experiment represent 1260 x 3 minutes of observation, e.g. 63 hours of images to check, e.g. about 3 hours of work per day over a month period for each traffic direction.

#### **GPS**

A number of trips can be done on the same network with GPS equipped cars, along the same period of time. 21 trips per day, 315 in total and for each direction would have to be done to match each period of 12 minutes.

#### Arterial

A 1.7 mile stretch of an arterial road on University between 6<sup>th</sup> St and Oxford St can be evaluated with a different manner; In the absence of loop one can suggest to compare the phone probes measurement to travel times observed from trips made by paid drivers on the segment in both direction. At least, 315 trips would have to be done in each direction over the 21 days period to match each period of 12 minutes. May be a solution can be found to lower this requirement figure by taking into account the phasing signal period during non peak hours as an estimate of travel time. The 630 trips would represent about 36 hours of driving.

#### Institutional aspects to consider along any field operational test

The cellular model (not yet applied) where the cellular carrier is the main source of data collection for the Dot has to be estimated along the testing phase of the technology. This model aims to bring the carriers and the telecom players as global partners of the DoTs in order to replace as much as possible traditional high cost of deployment and maintenance of traffic data acquisition from road based infrastructure by wireless technologies; the technologies would be deployed and maintained by Cellular operators. As quoted from By Oliver Yandle, ITS America,

"...The proliferation of wireless technology across the United States is providing ITS with an enormously valuable tool to improve transportation. More than 74 million Americans now carry mobile wireless phones. Telecommunications experts expect that number to double over the next several years. This instant access to communication is enabling transportation managers and service providers to provide real time travel information and speed emergency assistance to those in need....".

The cellular positioning technology will not replace all other existing sources of collecting the data. The experiment test on cell-phones-as-probes that we could conduct with the Berkeley Highway Lab could give us a good estimate of the cost figures to run such services. The region of L.A can also be considered as a potential zone for testing and deploying such technologies. One could try to optimize the parameters of road network segments which have to be covered, time period of collecting the data (peak, off peak periods), telecom network capacity and cost of operating in order to get an optimum usage of the cell phone positioning technologies along with other sources of data collections.

In the longer term one can think that GPS capabilities can be added to existing phones on a large market segment. This can lower the operating costs of obtaining the travel times from the cell phones positioning techniques and could allow us to obtain a better land coverage for the same cost. The benefits due to technology developments will be transferred to better land coverage on major road network of urban and rural environments in California. See chart below, appendix D, for the strategic deployment and the potential role of PATH in such testing phases.



## Appendix D: Long Term Vision Plan for Cell Phone Technology Applied to Travel Time Estimates

