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VII California: Development and Deployment Proof of Concept and Group-Enabled Mobility and Safety (GEMS)

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Final Report for Task Order 6217

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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

VII California: *Development and Deployment Proof of Concept and Group-Enabled Mobility and Safety (GEMS)*

Task Order 6217

FINAL REPORT

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Executive Summary

This PATH Research Report covers the (Vehicle-Infrastructure Integration) VII California Development and Deployment (Task Order 6217) efforts beginning in 2008 and concluding June 30, 2009. This is a successor to the report for TO 5217 and reports the applications-oriented research subsequent to that work.

The report is organized by a synopsis of the background and reasons for the VII California project, then it summarizes some of the antecedent (TO 5217) work: the "Innovative Mobility Showcase" (2005), which established the architecture and, importantly the applications (curve overspeed warning, probe messaging)) and the underlying testbed and enablers (High Accuracy National Differential GPS).

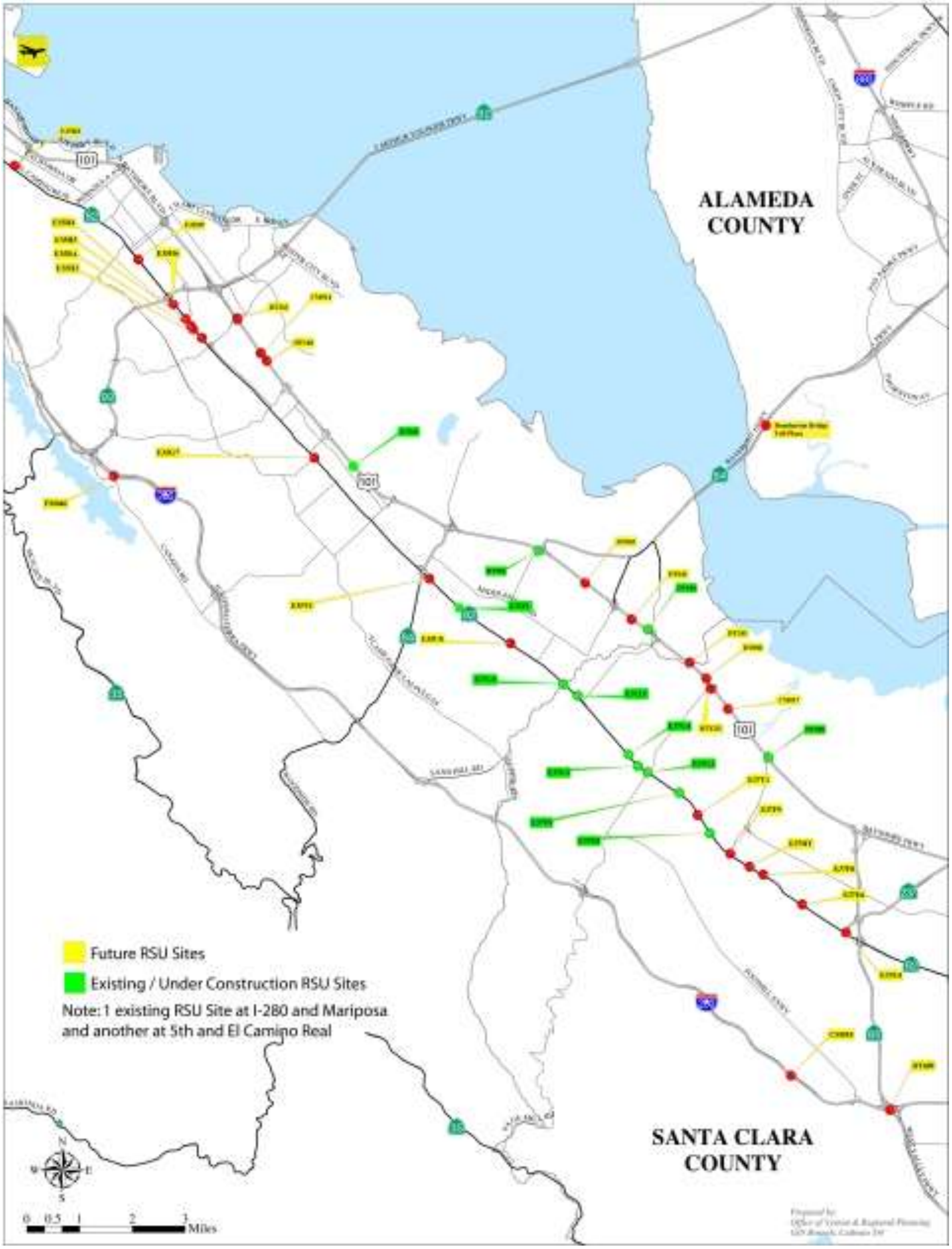
Let us begin with the question, "Why VII California was implemented?" It is important to begin with an understanding of a significant impetus: the national VII "movement". The VII system in the United States would be enabled by roadside wireless hotspots generated by Dedicated Short Range Communication (DSRC) transceivers operating within 75 MHz of free, FCC-licensed bandwidth near 5.9 GHz. These transceivers are incorporated in Roadside Equipment (RSE), which are connected by edge backhaul communications into a network architecture that addresses security, privacy and other design considerations (FHWA, 2005). Applications, standards and architecture are under active development. The goal of these efforts is a roadside-based network delivering low-latency, highly reliable data communications to support safety and mobility services to users. The coverage would be extensive: the proposed VII system has the potential to cover all urban roads within 2-minute travel times, 70% of all signalized intersections in 454 urban areas and up to 15 new million vehicles per year would be DSRC- and therefore VII-equipped (Cops, 2006).

The VII initiative is intended to lead to nationwide deployment of cooperating vehicle and infrastructure devices, producing an integrated transportation data network of unprecedented scope and complexity. The fully deployed system would include onboard equipment (OBE) installed on new vehicle manufactured after a specified date and roadside equipment (RSE) installed at all signalized intersections in major urban areas, at primary intersections in other areas, at all highway interchanges and along major intercity and many rural highways (representing about 240,000 RSE locations nationwide). This network would make it possible to collect transportation operations data of great breadth and depth, to implement sophisticated traffic safety systems, and to manage traffic flows with previously unthinkable precision.

To assess the feasibility and desirability of VII, many technical, economic and institutional questions need to be answered. Considering the magnitude of the commitments that was needed by a wide range of public and private sector organizations in order for VII to be deployed, these questions must be answered very convincingly before deployment can proceed. The process of developing the answers is just beginning, and is likely to require considerable time and effort.

Lessons for deployment might be learned from regional efforts, notably in Florida, Michigan and California (Florida DOT, 2004, Michigan DOT, 2007, Misener and Shladover, 2006) and most certainly in the forthcoming US DOT VII Proof of Concept experiments (Henry, 2007). Certainly, California is at the nexus of VII need and innovation. The same reasons to create a national VII program are acutely recognized in California: an obligation to better manage the safety and productivity of our highway system, and the understanding that a fusion of public, automotive and other private sector innovations can make this a reality.

However, California and regional stakeholders have specific transportation infrastructure, operating policies and needs than what may be universally addressed with a national VII program. These needs have led to a partnership between Caltrans and the San Francisco Bay Area Metropolitan Transportation Commission. Caltrans and MTC are addressing these needs with a multiyear effort to develop, demonstrate and deploy VII in a key corridor in Northern California. This corridor is comprised of roughly ten-mile segments of two routes North of Palo Alto and South of the San Francisco Airport. It encompasses two highways: State Route 82 and US 101. We note that this selection addresses both a high-volume freeway (US 101) and a major arterial complete with signalized intersections (SR 82), shown below:



A Map of the VII California Network (November, 2007)

Overall, Caltrans and MTC aimed to:

- Evaluate exemplar public use cases from which we can generalize VII feasibility;

- Evaluate institutional, policy and public benefit issues;
- Explore wireless communication deployment issues and options;
- Resolve key technical issues involving implementation and operation;
- Assess implementations of the VII infrastructure, architecture and operations; and
- Support private sector evaluation interests.

In support of *VII California*, PATH has conducted this project, VII California Development and Demonstration Deployment (VIIC D^3 or simply D^3) where the testbed was built and operated and where deployment and applications issues are investigated. Why? Because some of the technical questions can be addressed through analysis and simulation studies, while others need field testing under realistic conditions. Some of the most challenging questions, which will require the largest investments of time and effort, involve the scalability of system performance in advancing from small numbers of OBEs and RSEs to large numbers of OBEs for each RSE and then to large numbers of RSEs as well. Other questions involve the practical aspects of implementing RSEs in the real world of roadway operations, which can only be answered by starting to install and operate those RSEs and learning about the physical and institutional constraints, the failure modes and the maintenance needs that are encountered there. These have important ramifications for the design of the VII technology and for the long-term costs of deploying, operating and maintaining it in the field.

The Curve Overspeed Warning System (COWS) is one of the two cooperative active safety applications of VII California. (The other such time-critical safety of life applications that requires low latency, highly reliable and available vehicle-to-infrastructure and infrastructure-to-vehicle communication is Cooperative Intersection Collision Avoidance Systems (CICAS), not covered in this report.) The COWS system is aimed to integrate on-board sensors, digital map, GPS and the broadcasted information from the RSE to predict safety speed and provide speed advisory or warning messages to the driver.

To gain general applicability on production vehicles, the current system design adopted in this project utilizes a minimum set of common mobile sensors to achieve the required COWS functionalities. The prototype components include wheel speed sensors, yaw rate sensor, GPS with/without differential correction and a digital map. These four items would be coupled with a processor, communication devices, and a human-machine interface. The current research in VII California follows five main objectives:

1. Improve the integration of a digital map, GPS and mobile sensors for the COWS application
2. Conduct map-based road modeling for real-time road geometry estimation and prediction
3. Conduct dynamic lane-level vehicle positioning and detection with digital map and GPS or DGPS
4. Enhance map update by vehicle-infrastructure (V-I) communication
5. Enhance cooperative safety with V-I communication by estimating road surface condition and providing dynamic information to RSE

The California PATH program and Caltrans have a number of research applications that can benefit from a high-accuracy vehicle positioning implementation. The U.S. Department of

Transportation and U.S. Coast Guard in conjunction with the Interagency GPS Executive Board are currently developing a High Accuracy-Nationwide Differential Global Positioning System (HA-NDGPS), targeted at a variety of transportation-related applications. The HA-NDGPS program provides the capability to broadcast corrections to the Global Positioning System (GPS) over long ranges to achieve accuracy better than 10 centimeters (95 percent of the time) throughout the coverage area. HA-NDGPS is currently undergoing a research and development phase with a future implementation pending U.S. congressional budget approvals. Application of this technology will provide advanced safety features for transportation, including applications such as lane departure warning, intersection collision warnings, and railroad track defect alerts.

The VII California Program has established a testbed in the San Francisco Bay area that is being utilized for a variety of experiments. With the integration of vehicle and roadside communications (DSRC), the determination of vehicle location has become a critical component for several VII applications. One of the key objectives of this study is to demonstrate that the existing VII communication infrastructure (i.e., Dedicated Short Range Communications (DSRC), roadside equipment) can be utilized where possible for broadcasting corrections to the vehicles' GPS receivers. This eliminates the need to depend on other communication methods to receive correction signals, resulting in greater control and lower costs. This architecture compliments the potential use of existing DGPS broadcast networks such as the California statewide CORS, NDGPS, and/or NGS.

The architecture of the local base station integrated with the VII communications infrastructure provides both a low-cost lane-level positioning solution with the potential to upgrade to centimeter-level accuracy using carrier phase receivers that could be installed in a subset of vehicles. The pseudorange and carrier phase corrections could both be broadcast over the RSE DSRC transceivers or through an alternative wireless network. While this integrated approach has not been developed commercially, the methodology and experimentation (described in this report) has shown to be viable through similar university research programs. Initial integration may consist of only code corrections while future implementations could add carrier phase corrections with only software changes to be made in the base station and RSE hardware.
This study has implemented the DGPS/DSRC architecture and demonstrated the feasibility of broadcasting the DGPS code corrections over the DSRC network. Initial performance evaluations were completed to demonstrate the potential performance of the architecture. While initial performance has demonstrated the architecture to be successful for lane-level positioning applications requiring differential corrections, additional enhancements would be required for deploying the architecture beyond specific testbeds, pilots, and demonstrations. These enhancements would allow for a more commercially viable solution to improving GPS positional accuracies. Several research goals were achieved with this evaluation:

- Comparison of positioning performance using NDGPS corrections transmitted via beacon and via Internet – correction quality and positional accuracy has been demonstrated to be dependent on prompt acquisition of a DGPS correction message. The DGPS signal transmission via internet has been evaluated for TCP/IP transmission with a DSRC link to the rover vehicle. Rapid and effective acquisition of a DSRC link is critical for receiving DGPS corrections within a single cell DSRC coverage area;

- Potential of transferring HA-NDGPS corrections to standard formats – this study has reviewed and evaluated the protocols, formatting, and transmission of high accuracy signals. The HA-NDGPS protocol performs a message compression/decompression sequence which does not degrade the quality of the original RTCM correction message.

- Integration potential of alternative correction signals (RTK, WAAS, CORS etc.) – tests scenarios completed within this study have demonstrated that the DSRC/Ntrip architecture is compatible with any RTCM correction messages. Receivers capable of processing multiple sources of corrections can utilize alternate corrections in addition to corrections received via DSRC/Ntrip.

- Integration of HA-NDGPS receivers within CA VII vehicles/applications – the HANDGPS protocols have been found to provide a RTCM compatible correction which is suitable for any L1/L2 receiver accepting RTCM carrier phase corrections. Specifically configured receivers are not necessary if broadcasts are transmitted via TCP/IP protocols (DSRC/Ntrip).

- Geographical distribution accuracy requirements of corrections signals (regional, intersection-only, highway-only etc) – the range and performance of a single DSRC transmission site was evaluated. Performance was found to be greatly dependent upon the rate of acquiring a DSRC communication link;

- Frequency requirements of correction signals – the frequency of transmitting a correction signal was maximized for performance within the scope of this study. Decreasing the frequency would be possible for regions of continuous or semi-continuous DSRC coverage; and,

- Compatibility of RSE/DSRC system design with correction signal size, frequency, format, and vehicle densities – the current study results did not find limitations due to DSRC communication bandwidth. DSRC communication and position quality was limited primarily by DSRC coverage area.

The next step towards a final integration would be to create compatible software that would determine availability of suitable regional corrections and autonomously initiate transfer. The current architecture requires a manual selection of DGPS base stations. This future development would focus on these following components:

- A review and collaboration with entities maintaining DGPS broadcast networks to establish agreements for automated downloads;

- Create software that evaluates current location and searches for spatial-appropriate and available correction messages;

- create software that automatically adjusts configuration settings of DGPS Ntrip communications; and

- Implement and test the automated architecture in specific VII applications.

Successful implementation of this automated DGPS acquisition architecture would greatly simplify the methodology of acquiring DGPS corrections and provide improved positioning performance of future ITS implementations.

The current phase of research on VII probe data processing has produced (and is producing) the following results:

• Implementation of the Noblis Trajectory Conversion Algorithm (TCA) program to process simulation outputs from the PATH (PTTL) VISSIM simulation of El Camino Real, following the J2735 probe sampling protocols

• Analysis of TCA outputs to identify substantial latency in probe snapshot uploads under default conditions

• Examination of changes to probe message management protocol to significantly reduce latency to support the most time-critical probe data applications

• Exploration of effects of market penetration on aggregated probe data granularity (in both time and space)

• Evaluation of effects of local aggregation (at RSE) on backhaul data rate and RSE computational burden for some representative types of probe data (weather status, dropped load, traffic speed).

This work is still scratching the surface of a substantial topic, with the potential to influence the developing SAE J2735 standard and expectations for future use of VII probe data. We have been in close contact with Noblis, who are studying the probe data processing issues for the national VII program, with substantially larger resources at their disposal, to ensure that our work remains complementary to theirs rather than duplicative. They have been focusing on detailed evaluation of the SAE J2735 protocols and sensitivity studies to evaluate the suitability of the key features of SAE J2735, with a strong emphasis on the Day One VII applications and relatively low market penetrations. We have been considering the needs of some of the longer term VII applications and market penetrations up to 100% in order to ensure that the VII probe approach is scalable to a fully mature VII system. We plan continuing consultations with the Noblis staff to maintain the complementarity of our efforts.

During the coming year, we are planning to address the following important VII probe vehicle data sampling issues:

- •Testing performance in a new urban network currently being studied by Noblis (the Van Ness corridor in San Francisco), which appears to have some advantages over our current El Camino network;
- Developing improved algorithms for estimating network speed from probe samples, since simple averaging introduces significant biases;
- Developing and evaluating semantic approaches for reducing the backhaul burden associated with probe data, complementary to the aggregation approach currently being evaluated;

- Evaluating the effect of adjusting the in-vehicle snapshot buffer size and buffer management rules based on considerations of market penetration and density of RSE installations;
- Seeking another network model that can be used for freeway probe studies, and including urban fringe areas where RSEs was sparse or non-existent;
- Investigating strategies for maximizing the effectiveness of probe data sampling at the boundaries of regions that are equipped with RSEs, so that the snapshots collected in unequipped regions are not lost unnecessarily. Other issues that could potentially overlap with Noblis' work was considered, but only explored if we can determine that Noblis is not addressing them:
- Evaluating snapshot management alternatives to make most efficient use of the available buffer;
- Increasing the snapshot buffer size, particularly under low market penetration conditions;
- Evaluating the effect of changes in the snapshot management rules on the load imposed on the DSRC wireless channel;
- Evaluating suitability of the default snapshot sampling rules under a range of traffic conditions, including heavy congestion.

Background and Introduction

This PATH Research Report is organized to impart the very specific and generally very pragmatic implementation details first, beginning with an introduction, description of VII hardware, general network and installation, then progressing to a more detailed description of the network and operating software and finally to applications in development and prospective applications. Because it is not yet a final report but rather a 'research in progress' report, it does not comprehensively address every task in the VII California family of task orders; specifically, several of the applications described in Section 4 are represented as works in progress (as they are at this writing), and the on-ramp metering study is not yet reported. Again, the purpose, of this report is to provide the reader with an understanding of how VII California was implemented.

Let us begin with the question, "Why VII California was implemented?" It is important to begin with an understanding of a significant impetus: the national VII "movement". The VII system in the United States would be enabled by roadside wireless hotspots generated by Dedicated Short Range Communication (DSRC) transceivers operating within 75 MHz of free, FCC-licensed bandwidth near 5.9 GHz. These transceivers are incorporated in Roadside Equipment (RSE), which are connected by edge backhaul communications into a network architecture that addresses security, privacy and other design considerations (FHWA, 2005). Applications, standards and architecture are under active development. The goal of these efforts is a roadside-based network delivering low-latency, highly reliable data communications to support safety and mobility services to users. The coverage would be extensive: the proposed VII system has the potential to cover all urban roads within 2-minute travel times, 70% of all signalized intersections in 454 urban areas and up to 15 new million vehicles per year would be DSRC- and therefore VII-equipped (Cops, 2006).

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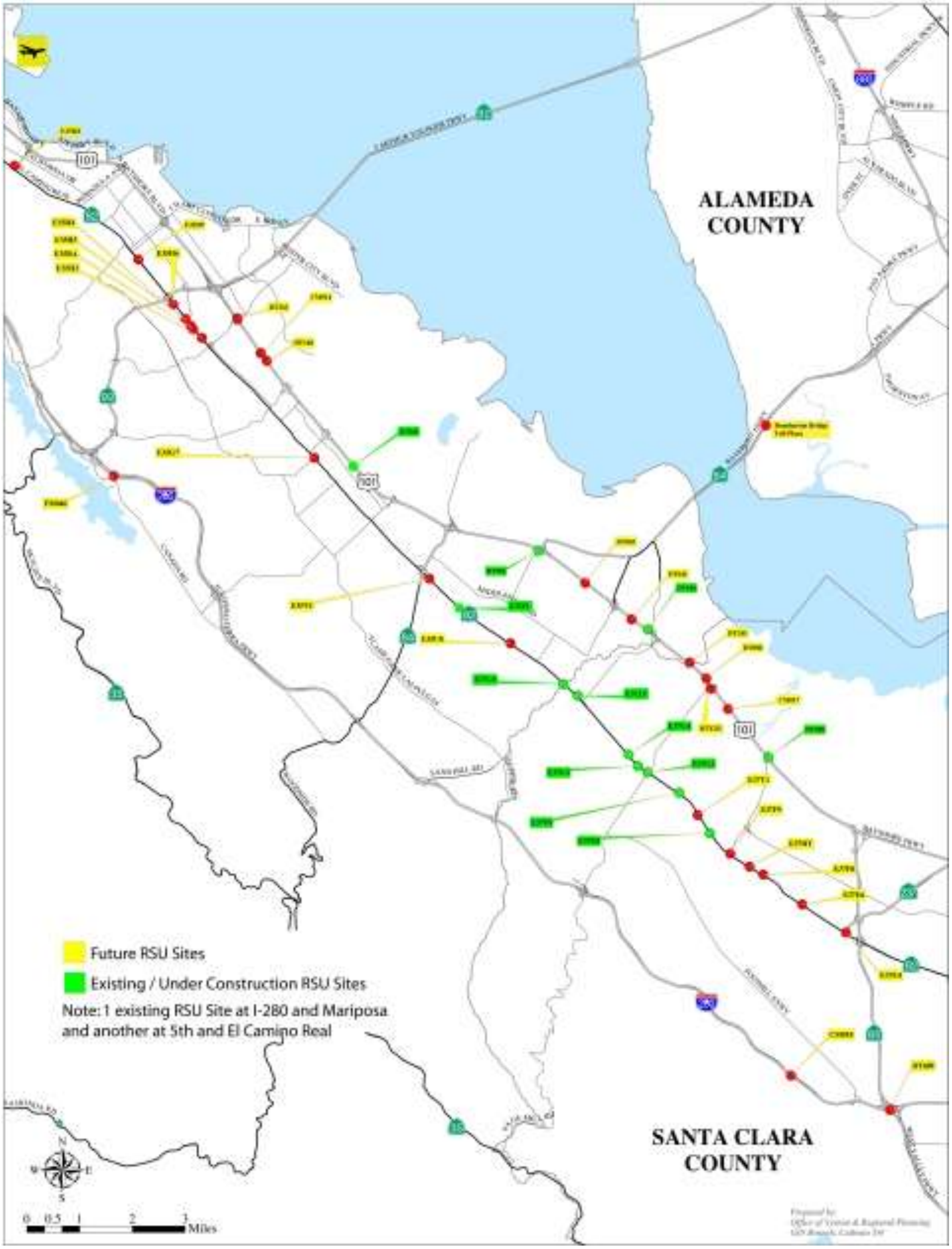

Figure 1-1: A Map of the VII California Network (November, 2007)

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This report describes the lessons learned in the all phases of the PATH effort.

Development and Deployment: Proof of Concept

1 Conduct “Innovative Mobility Showcases” Demo at the World Congress in 2005

The World Congress “Innovative Mobility Showcase (ISM)” will include a VII California demonstration of three vehicle original equipment manufacturer (OEM)-developed applications:

1) Vehicles as Traffic Probes:
Data from vehicles is sent to the central processing center and used to calculate travel times along specified link, routes, or paths.

2) Travel Time Data to Vehicles:
The central processing center sends accurate and up-to-date link travel times to the RSU and then the vehicle for use in real-time dynamic routing. The travel times was generated by the 511/TravInfo™ system.

3) In-Vehicle Signage:
Integration of roadside signage information into in-vehicle navigation system, e.g, speed limit, next exit information. Lays migration path to work zone warning.

In addition, there may be OEM applications which they choose to show to their corporate leaders: Encrypted message set specific to Original Equipment Manufacturer (OEM) requirements, passed between vehicle, RSU and OEM center.

This Task 1 provides resources for PATH to participate in the VII California IMS demonstration, to troubleshoot computer software or RSE hardware components in order to keep the aforementioned applications running, and to staff the VII California World Congress booth.

2 Develop Architecture

This task requires the TEAM to seamlessly integrate various data collection, processing components and routing features and construct traffic routing and information provision services, as illustrated in Figure 2-1. Specifically, the TEAM will work with the PATH team to provide three types of web services:

- Pre-trip and real-time routing,
- Traffic congestion along the route,
- Slow traffic ahead alert.

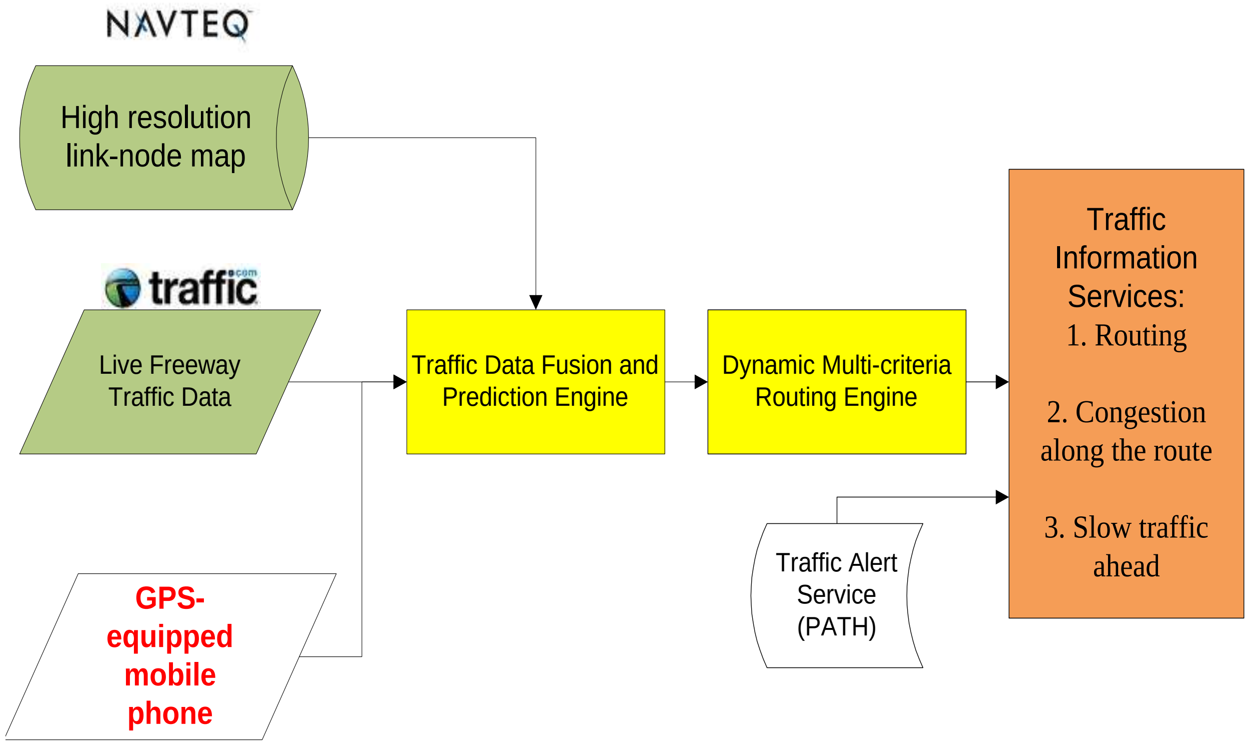


Figure 2-1: Integrated Multi-Criteria Routing Engine

3 Develop Applications

This chapter will discuss several applications that are currently being developed in association with the VII California effort. In addition, each application discussed will provide the current progress and a promising future outlook. The first section will discuss in details the Curve Overspeed Warning System (COWS), and then will proceed to discuss in details of additional applications organized in different sections including Traffic Probe Data Processing, Real-Time Arterial Performance Data, Intersection Safety, and lastly, High-Accuracy Nationwide Differential Global Positioning System (HAND-GPS).

3.1 Curve Overspeed Warning System (COWS)

The Curve Overspeed Warning System (COWS) is one of the two cooperative active safety applications of VII California. (The other such time-critical safety of life applications that requires low latency, highly reliable and available vehicle-to-infrastructure and infrastructure-to-vehicle communication is Cooperative Intersection Collision Avoidance Systems (CICAS), not covered in this report.) The COWS system is aimed to integrate on-board sensors, digital map, GPS and the broadcasted information from the RSE to predict safety speed and provide speed advisory or warning messages to the driver.

To gain general applicability on production vehicles, the current system design adopted in this project utilizes a minimum set of common mobile sensors to achieve the required COWS functionalities. The prototype components include wheel speed sensors, yaw rate sensor, GPS with/without differential correction and a digital map. These four items would be coupled with a processor, communication devices, and a human-machine interface. The current research in VII California follows five main objectives:

6. Improve the integration of a digital map, GPS and mobile sensors for the COWS application
7. Conduct map-based road modeling for real-time road geometry estimation and prediction
8. Conduct dynamic lane-level vehicle positioning and detection with digital map and GPS or DGPS
9. Enhance map update by vehicle-infrastructure (V-I) communication
10. Enhance cooperative safety with V-I communication by estimating road surface condition and providing dynamic information to RSE

This section describes the preliminary results with respect to Objectives 1 and 2 above. It details the development procedure of a new method for dynamic reconstructing of road curvatures using digital map as well as demonstrating its effective in a prototype COWS system implemented in a PATH vehicle. While digital map has been applied to many Advanced Driver Assistance System (ADAS) applications, one critical attribute – road/lane curvature is not available in the existing digital maps. Curvature derivation using *Splines* is a well-known method in the computer graphics modeling community; however it was also found that the direct application of the Spline method is often not appropriate for real-time safety applications due to the resultant discontinuities in the curvature estimates and the lack of robustness against map data errors.

This report presents a method to reconstruct road curvature attributes in real-time using existing digital map data based on the proposed Circle Center Search (CCS) and Circle Selection (CS) algorithms. Simulation and experimental results on a prototype system demonstrated that the proposed method can deliver curvature estimates that meet the desired accuracy for a typical Curve Over-Speed Warning system.

3.1.1 Introduction

In-vehicle navigation and telematics systems which utilize GPS, digital map databases and wireless communication to receive external information, are becoming popular in recent years. The increased use of the in-vehicle navigation systems has also motivated the exploration of extracting road information from the digital map databases for other in-vehicle applications. In particular, many safety-related systems are candidates benefiting from the use of digital map information. While ADAS are becoming more and more popular today, map data and positioning information of navigation systems are being developed to improve driver assistance functions, which facilitates the development of Predictive Information and Assistance functions. It is believed that there is a significant potential for the use of a digital map and the vehicle's position to predict the road geometry and to track related attributes ahead of the vehicle. Moreover, ADAS-Applications can benefit from this potential, and new functionality may likely be enabled. A curve warning system, an embodiment of this concept, based on a navigation system and enhanced by VII is one of such application example.

Nowadays many driver safety assistance and stability control systems, such as Lane Departure Warning System (LDWS), Adaptive Cruise Control (ACC), Electric Stability Program (ESP), and Active Rollover Prevention (ARP), are often equipped on modern vehicles. These systems typically react to an event that has already occurred. The idea of dynamically extracting incoming road attributes from a digital map database and treating the map as a virtual sensor, and integrating such a sensor into the vehicle positioning system in order to improve the ability of predicting an impending safety event becomes very appealing. Efforts have been made to realize this concept in the ITS industry such as in the US EDMap project and in the European IN-ARTE, NextMAP, ActMAP, and PReVENT projects.

The concept of “using the digital map as a virtual sensor” has been studied in some of the aforementioned projects in the sense of a “horizon-predictive sensor” to provide hot spot warnings to a driver; it has also been applied to enhance the GPS/INS-based positioning system for lane-identification purpose in this research project. This report presents a Curve Overspeed Warning System, which was developed under this concept. Figure 3-1 shows the block diagram of this COWS, which exploits digital map data in the following functional units: Map-Matching, Attribute Provider, Position Enhancement, and Safety Application modules.

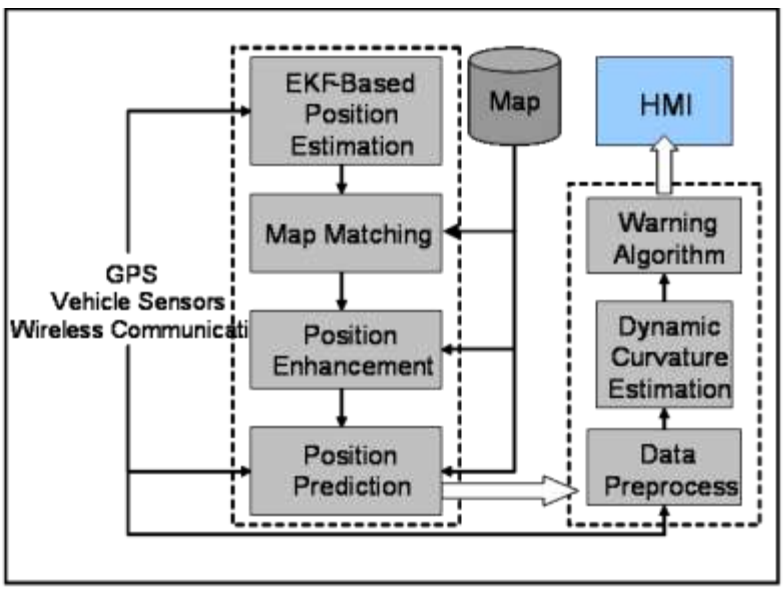


Figure 3-1: Functional Components of a COWS system

This report focuses on several prerequisites of the COWS: reconstructing dynamic road curve using digital map for Curve Speed Assistant[1] (CSA) system as well as assessing its applicability in COWS. Road or lane curvature, an important parameter for computing safe speed on a curve, is typically not available as an attribute in the existing digital maps. This attribute can be either dynamically estimated in real-time or extracted from a set of pre-processed data saved in the database. However, practical considerations, such as data storage limitation, map update frequency, accommodation of complex or dynamic road attributes (e.g. super-elevation, friction,

[1] Curve Speed Assistant includes Warning and Control functions (CSA-W and CSA-C). VII-based COWS is endeavored to be an enhanced CSA-W.

and road grade) motivate the researchers to seek out methods that provide reliable road/lane curvature estimates based on the existing digital map data. Curvature derived from splines was used in EDMap project, however, it was concluded that "systematic problems" exist that prevent the curve warning application from directly using curvature derived from the splines," and "more work must be done to improve the methods used for representing curvature to enable the curve warning functionality." To provide more accurate real-time curvature estimates, a new approach based on locating the centers of curve sections, a Circle Center Search (CCS) algorithm, was developed and validated through simulations and experiments. The resultant curvature estimate errors, varying from 5% to 10% depending on the map data accuracy, meets curvature accuracy requirements (10% for CSA-W and 5% for CSA-C) suggested by CAMP.

The outlines of this report are as follows. Section 3.1.2 describes typical map-based ADAS systems, in particular the COWS, as well as the framework of an enhanced ADAS system using vehicle infrastructure integration. Section 3.1.5 proposes a new method for curvature estimation based on the existing digital map and addresses the related design issues. Comparisons between the conventional spline approach and the proposed method are also provided. Section 3.1.8 shows the preliminary experimental results conducted at the Richmond Field Station for a prototype Curve Overspeed Warning System using a PATH vehicle. Conclusions are made in Section 3.1.9.

3.1.2 Digital Map as a Virtual Sensor for Advanced Driver Assistance System

3.1.2.1 <u>Overview of Digital Map and ADAS</u>

Over the years, the specifications of a digital map have gradually evolved to fulfill the requirements of various emerging in-vehicle applications, such as GPS-based navigations and ADAS applications. A typical digital map is a geographical database containing road geometrical and attributive data. Based on a specific road network model, the geometric relationship and road features can be described based on certain rules. Geographic Data File (GDF) map is currently an international ISO standard for navigation maps. It is both a data model and an exchange format for digital maps that can accommodate different map contents and data formats defined by individual map makers. Hence, different navigation systems can interpret all digital maps following this standard.

A modern navigation system typically has two main components: a map database and a GPS-based positioning unit that can be integrated with "dead reckoning" sensors such as gyroscope and odometer. The calculated vehicle position can be "projected" to the most likely point on the map and be associated with a road segment. Through this "map-matching" technique, the relevant road attributes and information can be extracted from the database. Given the destination provided by the driver and the continuously updated actual positions, the navigation system guides a driver to his destination through the best route.

In contrast to the relatively simple structure of a navigation system, ADAS applications often require two additional subsystems, ADAS Horizon Provider (AHP) and ADAS Horizon Reconstructor (AHR), to extract and process data for the ADAS computation. The processed ADAS specific map data (in both of geometrical and attributive contents) is called the ADAS horizon (AH), which is the extracted map data around the current position as well as in the "look-forward" direction. The "low-level" data extraction and aggregation into AH (2D) is executed by AHP based on the map-matched position received from the positioning unit. AHR receives AH (2D) from AHP and transmits only the incremental updates of AH (1D) to the ADAS application, i.e. AHR functions as a "filter" to accommodate bandwidth constraints in the application side. This interface between AHR and the application is referred to as the "high-level interface" since it can be developed as an internal API of an application.

Note that the correctness of the AHP and AHR functions hinges on accurate map-matched positions, especially for the high-accuracy ADAS applications such as Lane Following Assistant, Forward Collision Warning, and Curve Speed Warning or Control. Both the vehicle positioning system and the digital map may need to be enhanced for such ADAS applications. In addition to accuracy, the map database needs to be updated frequently to guarantee reliable up-to-date road information. As a consequence, an easily accessible and cost-effective map updating method needs to be provided for maintaining such map-based ADAS applications. VII is one such application candidate and its concept of operation is described below.

3.1.2.2 Architecture and Advantages of the ADAS and COWS Enhanced by VII

Figure 3-2 shows the main components of this new ADAS system enhanced by the vehicle and infrastructure integration in this report. This system integrates (D)GPS, vehicular sensors, wireless communication (e.g. Dedicated Short Range Communication: DSRC), and digital application map to perform safety-related applications such as curve overspeed warning, stop sign warning and junction/intersection speed warning. The application map is developed based on the commercial GDF map provided by NAVTEQ. Since most current digital maps are "road-level" maps, detailed road/lane attributes, such as number of lane, lane width, and stop sign location, are not available but are required for many safety applications. Therefore, this application map was generated by extracting relevant road geometrical and attributive information from the existing GDF map and adding the aforementioned detailed attributes to the new database.

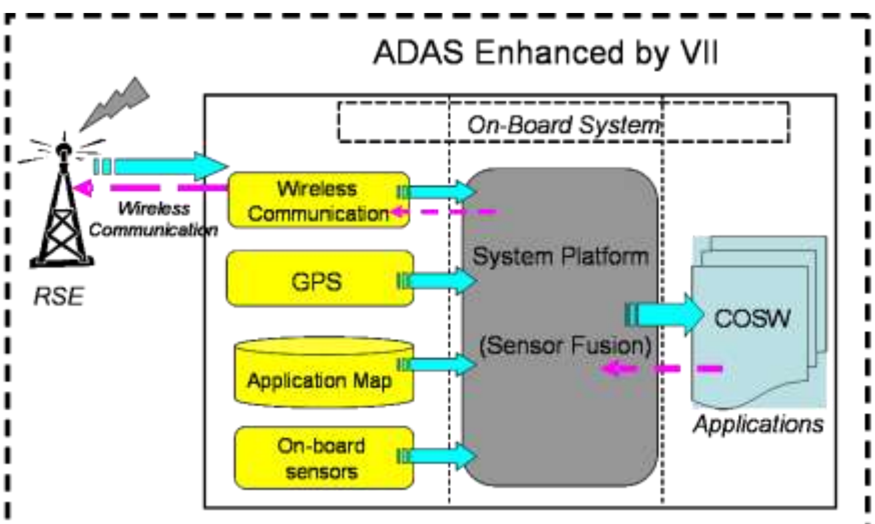


Figure 3-2: Concept of ADAS Enhanced by VII

The on-board system platform consists of the following functional modules: EKF-based GPS/INS positioning unit, Map-Matching processor, Attribute Provider, Position Enhancement unit, Safety Application module, and the Wireless Communication unit. The advantages of this system design are described as follows.

The system can not only operate in a stand-alone fashion using on-board sensors and digital map, but it can also operate in a cooperative enhancement manner through VII. When there are RSE) nearby, the equipped vehicle can exchange data with RSE via V-I wireless communication, e.g. DSRC. Detailed or dynamic road attributes such as super-elevation, grade, friction, traffic signal at ramp end (metering) etc., as well as event-based messages such as traffic accident, lane closures, detour, or construction zone, can be transmitted from the RSE to the vehicle. In addition, it is possible to provide GPS correction signal and map update service to the on-board system through VII. On the other hand, the equipped vehicle can transmit detected or computed data such as speed advisory, air bag activation and ABS activation, to the RSE, so that RSE can inform other nearby drivers of an incident ahead.

The system also employs a positioning enhancement unit to improve the map-matched position for lane identification using a “road-level” positioning unit. As opposed to the “lane-level” vehicle-map positioning system, which relies on measurements from the lane-level positioning unit, the proposed system has advantages in terms of robustness and cost-effectiveness.

The current and future road/lane curvature can be estimated in real-time based on the road “node” positions, and lane attributes, i.e. lane width and number of lane. The details was described in the next section.

3.1.3 Dynamic Road/Lane Curve Reconstruction Using Digital Map Data

This section focuses on one technical issue regarding road/lane curvature estimation using map data in certain specific ADAS applications such as Curve Over-Speed Warning: estimating in real time the radius of curvature, curvature direction, and the position of the curvature center. More complex road attributes such as super-elevation, grade and side friction, are expected to be taken into account for further curvature refinement[2].

Since the road or lane curvature is not an available attribute in the existing commercial digital map, this important attribute should either be estimated in real-time, or be created off-line and saved in advance before operation. However, if a reliable method utilizing the existing map data can be developed to estimate the road/lane curvature in real-time, significant data storage space can be saved.

The following sub-sections first explain the feasibility of the curvature derivation based on splines, a well-known mathematical tool in the computer graphics modeling community. Then a nonlinear filtering approach using CCS and CS algorithms was proposed and compared with the splines approach.

[2] In this report, those complex road attributes are not taken into consideration for curvature estimation.

3.1.4 Conventional Approach ─ Spline

Spline is a common tool for road geometry representation. A spline typically refers to a wide range of functions defined piecewise by polynomials that are used in applications requiring data interpolation and/or smoothing. Using the spline format, it is possible to interpolate road position coordinates at any point along the spline based on the discrete map positions called nodes. Road attributes, such as headings, tangents, and curvatures can also be derived using the resulting splines. It is therefore possible to deliver the road geometry information to the ADAS applications in the spline format. However, curvatures derived from splines may not be directly used by the ADAS applications as found in CAMP.

As shown in Figure 3-3, the curve represents the road center line of an exit ramp from northbound highway I-580 to Bayview Avenue. It is constructed by the cubic b-spline based on the “node” positions. This curve seems to be well-described by the spline function, y = f(x). One can derive the road curvature by the following formula using this spline function: $K(x) = \frac{1}{R(x)} = \frac{\left|\frac{d^2y}{dx^2}\right|}{\left[1+(\frac{dy}{dx})^2\right]^{3/2}}$ where K(x) and R(x) are the resulting curvature and radius, respectively. Figure 3-3(b) shows the estimates of the curvature radius by this approach.

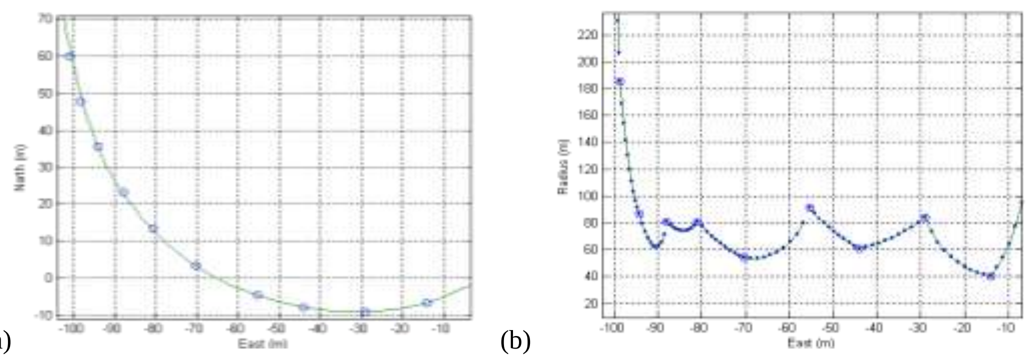


Figure 3-3: (a) Road curve fitted by splines (b) Radius of curvature derived from splines

Two main problems can be observed from this example. First, errors of the curvature estimates at the curve ends are large, which is due to the insufficient positional constraints. This type of errors would appear frequently especially when such data are delivered by the “incremental” AH. Second, the variance of curvature estimates is also large, and it can be detrimental to the performance of CSA as it may cause large undulation in the resultant safety speeds.

In addition, curve-fitting by splines cannot guarantee “robustness” against the positioning inaccuracy because of its intrinsic property. Unfortunately, the map data has relatively high positional inaccuracy due to the sensor noise and the accumulated errors in the repositioning process. Road information derived from splines may be mathematically correct but not necessarily physically justified.

3.1.5 New Approach ─ Data Pre-filtering and Parametric Curve Fitting

The new approach presented in this report includes two parts: data pre-filtering and parametric curve fitting. As discussed in the last section, curvature derivation from splines, a non-parametric cure-fitting approach, may not be able to be directly used by the ADAS applications. The main difficulty lies in the discontinuity and high variance in the curvature estimates. Although a possible remedy to the variance problem is adding some sort of filtering to the estimates from splines, the discontinuity in the curvature estimates would be more difficult to resolve in that the discontinuity could be a real road feature or it could be a result of positional inaccuracy. While an arbitrary filtering process may lead to missed detection of a curve, an un-filtered discontinuity due to "noise" could also cause false detection.

The above two problems raise some fundamental questions: "Is a non-parametric curve-fitting method effective for curvature derivation?" And "Is it possible that the shape of a road can be modeled in such a way that the resultant road curvature can be correctly estimated in a piece-by-piece fashion using this specific model assumption?" In addition, for time-critical applications, computation efficiency is another important issue. Considering all the above factors, a parametric curve-fitting approach that captures the "dynamics" of road curvature as well as rejects the "noise" from the road data is explored.

Figure 3-4 depicts the concept of this new approach. As shown in this figure, a vehicle is traversing a curve with speed V (at C.G.). This curve consists of several nodes, N1, N2 and N3, recorded in the digital map. For simplicity, the steady state curvature is of our interests, i.e. R1=R2=R3, C is the center of curvature, and R_v represents the turning radius of the vehicle. Assuming further that this vehicle is in quasi steady state, namely, the magnitude of V is constant and the center of turning radius ideally matches the center of road curvature C. Therefore, one can easily computed the radius of road curvature and curvature center based on the node positions N1, N2 and N3 regardless of positional inaccuracy. The safety speed can then be predicted based on the estimated curvature and the desired lateral acceleration before entering this curve.

As a matter of fact, drivers normally approximate the road curvature ahead based on the visible lane stripes and regulate the vehicle trajectory accordingly. The main idea of this new approach is to model the road shape from a driver's perspective. Since a vehicle at a fixed steering angle and constant speed follows a constant arc, a road curve can then be consisted of one or several arcs, and each arc (a portion of the circumference of a circle) has a constant curvature. For a straight road, the arc has an infinity radius of curvature. If the curvature of each arc can be identified, for example, by fitting the circle function as in Equation (1), to the node positions of arc, the road curvatures can then be obtained piece by piece. Hence, the road curvature estimation is rendered to be a "circle search" problem, which is realized by the Circle Center Search algorithm presented below in Figure 3-4.

However, position inaccuracy may still impede the direct use of the curvature estimates by the CCS algorithm. Therefore, the CCS algorithm is used together with the Circle Selection algorithm for data pre-filtering, i.e. curve-detection and curve-point selection. Based on the preliminary curvature estimates including curvature centers and radii of curvatures, a parametric curve fitting is employed to optimize the curvature estimates using a circle function. Figure 3-5 shows the overall processes of the proposed curve reconstruction method.

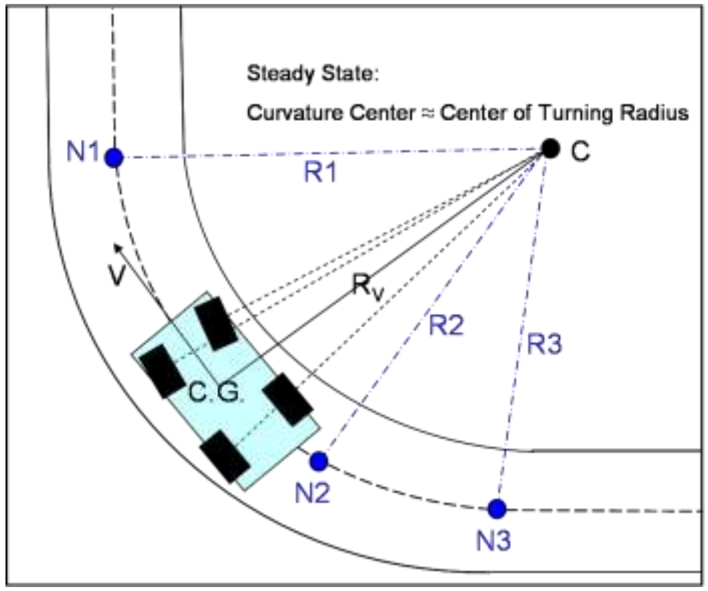


Figure 3-4: Concept of Circle Center Search algorithm

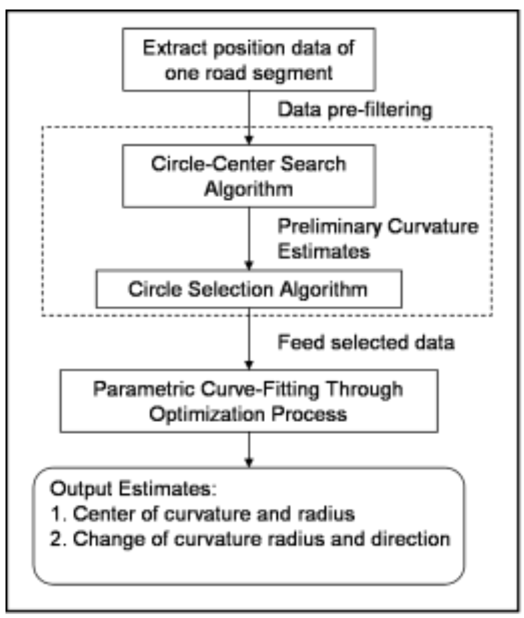


Figure 3-5: Proposed road curve reconstruction method

3.1.6 Data Pre-Filtering by Circle Center Search (CCS) and Circle Selection (CS) Algorithms

Figure 3-6 shows the satellite picture (from Google map) of the ramp. This curve can be roughly divided into two arcs with different radii of curvatures. The radius of initial portion is around 63 meters, and the curvature radii of the latter portion are greater than 90 meters. Figure 3-7(a) shows the preliminary curvature estimates by CCS algorithm. Blue stars are the so-called "node" data in a commercial digital map, and they are located on the road center line. The first node at entrance is circled in read. Red stars are the preliminary curvature center estimates, and each one is computed based on three consecutive nodes. The resultant estimates of curvature radii are shown in Figure 3-7(b).

Several interesting phenomena can be observed from Figure 3-7(a) and Figure 3-7(b): (1) the first six curvature center estimates are distributed in a relatively small region, i.e. they appear to converge to the true curvature center, (2) the last six curvature center estimates appear to diverge from the average position of the first six ones, (3) the first six curvature radius estimates vary around the average value of 65 meters within the 10 meter bound, (4) the seventh to ninth radius estimates appear to have a different average value of 95 meters, and (5) the radius estimates jump from 96 meters to 136 meters in the last portion. (Note that the last three radii are identical due to using the same three nodes in CCS computation. If the nodes of the straight road in connection with the curve end are used, the curvature radius estimates will diverge.)

In this example, the whole ramp can be divided into two parts. The first curve consists of the first to the sixth nodes, and the second curve is between the sixth and the last nodes. Since the ramp end is connected to a straight road, curvature of the second curve is not stationary. However, the errors appear to be within an acceptable range for application use after further process by parametric curve fitting discussed below.

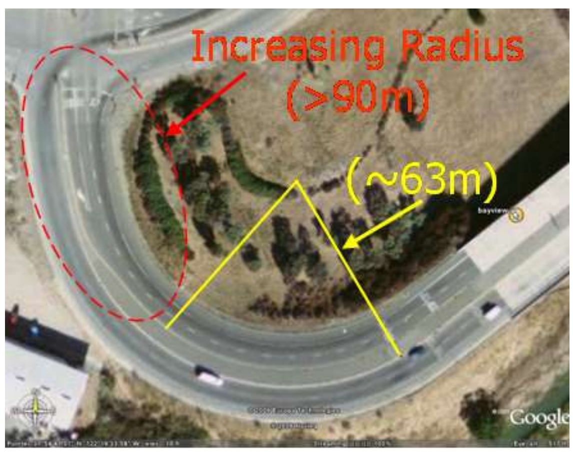
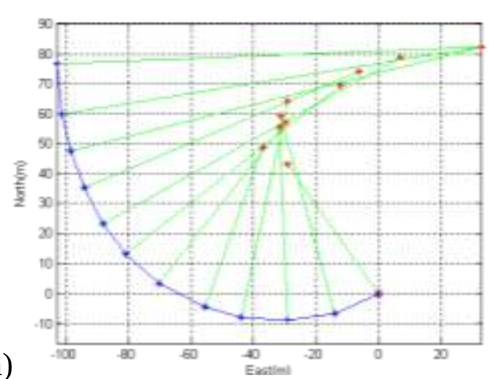


Figure 3-6: Exit ramp from northbound I-580 to Bayview Ave. (Google Map)

(a) 

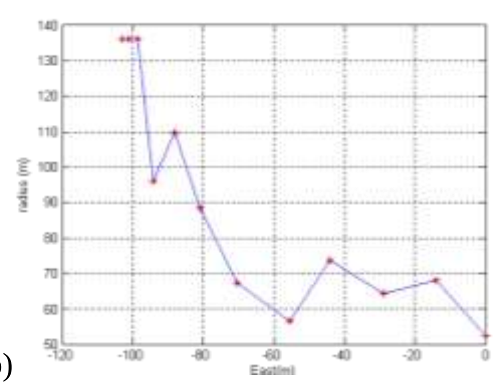
(b) 

Figure 3-7: (a) Preliminary Curvature Estimates by CCS Algorithm (b) Preliminary Estimates of Curvature Radii by CCS Algorithm

The main idea of Circle Selection algorithm is to group proper nodes based on the preliminary curvature radius estimates by CCS algorithm. By detecting relative large difference between two consecutive radius estimates, a discontinuity of road curvature and the connection node between two curves can be identified. The thresholds for detecting curvature discontinuity can be defined in terms of absolute radius difference or relative radius difference depending on (1) the desired sensitivity determined by the application need and (2) the map quality in terms of "relative accuracy" as well as the number of nodes on a curve. In general, thresholds defined in terms of "relative difference" can better fit high sensitivity demanding application using high quality map.

In summary, the CCS and CS algorithms function as a nonlinear filter, which can be used to detect a road curve and distinguish road curvature differences. However, for more accurate curvature estimates, further parametric curve-fitting is required as described below.

3.1.7 Parametric Curve-Fitting

Based on the previous data pre-filtering results, the selected node positions (x_i,y_i), i = 1~n, of each portion of curve are used in the curve-fitting. The objective function *J* for the curve-fitting is defined in Equation (1):

$$J = \sqrt{(x-x_0)^2 + (y-y_0)^2 - R^2} \qquad (1)$$

By minimizing this objective function using (x_i,y_i), the position of curvature center (x_0,y_0) and radius of curvature *R* can be estimated.

Figure 3-8(a) shows the optimized curvature estimates for the ramp. It shows clearly that this ramp can be divided into two curves as suggested earlier in Figure 3-8. Although the last node, which is a connection point with a straight road, is taken for the second curve-fitting, it does not noticeably affect the fitting result. The enhanced curve radius estimates are quite accurate as shown in Figure 3-8(b).

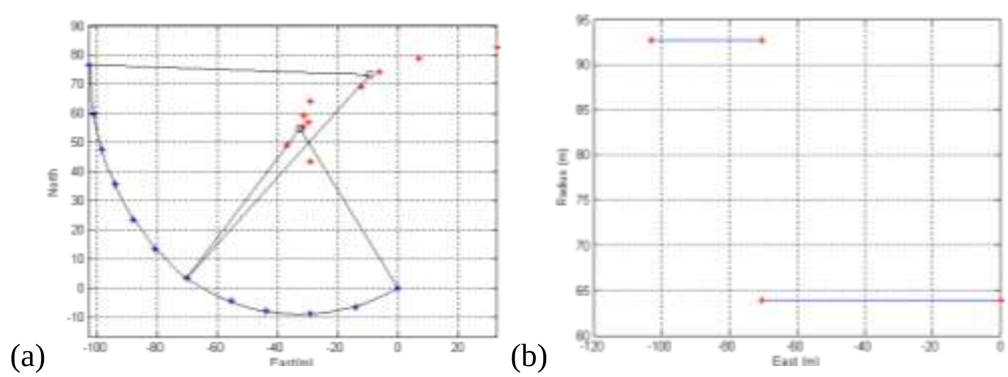


Figure 3-8: (a) Optimized estimates of road curvatures through parametric curve-fitting (b) Optimized estimates of curvature radii

Another example is carried out for an on-ramp from Marsh Road to southbound US 101 as shown in Figure 3-9. This example shows a more complete ramp that can be divided into three parts. The first and the last portions are straight roads, and the intermediate part is one curve with radius of curvature of about 37~38 meters. Figure 3-10(a) and Figure 3-10(b) show the preliminary curvature estimates by CCS algorithm using the map data from the existing commercial digital map. The curvature center estimates of the intermediate portion are distributed within the ramp except two nodes due to the undulation of the curve shape. The result also reflects that the map quality is an important factor for the threshold design of the CS algorithm. Figure 3-10(b) shows that the curvature radius estimates appear to converge in the direction from ramp entrance to the intermediate portion and diverge in the direction toward the ramp end. The optimized curvature estimates are shown in Figure 3-11(a) and Figure 3-11(b).

Figure 3-9: On ramp from Marsh Rd. to southbound US 101 (Google map)

(a) (b)

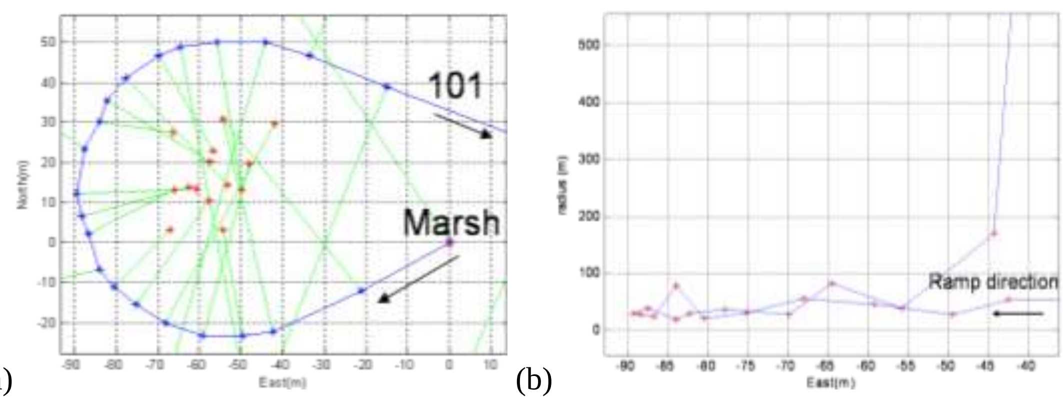
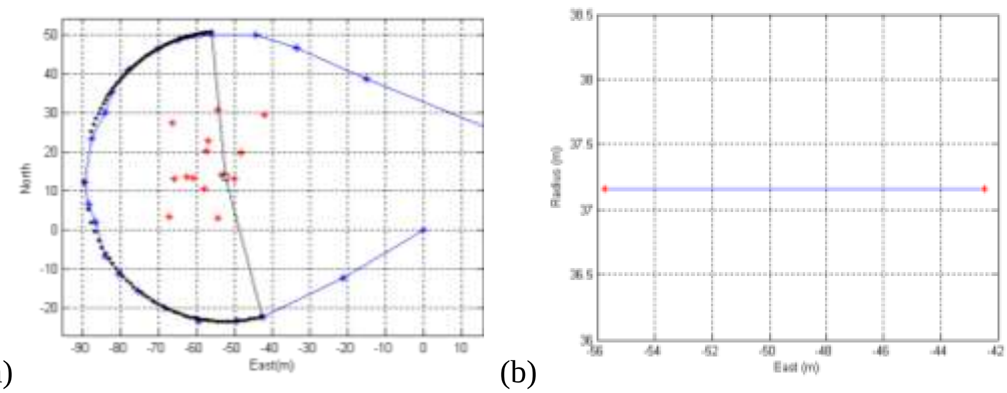


Figure 3-10: (a) Preliminary curvature estimates by CCS algorithm (b) Preliminary estimates of curvature radii by CCS algorithm



(a) (b)

Figure 3-11: (a) Optimized road curvature estimates through curve-fitting (b) Optimized curvature radius estimates

3.1.8 Curve Overspeed Warning Experiment

This section presents a preliminary result of a prototype curve overspeed warning application using an experimental ADAS system at the California PATH Program. Currently, the on-board experimental system integrates GPS measurements, available vehicular sensors (e.g., odometer, gyroscope, and accelerometer), and digital map for safety applications in an autonomous mode. Incorporating the vehicle-infrastructure communication into this system platform for further performance enhancement is one of the on-going tasks in the project and left for future discussion.

The proposed dynamic curvature estimation algorithm was implemented in the experimental system and tested in real-time at the Richmond Field Station test tracks. Figure 3-12 shows one test result on a curve in one of the test track where GPS satellites are not available due to the surrounding tall trees. The safe speed for negotiating this curve is 9.3 m/s as computed by the COWS algorithm in real-time. The experiment showed that the COWS system did provide appropriate warnings when it detected the vehicle speed was unsafe for an upcoming curve based on both the positioning system and the map information. Figure 3-13 shows the corresponding vehicle speeds, number of satellites used in position computation, and the HDOP of GPS. When approaching this curve, GPS speed was constant due to satellite signal outage. The wheel speed was higher than the safety speed between 163~ 165.3 seconds, and the speed warning was activated. After the vehicle was slowed down, the warning was automatically turned off by the system.

One can also see that the satellite signal outages did adversely affect the EKF-based GPS/INS position accuracy. A position enhancement method through sensor fusion of digital map was developed to address this issue; however the development is not yet finished and therefore was left for the future report. Figure 3-12 does show that the enhanced EKF-based positions have the potential to achieve the desired “lane-level” positioning requirement.

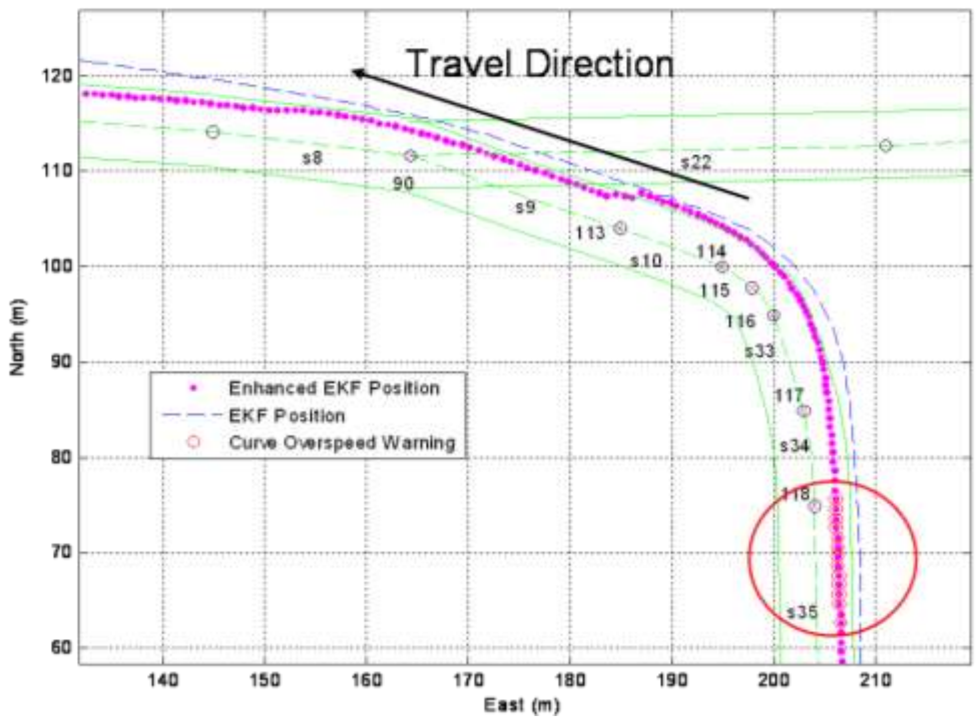


Figure 3-12: Example of COWS Field Test at the RFS Test Track

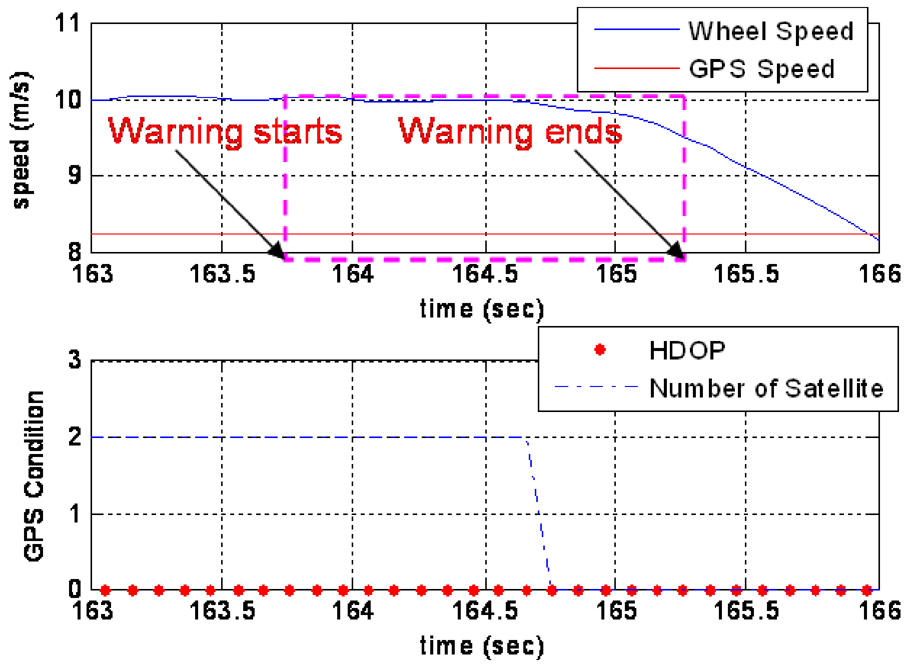


Figure 3-13: Vehicle speed and GPS condition when approaching the curve (when the GPS is in outage, the resultant HDOP is set to zero by the GPS receiver)

3.1.9 Conclusion and Future Work

This report describes the general framework of a Curve Overspeed Warning System and presents a dynamic road curve reconstruction method using the existing map database information for this specific application. The curve attributes computed by this approach appear to be better than those from the conventional spline approach.

This new approach following a typical stochastic estimation approach by combining a data pre-filtering and parametric curve-fitting function under the assumption that the characteristics of road curve can be modeled in terms of various connecting “circles.”. Under this assumption, any given road curve consists of a number of connecting arcs where each arc corresponds to a specific circle. If each of these circles can be identified, the correct curvatures along this curve can therefore be derived. In order to deal with the positioning inaccuracy in the map data, the parametric curve fitting is conducted based on this circle model. Data pre-filtering (that detects curvature changes as well) selects specific “nodes” of each identified circle, which is conducted by the proposed Circle Center Search and Circle Selection algorithms, while curve-fitting is utilized to remove the variance in the curvature estimates.

Preliminary experimental results demonstrated that this prototype COWS achieved the basic performance requirements for a purely map-based COWS without involving vehicle-infrastructure communication. To achieve the optimal system performance, the enhanced map data and dynamic road information was incorporated into the COWS computation through VII.

The future work to accomplish the VII COWS is summarized below.

1. Develop a robust position enhancement module based on current scheme, so that the GPS-based positioning unit can still achieve “lane-identification” accuracy as GPS differential correction is not available.
2. Develop the on-board wireless communication module.
3. Develop the DSRC map information message format.
4. Incorporate the enhanced map data and dynamic road information transmitted from the RSE into the COWS algorithms.
5. Develop the required software and hardware for vehicle-infrastructure communication.
6. Develop the vehicle-to-infrastructure information feedback mechanism for event, hazard or accident detection.

4 Transition VII California Proof of Concept Testbed to US DOT Development Test Environment

4.1 Build and Expand Testbed

An expanded VII California testbed was designed to accommodate emerging US DOT POC and DTE requirements. Elements of the design will include determination of the adequacy of the RSE locations and site characteristics determined to date. The likely scenario was to fulfill the Roadside Equipment (RSE) network already determined under prior effort. Also investigated under this task was transition of RSE components to DTE requirements, with most of the focus replacement of the Denso WRM for candidate sites into POC DSRC transceivers. As part of this task, an experimental RSE, complete with intersection state capabilities was installed at the PATH Richmond Field Station (RFS) "intelligent intersection" for use in testing and demonstration.

4.2 Examine Suitability of HA-NDGPS

The California PATH program and Caltrans have a number of research applications that can benefit from a high-accuracy vehicle positioning implementation. The U.S. Department of Transportation and U.S. Coast Guard in conjunction with the Interagency GPS Executive Board are currently developing a High Accuracy-Nationwide Differential Global Positioning System (HA-NDGPS), targeted at a variety of transportation-related applications. The HA-NDGPS program provides the capability to broadcast corrections to the Global Positioning System (GPS) over long ranges to achieve accuracy better than 10 centimeters (95 percent of the time) throughout the coverage area. HA-NDGPS is currently undergoing a research and development phase with a future implementation pending U.S. congressional budget approvals. Application of this technology will provide advanced safety features for transportation, including applications such as lane departure warning, intersection collision warnings, and railroad track defect alerts.
The California VII Program has established a testbed in the San Francisco Bay area that is being utilized for a variety of experiments. With the integration of vehicle and roadside communications (DSRC), the determination of vehicle location has become a critical component for several VII applications. One of the key objectives of this study is to demonstrate that the existing VII communication infrastructure (i.e., Dedicated Short Range Communications (DSRC), roadside equipment) can be utilized where possible for broadcasting corrections to the vehicles' GPS receivers. This eliminates the need to depend on other communication methods to receive correction signals, resulting in greater control and lower costs. This architecture compliments the potential use of existing DGPS broadcast networks such as the California statewide CORS, NDGPS, and/or NGS.

The architecture of the local base station integrated with the VII communications infrastructure provides both a low-cost lane-level positioning solution with the potential to upgrade to centimeter-level accuracy using carrier phase receivers that could be installed in a subset of vehicles. The pseudorange and carrier phase corrections could both be broadcast over the RSE DSRC transceivers or through an alternative wireless network. While this integrated approach has not been developed commercially, the methodology and experimentation (described in this report) has shown to be viable through similar university research programs. Initial integration may consist of only code corrections while future implementations could add carrier phase corrections with only software changes to be made in the base station and RSE hardware.
This study has implemented the DGPS/DSRC architecture and demonstrated the feasibility of broadcasting the DGPS code corrections over the DSRC network. Initial performance evaluations were completed to demonstrate the potential performance of the architecture. While initial performance has demonstrated the architecture to be successful for lane-level positioning applications requiring differential corrections, additional enhancements would be required for deploying the architecture beyond specific testbeds, pilots, and demonstrations. These enhancements would allow for a more commercially viable solution to improving GPS positional accuracies. Several research goals were achieved with this evaluation:

- Comparison of positioning performance using NDGPS corrections transmitted via beacon and via Internet – correction quality and positional accuracy has been demonstrated to be dependent on prompt acquisition of a DGPS correction message. The DGPS signal transmission via internet has been evaluated for TCP/IP transmission with a DSRC link to the rover vehicle. Rapid and effective acquisition of a DSRC link is critical for receiving DGPS corrections within a single cell DSRC coverage area;

- Potential of transferring HA-NDGPS corrections to standard formats – this study has reviewed and evaluated the protocols, formatting, and transmission of high accuracy signals. The HA-NDGPS protocol performs a message compression/decompression sequence which does not degrade the quality of the original RTCM correction message.

- Integration potential of alternative correction signals (RTK, WAAS, CORS etc.) – tests scenarios completed within this study have demonstrated that the DSRC/Ntrip architecture is compatible with any RTCM correction messages. Receivers capable of processing multiple sources of corrections can utilize alternate corrections in addition to corrections received via DSRC/Ntrip.

- Integration of HA-NDGPS receivers within CA VII vehicles/applications – the HANDGPS protocols have been found to provide a RTCM compatible correction which is suitable for any L1/L2 receiver accepting RTCM carrier phase corrections. Specifically configured receivers are not necessary if broadcasts are transmitted via TCP/IP protocols (DSRC/Ntrip).

- Geographical distribution accuracy requirements of corrections signals (regional, intersection-only, highway-only etc) – the range and performance of a single DSRC transmission site was evaluated. Performance was found to be greatly dependent upon the rate of acquiring a DSRC communication link;

- Frequency requirements of correction signals – the frequency of transmitting a correction signal was maximized for performance within the scope of this study. Decreasing the frequency would be possible for regions of continuous or semi-continuous DSRC coverage; and,

- Compatibility of RSE/DSRC system design with correction signal size, frequency, format, and vehicle densities – the current study results did not find limitations due to DSRC communication bandwidth. DSRC communication and position quality was limited primarily by DSRC coverage area.

The next step towards a final integration would be to create compatible software that would determine availability of suitable regional corrections and autonomously initiate transfer. The current architecture requires a manual selection of DGPS base stations. This future development would focus on these following components:

- A review and collaboration with entities maintaining DGPS broadcast networks to establish agreements for automated downloads;

- Create software that evaluates current location and searches for spatial-appropriate and available correction messages;

- create software that automatically adjusts configuration settings of DGPS Ntrip communications; and

- Implement and test the automated architecture in specific VII applications.

Successful implementation of this automated DGPS acquisition architecture would greatly simplify the methodology of acquiring DGPS corrections and provide improved positioning performance of future ITS implementations.

4.2.1 GPS

The Global Positioning System (GPS) is one of the most convenient and accurate methods for determining a vehicle's position within a global coordinate system [Farrell & Barth, 1999; Farrell & Givargis, 2000]. Utilization of a GPS receiver has become the most prominent method of determining the physical location of a vehicle. A detailed and concise description of GPS is provided in [Farrell & Barth, 1999]. The system is built around a set of 24 satellites (with additional, spares, replacements, upgrades) that orbit the Earth. The orbits are designed in a manner that allows the signals from at least four satellites to be received simultaneously at any point on the surface of the Earth (neglecting obstacles such as tunnels, urban canyons, dense forest etc.). A GPS receiver on the surface of the Earth utilizes the signals from at least four satellites to determine its own antenna position (x, y, z) according to various measurements of the pseudoranges between the satellites and the receiver antenna. The receiver measurements include various code-based pseudoranges and potentially carrier phase information. The standard deviation of uncorrected GPS position estimates is on the order of 10-20 meters. Increased accuracy better than 3 meters can be achieved through the use of code-range based differential GPS (DGPS) techniques, such as those described in [Navstar, 1991; Kee, 1994; Blomenhofer, 1994; and Farrell & Barth, 1999].

Satellite transmission of orbital position (ephemeris), timing, and satellite status data to GPS receivers is known as 'code,' and measurements of the distance between the satellite and the receiver using this 'code' information are called code-based measurements. The GPS receivers utilize the ephemeris data to calculate the positions of each satellite. With the position of a satellite known, the distance between the receiver and the satellite (called the pseudorange) can be determined using the propagation delay of the signal. When the distance between a receiver and at least four distinct satellites is known, a position lock can be obtained [Bajikar et al., 1997].

Most low-cost GPS receivers are single frequency L1 (1575.42 MHz) C/A code sensors, which measure the distances between a receiver and satellites and estimate the receiver's antenna position based on these pseudorange measurements. Given the range standard deviation of common-mode noise on the order of 10 – 20 meters [Farrell & Barth, 1999] and non-common mode noise at order of 0.1 to 4.0 meters [Farrell & Barth, 1999; Farrell & Givargis, 2000], a standalone GPS receiver has a horizontal standard deviation of position error around 20 meters.

This accuracy is sufficient for the road-network-level navigation of route finding/planning and guidance, which usually positions the vehicle at street level with the assistance of map matching algorithms. Most of the current existing vehicle navigation systems utilize the GPS receivers that are in this category.

In terms of vehicle spatial positioning, a standard GPS receiver with the accuracy of 20 meters coupled with map matching has performed well over years in the route guiding navigation systems. More accurate vehicle navigation, such as differentiating the vehicle's lane, requires higher accuracy positioning capability. Positioning systems of centimeter-level accuracy for vehicle operational control, e.g., GPS coupled with Inertial Navigation Systems (INS), have been tested over years and demonstrated sufficient performance in the control applications. However, they are currently too expensive for general navigation or lane-level VII applications. Improved accuracy can be obtained by using differential GPS techniques to remove the common-mode error from the measurements, making the standard deviation of the error small enough to satisfy the lane-level accuracy requirements. Increasing accuracy beyond the lane level requires additional corrections such as carrier phase corrections and/or dual channel corrections.

It is apparent that a low-cost positioning system capable of discriminating between lanes is needed for lane-based VII applications, requiring approximately 1 to 2 meter level accuracy. A DGPS system that uses carrier-phase based range observations can provide accuracy up to 1-3 centimeters, however these receivers require dual frequency reception and additional algorithms to solve integer ambiguity issues, resulting in significantly higher cost (see, e.g., [Navstar, 1991; Blomenhofer, 1994; Farrell & Givargis, 2000]). Vehicle applications requiring lane-level accuracy (2 meters) can potentially utilize a low-cost GPS receiver coupled with other on-board electronics and firmware to increase the accuracy. These lower cost configurations require the use of differential corrections originating from a base station in relatively close proximity.

4.2.2 Differential GPS and Carrier-Phase GPS

Several sources of error contribute to calculation inaccuracies of the pseudoranges, including satellite clock bias, atmospheric delay, ephemeris prediction data, and receiver tracking error noise [Bajikar et al., 1997]. These errors are frequently referred to as the 'common mode errors' because they are common to all receivers in a local (< 50 km) area. Because these errors are common to all receivers in a local area, they can be eliminated through differential GPS (DGPS). Utilizing a stationary base station receiver whose position has been accurately surveyed, common mode errors can be determined for the local area surrounding the base station. The methodology of transmitting these local errors to nearby mobile receivers (rovers) forms the basis of a differential GPS architecture. A breakdown of GPS and DGPS errors are provided in Table 4-1.

There are three primary types of DGPS position corrections that can be provided by the base station: code (or range-space), carrier-phase, and Doppler corrections. Within the context of this study, code and carrier-phase corrections are described. Carrier-phase corrections, which typically produce centimeter level accuracy, are traditionally achieved with post processing algorithms while code-based DGPS corrections are frequently utilized for real-time applications, resulting in 2-3 meter accuracy. However, it is possible to also transmit carrier-phase correction in real time, resulting in what is called Real Time Kinematic (RTK) positioning.

For code-based DGPS, the base station receives the satellite signals and calculates the common mode errors from each satellite, using the known accurate position of the base station. Once the common mode errors for a given time instant are known, they can be transmitted to all receivers within a local area. The rover receivers subtract these transmitted common mode errors for the satellites in its view to calculate its position, resulting in a typical accuracy of 2-3 meters. The accuracy is also influenced by the age of the correction, which is the time between the base station's calculation of the errors and the receiver's calculation of its position. To maintain the accuracy integrity, correction updates are typically needed at least every 10-15 seconds [FHWA, 2005; Barth et al., 2005].

Typical Error in Meters (per satellite)	**Standard GPS**	**Code-Phase Differential GPS**
Satellite Clocks	1.5	0
Orbit Errors	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Receiver Noise	0.3	0.3
Multipath	0.6	0.6

Table 4-1: Summary of GPS Error Sources. [Trimble, 2006].

The carrier frequency is used for transmitting the code-based signal from the satellite to the receiver. Carrier-phase DGPS functions through phase measurements of the carrier signal, detecting the change in the number of carrier cycles between the receiver and a given satellite. The total number of carrier cycles between the receiver and a given satellite multiplied by the carrier wavelength can provide a more accurate measurement of the range. An 'integer phase ambiguity' arises when the total number of carrier cycles is not known; only the change in this total number of cycles can be directly observed. If the code measurement can be made accurate to within a few meters, then there is only a few wavelengths of the carrier signal to consider to determine which cycle really marks the edge of the carrier frequency timing pulse. Resolving this carrier phase ambiguity for just a few cycles is a much more solvable problem and with increasing processing power and functionality, it's possible to make this kind of measurement in real time. In this method, the common mode errors are identical to the common mode errors encountered in the code-based measurements, but the non-common mode errors are approximately 100 times smaller than their corresponding errors in the code-based measurements. Eliminating the common mode errors with code and phase corrections, it is then possible to achieve centimeter-level accuracy using carrier-phase DGPS.
The process of transmitting carrier-phase corrections in real time from a localized based station to a rover receiver capable of processing carrier-phase corrections is commonly referred to as Real Time Kinematics (RTK). The RTK methodology is commonly utilized by the survey industry to achieve accurate geographic positions within a localized area. While the traditional survey techniques have typically required the rover receiver to be stationary for several minutes to achieve centimeter level accuracy, improved methods are allowing for real time, second-bysecond, carrier-phase corrections. Table 4-2 summarizes the correction techniques and their accuracies.

4.2.3 Real-Time Differential Corrections

Several industry standard DGPS correction signals have been implemented for various differential services, including RTK. Differential correction formats were created for marine, aviation, navigation, and proprietary systems. The most frequently utilized correction streams that are non-proprietary are termed:

a) RTCM-104, and
b) RTCA-159 (WAAS)

Measurement Type	Real-time or Post-processing	System Type	Accuracy	Coverage Area
Code	Post-processing	Post-processed DGPS, post-processed LADGPS or post-processed WADGPS	from 1 m to ~10 m	Nationwide
Code	Real-time	DGPS, LADGPS, or WADGPS	from ~2 m to ~10 m	Nationwide
Carrier phase	Post-processing	Kinematic, rapid static or static	from < 1 cm to several cm	From several km to several 1000 km
Carrier phase	Real time	Real-Time Kinematic (RTK)	from < 1 cm to several cm	From several km to several 10 km

Table 4-2: Summary of GPS signal correction methods. [Magellan, 2006].

Many GPS receivers are "RTCM-capable" meaning they accept DGPS correction messages through a real-time data communication link (e.g., VHF or UHF radio, cellular telephone, FM radio sub-carrier, or satellite com link). The Radio Technical Commission for Maritime Services Special Committee 104 recommended standards for DGPS correction messages, which have become termed RTCM-104. Several versions exist which include the recent addition of message types 18/19/20/21 for carrier phase solutions such as RTK. For RTK applications, RTCM version 2.1 provides Type 18 (carrier phase raw data) or Type 20 (carrier phase corrections). Radio Technology Committee for Aviation Special Committee 159 developed minimum standards that define the basis for FAA approval of equipment using GPS for aircraft navigation in the United States. The RTCA DO-229 document entitled "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment" was prepared by Special Committee 159 in 1996. It contains the standards for airborne navigation equipment using GPS augmented by a Wide Area Augmentation System (WAAS).

As described previously, several proprietary differential data streams exist including systems such as Starfire, and Omnistar. While these systems may be adaptable for VII applications, it is presumed that an open architecture method is preferred for achieving the accuracy requirements desired. Similarly, numerous proprietary survey grade (<5cm) DGPS systems exist which could be modified to meet VII requirements, but have also received limited focus due to proprietary correction signals that would become an issue for VII implementation. While the GPS industry has integrated WAAS and RTCM (RTK capability) corrections into many receivers, there is a third DGPS correction architecture evaluated in this study, referred to the National Differential GPS (NDGPS) architecture. Greater detail is provided on WAAS, RTK, and NDGPS correction methodologies below.

4.2.4 Wide Area Augmentation System (WAAS)

The Federal Aviation Administration (FAA) developed a Wide Area Augmentation System to transmit satellite based DGPS correction signals for civil aviation. WAAS utilizes a network of precisely-located ground reference stations that monitor GPS satellite signals. These wide-area reference stations (WRS) are located throughout the continental United States, Hawaii, Canada, Mexico and Alaska. These stations collect and process GPS information and send this information to WAAS Ground Uplink Stations (GUS). The WAAS ground uplink stations develop a WAAS correction message that is sent to user receivers on the L1 transmission signal via geostationary satellites. Using WAAS, GPS signal accuracy is improved from 20 meters to approximately 3 meters in both the horizontal and vertical dimensions.

WAAS reached initial operational capability for aviation use on July 10, 2003 as the first of several Space-Based Augmentation Systems (SBAS) being developed throughout the world and is compatible with all other international satellite-based augmentation systems. Although the WAAS was designed for aviation users, it supports a wide variety of non-aviation uses including agriculture, surveying, recreation, and surface transportation. The WAAS signal has been available for non safety-of-life applications since August 24, 2000, and numerous manufacturers have developed WAAS-enabled GPS receivers for the consumer and OEM market.

The next phase of WAAS is referred to as the Global Navigation Satellite System Landing System (GLS) segment. The GLS phase of WAAS is scheduled to coincide with the operational capability of GPS modernization and is scheduled to be completed in 2013. GLS will utilize, and depend upon, improvements that the Department of Defense (DoD) will make as part of its GPS modernization program. GPS modernization will improve WAAS performance during periods of severe solar storm activity and provide additional security against interference to the GPS.

4.2.5 Real Time Kinematic (RTK) and CORS

RTK is a process where carrier-phase GPS signal corrections are transmitted in real time from a reference receiver at a known location to one or more remote rover receivers. The use of an RTK capable GPS system can compensate for atmospheric delay, orbital errors and other variables in GPS geometry, increasing positioning accuracy up to and sometimes within a centimeter. Used by engineers, topographers, surveyors and other professionals, RTK is a technique employed in applications where high precision is necessary. RTK is used, not only as a precision positioning instrument, but also as a core for navigation systems or automatic machine guidance, in applications such as agriculture, civil engineering, and dredging. It provides advantages over other traditional positioning and tracking methods, increasing productivity and accuracy. Using the code and carrier phase of the GPS signals, RTK provides differential corrections to produce the most precise GPS positioning.

The RTK process begins with a preliminary integer ambiguity resolution. This is a crucial aspect of any kinematic system, particularly in real-time where the velocity of a rover receiver should not degrade either the achievable performance or the system¡¦s overall reliability. The base station is responsible for assembling the base station carrier phase correction message, which aids the receiver in solving the integer ambiguity. With integer ambiguity solved, the receiver is capable of centimeter level accuracy at frequencies of 1 Hz.

With increased prevalence of centimeter level applications, RTK correction messages are being integrated within a network of reference stations. The National Geodetic Survey (NGS), an office of the National Oceanic and Atmospheric Administration¡¦s (NOAA) National Ocean Service, coordinates two networks of Continuously Operating Reference Stations (CORS):

- the National CORS network; and,
- the Cooperative CORS network.

The national CORS network is operated, managed, and maintained through NGS agreements with site data available through NGS; while the Cooperative CORS is a network of independent equipment operators each responsible for their own data collection, storage, and transmission. Each CORS site provides GPS carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States. Currently, only a small portion of the sites provides real time (1 Hz) correction data capable of supporting RTK applications.

The CORS system benefits from a multi-purpose cooperative structure involving many government, academic, commercial and private organizations. New sites are evaluated for inclusion according to established specifications and criteria. Cooperative CORS data are available from the participating organization that operates the respective site. Specific to California, an additional collaborative effort has evolved to operate and maintain reference stations with real time correction capability.

The California Spatial Reference Center (CSRC) is operated through the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics at UCSD's Scripps Institution of Oceanography. In partnership with surveyors, engineers, GIS professionals, the National Geodetic Survey, the California Department of Transportation, and the geophysics community, CSRC has developed a plan to establish and maintain a network of GPS control stations necessary to meet the demands of government and private businesses for a reliable spatial reference system in California.

CSRC has had significant influence on the implementation, development, and operation of reference stations in and around Southern California. The implementation of these sites has predominantly been associated with geophysics (earth crust movements) and municipal survey requirements. The real time data requirements for these applications are compatible with RTK data requirements.

4.2.6 United States Coast Guard National Differential GPS System

Another system for providing differential corrections is the U.S. Coast Guard's Nation-wide Differential Global Positioning System (NDGPS). This service is a land-based differential correction system that receives and processes signals from orbiting GPS satellites, calculates corrections from known positions, and broadcasts these corrections via a Medium Frequency (307 kHz) beacon transmitter to DGPS users in the broadcast site's coverage area [Wolfe et al., 2000].

As the DGPS concept was being developed in the late 1980's, a variety of alternate methods to enhance the accuracy and integrity of GPS through differential correction were considered. The motivation that guided development of the USCG NDGPS service were redeployment of decommissioned radio beacon sites distributed throughout the United States, availability of radio beacon frequencies (285-325kHz), and the need for harbor navigational aides [USDOT, 2001]. NDGPS sites were engineered to broadcast applicable pseudorange corrections at 200 bits per second or less up to a range of 450 km. At the time, the selective availability (S/A) dithering error was the greatest error to correct, dwarfing other errors such as atmospheric, multipath, algorithmic, and noise errors. Correcting for pseudorange errors allowed DGPS receivers to meet the 10 meter accuracy requirement for positioning aids to navigation and for the 8-20 meter accuracy requirement for harbor and harbor approach (H/HA) [USDOT, 2001].

Selective Availability was eliminated for GPS broadcasts on May 2, 2000, in accordance with a

Presidential Decision [USPDD, 1999]. With GPS unencumbered by S/A, GPS receiver accuracy achieved dramatic improvements. DGPS receivers also benefited by the removal of S/A by using algorithms to correct remaining GPS errors, achieving accuracies of 1-3 meters [USDOT, 2001]. Atmospheric errors from the effects of the ionosphere, as well as the wet and dry portions of the troposphere, are now the largest contributor of error to the GPS signal. While DGPS pseudorange corrections effectively minimize these errors at the DGPS reference location, spatial decorrelation degrades these corrections as the distance between the receiver and reference station increases. Modeling techniques using real time monitoring show significant potential to achieve sub-meter accuracies by supplementing the pseudorange corrections with improved atmospheric models [Gutman et al., 1999].

The NDGPS system is in the process of finalizing a nationwide network of DGPS broadcast sites to provide dual terrestrial coverage in the continental U.S. Spatial decorrelation effects are minimized by the utilization of these multiple reference stations. New generation DGPS receivers take advantage of this dense network to compare the signals of multiple broadcast sites to enhance positional accuracy. Data from multiple locations can be transferred to other locations to rebroadcast or be combined at a central location and then rebroadcasted [Last et al., 2002]. When the required coverage is met, DGPS users in the U.S. will possess signal availability of better than the required 99.9% (availability represents the percentage of time the DGPS signal is usable). The NDGPS system provides users with broadcast messages as defined by the Radio Technical Commission for Maritime Services (RTCM) and utilizes Reference Station Integrity Monitor (RSIM) messages for intra-system communication [RTCM, 2001a; RTCM, 2001b]. Figure 4-1 shows the estimated coverage area for installed NDGPS sites as of 2009. Single coverage regions (gray areas) and regions where more than one signal is available (yellow areas) were identified using Millington's method for determining ground wave signal strength [USCG NAVCEN, 2009]. Table 4-3 gives the current status of California's NDGPS broadcast stations.

Site ID	Location	Status
899	Petaluma	Engineering Test Site
875	Essex	OPERATIONAL
882	Lompoc	OPERATIONAL
764	Lincoln	OPERATIONAL
881	Point Loma	OPERATIONAL
878	Chico	OPERATIONAL
795	Bakersfield	OPERATIONAL
885	Cape Mendocino	OPERATIONAL
883	Pigeon Point	OPERATIONAL

Table 4-3: Status of California NDGPS broadcast stations [USCG NAVCEN, 2009].

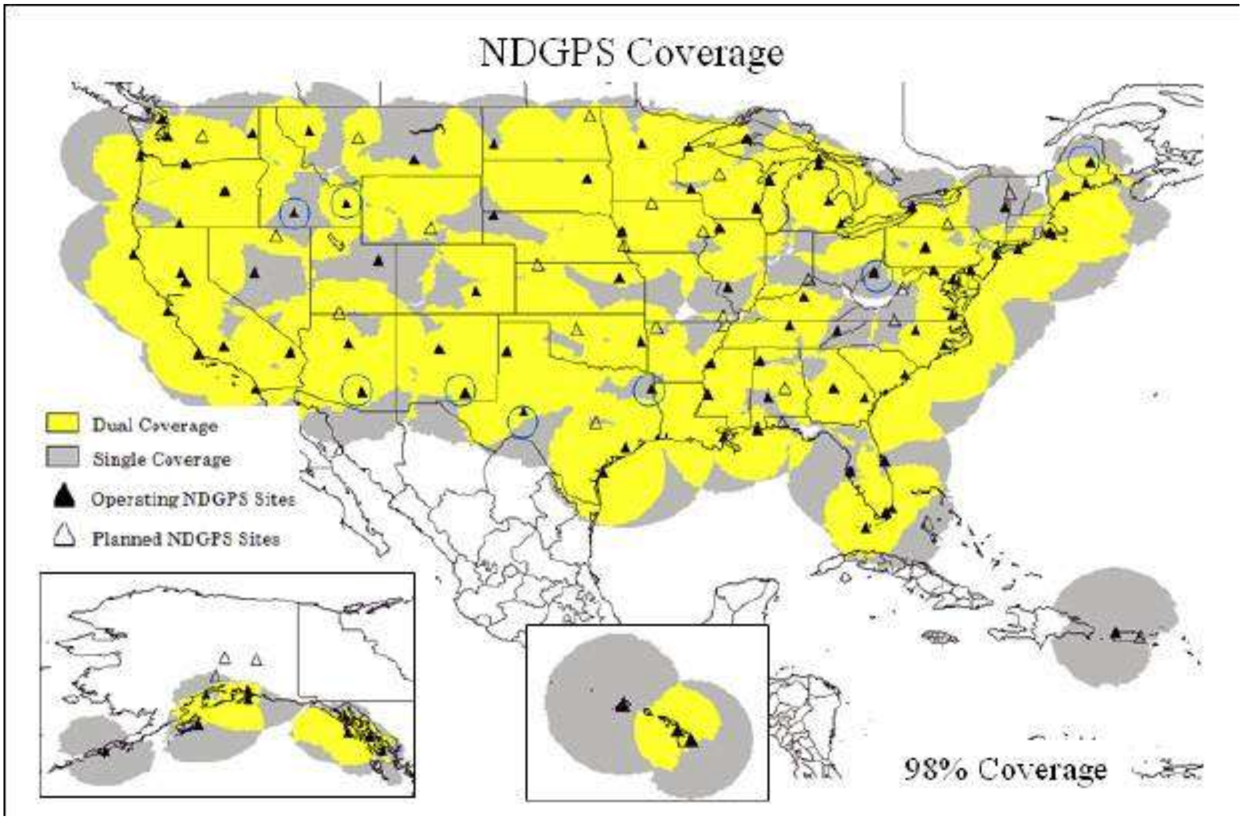


Figure 4-1: NDGPS coverage in 2009 [USCG NAVCEN, 2009].

The U.S. Coast Guard developed the original NDGPS network. The U.S. Army Corps of Engineers (USACOE) needed similar capability along inland waterways and, with the help of the USCG, established similar broadcast stations. USACOE later adopted the NDGPS concept and developed additional stations. The US Department of Transportation (USDOT) continues to install NDGPS stations at retired Air Force Ground Wave Emergency Network (GWEN) sites. When all proposed installations are complete, there was approximately 137 similar stations broadcasting Course/Acquisition (C/A) code correctors to users. This will enable meter-level positioning with an associated level of integrity, according to the Federal Highway Administration [FHWA, 2005].

These beacons today broadcast single-frequency GPS code range correctors enabling few-meter level positioning and navigation along the U.S. coasts and inland waterways. An expected pseudorange value is computed for each GPS satellite in view at the NDGPS sites. These computed values are compared with the actual pseudorange measurements made at the sites; the difference is known as a pseudorange corrector. The assumption is that the errors are common to both the reference site and any user site. These correctors are placed in a formal bit stream with message header, message type, and with parity considerations and broadcast to users as a Type 9 RTCM message. This message is one of many broadcast as part of the RTCM-104 protocol developed by the Radio Technical Committee for Maritime Services (RTCM) [FHWA, 2005]. Based upon the RTCM-104 message, users are able to perform meter-level positioning in static or moving applications. This message requires approximately 660 bits to send C/A code pseudorange correctors for 12 satellites. It should be noted that correctors are sent because correctors are expected to require fewer bits than observations. Real Time Kinematic (RTK) techniques applied to this 200 baud system may not provide the accuracies of a traditional RTK application, but may show merit in achieving decimeter level accuracies at a limited range from the DGPS broadcast location.

The USCG and others are currently enhancing the NDGPS system, providing for higher accuracy in the sub-meter range. This effort is referred to as the High Accuracy NDGPS (HANDGPS) system, which is described in greater detail in the following chapter.

The U.S. Department of Transportation approved a decision to continue the inland component of the Nationwide Differential Global Positioning System (NDGPS) on April 18, 2008. The decision was based on the results of the NDGPS user assessment conducted by the Research and Innovative Technology Administration (RITA). RITA assessed the existing user needs and systems requirements for the inland component of NDGPS. Information was gathered through public response (including responses from state and local governments, the private sector, and the non-profit sector), and through quantification of the mission requirements of other federal agencies using inland NDGPS.

To date, the US Coast Guard monitors and controls 38 operational NDGPS sites that belong to the DOT. The Coast Guard is a key member of the seven-agency partnership for the Department of Transportation's NDGPS expansion initiative. The Coast Guard brings its expertise in building, operating and maintaining DGPS sites to the partnership. The other members of the NDGPS expansion initiative are the U.S. Air Force, the U.S. Army Corps of Engineers, the Federal Highway Administration, the National Oceanic and Atmospheric Administration, the Office of the Secretary of the Department of Transportation, and most recently appointed sponsor for the project is the Research and Innovative Technology Administration (RITA). [USCG NAVCEN, 2009]

The continued evaluation and expansion of the high accuracy (HA) NDGPS concept has been planned for 2008 and 2009. Currently, Hawk Run, PA; Hagerstown, MD; and the Topeka, KS NDGPS sites are equipped to broadcast code and carrier phase observables under a test scenario. Testing is expected to continue to support ongoing system development. Pueblo, CO is expected to become the next HANDGPS broadcast site in FY 09. [USCG NAVCEN, 2009]

4.2.7 DSRC Background

Dedicated Short Range Communications (DSRC) is a general purpose RF communications link between the vehicle and the roadside (V2R), or between two vehicles (V2V). The technology draws upon the increasingly popular IEEE 802.11 Wi-Fi standard. Within the IEEE 802 context, Wireless Access in Vehicular Environments (WAVE) utilizes the DSRC technology for V2V communication and V2R communications. The 802.11 efforts in WAVE applications are being developed into the 802.11p standard. Equivalent efforts are occurring with the IEEE 1609 working group and standard for Dedicated Short Range Communications. The 802.11p and 1609 standards are for data-only systems and operate on radio frequencies in the 5,725 MHz to 5,875 MHz Industrial, Scientific and Medical (ISM) band. The set of standards developed to support this interface provide a short to medium range communications service for a variety of applications, including public safety (obstacle detection, collision warnings and avoidance, intersection safety), commercial vehicle applications (weigh-in-motion/inspection clearances, border crossing), electronic toll collection, parking lot payment, in-vehicle signing, and many others.

DSRC technology provides secure, reliable communication links between vehicles and infrastructure safety subsystems that can increase highway safety. The 5.9 GHz DSRC link uses RF broadcast techniques to transfer data over short distances between roadside and mobile units, between mobile units themselves and between portable and mobile units. This link enables operations related to the improvement of traffic flow, highway safety, and other ITS applications in a variety of application environments called DSRC/WAVE. 5.9 GHz DSRC system requires robust, fast, localized transmissions from vehicle¡Vto-vehicle and roadside-to-vehicle to serve the many public safety and private commercial applications. However, for high-speed vehicular applications, significant changes were required to provide latency minimization, channel switching/prioritization, authorization, prioritization and anonymity without compromising messaging integrity, correctness, privacy, & robustness attributes.

The National ITS Architecture has identified DSRC as a primary means of communicating between the roadside and vehicles, and from vehicle-to-vehicle. There are a large number of applications planned within the ITS domain, including collision avoidance, traffic management, toll collection, transit operations, commercial vehicle operations, and traveler information. In addition to these ITS applications, WAVE and DSRC are expected to support another set of applications that would be of broader interest to motorists and those interested in providing services to these motorists. Some of these applications would be using the DSRC device as a means of connecting the vehicle to the Internet.

4.2.8 NTRIP Broadcasting Methods

Networked Transport of RTCM via Internet Protocol (Ntrip) is an application-level protocol that supports streaming DGPS corrections over the Internet. Ntrip is a generic, stateless protocol based on the Hypertext Transfer Protocol HTTP/1.1. Ntrip supports wireless Internet access through Mobile IP Networks like GSM, GPRS, EDGE, or UMTS.
Ntrip consists of three system software components: NtripClients, NtripServers, and NtripCasters:

- NtripServers - transfer the data streams from a source to the NtripCaster;
- NtripCaster - the major system component; and
- NtripClients - receives data streams of desired NtripSources on the NtripCaster.

The NtripCaster is the actual HTTP server program, while NtripClient and NtripServer act as HTTP clients. Figure 4-2 provides a line drawing of the Ntrip architecture.

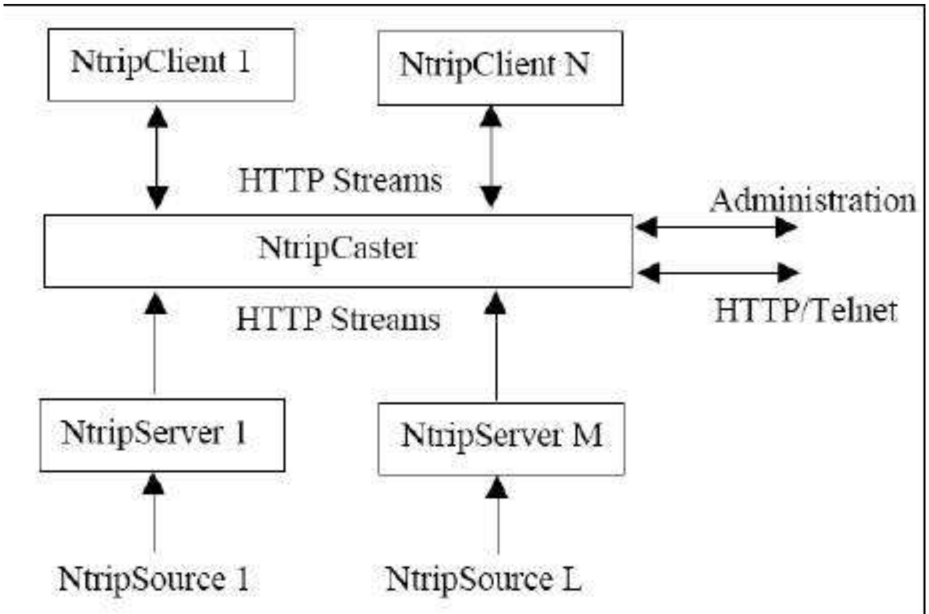


Figure 4-2: Ntrip architecture [GNSS Data Center, 2009].

NtripServers define a source ID called "mountpoint" for every streamed NtripSource. Several NtripClients can access the data of desired NtripSources at the same time by requesting a source by its mountpoint on the NtripCaster. If implemented in the NtripCaster program, authorized personnel may remotely control the NtripCaster via a password-protected Telnet, VPN, or receive status information via a password-protected HTTP session using an Internet Browser. An administrator running an NtripCaster is responsible for allowing new NtripServers to connect with new NtripSources. The administrator organizes all available NtripSources and defines all source IDs (mountpoints).

NtripClients must be able to choose an NtripSource by its mountpoint on the NtripCaster. Therefore a source-table is introduced into, and maintained on, the NtripCaster. Each record of this source-table contains parameters describing attributes of a data stream, a network of data streams, or an NtripCaster. Stream attributes (identifier, coordinates, format, nav-system, mountpoint, etc.) are defined at the NtripServer side for each NtripSource.

4.2.9 Integration of DSRC and NTRIP

4.2.9.1 Hardware Architecture of DSRC/NTRIP Broadcasts

The transmission of DGPS corrections requires the integration of numerous hardware components which aid in minimizing transmission delays and promote reliable communication. Figure 4-3 shows the hardware and communications architecture for the integration of DSRC and

Ntrip DGPS broadcasts.

The architecture consists of the following components:

- Base station receiver - dual channel carrier phase receiver (Trimble 5700);
- Ntrip server computer – networked windows computer capable of running Ntrip server program;
- Ntrip caster – networked computer capable of running as a server;

- DSRC RSE – combination of DSRC transceiver, internet backhaul, and support equipment;
- OBE – rover GPS receiver, mobile DSRC, computer capable of running Ntrip client; and,
- Misc. – GPS transmission, antennas, cables, connectors and power sources.

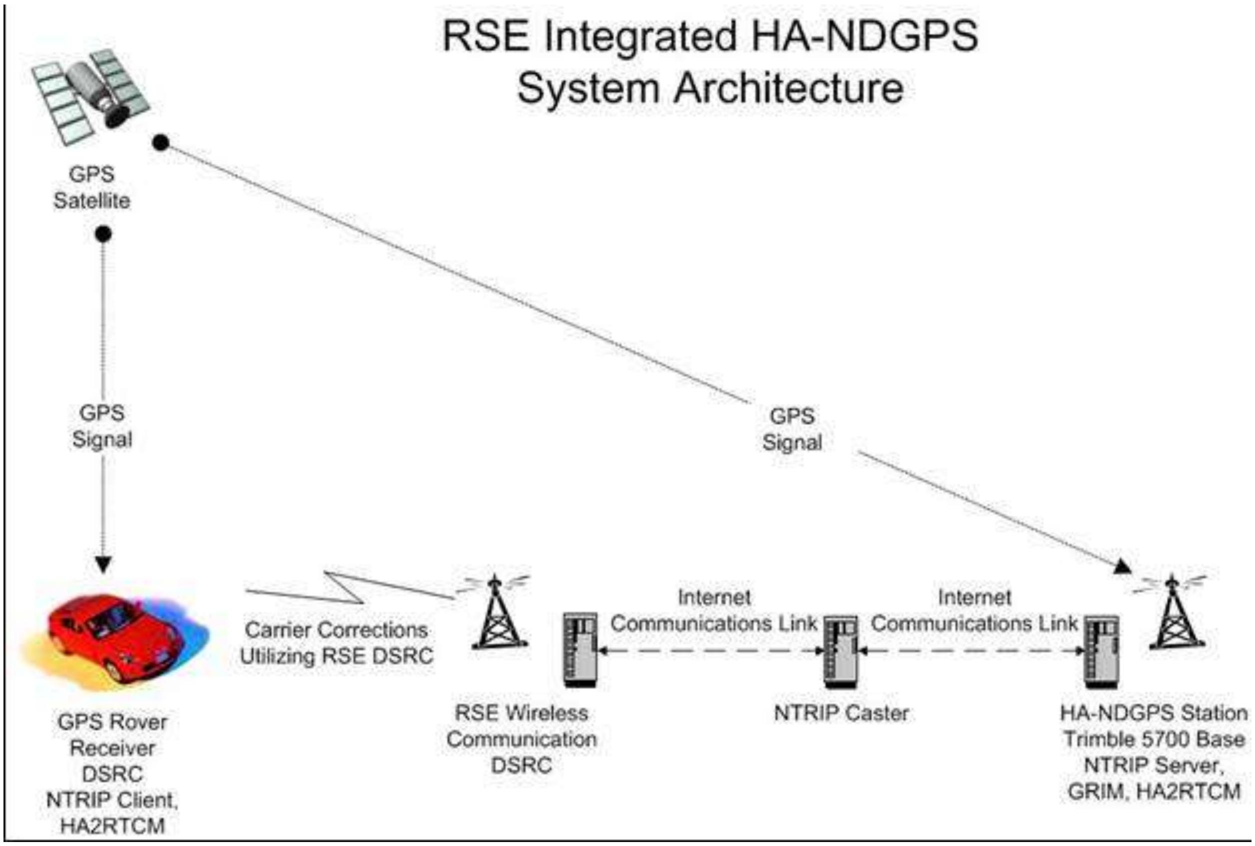


Figure 4-3: Ntrip/DSRC hardware architecture

The GPS base station consists of a GPS receiver, computer, GPS base station antenna, high speed internet connectivity, backup power, climate control (if needed), reliable power, and cabling. The base station receiver serves the purpose of receiving GPS satellite transmissions and formulating code and carrier phase corrections in RTCM format. The receiver selected for this demonstration is a Trimble 5700 CORS base station, but any L1, L2 receiver configured for RTCM corrections would suffice. The receiver is configured and connected to a local computer which is installed with the NtripServer program. This computer simply receives the corrections from the GPS base station and utilizes the TCP/IP Ntrip protocol to forward the corrections to the NtripCaster. The NtripServer computer does not require computational intensive tasks, but must be suitable for serial communications to the receiver and high speed transfer of TCP/IP packets.

The NtripCaster operates as a server and therefore should possess a suitable OS, internet connectivity, power backup, processing power, data storage, and technical support. The current NtripCaster is housed at the University of California, Riverside CE-CERT computer laboratory server facility. The facility is climate controlled with power backup and full administrative support. The server has high bandwidth T1 internet connectivity with advanced firewall integration. The server is a LINUX OS with proper configurations to serve as an Ntrip Caster. For testing purposes at UC Riverside, a temporary DSRC RSE portable station was created. This unit was housed in a vehicle and consisted of a Technocom DSRC unit, power inverters, computer, cables, antennas, and wireless communications. This hardware configuration was responsible for receiving the TCP/IP DGPS packets and forwarding to the mobile DSRC OBE. The rover OBE consisted of a Technocom DSRC unit, power inverters, computer, cables, antennas, and DGPS capable receiver (Novatel OEM V3), and data collection computer. For position validation the vehicle also consisted of a vision capture system for lane marker detection.

4.2.9.2 Software Integration of DSRC/NTRIP Broadcasts

The NtripServer is used to transfer DGPS correction data of an NtripSource (Trimble 5700 CORS base DGPS receiver) to the NtripCaster (server located at UC Riverside). Before transmitting DGPS corrections to the NtripCaster using the TCP/IP connection, the NtripServer sends an assignment of the mountpoint (communication port assignment). Server passwords and mountpoints must be defined by the administrator of the NtripCaster and provided to the administrators of the participating NtripServers. An NtripServer in its simplest setup is a computer program running on a PC that sends correction data of the GPS base station receiver to the NtripCaster.

The NtripCaster is basically an HTTP server supporting a subset of HTTP request/response messages and adjusted to low-bandwidth streaming data (from 50 up to 500 Bytes/sec per stream). The NtripCaster accepts request-messages on a single port from either the NtripServer or the NtripClient. Depending on the content of these messages, the NtripCaster determines whether there is streaming data to receive or to send.

An NtripClient was accepted by and receive data from an NtripCaster, if the NtripClient sends the correct request message (TCP connection to the specified NtripCaster IP and listening Port). The Ntrip methodology uses only non-persistent connections with respect to the message format and status code, the NtripClient-NtripCaster communication is otherwise fully compatible to HTTP 1.1. Figure 4-4 and Figure 4-5 show that DSRC/WAVE standards manage the radio transceiver communication requirements and can transmit TCP/IP packets. The DSRC communication method is entirely compatible with the Ntrip TCP/IP communication architecture.

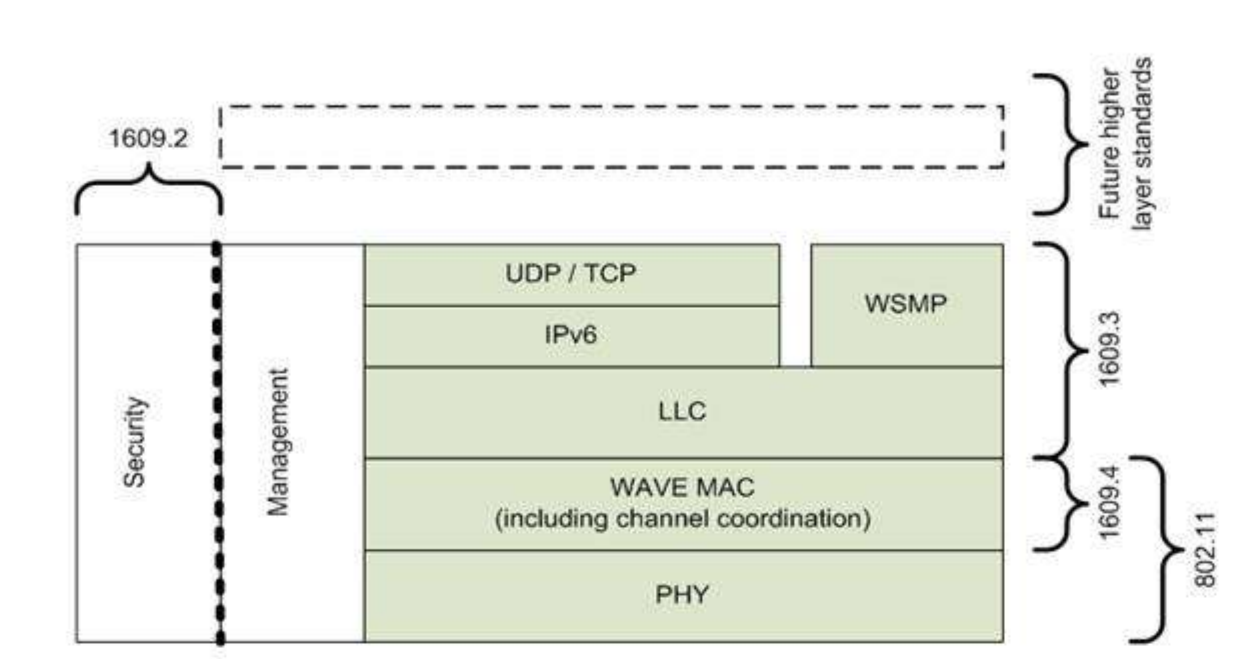


Figure 4-4: DSRC architecture [IEEE 1609.3-2007]

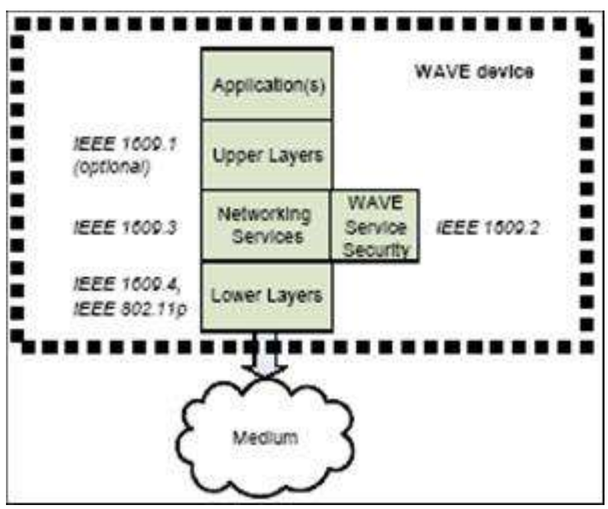


Figure 4-5: WAVE/DSRC architecture [IEEE 1609.3-2007]

Figure 4-6 shows the Ntrip Client and Server configuration windows for the tested architecture. The required fields, ports, IP addresses and passwords must be configured as shown for the proposed architecture.

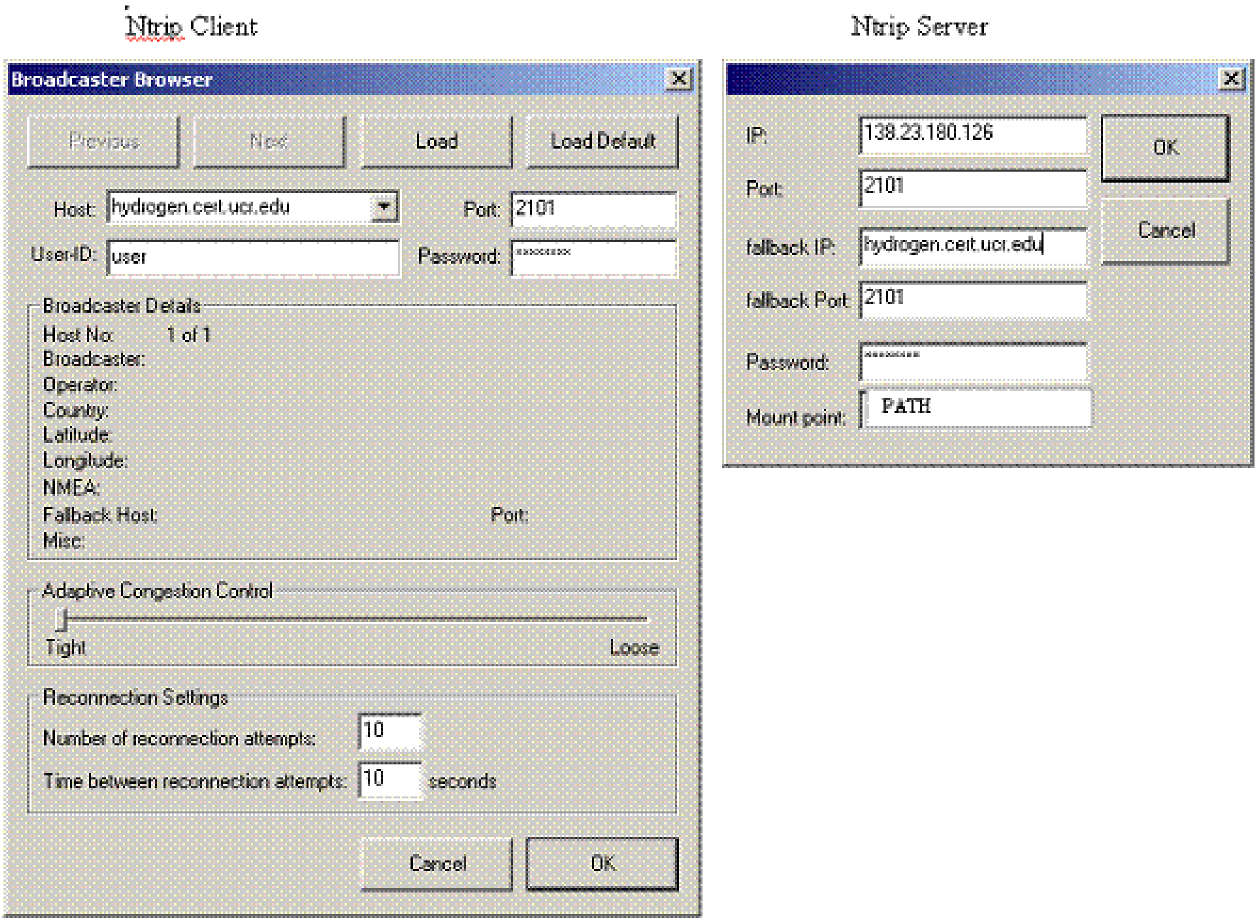


Figure 4-6: Configuration screens for the Ntrip Server and Ntrip Client programs.

4.2.9.3 Architecture Implementation for VII

The base station architecture that has been tested and evaluated at UC Riverside was duplicated for the California VII testbed. The VII California testbed extends along approximately 60 miles of roadway (freeways and arterials), and is a significant collaborative effort between University of California, Caltrans, MTC, and vehicle OEMs. The VII California testbed consists of a network of DSRC roadside units, applications with on-board equipment (on light duty and transit vehicles), and a leveraged, established backhaul network. The California VII strategy is to deliver a testbed that will showcase the value of VII in terms of safety and mobility benefits. The viability of the VII California applications are reviewed, monitored and evaluated by Caltrans, MTC and their contractors. Mobility benefits are evaluated in terms of user perception of the usefulness of VII-generated traveler information delivered in vehicles as well as value provided to the public agencies. Caltrans, MTC, and PATH begun the deployment of the testbed, through initial installations of roadside equipment (RSE) locations equipped with 5.9 GHz radio units in the Palo Alto area. Figure 4-7 shows the VII architecture with RSE implementation example

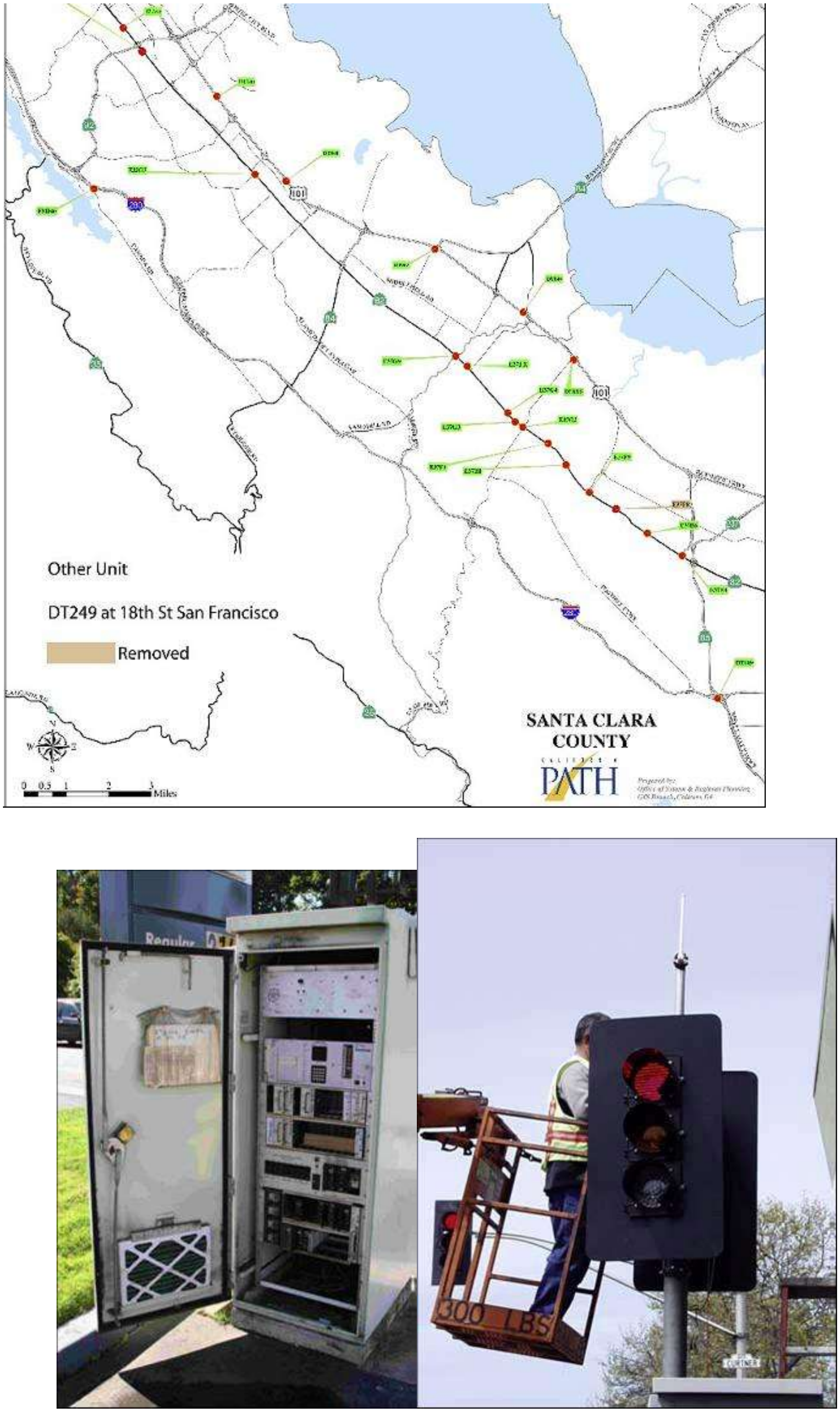


Figure 4-7: California VII testbed deployment [www.californiavii.org]

To facilitate the integration of the DSRC/Ntrip architecture, a DGPS base station was installed at the Mercedes Benz R&D North America facility in Palo Alto California. The MBRDNA facility is centrally located to the California VII testbed and provides an ideal location for regional DGPS corrections. Figure 4-8 shows the Trimble 5700 CORS base station receiver and NtripClient computer. It also shows a VII DSRC testbed installation.

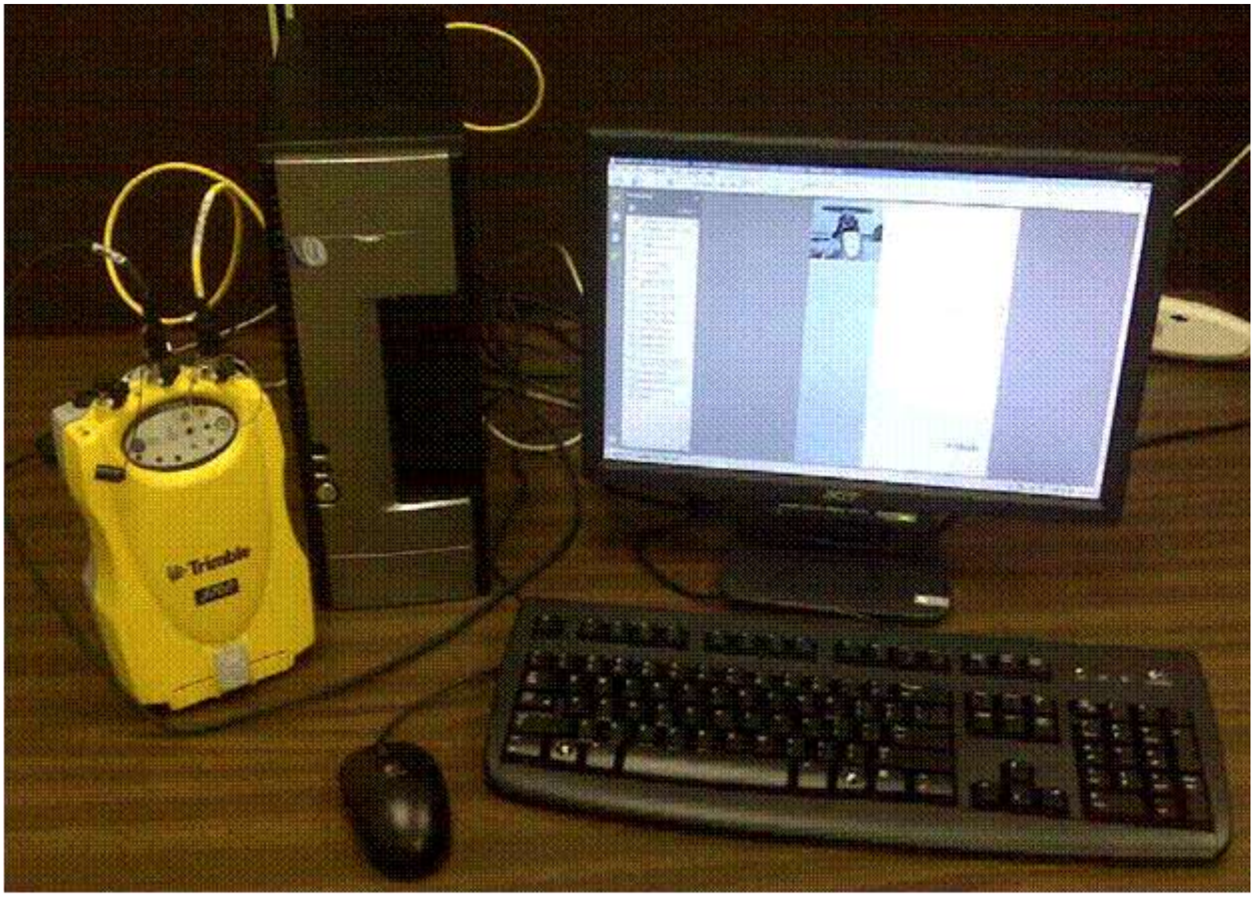


Figure 4-8: DSRC communication installation for VII testbed [www.vii.path.berkeley.edu]

4.2.10 Performance Testing and Evaluation

4.2.10.1 DSRC Performance Testing

Evaluation of the DSRC performance occurred on a four lane arterial with prominent solid white shoulder markings. Figure 4-9 shows the east/west arterial with the RSE labeled as the base station. Numerous tests were completed to evaluate the communication performance of the DSRC prior to implementing the DSRC/Ntrip architecture. The test results were compiled to determine the distance of effective communication for the V2R communication scenario.

Figure 4-9: UC Riverside DGPS arterial test site

The local UC Riverside testbed has an unobstructed DSRC transmission path between the RSE and OBE antennas. Numerous test runs were completed to determine the distance a vehicle could travel before losing communication (go-out point) and the approach distance at which DSRC communication was established (connected point). The average distance was calculated to be approximately 745 meters for losing an active DSRC connection. The average distance was calculated to be approximately 697 meters for regaining an active DSRC connection. Table 4-4 provides the communication distances based on two different calculation methods. The bearing calculation was determined from latitude, longitude, elevation differential distance calculations, while the map measured average was determined from Google Earth's line distance determination.

	Bearing Calculated Average	Map Measured Average
Connection Lost	694.86 m	743.40 m
Connection Initiated	699.66 m	746.93 m

Table 4-4: Summary of DSRC transmission distance.

4.2.11 NTRIP Broadcast Evaluation of Positional Accuracy

To determine the accuracy of the DSRC/Ntrip architecture a vision based validation system was created for the UC Riverside test track. The test track is shown in Figure 4-9 and consists of a four lane arterial roadway. The roadway possesses a solid white shoulder marking which serves as a reference for positional "ground truth". The positional ground truth was experimentally determined through stationary DGPS measurement techniques of a carrier phase L1/L2 receiver.

The measurement technique involves a rover vehicle carrying DGPS and a camera. GPS provides latitude, longitude and altitude data for the vehicle's trajectories. The camera captures continuous video of lane markers and relates the lane marking position to the offset of the camera recorded vehicle position. The purpose of this strategy is to accurately determine the GPS error of an independent recording relative to the position of the vehicle recorded with the integrated vision sensor. Figure 4-10 shows the equipment setup to monitor lane markings for positional accuracy determination. Figure 4-11 is an lane marking image utilized for determination positional accuracy.

Figure 4-10: Vehicle with mounted vision system for positional accuracy determination.

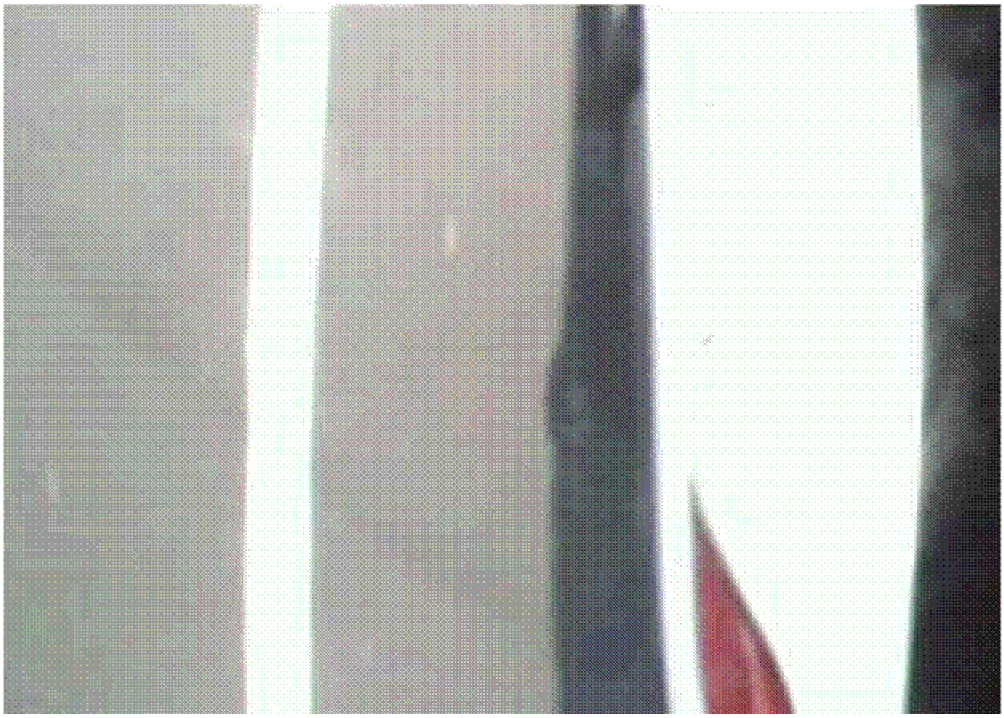


Figure 4-11: Image capture of lane marking for positional accuracy determination

4.2.11.1 Experimental Coordinate Systems

There are several coordinate systems used in this project, such as camera reference system, LLA, ECEF and NED frame reference system. They are introduced as follows.

Camera Frame of Reference The camera frame of reference is given with respect to the camera lens. The normal vector of the lens surface is the camera's Z frame denoted as c Z . The X and Y coordinates are defined by the image reference system, which are denoted as c X and c Y , respectively. In this project, the lens is mounted to be strictly looking down, as is shown in Figure 4-12.

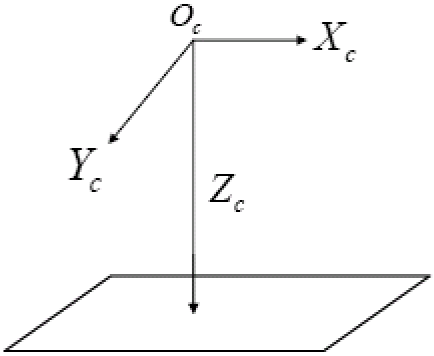


Figure 4-12: Camera frame of reference

4.2.12 Evaluation of VII-Compatible DSRC/NTRIP Architecture

The previous sections have described the testbed location, architecture, equipment, and procedure used to evaluate positional accuracy with the DSRC/Ntrip integrated configuration. This section presents the preliminary results obtained from three different types of experimental procedures. The first procedure was to complete a series of driving routes along the testbed while collecting non-differential GPS data coupled with vision based location measurements. The absolute (ground truth) vehicle location was determined from the vision sensor calculation method. This test procedure was intended to determine the accuracy of the GPS receiver when no DGPS corrections were provided via DSRC. Differential corrections were achieved via WAAS satellite. A total of five driving traces were completed that were approximately 600 m each in length. The average error per driving trace ranged from 0.62m to 0.76m. The average accuracy of all five driving traces was 0.70 m. The Root Mean Square of each driving trace ranged from 0.11m to 0.20m. The average RMS from all five driving traces was 0.17m. These results are summarized in Table 4-5.

	Accuracy(m)	RMS (m)
Test 1	0.756	0.113
Test 2	0.691	0.136
Test 3	0.620	0.159
Test 4	0.732	0.187
Test 5	0.689	0.197
Average	0.698	0.170

Table 4-5: Summary of positional accuracy with no DSRC differential corrections.

A total of 3 tests were completed with the vehicle receiving DGPS corrections via DSRC (Table 4-6). These tests show a significant improvement in average accuracy and a slight improvement in RMS. These results are expected since the corrections transmitted via DSRC are nearly identical to WAAS corrections while originating from a base station in close proximity.

	Accuracy(m)	RMS (m)
Test 1	0.476	0.150
Test 2	0.396	0.101
Test 3	0.237	0.142
Average	0.374	0.166

Table 4-6: Summary of positional accuracy with DSRC differential code corrections

A more elaborate test scenario was completed to demonstrate the variation in positional accuracy. This test scenario consists of 3 conditions:

- Pre-connection - DSRC signal is not available, WAAS DGPS corrections only;
- DSRC acquired – DSRC communication is established and DGPS messages are received via Ntrip; and
- Post-connection – DSRC communication is lost and WAAS DGPS corrections only.

Three tests were completed that allowed the rover vehicle to travel with each connection status.

Table 4-7 provides the results. The positional accuracies are within agreement of the previous tables.

	Accuracy pre-connection(m)	Accuracy with DSRC acquired(m)	Accuracy post-connection (m)
Test 1	0.427	0.246	0.681
Test 2	0.632	0.283	0.390
Test 3	0.681	0.480	0.854
Average	0.506	0.326	0.611

Table 4-7: Summary of positional accuracy with intermittent DSRC differential code corrections.

4.2.13 Recommendations, Conclusions, and Future Work

4.2.13.1 __Summary__

This study has evaluated numerous high accuracy differential GPS correction architectures suitable for California VII implementation. The California PATH program and Caltrans have a number of research applications that can benefit from these high accuracy vehicle positioning implementations. Hardware, software, and configurations have been established to successfully transmit differential GPS corrections via DSRC within the VII architecture. A L1/L2 CORS Trimble base station receiver was purchased, installed, and configured for the CA VII testbed at the MBRDNA facility in Palo Alto. Extensive validation and testing of the DSRC/Ntrip architecture was completed at UC Riverside to verify proper communication and processing of DGPS transmissions within the VII architecture. Positional information was verified with independent vision positioning technology referencing lane markings. Several research goals were achieved with this research evaluation:

- Comparison of positioning performance using NDGPS corrections transmitted via beacon and via Internet – correction quality and positional accuracy has been demonstrated to be dependent on prompt acquisition of a DGPS correction message. The DGPS signal transmission via internet has been evaluated for TCP/IP transmission with a DSRC link to the rover vehicle. Rapid and effective acquisition of a DSRC link is critical for receiving DGPS corrections within a single cell DSRC coverage area;

- Potential of transferring HA-NDGPS corrections to standard formats – this study has reviewed and evaluated the protocols, formatting, and transmission of high accuracy ignals. The HA-NDGPS protocol performs a message compression/decompression sequence which does not degrade the quality of the original RTCM correction message.

- Integration potential of alternative correction signals (RTK, WAAS, CORS etc.) – tests scenarios completed within this study have demonstrated that the DSRC/Ntrip architecture is compatible with RTCM correction messages. Receivers capable of processing multiple sources of corrections can utilize alternate corrections in addition to corrections received via DSRC/Ntrip.

- Integration of HA-NDGPS receivers within CA VII vehicles/applications – the HANDGPS protocols have been found to provide a RTCM compatible correction which is suitable for any L1/L2 receiver accepting RTCM carrier phase corrections. Specifically configured receivers are not necessary if broadcasts are transmitted via TCP/IP protocols (DSRC/Ntrip).

- Geographical distribution accuracy requirements of corrections signals (regional, intersection-only, highway-only etc) – the range and performance of a single DSRC transmission site was evaluated. Performance was found to be greatly dependent upon the rate of acquiring a DSRC communication link;

- Frequency requirements of correction signals – the frequency of transmitting a correction signal was maximized for performance within the scope of this study. Decreasing the frequency would be possible for regions of continuous or semi-continuous DSRC coverage; and,

- Compatibility of RSE/DSRC system design with correction signal size, frequency, format, and vehicle densities – the current study results did not find limitations due to DSRC communication bandwidth. DSRC communication and position quality was primarily by limited DSRC coverage area.

Integration of standard RTCM correction signals with the VII communication infrastructure possesses several desirable characteristics:

- corrections can be sent in a standard RTCM format that many GPS receivers are able to read;
- base station(s) can be placed centrally to the VII areas (e.g., within 50 km of vehicles);
- software and hardware are not proprietary (DSRC/Ntrip);
- the architecture can be expanded to send carrier phase corrections (RTCM 19/20, CMR) for greater accuracy (< 10cm);
- low cost receivers can be utilized for 2m accuracy requirements while more expensive dual channel receivers are utilized for centimeter level accuracy;
- the infrastructure can also be integrated with CORS (in the event HA-NDGPS is not available); and
- the system is easily upgradeable as GPS technology continues to improve.

This DGPS technology implementation and evaluation for the California VII testbed has detailed a new technology architecture suitable for the Group Enabled Mobility and Safety (GEMS) program. This study evaluated this technology in four tasks:

- Acquisition of hardware and software – CORS base station suitable receivers were purchased, Ntrip Caster, Server, and Client computers were acquired, and software was obtained for implementation;
- Configuration of hardware and software – once the necessary components were acquired the integration of software and hardware required detailed configuration of programs, protocols, settings, and communications;

- DGPS Performance evaluation – the detailed evaluation of DSRC/Ntrip positioning performance required a systematic vision implementation of "ground truth" positioning; and,
- VII testbed preparation – having integrate the base station within the CA VII testbed, numerous test scenarios were completed to validate the communication strategies. The system is now ready for testing on a broader scale.

4.2.14 Next Steps

This study has implemented the DGPS/DSRC architecture and demonstrated the feasibility of broadcasting the DGPS corrections over the DSRC network. Initial performance evaluations have demonstrated the potential performance of the architecture. While initial performance has demonstrated the architecture to be successful for positioning applications requiring differential corrections; additional enhancements would be required for deployment beyond specific testbeds, pilots, and demonstrations.

The next step towards a statewide or national integration would be to create compatible software that would determine availability of suitable regional corrections and autonomously initiate transfer. This future development would focus on these following components:

- a review and collaboration with entities maintaining DGPS broadcast networks to establish agreements for automated downloads;
- create software that evaluates current location and searches for spatial appropriate and available correction messages;
- create software that automatically adjusts configuration settings of DGPS Ntrip communications;
- implement and test the automated architecture in VII applications.

Successful implementation of this automated DGPS acquisition architecture would greatly simplify the methodology of acquiring DGPS corrections and provide improved positioning performance of future ITS implementations.

4.2.15 Conclusions

The California PATH program and Caltrans have a number of research applications that can benefit from a high-accuracy vehicle positioning implementation. The U.S. Department of Transportation and U.S. Coast Guard in conjunction with the Interagency GPS Executive Board are currently developing a High Accuracy-Nationwide Differential Global Positioning System (HA-NDGPS), targeted at a variety of transportation-related applications. The HA-NDGPS program provides the capability to broadcast corrections to the Global Positioning System (GPS) over long ranges to achieve accuracy better than 10 centimeters (95 percent of the time) throughout the coverage area. HA-NDGPS is currently undergoing a research and development phase with a future implementation pending U.S. congressional budget approvals. Application of this technology will provide advanced safety features for transportation, including applications such as lane departure warning, intersection collision warnings, and railroad track defect alerts. The California VII Program has established a testbed in the San Francisco Bay area that is being utilized for a variety of experiments. With the integration of vehicle and roadside communications (DSRC), the determination of vehicle location has become a critical component for several VII applications. One of the key accomplishments of this study is to demonstrate that the existing VII communication infrastructure (i.e., Dedicated Short Range Communications

(DSRC), roadside equipment) can be utilized where possible for broadcasting corrections to the vehicles' GPS receivers. This eliminates the need to depend on other communication methods to receive correction signals, resulting in greater control and lower costs. This architecture compliments the potential use of existing DGPS broadcast networks such as: the California statewide CORS, NDGPS, and/or NGS. Further development of this DSRC/Ntrip architecture will allow for additional sources of GPS corrections without limiting alternatives. Finally, the implementation of the DSRC/Ntrip architecture utilizes differential corrections which are available and broadcast nationally, as well as, internationally.

5 Conduct Testbed Operations

5.1 Support VII California Operation and Maintenance

5.1.1 Provide Physical Support

Provide RSE and other roadside operations and maintenance support and interface with Caltrans DRI and District 4 as an adjuct to Task 1a, which develops the expanded VII California testbed to accommodate emerging US DOT POC and DTE requirements.

5.1.2 Perform Automatic RSU Monitoring

Monitoring more than a few RSUs is labor intensive and error prone. Likewise, maintaining a table of installed RSUs and their status is labor intensive and inevitably out of sync. We propose to develop two programs, the RSU monitor client and the RSU monitor server. The RSU monitor client runs on the RSU host device and periodically checks hardware and software status, fixes what can be fixed, and reports status to a port on a central server. The RSU monitor server listens for those RSUs (possibly taking action if an RSU is not heard from), digests the reports, and formats them for display on the web, where status information was available for the use of Caltrans and of automobile manufacturing partners. The RSU monitor server will also produce periodic summary reports of RSU performance over time.

The RSU monitor client will report on the host device hardware and operating system, the Denso WRM, the type and status of the backhaul connection to the Internet, the GPS location, any information from a co-located traffic signal controller, and installed software version and status. The RSU monitor server at PATH will listen for RSU monitor client connections and display a table of active RSUs, showing ID, location, configuration, status, etc., with options to access more detailed information. The server will also send an alert email to administrators if anything needs attention.

5.2 Support User Experiments and Demonstrations

In this task, other participants of VII California was individually queried and supported on a level of effort basis to ensure that VII California Proof of Concept testbed meets their requirements, if possible within technical and cost constraints of testbed installation and future maintenance.

Part of this user experiment support was to consider on-board equipment interface with tolling applications on the Dubmbarton Bridge, which would scope any build activity and specify the necessary bill of materials.

Also, as part of this task, demonstrations that integrate VII California applications was provided. The intent is to show VII California successes and development in an integrated fashion to current and future stakeholders. Importantly, this integrated demonstration will 'prove' to the Caltrans constituency the viability of VII, at least to the extent that it could be replicated within the Proof of Concept testbed. While the period of performance for this subtask is one month, the actual test is expected to fall within that range.

6 Conduct Testbed Applications Research

6.1 Examine Probe Messaging

The current phase of research on VII probe data processing has produced (and is producing) the following results:

- Implementation of the Noblis Trajectory Conversion Algorithm (TCA) program to process simulation outputs from the PATH (PTTL) VISSIM simulation of El Camino Real, following the J2735 probe sampling protocols
- Analysis of TCA outputs to identify substantial latency in probe snapshot uploads under default conditions
- Examination of changes to probe message management protocol to significantly reduce latency to support the most time-critical probe data applications
- Exploration of effects of market penetration on aggregated probe data granularity (in both time and space)
- Evaluation of effects of local aggregation (at RSE) on backhaul data rate and RSE computational burden for some representative types of probe data (weather status, dropped load, traffic speed).

This work is still scratching the surface of a substantial topic, with the potential to influence the developing SAE J2735 standard and expectations for future use of VII probe data. We have been in close contact with Noblis, who are studying the probe data processing issues for the national VII program, with substantially larger resources at their disposal, to ensure that our work remains complementary to theirs rather than duplicative. They have been focusing on detailed evaluation of the SAE J2735 protocols and sensitivity studies to evaluate the suitability of the key features of SAE J2735, with a strong emphasis on the Day One VII applications and relatively low market penetrations. We have been considering the needs of some of the longer term VII applications and market penetrations up to 100% in order to ensure that the VII probe approach is scalable to a fully mature VII system. We plan continuing consultations with the Noblis staff to maintain the complementarity of our efforts.

During the coming year, we are planning to address the following important VII probe vehicle data sampling issues:

• Testing performance in a new urban network currently being studied by Noblis (the Van Ness corridor in San Francisco), which appears to have some advantages over our current El Camino network;

• Developing improved algorithms for estimating network speed from probe samples, since simple averaging introduces significant biases;

• Developing and evaluating semantic approaches for reducing the backhaul burden associated with probe data, complementary to the aggregation approach currently being evaluated;

• Evaluating the effect of adjusting the in-vehicle snapshot buffer size and buffer management rules based on considerations of market penetration and density of RSE installations;

• Seeking another network model that can be used for freeway probe studies, and including urban fringe areas where RSEs was sparse or non-existent;

• Investigating strategies for maximizing the effectiveness of probe data sampling at the boundaries of regions that are equipped with RSEs, so that the snapshots collected in unequipped regions are not lost unnecessarily. Other issues that could potentially overlap with Noblis' work was considered, but only explored if we can determine that Noblis is not addressing them:

• evaluating snapshot management alternatives to make most efficient use of the available buffer;

• increasing the snapshot buffer size, particularly under low market penetration conditions;

• evaluating the effect of changes in the snapshot management rules on the load imposed on the DSRC wireless channel;

• evaluating suitability of the default snapshot sampling rules under a range of traffic conditions, including heavy congestion.

6.1.1 Background

Increasing interest has been shown in recent years in the use of vehicles or mobile devices as traffic data probes, as these have become more economically attractive. They offer the potential for collecting real-time traffic and other condition data on all roads without requiring widespread installation of special-purpose traffic detectors. The large national and international projects on vehicle-infrastructure cooperation have accelerated development of probe data collection ideas and methods.

In the U.S., Vehicle-Infrastructure Integration (VII), recently rebranded as IntelliDrive, assumes that probe vehicle data was collected by large numbers of vehicles (eventually, all road vehicles) and uploaded to the roadside using DSRC (dedicated short-range communication) wireless transceivers. The VII development activities have included definition of rules for sampling and uploading probe vehicle data, which are described in a "Recommended Practice" under development by the Society of Automotive Engineers (SAE J2735). Although SAE J2735 has been developed based on the specific characteristics of DSRC communications, the J2735 Traffic Information Subcommittee that focuses on the probe issues intends for its probe message to be used with other communication media, not only DSRC.

The VII program has developed a broad set of principles for protecting the privacy of drivers whose vehicles are equipped with VII capabilities (1). The authors of SAE J2735 have adopted a variety of restrictions on probe sampling to try to protect privacy, but the implications of these restrictions have not previously been fully explored. In our current work, we have extended our prior simulation work on probe data sampling, reported in our previous VII California report and two technical papers (2, 3) to explicitly show how the J2735 probe sampling rules are likely to affect both privacy and the quality of the resulting traffic condition estimates.

6.1.2 Technical Approach

Since it would be extremely costly to conduct full-scale probe data collection experiments with the density of vehicles needed to obtain high-quality data, the approach chosen here is traffic micro-simulation. A VISSIM simulation of a 10 km section of El Camino Real, a major arterial in Palo Alto and Mountain View, CA provides the "truth model" of individual vehicle motions in dense traffic. VII Roadside Equipment (RSE) are assumed to be installed at 20 signalized intersections along this corridor, in addition to nearby intersections on the cross streets. The probe snapshot sampling and uploading are represented according to the SAE J2735 rules by using the TCA post-processor of the simulated vehicle trajectories, which was originally provided to us by Noblis but has been heavily modified to model more recent revisions of the probe snapshot sampling rules.

The results reported in our previous VII California report and technical papers (2,3) were based on earlier versions of SAE J2735 with less stringent privacy protections, and some of the privacy protections were not fully implemented in our simulations at that time. Those simulations also represented an earlier model of the El Camino Real corridor, which has subsequently been updated to include more recent trip generation data and the current traffic signal timing. Additional changes to the traffic simulation, which make it difficult to directly compare our previous simulation results with the results to be reported here, include:

- removal of heavy vehicles, which were producing anomalous traffic speed distributions as they were modeled in VISSIM
- increasing the maximum speed from 30 to 45 mph to more accurately represent conditions on the corridor
- extending side streets up to 1 km away from the mainline El Camino Real, providing room for additional RSEs on those side streets, where probe snapshots from turning vehicles could be captured.

The TCA post-processor has been modified to represent alternatives to the J2735 rules, so that their effects on the quality of the traffic condition estimates can be quantified, at the same time that their implications for privacy are discussed. Additional changes to the TCA since the prior studies, primarily to provide more accurate representation of the new J2735 rules, include:

- more frequent probe sampling at slower speeds
- no generation of snapshots while vehicles are stopped

- added randomized gaps in snapshot generation between temporary vehicle ID number assignments, which occur each time the vehicle uploads its accumulated snapshots when it first comes within range of a new RSE
- deleting snapshots that would cause the same temporary vehicle ID number to be broadcast to more than one RSE
- over-writing periodic snapshots when the snapshot buffer is filled, following a strategy that preserves some of the oldest data while adding the newest data
- added ability to modify all parameters that could be specified by the Probe Message Management function, which has provisions that enable each RSE to override the default probe message management rules
- added ability to track elapsed time and distance traveled between snapshots (for diagnostic purposes only, since this is not permitted by J2735 in order to prevent snapshot association that could theoretically facilitate data mining to undermine privacy).

6.1.2.1 Effects Of Changes On Probe Data

The simulations of the original scenarios were repeated with the modified VISSIM model and TCA to determine the extent to which they would change the results. One of the primary changes resulting from the revisions to the TCA was in the snapshot latency, which was reduced somewhat from the previous values for the default conditions, as shown in Figure 6-1. These changes provide some improvement in the usability of the data for general traffic management and traveler information applications, but are not significant enough to improve usability for real-time adaptive traffic signal control. The expansion of the VISSIM model to include additional RSEs on the cross streets, which is a more realistic representation of the likely real-world implementation of VII, increased the percentage of snapshots that were successfully uploaded to an RSE from approximately 80% (as reported in our previous simulation results) to approximately 90% as shown in Figure 6-1.

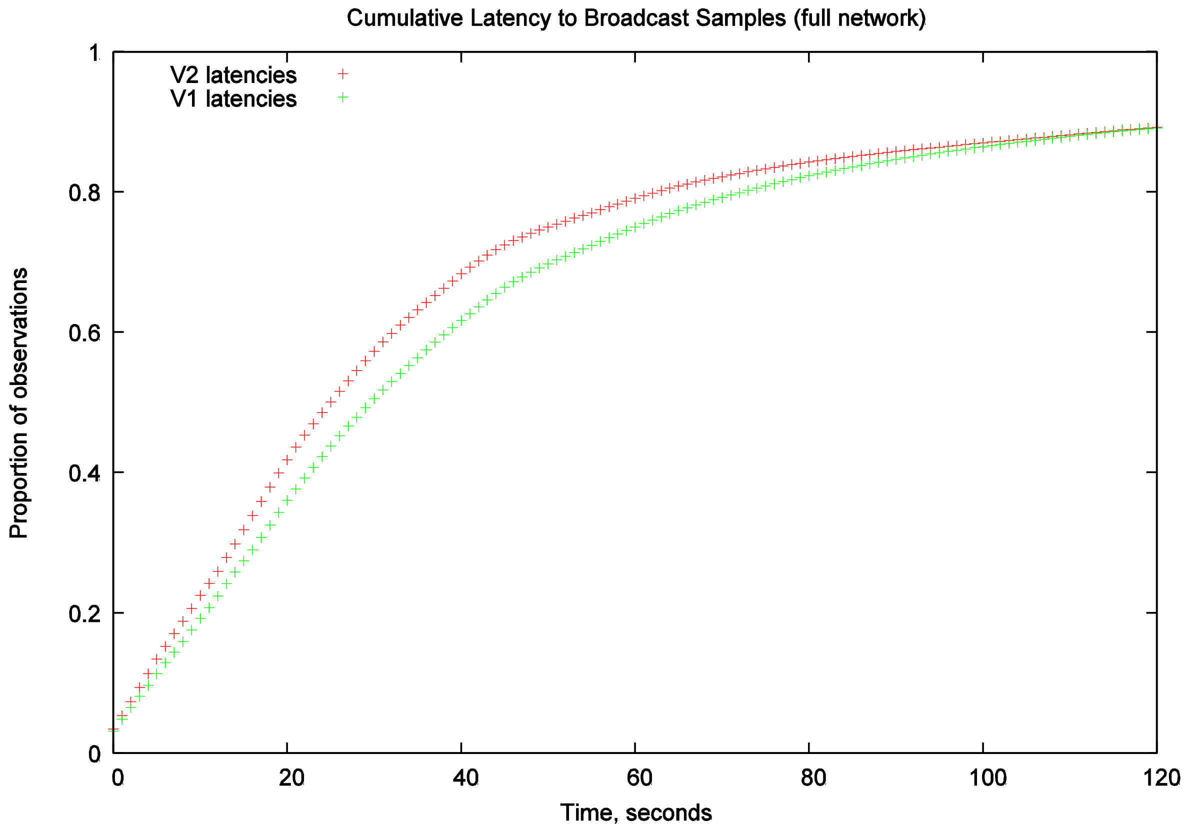


Figure 6-1: Cumulative Distribution of Snapshot Latency from Original TCA (Lower Curve) and Updated TCA (Upper Curve)

The correction of the representation of the J2735 sampling of stopped vehicle cases (no snapshots generated once vehicles have stopped, with snapshots not resumed until they have accelerated to 10 mph) leads to a significant under-reporting of stopped compared to moving vehicles. Figure 6-2 is a histogram of the numbers of snapshots at various speeds, compared to the number of ground-truth simulation observations at the same speeds. The zero speed cases represent more than 26% of the ground truth samples, but they are less than 15% of the probe snapshots. In contrast, the probe snapshots are somewhat over-represented at the speeds below 20 mph because the snapshot sampling frequency is reduced as the speed increases above 20 mph. The net effect of these artifacts of the snapshot sampling rules is that simple averaging of snapshots will produce biased estimates of speeds and travel times unless the speed values can be weighted by the time between the snapshots. Unfortunately, the privacy protection provisions do not permit inclusion of the time between snapshots in the message, since these could facilitate snapshot association and off-line trajectory reconstruction. While the time between snapshots can be calculated for associated snapshots, in the suburban arterial setting studied here there are a substantial number of cases where such data cannot be computed because temporary vehicle IDs must change frequently.

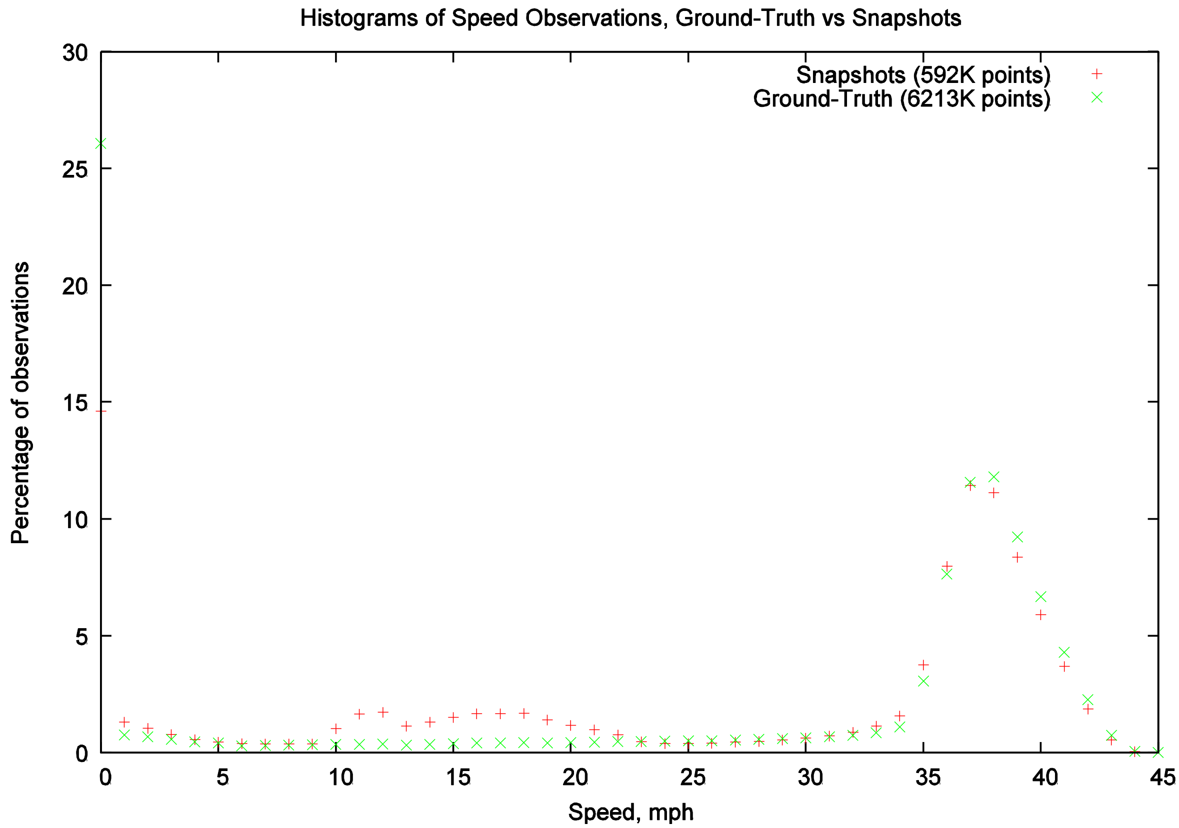


Figure 6-2: Histograms of Speed Samples from Ground Truth Simulation and Probe Snapshots Sampled According to SAE J2735, for Complete Corridor

6.1.3 Privacy-Protection Strategies

Several strategies have been adopted in SAE J2735 in the name of privacy protection, with varying impacts on the usability of the probe data:

(1) No snapshots are saved from first 500 m of driving to conceal precise trip origin. This is likely to have a limited impact on traffic condition data, except for loss of precise origins and loss of very short trips.

(2) Vehicle temporary identification attached to each snapshot sample is changed after 120 seconds or 1 km of travel, whichever comes later, and also when each vehicle enters within DSRC range of a new RSE. This means that estimates of travel time or average travel speed can only be calculated for these short segments, but cannot be associated over longer ranges. Furthermore, an interval of random duration between 3 and 13 seconds or random length between 50 and 250 meters is inserted before snapshot sampling can resume with the new temporary ID, leaving blind spots in the simulation record so that the consecutive temporary ID numbers cannot be linked together for any individual vehicle in off-line data mining.

(3) Snapshots contain only instantaneous sampled measurements, but do not contain any measurements that permit association with prior snapshots (such as time or distance elapsed since previous snapshot). This makes weighted averaging of snapshots to obtain more realistic

aggregation of snapshot data difficult at best, except when it is impossible because snapshots cannot be associated across temporary ID boundaries

The prohibitions on association of snapshots were motivated by concerns about possible data mining of snapshot databases to reconstruct individual vehicle trajectories that could lead to identification of individual travel behaviors. However, if the snapshots were to be aggregated at the RSE and only the aggregate values were reported on the backhaul network for access by subscribers, all the privacy-sensitive information would die at the RSE. In this case, it should be possible for the probe messages to permit complete association of snapshots into full vehicle trajectories at the RSE, without compromising privacy.

The direct effect of the random-duration gap between temporary ID numbers, with no snapshots being taken, can be seen in Figure 6-3. This represents the locations of the probe snapshots for the full simulation period covering an hour of simulation and 40 minutes of warmup at the intersection of El Camino Real and Showers Drive in Mountain View, CA. Each dot represents a snapshot, and the figure shows that the changes of temporary ID around the maximum communication range of the RSE produce consistent blind spots in the probe sample data record. This can be particularly detrimental to traffic management applications if the blind spots occur near the ends of the queues produced by the traffic signals because it then becomes impossible to determine the length of these queues.

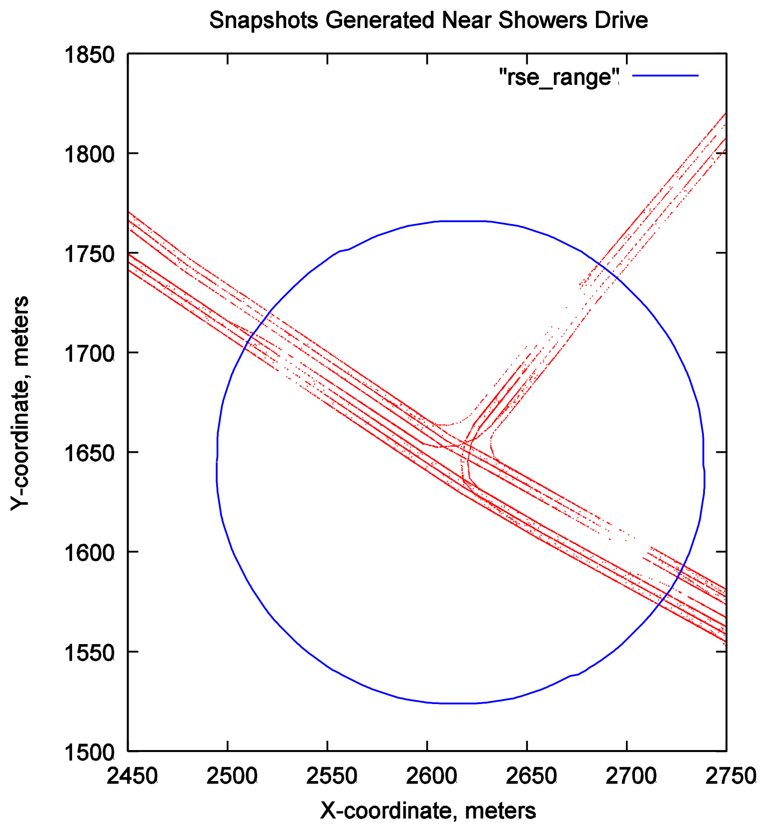


Figure 6-3: Simulated Probe Snapshots at El Camino Real and Showers Drive, Showing Blind Spots Where Temporary ID Numbers are Changed

6.1.4 Distortions To Speed Estimates At Signalized Intersections

The default snapshot sampling rules appear to have been designed to minimize the number of snapshots created, with a particular focus on highway applications rather than signalized arterials. The representation of stop-and-go traffic patterns at traffic signals is significantly impacted by the restrictions on snapshot sampling, particularly the absence of snapshots when vehicles are stopped and the restriction on generating snapshots until they have accelerated to at least 10 mph. The effects of this on the distribution of speed samples was tested at two intersections along the simulated corridor, one that required relatively limited stopping by the traffic along El Camino and another that required significant stopping (because of heavy traffic that has to be served on the cross street).

The probability density and cumulative distribution of speed samples on southbound El Camino at the minor intersection, Calderon, are shown in Figure 6-4 and Figure 6-5 for both the ground truth simulation results and for the snapshot samples generated according to the J2735 rules. In the ground truth simulation, vehicles were stopped an average of about 27% of the time, but only 20% of the snapshots were for stopped vehicles. All the speeds below 13 mph were under-represented in the snapshots, while speeds above 13 mph were over-represented. The true average speed on this network link was 21.7 mph, but the average of the snapshots that were uploaded was 20.5 mph, representing a 5.5% under-estimate of the link speed. When these snapshots were used to estimate a weighted average speed (weighted by the time since the previous snapshot), this produced an average of 22.8 mph, a 5% over-estimate of the link speed.

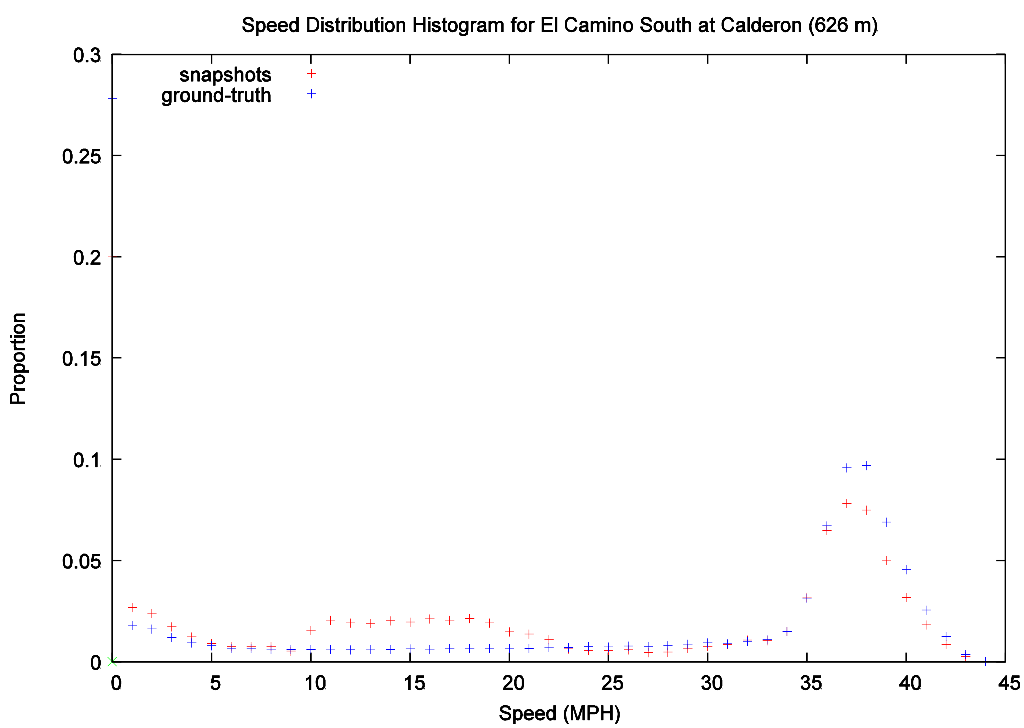


Figure 6-4: Probability Density of Ground Truth and Probe Snapshot Speeds at a Minor Signalized Intersection

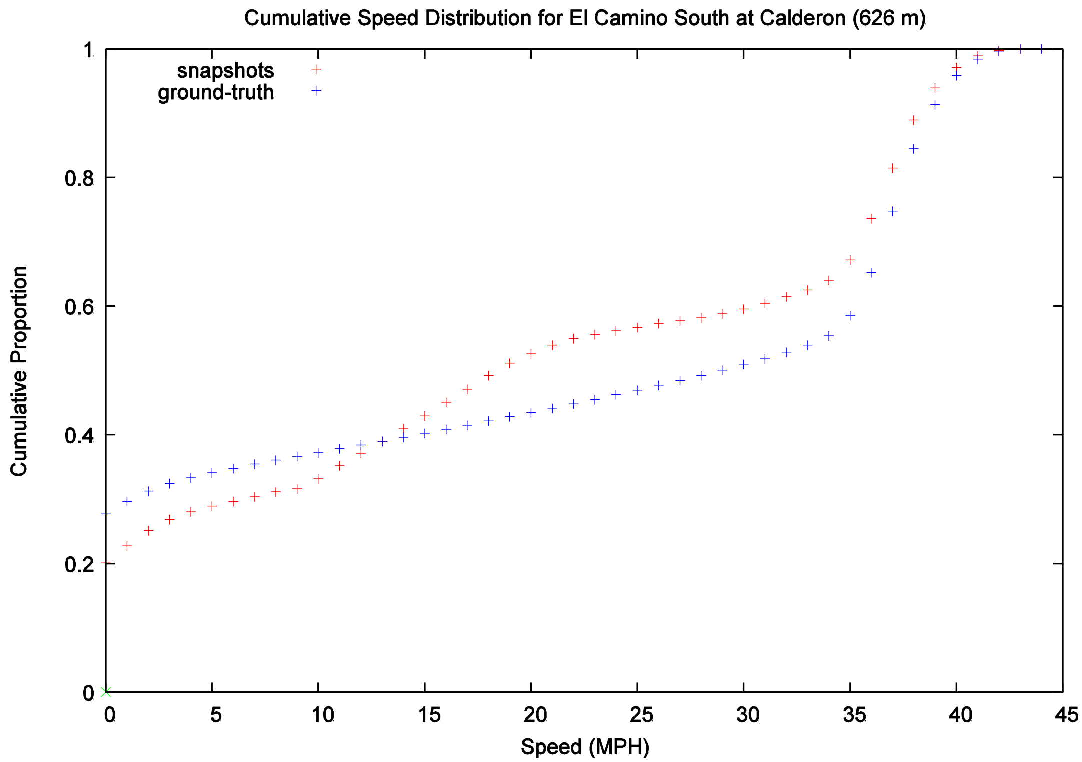


Figure 6-5: Cumulative Distribution of Ground Truth and Probe Snapshot Speeds at a Minor Signalized Intersection

The speed accuracy problem was significantly more serious at the major intersection with Page Mill Road, where much more of the southbound El Camino traffic was required to stop at the traffic signal, as shown in Figure 6-6 and Figure 6-7. Here, the ground truth simulation results show that 44.5% of the samples were for stopped vehicles, but only 23% of the probe snapshots were at zero speed. As Figure 6-7 shows, all speeds below about 35 mph are under-represented in the snapshots, producing a serious negative bias in speed estimates. The ground truth average speed on this link was 16.7 mph, but the average value of the speeds of the probe snapshots that were uploaded was 20.5 mph, which is high by almost 23%. When the snapshot speeds were weighted by the time since the previous snapshot (likely to be a laborious process in real-time probe data processing, with each snapshot having been uploaded as an independent sample), the average speed came down to about 20 mph, which was still high by 19%.

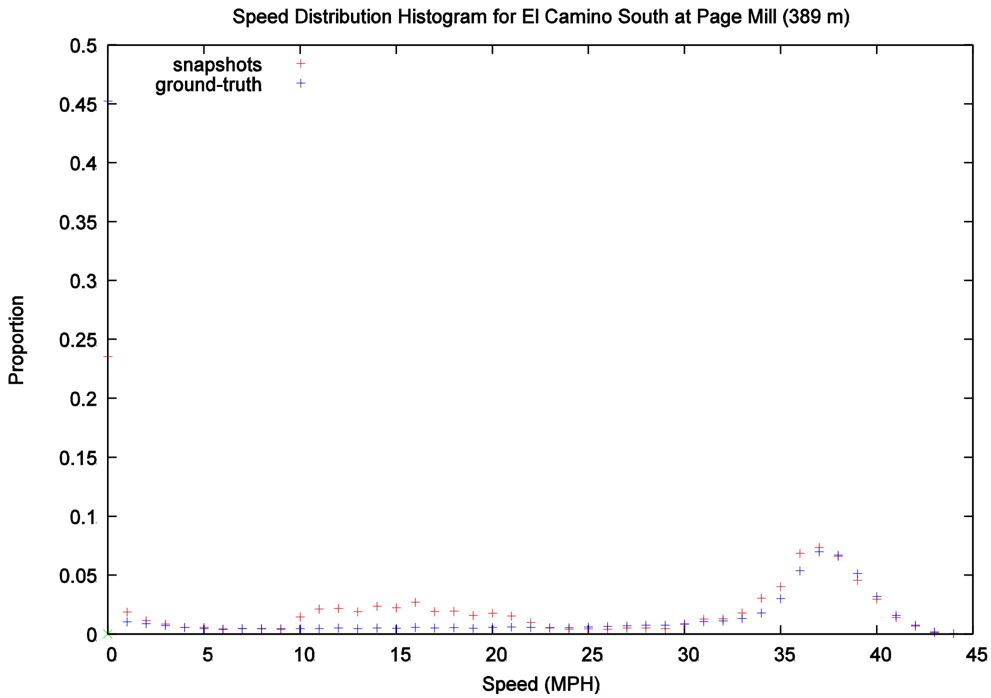


Figure 6-6: Probability Density of Ground Truth and Probe Snapshot Speeds at a Major Signalized Intersection

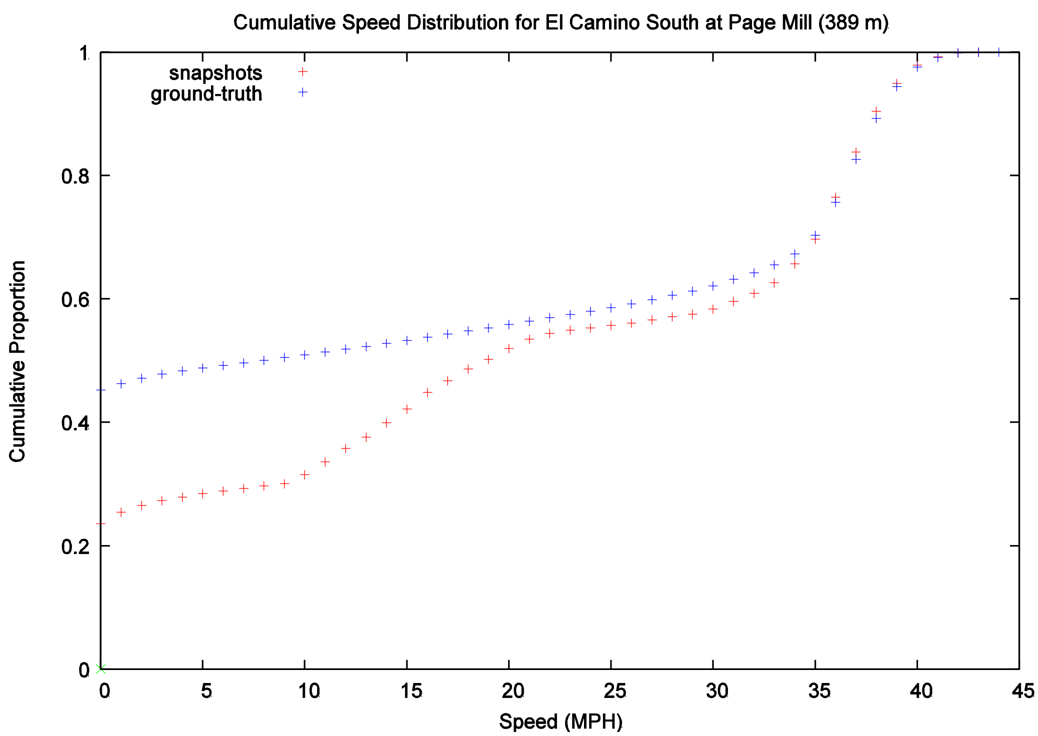


Figure 6-7: Cumulative Distribution of Ground Truth and Probe Snapshot Speeds at a Major Signalized Intersection

In order to advance beyond relatively simple averaging of the biased snapshot samples as seen in these figures, it is necessary to associate sequences of snapshots to reconstruct vehicle trajectories. The privacy protection rules impose severe limits on the lengths of snapshot segments that can be associated, which limits the usability of the data. In order to determine how severe a constraint this would be in practice for a signalized arterial application, the distribution of snapshot segment sizes was investigated for the simulated corridor. The cumulative distribution of the number of snapshots per segment is shown in Figure 6-8, followed by the duration of each segment in Figure 6-9 and the physical length of each segment in Figure 6-10.

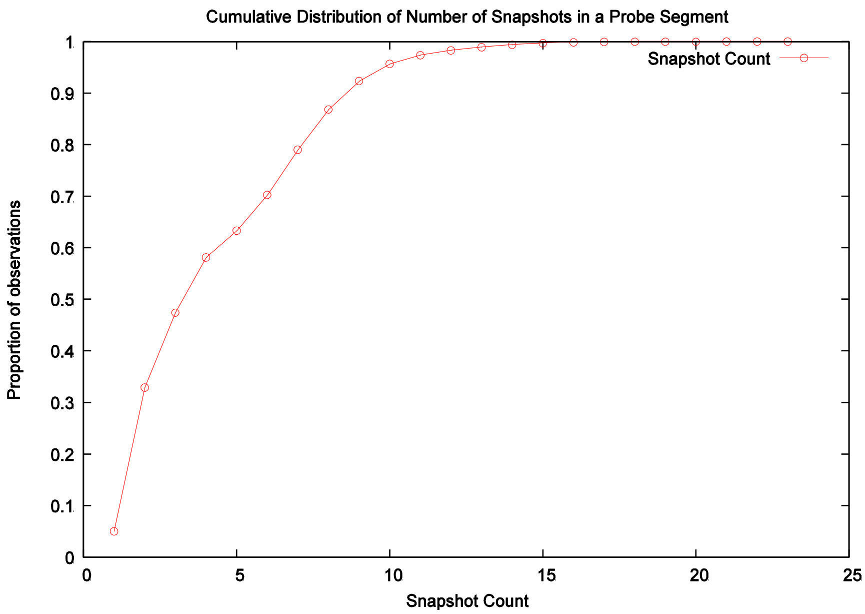


Figure 6-8: Cumulative Distribution of Number of Snapshots per Segment

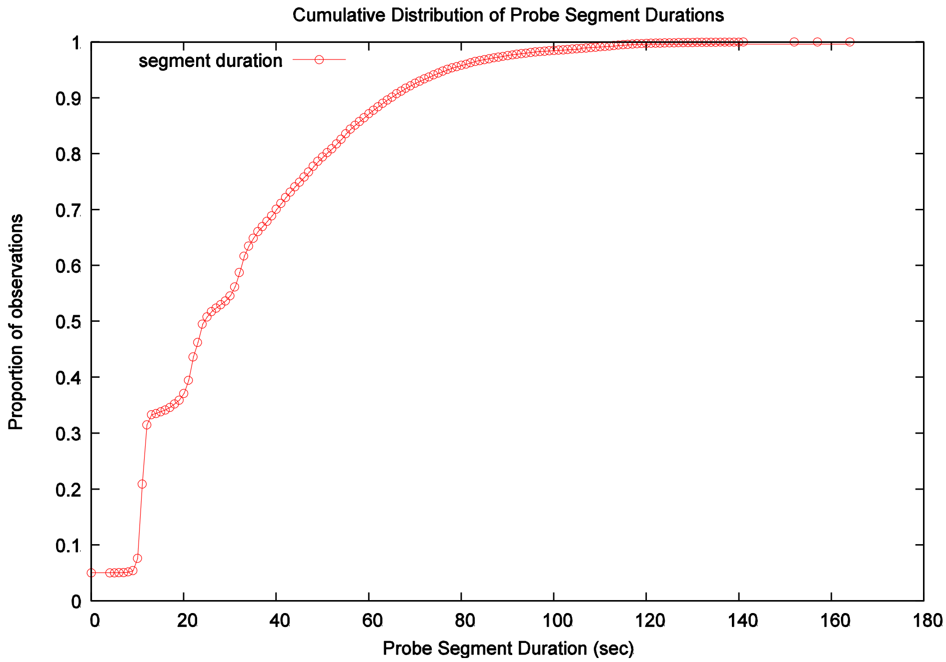


Figure 6-9: Cumulative Distribution of Snapshot Segment Duration (seconds)

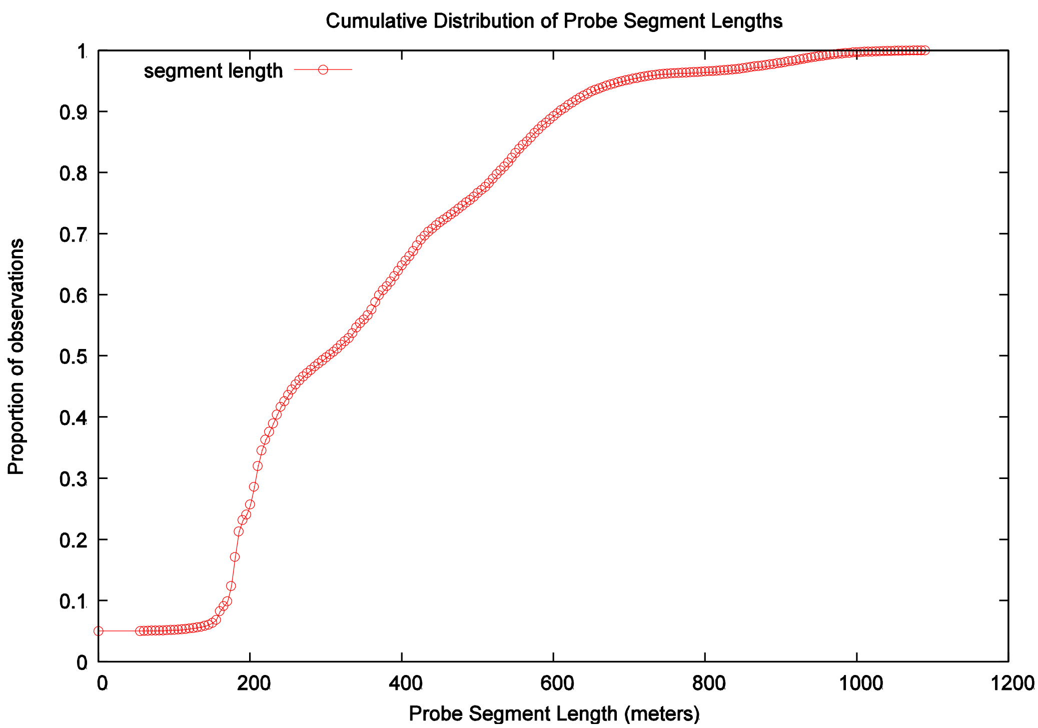


Figure 6-10: Cumulative Distribution of Snapshot Segment Length (meters)

In the simulated corridor, the median number of snapshots per segment is only three, the median duration is only about 25 s and the median distance covered during this time is only about 300 m. This preponderance of short snapshot segments means that in general only very short sections of vehicle trajectories can be estimated, making it difficult to provide accurate estimates of key traffic condition parameters such as speeds, travel times and queue lengths. Note that the large majority of these snapshot segments are already much shorter than the limits defined in SAE J2735 (120 s or 1000 m, whichever is larger) because their lengths are governed by the requirement to change temporary ID, thereby terminating that probe snapshot segment, each time a vehicle encounters a new RSE.

If the RSEs were installed further apart than in the simulated example, the probe segments would be longer. Even here, we did not assume an RSE to be installed at every signalized intersection along the corridor we simulated, while the VII program has assumed RSEs to be provided at all signalized intersections within the largest urbanized areas. Although reducing the RSE density would reduce the cost of RSE installation, it would also have important negative consequences:

- Significantly increasing the latency from snapshot sample time to snapshot upload to the VII network
- Increasing the data traffic that each RSE's backhaul communication link needs to handle
- Increasing the risk of onboard snapshot buffer overflows, leading to the loss of some snapshots.

6.1.5 Alternative Strategies for Consideration

The current default privacy-protection strategies render it impossible to collect the complete linked origin-destination data that transportation planners covet, unless individual travelers "opt in" to permit their travel behavior to be monitored. It is unlikely that the travelers who would elect to opt in would be genuinely representative of all travelers, so any such estimates are likely to be biased. This restriction may be unavoidable, but it has not been widely recognized how severely the privacy protections also limit the fidelity and usefulness of more aggregate real-time traffic volume, speed, queue length and travel time information that transportation operations people need. Serious thought needs to be given to this issue, so that the costs and benefits of the current privacy protection strategies can be weighed against each other. In particular, it's important to make sure that the pendulum does not swing so far to the side of privacy protection that the probe data are not adequate to serve their intended purposes for traffic management, as well as traveler information.

Strategies that are worth consideration for enhancing the effectiveness of VII traffic probe data include:

(a) Eliminating the restrictions on snapshot association, but protecting privacy by doing the data aggregation locally at the RSE and not sending any of the raw snapshot data on the backhaul link.
(b) Establishing uniform sampling rates (by time or distance) that would allow simple aggregation strategies to produce accurate results, for instance by causing each vehicle to create

a snapshot every 6 seconds or 50-100 meters. Accurate aggregation of data from the snapshots could then be done by simple averaging, without the need for association.

(c) Allowing individual vehicles to broadcast probe snapshots only to every other (or every Nth) RSE. This would allow generation of longer trajectory fragments in arterial environments and would avoid the problem of gaps in the sampling at RSE boundaries. This would require higher market penetration rates to generate data of comparable completeness, would increase latency between the time a snapshot was sampled and when it was received by an RSE, and would require aggregation to be done on a regional level rather than at individual RSEs, so it is probably less desirable and (a) or (b) above.

In arterial settings, the default sampling rules interact poorly with the default privacy rules. The default sampling strategy imposes nonlinear biases in the snapshots that preclude simple aggregation of the probe data in a completely unassociated way, and the privacy rules force the trajectory segments to be small, severely limiting the applicability of association to snapshots within those segments.

Strategy (a) would represent a significant change from the current VII information architecture, but it would have several additional benefits:

- greatly reducing the volume of probe data that needs to be accommodated on the backhaul communication link from the RSE, saving significant backhaul costs;
- providing a more efficient distributed data processing architecture, requiring much less central data processing capability;
- greatly simplifying the job of the subscribers to the probe data service, who would not need to manage such large data flows and would not need to implement their own data aggregation systems.

Strategy (b) represents a more modest change from the current approach, with some loss of efficiency in snapshot creation (creating more snapshots), but it could produce much more useful outputs. The potential efficiency loss (larger than minimum possible number of snapshots uploaded) would only become a problem at later stages of implementation, when the market penetration of equipped vehicles is very high. Strategy (c) is in some sense comparable to lowering the density of RSE installations, with similar disadvantages to those explained earlier, but it might be acceptable when there is already a high market penetration of VII probe vehicles.

Additional simulation studies are needed to explore these strategies in more depth, so that their advantages and disadvantages can be quantified and incorporated in VII system design trade-offs. This will involve coding the data aggregation processes and then simulating them over a range of market penetrations and traffic conditions, determining the quality of the useful transportation output data that can be extracted and the volume of data that has to be transmitted, stored and manipulated in the process. The results of these studies need to be brought into the J2735 standardization process so that the probe management rules can be adjusted accordingly to find a better balance among privacy, efficiency and data usefulness.

6.1.6 *Additional Probe Data Research Needed*

The current study has focused on the specific limitations that privacy concerns have imposed on VII probe data sampling. This is just one many issues that need attention in the development of comprehensive probe data collection and processing systems. Probe vehicle systems have been gaining increasing attention within the past year, extending beyond the scope of the original VII program.

The national VII program included a probe data collection function in its Proof of Concept (POC) test in Michigan, and following that test UMTRI has been doing simulation studies to extrapolate from the POC test to explore the implications of broader probe vehicle deployment. Meanwhile, the Mobile Millennium project at CCIT has been developing a dramatically different approach to probe data collection using GPS-enabled cellular phones. U.S. DOT has expressed a broader interest in the use of probe data from any available sources, and has organized national workshops on that subject. The emphasis in the latter two projects has been heavily weighted toward creation of information that travelers can use to make better trip choices based on current aggregate traffic conditions. These kinds of applications require less precision, timeliness and spatial and temporal resolution than the more microscopic traffic management applications that have been considered in the current study.

Other aspects of traffic probe data collection and processing that need attention include:

- testing probe sampling strategies on diverse networks beyond the suburban arterial corridor that was tested here, including urban downtowns, urban fringes, metropolitan freeway systems, and rural roads;

- developing improved strategies for estimating network speeds from the available probe samples

- evaluating a range of snapshot buffer sizes and strategies for managing snapshot buffers (when to over-write old snapshots, how to adapt buffer strategies when expected uploading opportunities are delayed, etc.)

- investigating strategies for maximizing the effectiveness of probe data sampling at the boundaries of regions that are equipped with RSEs, so that the snapshots collected in unequipped regions are not lost unnecessarily

- testing local aggregation of snapshots at individual RSEs and at clusters of RSEs, assessing the data processing and communication burdens and quality of outputs achieved

- developing and evaluating semantic approaches for reducing the backhaul burden of probe data collection, complementary to the aggregation approach

- developing and evaluating strategies for automatically modifying default probe sampling strategies when incidents occur, so that more comprehensive data can be collected about the incident conditions.

6.2 Develop VII-enabled Curve Speed Warning

6.2.1 Introduction

The objective of this work is to realize one of the concept of improving drivers' safety in a preventative and cooperative manner by VII: effectively assisting drivers in safely and rapidly negotiating curves using the on-board curve speed warning (CSW) system. This system will integrate critical information provided by RSE, digital map and the on-board sensors to enhance its performance. The effectiveness of the developed system was demonstrated on a number of chosen ramps equipped with the RSE.

To address this, a VII California RSE installation at March Rd and US-101 was established last year; it was selected on basis of relatively high curvature and incidence of crashes at that locale. The four technical components shown in the Marsh Rd installation (and Figure 6-11) can be explained as follows:

Detection of a Ramp: The RSE broadcasts messages at a constant rate (~1Hz) to notify approaching vehicles of the existence of the ramp ahead. Typically, the antenna of the RSU are located within the normal transmission range (~200 m)[1] from the entrance of the ramp in such a way that the missed reception of the RSU messages can be minimized[2] and that the system has ample time for computation and reaction.

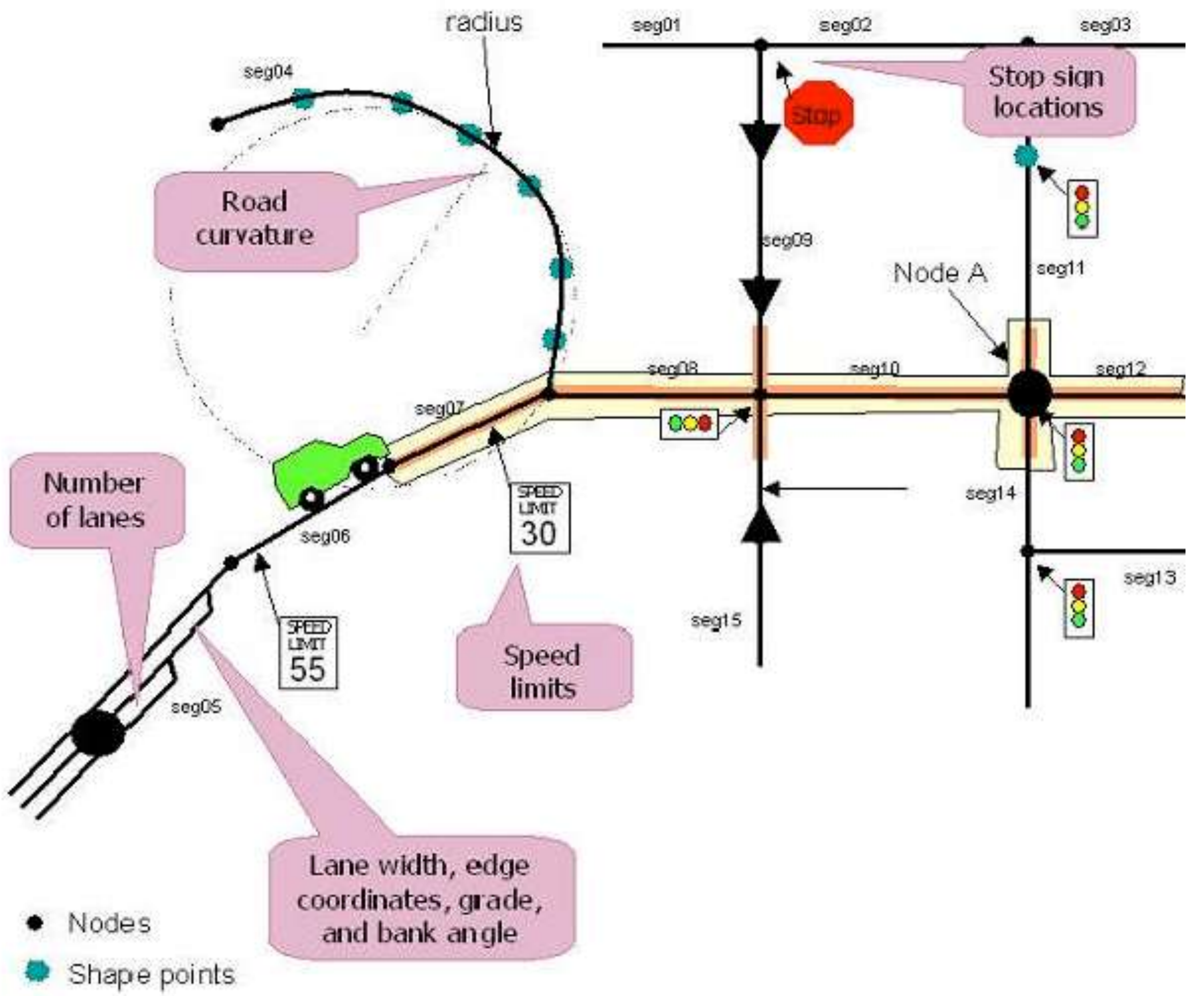


Figure 6-11: Concept of operation for the ramp example of CSW

6.2.2 Data Transmission and On-board Computation:

Besides notifying the approaching vehicles of the upcoming ramp, the RSU transmits position data and associated static and/or dynamic attributes corresponding to pre-selected points on the curve. Appropriate speed limits will then be computed in the host vehicle using received road attribute data[3], road curvature derived from the map as well as static/dynamic vehicle parameters.

6.2.3 Decision Making:

The system determines if the host vehicle indeed enters the ramp and thereby applies computed

1 The limit of transmission range is assumed to be the normal DSRC transmission range.
2 Vehicles may receive identical messages multiple times, which enhances the robustness against packet loss of wireless communication.
3 Presumably, speed advisory provided and/or anomalous road surface condition detected by previous vehicles are also in the transmitted message from RSU.

speed limits to monitoring the subsequent vehicle movement on the ramp. In addition, the system utilizes the on-board sensors to observe the dynamic response of the host vehicle in order to report dynamic speed advisory as well as the detected dynamic attributes if applicable, e.g. icy/slippery spots, to the nearby RSU[4].

6.2.4 Warning Generation:

An appropriate warning message or alarm is given to the driver through an in-vehicle HMI[5] (Human-Machine Interface) when the actual speed exceeds the speed limit. If any potential hazard is detected, a warning message can also be sent to the RSU to further warn or advise other unequipped vehicles.

In the continuation of the first year work, the objectives are to develop a prototype CSW system and to demonstrate the CSW effectiveness on several chosen ramps on highway US 101 (close to Palo Alto). The prototype system will integrate information from the on-board sensors, digital map, and RSU to provide speed advisory signals via appropriate computation. Field tests was conducted in collaboration with participating automobile companies.

7 Management

7.1 Outreach

This task is an ongoing level of effort for the entirety of the project, as it is important that all along outreach and education to a host of stakeholders is continually achieved. While it is important to increase participation from stakeholders, it is also important that other organizations understand and as they feel fit, input, to the *VII California* project. As part of this outreach, the VII California website (www.viicalifornia.org) was updated and maintained.

Outreach will not be limited to vehicle OEMs. While the field of automobile OEMs was expanded if possible, to include other automobile manufacturers, additional contacts was made with truck manufacturers (individually and through the California Trucking Association and American Trucking Associations), bus manufacturers and operating agencies. Other targets will include the "backhaul" industry – those that can effect efficient transport of VII data and information to center and back to the driver, e.g., communication companies, and potential service providers.

7.2 Testbed Coordination

This task focuses on providing VII California testbed meeting, scheduling and other coordination activities that team partners entrust to PATH (e.g., agenda and minutes from team meetings).

7.3 Reporting

We will provide written quarterly status reports, along with a task report at the completion of each of the six steps described above. We will also schedule quarterly meetings with DRI representatives to discuss progress and was available for more frequent teleconferences as required. The final report will combine the results of Tasks 1 – 7 and was accompanied by a briefing to DRI.

Group-Enabled Mobility and Safety (GEMS)

1 Introduction

With the “Group-Enabled Mobility and Safety” project (GEMS), California PATH demonstrated a thorough implementation of the kinds of applications that leverage the considerable connectivity and infrastructure investment of SafeTrip-21, bringing safety and mobility to consumer devices.

In this report we was describing the implementation of these applications, and the fulfillment of the tasks set out in TO6217.

We will discuss our situational awareness applications, which gives driver access to a wide range of information. This kind of information includes pedestrian crossing, trucks entering, street closure, school zone, speed changes, and workzones. Increased driver alertness in these areas would have a tremendously positive effect on safety. We describe the system architecture and database development necessary to implement this application.

We describe the transit applications we demonstrated, including public transit trip planning with real-time transit travel times, incorporating the dynamically updated location of the bus. Furthermore we will show why our transit arrival estimates are accurate, which could improve adoption of public transit. We describe our transfer notifications, and transfer times, and how we deliver these to consumer devices.

We will also describe our revolutionary safety application for pedestrians, a “watch out for me!” alert which communicates from a pedestrian’s consumer handheld device to an oncoming vehicle. This application generated a tremendous amount of interest when it was shown in New York. The underlying technology and challenges are described below.

Furthermore, we will also discuss how we demonstrated a dynamic parking application which would enable a driver in Manhattan to use his consumer device to find an available parking spot efficiently, easing the congestion and pollution caused by drivers circling for parking.

Some of our research also necessarily addresses usability. We will discuss how we address the particular challenges of the small screen space on mobile devices. We will also report on another application developed as part of GEMS, a car-to-car application built using the DSRC control channel.

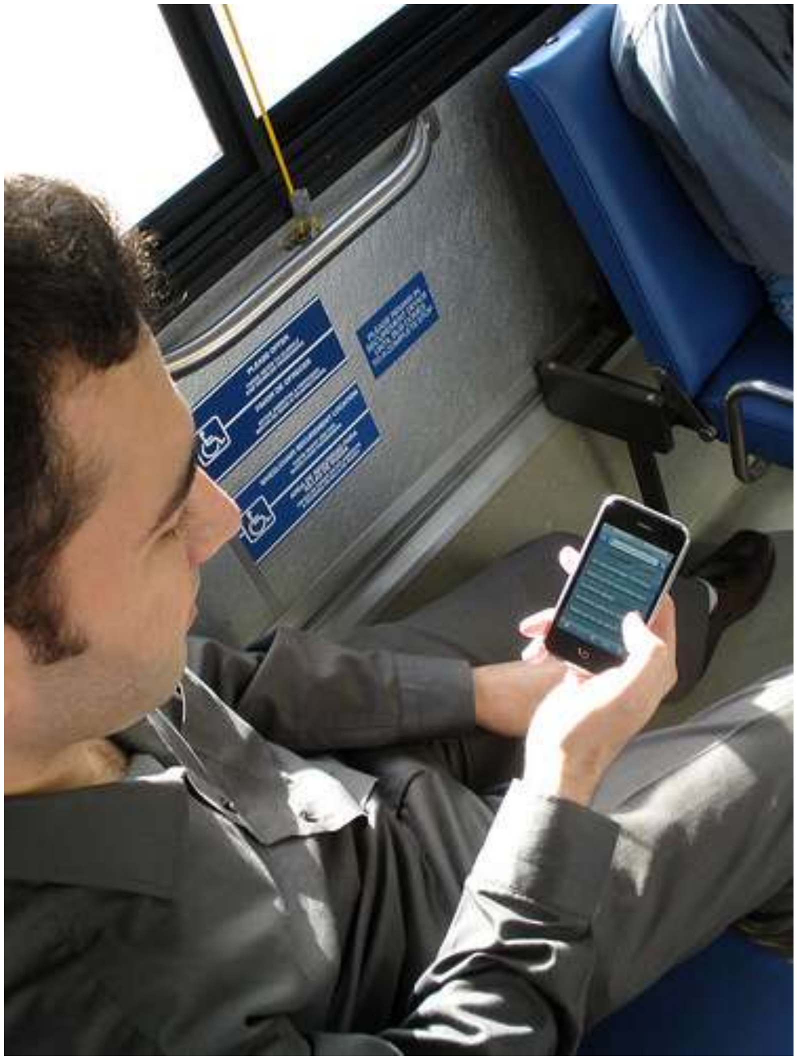


Figure 1-1: GEMS application on a mobile phone

2 Outreach of GEMS users

2.1 Define GEMS Applications

We defined the following applications:

1) Application to alert pedestrians about approaching cars
2) Application to alert drivers about pedestrian crossing or about to cross road
3) Application to deliver to drivers situational awareness alerts below:
    a. Work-zone
    b. School-zone
    c. Speed limit
4) Application to alert drivers about vehicle ahead to prevent rear-end crash
5) Application to deliver information below to transit riders:
    a. Real-time trip planner
    b. Real-time travel time

c. Next stop in “x” minutes
d. Your Bus/Train is coming in “x” minutes
e. Amount of carbon footprint reduction as a result of using public transit when compared to driving
f. Signal-Phase-Timing (SPAT) of traffic light

6) Application to implement Traffic Signal Priority (TSP) for a bus in order to extend green light at intersection

2.2 Find Application Users

We worked with these agencies to find users who will use GEMS applications:

- CSAA Members, employees, Silicon Valley Leadership Group member companies), and MTC

This effort began at the start of the project. We calculated statistically that the target number of users would be on the order of 100s of drivers: 100 WiFi device users, 200 DSRC users would constitute a success in terms of user pool size.

2.3 Find Application Developers

We collaborated with these companies and institutes to develop GEMS applications:

- Savari Networks Inc (www.savarinetworks.com): Savari networks built the so called Savari On-Board Units (SOBU) which is described in details in the next section.

- Professor Xuesong Zhou (www.civil.utah.edu/~zhou) and his research team at Civil Engineering Department of University of Utah developed a multi-modal trip planner client-server application.

- Navteq provided PATH with access to Traffic.com real-time traffic data, and also Navteq digital map database.

2.4 Conduct Evaluation (Business Case / Effectiveness)

We approached Caltrans, Metropolitan Transportation Commission (www.mtc.ca.gov), SF Transportation Management Association (www.tmasf.org), AAA, Santa Clara Valley Transportation Authority (VTA), Caltrain, SamTrans, and the University of Stanford Commuter Club to understand institutional and other arrangements which may be issues toward short- and medium term experimentation and deployment objectives of GEMS. While the entire subtask aims was comprehensive, the initial focus was to identify issues in order to begin work toward overcoming them. We note that there was no parallel independent evaluation of the GEMS approach.

3 Development of RSE and OBE components

3.1 Develop Mobile WiFi/DSRC Gateway

The necessity to communicate with the DSRC RSE dictated the development of an in-vehicle gateway unit which was able to operate in the DSRC frequency as well as in the WiFi frequency range with WiFi enabled cell phones and PNDs. For ease of use it was designed to be a plug-in system supporting DSRC (802.11p and 1609) and WiFi. The OBE was developed in collaboration with Savari Networks.

A brief hardware description of Savari On-Board Unit (SOBU):

The main hardware components are –

- Mother board
- Enclosure
- AC Power adapter
- Car Power adapter
- Two outlet car adapter
- USB based GPS receiver
- USB based Bluetooth
- WiFi Radio
- DSRC Radio
- Antennas for WiFi and DSRC Radio.

Depending on usage, the power consumption of the unit is between 10W to 15W.
The operating temperature is approximately -20C to 55C. The mother board has built-in voltage stabilizer (7-20V) and built in circuitry to prevent voltage spikes. The unit could be plugged to a standard wall outlet or powered by a 12V, 2A (fused) standard car adapter.

Bluetooth USB dongle:

WiFi and Bluetooth are two ways of communicating with cell phones and PNDs. The SOBU was designed to support both WiFi and Bluetooth connectivity. Most current day cell phones and PND support Bluetooth standard 2.0 with EDR. The Bluetooth USB dongle used in SOBU is a Class 2 device covering up to 10m, works in the 2.4GHz frequency and supports frequency hopping for robustness of the connection.

The salient features are:

- Bluetooth Specification 2.0 EDR / v 1.2, Class 2
- Operating Frequency 2.402 GHz - 2.4835 GHz ISM Band
- Enhanced Data Rata (EDR) compliant for both 2Mbps and 3Mbps modulation modes
- Full speed Bluetooth operation with full Piconet support
- Support for Scatternet
- Support for 802.11 coexistence

- RoHS compliant
- Full speed USB v 2.0 interface support OHCI and UHCI host interface
- Receiver Sensitivity -90dBm
- Stable, Accurate search ability

GPS USB dongle:

Since we are mostly concerned with location based applications having a reliable and accurate GPS in the system is necessary. The GPS used with the SOBU is USB powered with a 5ft cable for ease of use and it comprise of SiRF based chipset given they support higher number of satellites, higher update rate and supports standard NMEA protocol to read the data. Globalsat – BU-353 USB GPS receiver is used.

The salient features are:

General Specifications-

GPS Chipset: SiRF Star III e/LP
Frequency: L1, 1575.42 MHZ
C/A Code: 1.023 MHz chip rate
Channels: 20 all-in-view tracking
Sensitivity: -159 dBm

Accuracy:

5m 2D RMS WAAS enabled
10m 2D RMS WAAS disabled

Acquisition Rate

Hot start: 8 sec., average
Warm start: 38 sec., average
Cold start: 45 sec., average
Reacquisition: 0.1 sec. average

Protocol

GPS Protocol: Default: NMEA 0183
GPS Output Data: SiRF Binary
GPS transfer rate: Software command setting (Default : 4800,n,8,1 for NMEA)

Dynamic Condition

Acceleration Limit: Less than 4g
Altitude Limit: Max 60,000 Feet (18,000 meters)
Velocity Limit: Max 515 Meter / sec (1000 Knots / 1,152.02 mph)
Jerk Limit: 20 m/sec**3

Environmental Specifications

Operating: -40°~ 176°F (-40°~ 80°C)
Storage: -40°~ 176°F (-40°~ 80°C)
Humidity: Up to 95% non-condensing

Electrical Characteristics

Voltage: 4.5V - 6.5V
Current: 50mA typical

The performance of the GPS was thoroughly tested for positional accuracy and update rate.

WiFi MiniPCI radio

A WiFi Radio, dual band support is (2.4G, 5G) is required for the broader access to the public hotspots. Since almost all high powered cards come with single band support, a 200mw power WiFi card is used. Some of the units will support only the 2.4GHz band but have higher powered cards. The higher powered (within FCC regulations) are used to demonstrate various WiFi related applications viz. Pedestrian warning.

The salient features are:

- WiFi : Compex WLM54AG-23dbm -200mw
- IEEE 802.11a/b/g (2.4/5GHz)
- AR5413/5414(AR5006X/XS) Atheros Chipset
- "ClearVoice" Band
- Non-overlapping Channels
- 23dBm output in a/b/g-Band
- Speed up to 54/108Mbps
- Atheros eXtended Range (XR)
- Dynamic Frequency Selection
- WPA & WEP Support
- Transmission Power Control
- Multi-Country Roaming Support

DSRC MiniPCI Radio:

To talk with standard DSRC devices the SOBU has a DSRC radio with support for 802.11p and the 1609 protocol developed during the course of the project. Interoperability with other DSRC devices available in the market is a design requirement.

The salient features are:

- DSRC interoperability Interoperable with DSRC devices in the control channel
- Chipset Atheros, 6th Generation, AR5414 with SuperA/Turbo Support
- Radio Operation IEEE 802.11a, 5GHz
- Interface 32-bit mini-PCI Type IIIA
- Operation Voltage 3.3VDC
- Antenna Ports Single MMCX
- Temperature Range -45 to +85C (extended temp version up to +95C)
- Security 802.11i, AES-CCM ,TKIP Encryption, 802.1x, 64/128/152bit WEP
- Data Rates 6Mbps, 9Mbps, 12Mbps, 24Mbps, 36Mbps, 48Mbps. 54Mbps
- TX Channel Width Support 5MHz / 10MHz / 20MHz / 40MHz
- RoHS Compliance YES
- Avg. TX Power 28dBm, +/-1.5dB
- Max Current Consumption 1.80A, +/-100mA

DSRC and WiFi Antennas:

For DSRC and WiFi Radios, Omni directional antenna is preferred for better alround coverage and to compensate for the curvature of roadways. Antennas are mounted on the SOBU.

WiFi Antenna:
RP-SMA Rubber Duck Indoor Antenna (3dB @ 2.4GHz and 5dBi@5GHz)

DSRC Antenna:
Dual Band Omni Antenna N Male (Peak Gain: 7 dBi @ 5150 - 5875 MHz)

Motherboard:

The motherboard is from PC Engine and has a 500MHz ARM based processor with 256 MB RAM. The ARM based processor necessitates cross compilation of programs for native use. A cross compiler was set up to facilitate porting of programs to the SOBU.

The salient features are:

CPU: 500 MHz AMD Geode LX800
DRAM: 256 MB DDR DRAM
Storage: CompactFlash socket
Power: DC jack or passive POE, min. 7V to max. 20V
Three LEDs
Expansion: 2 miniPCI slots, LPC bus
Connectivity: 1 Ethernet channel (Via VT6105M 10/100)
I/O: DB9 serial port, dual USB
Board size: 100 x 160 mm

A 512MB industrial grade compact flash from Innodisk is used for storage.

The SOBU was tested in conjunction with various phones (e.g. Nokia N95, Blackberry, LGKS20 etc.) and PNDs (Nokia N810). The method of display and delivery to the handhelds was mostly through the mobile browsers available on them along with some mobile Java based programs.

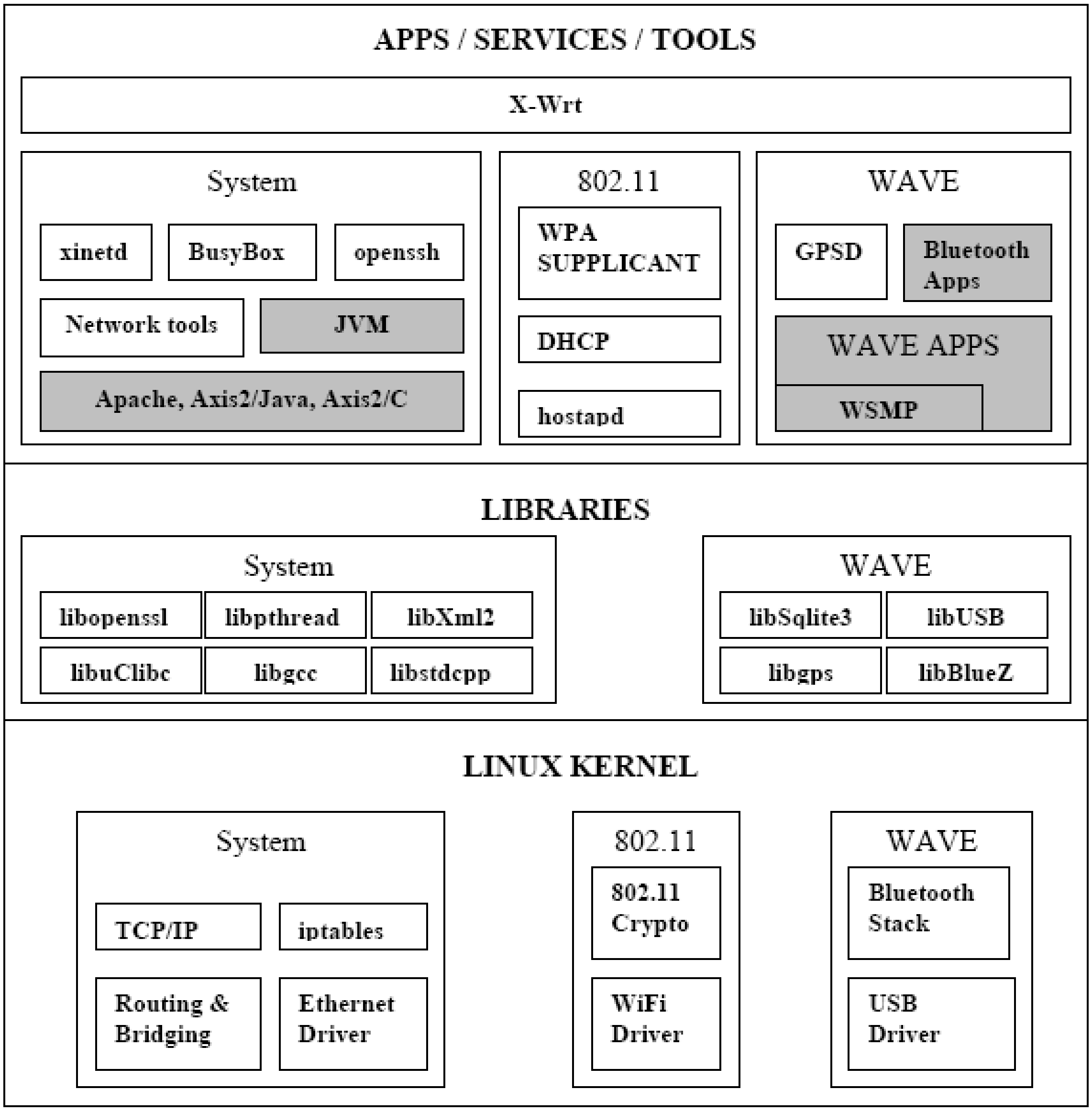


Figure 3-1: Software architecture of SOBU

3.2 Develop Multi-Device/Multi-Spectrum Web Services

As part of GEMS, PATH built a web application for personalization of transportation information delivered to mobile phones. This web application's functionality was demonstrated at the ITS World Congress 2008. This website was built to support multiple devices: computers and web-enabled mobile phones.

Figure 3-2: Front page of the Networked Traveler website

Consumer mobile devices present a big usability challenge for designers: screen size is very limited, and wireless bandwidth is often extremely limited. Calls to the server can be very slow, making it important to streamline navigation through an application to limit the number of calls to the server.

Content delivery is still structured to be delivered to large-screens, stationary devices, and in large quantities making it difficult to process on the small screen limited resources and often limited bandwidth interfaces of mobile devices. A large amount of the data might have no relevance to the individual user; you might be interested in knowing about the incident that is on your way but not interested in knowing about pedestrians, stop signs, etc, yet you get that data.

We are using a traditional website to allow a user to choose exactly what transportation related information will get delivered to her web-enabled phone. Using a website to personalize a wireless application is the big innovation in usability we are presenting. We hope this leads to wider adoption, and ultimately to more informed and efficient travelers.

Using PHP and a MySQL database, we capture user preferences on a “traditional” website. The user creates an account on the website and specifies what location services she’s interested in having delivered, and where she will access these services - maybe she wants “parking near me” delivered to her phone based on her current location, or she wants to plan her public transportation trip on the web, and then when she’s on the bus perhaps she wants an alert on her phone that her stop is next.

The user-defined username and password identify who is using the service. Browser detection on the server allows the application to tell the difference between web viewing and wireless device viewing, tailoring the content to fit the screen size, using the user-chosen preferences as the guide for what content to display.

The functionality includes user account creation, and selecting from many kinds of information for delivery to the mobile phone, including the following:

Transit Preferences
Public transit trip planning for

- Real-time transit travel times
- Transit arrivals
- Transfer notifications
- Transfer times

Safety Preferences

For pedestrians:

- send alert to cars that you are in the area

For drivers, send & receive alerts:

- pedestrian locations
- vehicle locations
- speed changes
- special driving zones

Parking & Tolls Preferences

- Find parking
- Make parking reservations

3.3 Implement Application Components

3.3.1 Mobility Applications

3.3.1.1 Introduction

With significant failure rates, existing in-pavement and road-side traffic sensors are typically located on a small subset of freeway links, and accurate travel time and traffic flow information on ramps and arterial corridors are critically needed but very costly to collect. In past several years, in-car navigation and cell phone systems using the Global Positioning System (GPS) technology have matured into a rapidly growing industry and its penetration rate in the U.S. is expected to exceed 9% in 2008. Recently, a new generation of commercial navigation system has been successfully developed to provide two-way connectivity through a built-in Wi-Fi or cellular connection, which allows a network of equipped drivers to anonymously share their speeds and locations, obtain up-to-date traffic flow information, and more importantly make smart route decisions.

The new generation of automobile navigation devices presents a data rich environment for regional traveler information systems to accurately measure route-based travel time and network-wide traffic flow distribution and evolution. It also offers an effective mechanism for traffic management centers (TMCs) to balance traffic on freeway and arterial corridors by delivering precise en-route diversion guidance. On the other hand, utilizing mobile traffic probe data, especially in their early deployment stage, could be constrained by low market penetration rates, leading to small data samples in statistical inference and thus high variances in travel time and network flow estimates. Moreover, without fully integrating traffic management strategies from TMCs, independent real-time drivers acting non-cooperatively might also affect and even worsen the traffic conditions.

By designing and implementing a mobile probe-based traffic monitoring and information provision prototype system, this research aims to:

1) Provide internet-connected traffic visualization interfaces to end users. Specifically, it offers traffic operators with more information for network-wide and path-level decision support. It also gives travelers with more options that can avoid traffic jams and reduce commuting delays through routes, departure times, and modes changes; and encourages both transportation system users and managers to make better informed decisions.

2) Demonstrate potential benefits in increasing arterial street traffic observation and eventually improving system-wide traffic conditions.

To achieve the above goals, the prototype system is constructed to include several key features: multi-criteria routing, path-level temporal/spatial traffic visualization, real-time guidance for traffic avoidance, and GPS-based trip data collection and mining.

Multi-criteria routing: In order to satisfy the requirements from various drivers for different trip purposes, a set of routes with different user criteria are provided as follows:

- The **fastest** route shows users the least average travel time route under normal conditions;
- The **shortest** route optimizes the total travel distance of a route.
- An **eco** route aims to minimize total vehicle emissions;
- A **toll-free** route helps users to minimize monetary cost spent on toll roads;
- A **safe** route offers travelers (e.g. teen drivers) a path that can minimize the probabilities of having traffic incidents;
- A **reliable** route provides a path that may take longer average time but with a higher probability of arriving on time;
- A **park & ride** route encourages drivers to use transit mode (e.g. bus or commuter rail) to avoid traffic jam on freeway systems.

Path-level temporal/spatial traffic visualization: To help network operators have better understandings on traffic situations, advanced visualization interfaces are developed to show the traffic in time and in space.

Real-time guidance for traffic avoidance: To delivery live traffic information to drivers directly, a real-time guidance component is included in the system. It frequently updates route travel time estimation and then generates and provides possible alternative routes when prevailing traffic conditions change.

GPS-based trip data collection: To supply up-to-date traffic data on both highway and arterial roads, this system embeds a mobile phone-based GPS trip data collection component and the corresponding server-side data mining module.

3.3.1.2 System Architecture

The system under consideration contains several major components: data receiver, routing server, web-based client interface and mobile phone-based client interface. The architecture is shown in Figure 3-3.

The data receiver includes underlying roadway map data, historical and live traffic databases, and transit schedule data. In particular, converted from Navteq map data, the roadway network data layer provides network topology, road names, speed limits, road lengths and other fundamental road classification information. The live traffic data streams from Traffic.com, which is collected through in-pavement and road-side sensors covering all the freeway and highway systems. Furthermore, in order to provide routes for park and ride mode, transit network data and bus/commuter rail schedules are represented as additional data layers in the system.

The server is composed with three computational engines and a server-client communication interface. The traffic data fusion and prediction engine combines the external traffic data from both location-fixed sensors and (internal) mobile phone-based clients to provide real-time link travel times to the traffic routing engine. It also calculates/predicts route-based travel time using the historical travel time pattern and the prevailing traffic conditions. As the building block of the entire traffic information provision system, the routing engine finds routes under different criteria and applies live traffic data from the traffic data fusion and prediction engine to supply final route guidance information to end users. Moreover, to process the GPS trace data collected from mobile phone-based client programs, a GPS probe data mining engine is implemented on the server side. The probe trajectories are mapped to road networks and converted to travel times by the GPS data mining and analysis engine, and the information further is imported into the traffic data fusion and prediction engine for traffic estimation and prediction. Finally, an AJAX (asynchronous JavaScript and XML) based interface is developed to provide unified real-time routing information interface for the client programs.

On the client side, two types of software application have been developed to fulfill needs of both commuters and traffic system operators. The web-based application works as a network-wide traffic analysis tool for system operators and a pre-trip planner for commuters. Specifically, as a traffic analysis tool, it visualizes path-level traffic estimation/prediction results and allows users to conduct temporal/spatial sensitivity analysis. As a pre-trip planner, it offers commuters a variety of options for route, travel mode and departure time choices. For smart-phone users, a Windows Mobile-based application is developed to provide customized real-time route guidance and up-to-date traffic information. Additionally, a GPS travel trace collection module is embedded in the mobile phone-based software application to gather precise and personalized driving data for proactive traffic diversion on both highways and arterial roads.

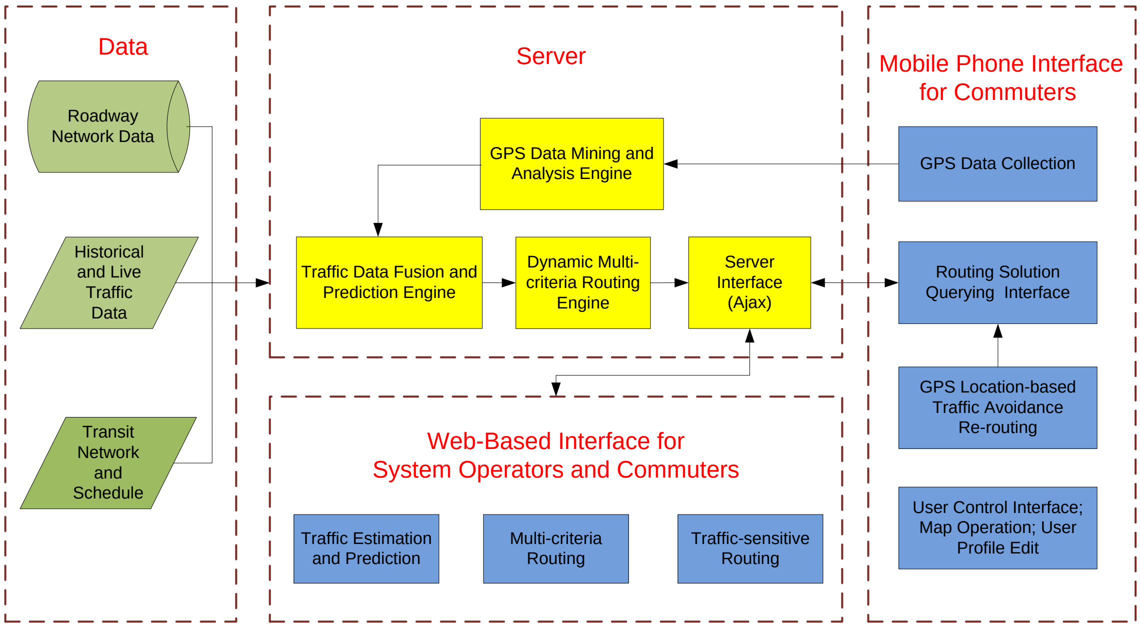


Figure 3-3: Traffic Information Provision System Architecture with Multi-criteria Routing

3.3.1.3 Routing Server

The traffic routing engine and some related server components are described in detail in this section.

Multi-criteria routing engine:

The multi-criteria routing engine is designed to offer different routes for commuters with different user needs. For this purpose, we chose several common and quantifiable criteria for drivers. A list of routing objectives is shown in Table below. In addition, to encourage the usage of transit, a park & ride route is provided to help commuters avoid highway traffic and improve travel time reliability by taking bus or rail transit.

Routes	Criteria	Description
Fastest Route	Travel time	smallest travel time
Shortest Route	Distance	shortest travel distance
Eco Route	Ecology	average link travel speed is close to eco-driving speed (50-60 mph)
Avoid Toll Route	Toll	Avoid tolling roads and bridges
Safe Route	Safety	Smallest probability of getting involved in a traffic incident along the route
Detour	Reliability	Highest travel time reliability
Park & Ride Route	Transit	Find available intermodal option to avoid highway traffic and use transit service

In order to select routes based on different criteria, a candidate route set is required to implicitly enumerate possible alternatives for travelers. To improve the computational efficiency, an improved bi-objective K-shortest path generation algorithm is designed and implemented in this study. This algorithm considers both travel costs and route representativeness so that only a sufficient number of candidate routes is necessary to represent the population choice set.

Traffic data fusion and prediction engine:
The traffic data fusion and prediction engine is designed to assemble different information sources and supply live travel time estimates for the routing engine. It contains two major data processing parts: data fusion and travel time prediction. In the data fusion module, the link-level and path-level travel time is estimated using raw data from various sources: in-pavement and road-side sensors, GPS probes (i.e. our mobile phone-based clients), AVI (automatic vehicle identification) probes. The travel time prediction module integrates both historical and live data together to generate the reliable traffic forecasts along different routes under regular and irregular conditions.

Routing service interface:
The AJAX technology is embedded in the client interface to query routing information dynamically from the server. The response message of each route includes a large of information elements for visualization and further decision making. To name a few, these items include travel time, travel distance, travel cost, geographic data for plotting routes, traffic congestion color code link identification , as well as road names for driving guidance. A structure of response message from the routing server to client programs is shown below.

```
for each route
   Route name (Highway on the route) $ Travel time * Distance * Cost *
   for each node of this route
      Latitude : Longitude : Congestion color code :
   end
   %
   for each link of this route
      Link ID (with direction) ,
   end
   @
end
^_^
for each route
   Route name: names of roads on the route
End
```

Web-based traffic analysis interface and pre-trip planner:
Built on the routing service in the "Networked Traveler" system, a web-based client interface is developed for both transportation network operators and commuters. The user instruction and key features are described in this section.

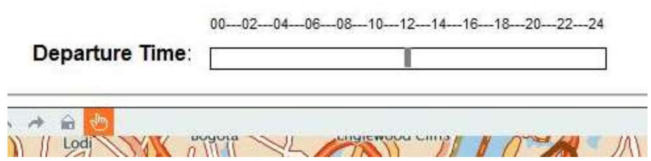
1) User introduction
Figure 3-4 gives an overview snapshot of the web-based client program, which has a system control panel on the top and a map interface using multiple routes. Two floating windows, namely routing information window and traffic contour window, are activated when a user selects a particular route of interest.

Figure 3-4: Snapshot of Web-based Client with Multiple Routes

The system control panel permits the following convenient functions:

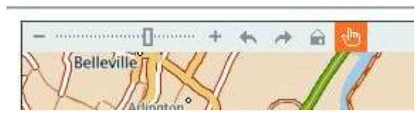
- Hide/Show Routing Info button (as shown below), which hides or shows the routing information floating window.

- Departure Time Bar (as shown below). A user can move the time slider to select different departure times to view time-varying travel times along different routes. When live traffic data are available, time-dependent routes are calculated accordingly for different departure times.



- As depicted in figure below, the Help button opens an on-line help document for user introduction and the “Toll Info” hyperlink will link to the webpage with bridge, tunnel and road tolls information in the area of interest.

- The route display interface used in this application is built on the Map24 visualization engine from NAVTEQ. The control panel of Map24 is located on the top of the map (see figure below for an enlarged snapshot). There are a number of commonly used functional buttons from left to right: zoom out/zoom in, return to previous view, step forward to next map view, navigate to the map's origin, and pan mode on/off.



- To start the path-level traffic analysis or trip planning, a user first needs to turn on the pan mode of the map and then use pan/zoom to specify traveling origin and destination. To do so, the user can turn off the pan mode, and select the origin and destination sequentially by left-click on the map. The above user input on the web-based application will active and send a route request back to the server. Upon receiving the response message from the server, the routing information window (shown in figure below) was shown on the top of the map.

- On the routing information window, seven routes are sequentially listed with their corresponding color codes, travel time in minutes and distance in miles. In addition, two check boxes are associated with each route for users to directly view particular paths. A single click on the left check box will highlight the selected path on the map, while another check on the right side (of each route attribute) triggers the displaying of the traffic window with a travel time plot and a speed contour.

2) ***Departure time choice: travel time plot:***

The time-dependent travel time plot (Figure 3-5) shows the varying travel time series at different departure times of day. By visualizing the dynamic route travel time information, this profile aims to assist network operators to identify the congested peak hours and/or bottlenecks for a particular route, and also allows commuters to quickly evaluate and select the best departure time in order to avoid the traffic while meeting their preferred arrival time constraints.

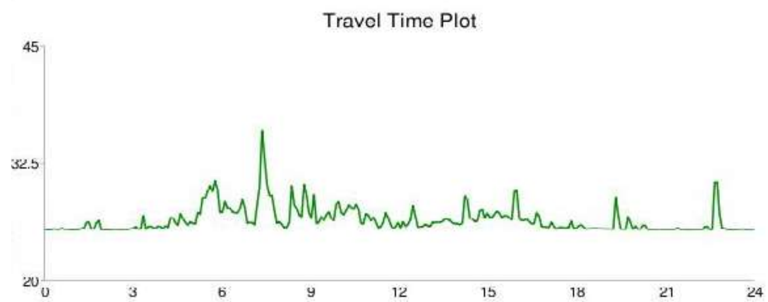
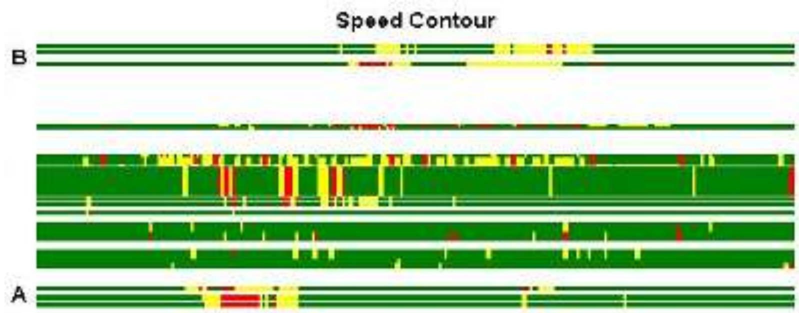


Figure 3-5: Travel Time Plot

3) ***Traffic analysis: speed contour:***
The speed contour (figure below) illustrates the temporal/spatial traffic conditions measured from road sensors along the selected path. In this contour, the horizontal axis represents the time of day while the vertical axis represents the distance along the route from the origin A to the destination B. From this time-space traffic plot, network operators can rapidly identify the bottleneck(s) and understanding complex traffic evolution on a particular route.

The color legend used in this figure is shown below:
Red: Highly congested.
Yellow: Relatively congested.
Green: Free-flow condition.
Blank/White: No data available.



Mobile phone-based real-time route guidance:
A mobile phone-based software application is developed for commuters with smart phones. The user guide and traffic re-routing feature are detailed in this section.

1) **User introduction:**
A step-by-step illustrative tutorial on how to use the mobile phone-based application is offered in Figure 3-6. After launching the application on the smart phone, the main interface is first displayed with the Map24 map centered at the pre-defined home location, along with an

information box located on the top and control panel at the bottom (see sub-figure 1). On the control panel, four buttons are listed sequentially: Route, Exit, Options and Home (table below).

Buttons	Functions
Route	Request a routing for a new trip.
Exit	Exit the application
Options	See routing demo and edit profile ("Home" location and address book).
Home	Center the map at "Home" location.

By clicking on "Route" button, a user will see a new window displayed for choosing origin and destination of the trip (Sub-figure 2). In this window, the program offer multiple ways for selecting a location: using current GPS location, defaulting to "Home" location, pointing a new location from the map or selecting an address from the address book. After the "OK" button is pressed at the left bottom, the client program sends route requests back to the routing server and then displays the route calculation results on the map. As showing in sub-figure 3, the detailed information of a route, including route criterion, major highway used, travel time and travel distance, is displayed in the information box on the top of the map. Users may use the left and right arrows at the bottom to switch routes. By clicking on the information box, the user can have a window with detailed road names displayed for better route guidance (Sub-figure 4).

Figure 3-6: User Introduction for Mobile Phone-based Application

Figure 3-7 illustrates how to select a new location and add it into the address. First, a user needs to click the “New Location” button on the routing window, which will lead the user to the map interface. Then he/she is required to select the desired location on the map, with the help of map control panel. After pressing “Save” button at the bottom, a user was able to type in the name of the new location and save it into the address book.

Figure 3-7: Add New Address in Address Book

3.3.2 *Safety Applications*

3.3.2.1 Ped Alert:

Objective: The objective is to augment present Pedestrian Alert (PedAlert or Watch-Out-For-Me (WOFM)) application with GPS, accelerometer, and digital map such that alerts could be triggered automatically and false warnings are prevented.

System Architecture of the Present System:
Figure 3-8 illustrates the system architecture of the PedAlert system that was demonstrated in 2008 ITS World Congress in New York. The system is all web based: the pedestrian triggers (activates) the warning by hitting a button or tapping on screen of his/her smart phone and then the driver receives the warning on his/her smart phone. This application requires an on-board unit (SOBU, Savari On-Board Unit, was used in the World Congress demonstration) inside the vehicle to enable communication between the phones of the pedestrian and driver.

Figure 3-8: A demonstration of PedAlert application in 2008 ITS World Congress

Next Phase: GPS/Accelerometer/Map Driven Modality
In the current PedAlert system, the pedestrian triggers the warning. We envision that by integrating the digital map, GPS sensor, and the accelerometer sensor of the smart phone, we can eliminate this constraint. We want to make it so that the application triggers the warning by itself

when a pedestrian crosses a street or road that has a curb on its entering side. The iPhone, G-Phone, and Nokia N95 are three very popular smart phones that are equipped with both GPS and a 3-axis accelerometer sensor. The conceptual design is as following:

1) Using the GPS position of the phone and digital map information, we can infer the general heading of the pedestrian and the road the pedestrian might cross. The accuracy of a GPS position of a smart phone is at the multi-meter level. This accuracy is strong enough to decide on the rough location and heading of the pedestrian relative to the road.
2) If the above criterion is satisfied, then we look at standard deviation of the accelerometer's measurements (for a time window of few seconds). When the pedestrian steps down a curb (Figure 2), a big jump occurs in standard deviation of accelerometer measurements. This jump can be detected with very small latency because the accelerometer's update rate is more than 10 Hz.

Results of Some Field Experiments

GPS Accuracy:

The first experiment was carried out with an iPhone in order to find out its GPS position accuracy. The experiment was done by one of PATH engineers in front of building 180 at the Richmond Field Station (RFS). During the experiment, the phone was essentially stationary (moving no more than 2 m). Figure 3-9 shows relative absolute distance between GPS positions.

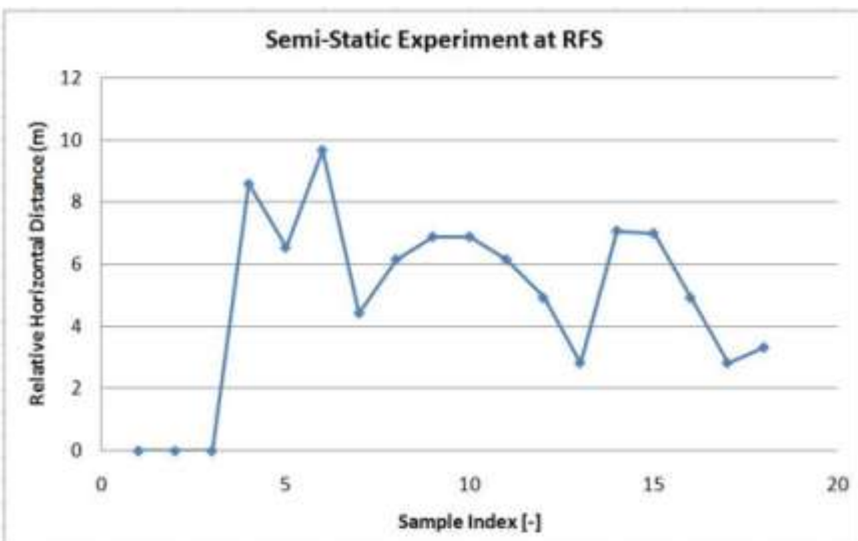


Figure 3-9: Relative distance between GPS position measurements

Accelerometer Accuracy:

In this experiment, an iPhone was placed on top of a table. The phone remained static during the experiment. Figure 3-10 shows the variation of accelerometer values (divided by 1g, Earth gravity acceleration 9.81 m/s^2) along x-axis versus time. As seen, resolution of measurements is about 0.2 m/s^2. Axes are shown in the diagram below.

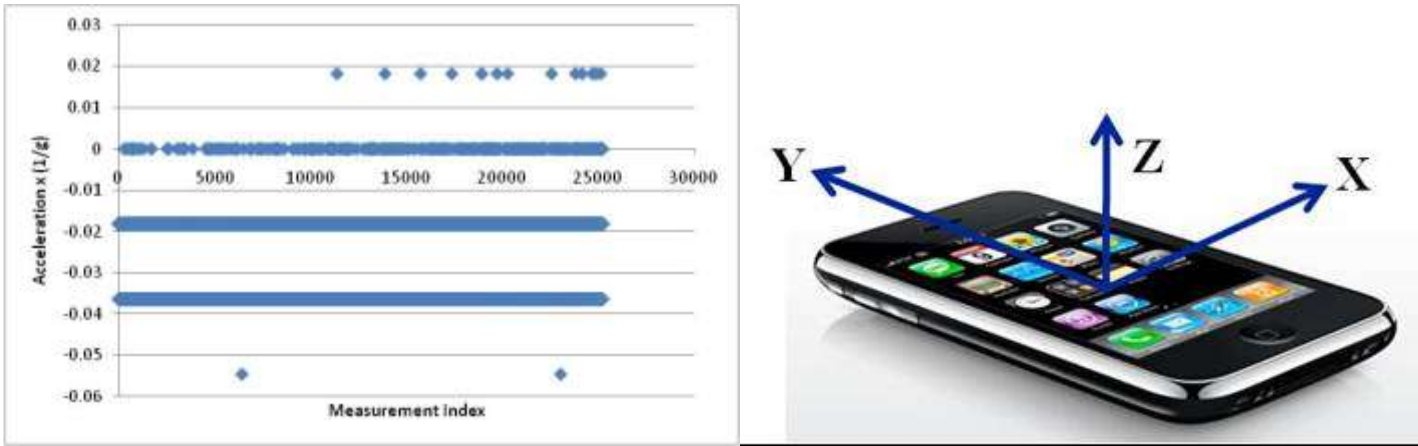


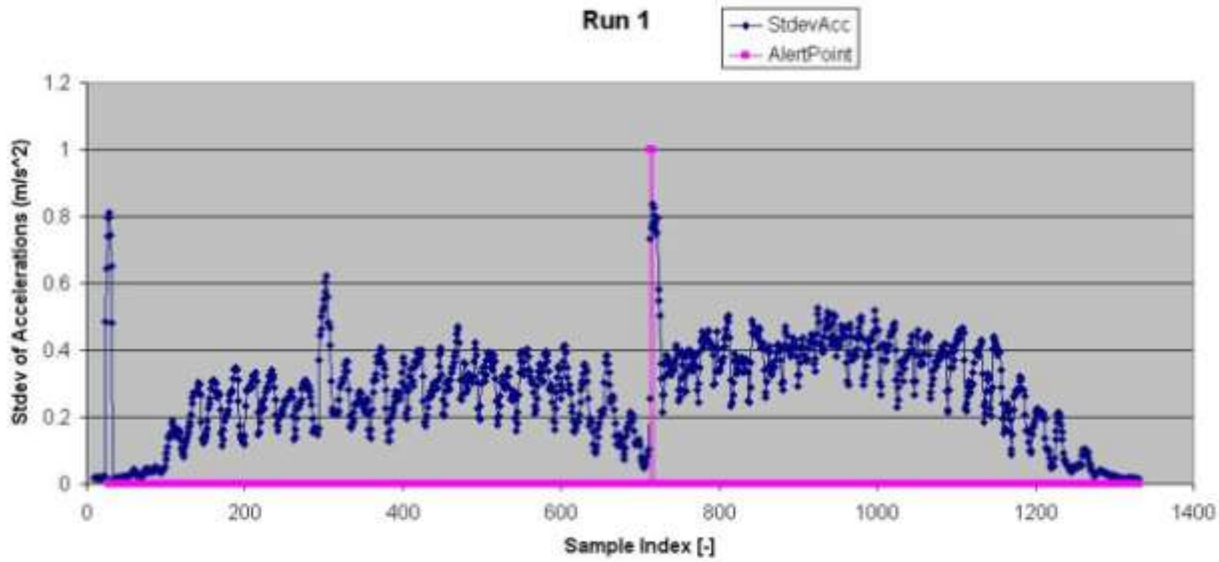
Figure 3-10: iPhone accelerometer measurements along an axis perpendicular to Earth gravity direction

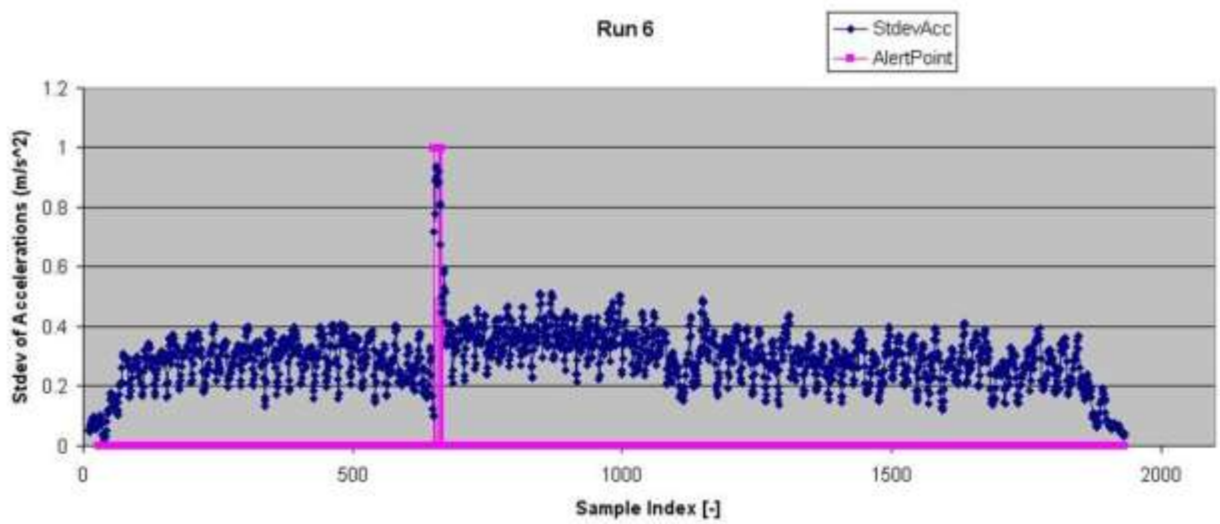
<u>Road Entrance Time Detection Using Accelerometer Data:</u>

Using an accelerometer, we can detect, with high confidence (based on experiments done so far), when a pedestrian enters a road, provided that the road has a curb and he/she steps down from the curb. Using an iPhone, we did several experiments in Meade St (Figure 3-11) just outside RFS entrance gate. This street has curb on both sides. In these experiments, the pedestrian walked along the street and then crossed the street.

Figure 3-11: Meade street outside RFS.

Figure 3-12 contains several plots that show how the beginning of pedestrian crossing time could be detected. In these plots, AlertPoint refers to the start of a crossing. The y-axis is the RMS (root mean square) of a standard deviation of accelerations along three axes. We determine the AlertPoint by using a threshold crossing policy that compares a new parameter, derived from standard deviation of accelerations during a time interval, against a threshold.





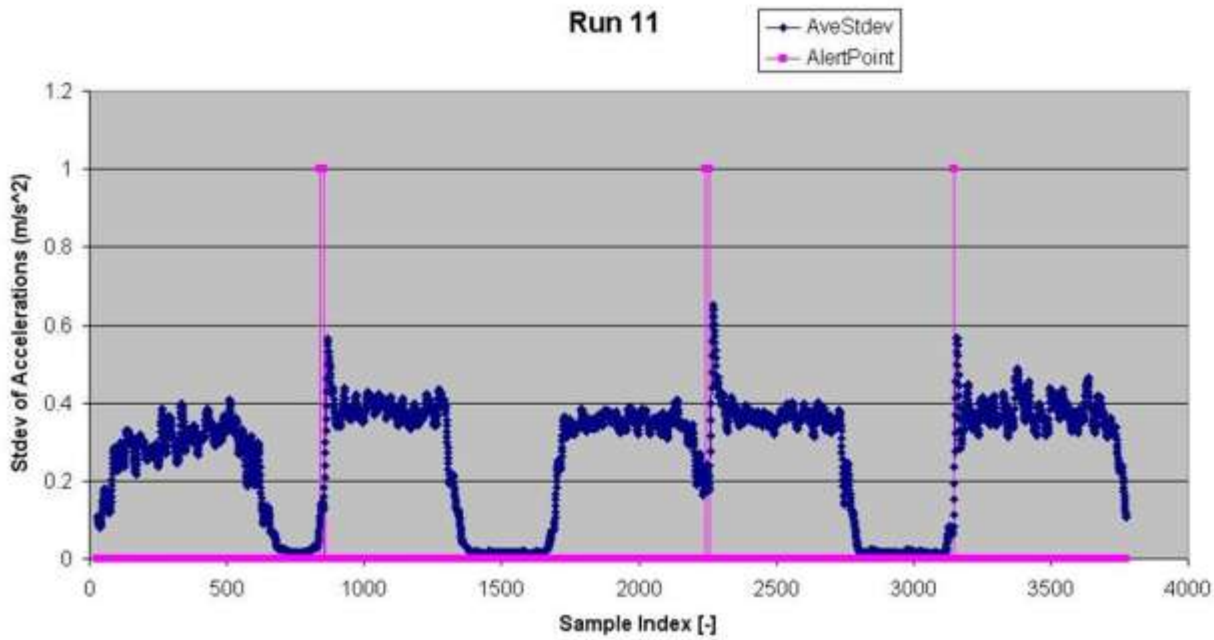


Figure 3-12: Results of some field experiments in order to determine beginning of crossing time

Future research ideas

Our goal is to determine the position of a pedestrian and detect when that person crosses the street and reliably warn the pedestrian and the relevant drivers for mutual safety. As simple as it sounds, to reliably do the above with low latency would require inputs from more than one sensor and intelligent processing – i.e. sensor fusion to get the job done. To this end, we already have a plan to fuse the GPS and accelerometer data. This is a great improvement from our first effort but still leaves some unanswered questions and, hence, room for improvement.

We are now heavily dependent on the availability of GPS and its signal quality. It is a known fact that GPS accuracy is not at its best in urban scenarios; however, even if we assume perfect GPS condition, we are constraining ourselves to people who have smart-phones with GPS and accelerometer. We need strive to aim our research toward a broader spectrum of the populace, with the intent of decreasing pedestrian fatalities and increasing driver and pedestrian awareness. Another aspect we plan to work on is to make both the pedestrian and the driver aware of their surroundings. Currently the pedestrian can trigger an alert, but has no idea of vehicles around him. The concept assumes importance in warning drivers coming around corners, blindly driving through what may be a collision path; moreover, the idea becomes even more significant in warning the visually impaired in a variety of situations. Not only would this help the visually impaired in crossing streets safely, but it would also project warnings about incoming modern, silent cars. The problem is not only limited to electric or hybrid cars, but also to modern conventionally powered cars. Around crossings and corners, cars tend to be quieter as they coast at lower speeds. Another use of this feature could be to signal bus drivers of passengers who got off the bus and warn other people who might be around when he embarks from a bus station/stop.

This approach, where both the pedestrian and the driver are aware of their surroundings, would require a balanced development and improvement of both the in-vehicle and pedestrian side applications/appropriate devices to use. This also opens up the question: how would the vehicle and pedestrian device communicate? There are number of options we should investigate:

1. Firstly, we could consider a web service, which assumes that both the pedestrian and vehicle have smart phones with GPS, an accelerator, and a fast data plan. All parties communicate with a back end server, sending back their speed, location etc. On receiving the trigger, or deciding on its own based on relative velocity, location etc., the server can send appropriate warnings to the relevant parties. The cons of this system are that the communication would become dependent on the server and the system latency lower bound by the roundtrip communication times. On the bright side, considering high server reliability these days and fast 3G data communication, this method is still a feasible and implementable solution.

2. Another method is to use DSRC enabled devices. There needs to be a specific PSID for this service. In this case, the on-board DSRC unit in the vehicle has to monitor distance of pedestrians carrying DSRC devices in the vicinity using signal processing. An approximate measure of distance and its change can be obtained from RSSI values or similar ranging methods. The device calculates approximate distances of other units in range (ignoring far off units) and then stores/sends that information to the units using the same PSID. At DSRC latency, the units in range will have a neighbor database updated. With that knowledge, each unit can build an approximate map of the neighborhood using multi-dimensional scaling algorithms and continuously update it. Based on the maps thus created, the pedestrians and drivers can be suitably warned. This, while technically challenging, will allow pedestrians to carry low end DSRC devices, without GPS, to receive warning beeps and/or vibrations (for the hearing impaired). Cons of this system are that the positional accuracy was lower, thus giving relatively more false warnings, or no warnings at all, than the first method. What makes this a worthwhile research effort is that the system is a low latency localized system and, coupled with smart processing of the data, could turn out to be the cheap general system to warn pedestrians and vehicles. This method does not assume presence of road side DSRC units. Presence of those units, however, would only help to make this method much better in terms of accuracy and reliability.

We also plan to research on certain, related important topics such as the appropriate time to warn vehicles of various speeds and the best way to unobtrusively warn the driver. Moreover, we plan to continue to search for better methods to detect when the pedestrian is about to cross the street in ample time. For example, when we detect the pedestrian based on the time he steps down from the curb based on accelerometer data, the pedestrian is already on the road, eating into valuable system reaction time. Also, the system becomes less sensitive when the pedestrian uses the gently sloping pedestrian crossings.

To sum it up, though this is a challenging research topic, we have a tentative plan of approaching this at an immediate, intermediate, and long term basis.

3.3.2.2 Car2Car Application:

The Car-to-car demo was a DSRC based demo in which a two SOBU equipped cars were used where the following car was alerted of sudden braking or drastic decrease of velocity of the leading car if they are on collision course. The communication between the cars was via DSRC control channel (Channel 172). For enhanced accuracy the GPS update rate was increased to 5MHz from the normal 1MHz. The method of warning was through audio. Since, originally there was no support for audio output an USB based audio solution was implemented.

3.3.3 Situational Awareness Applications for Drivers:

3.3.3.1 Introduction

The goal of the situational awareness applications is to give the driver information that is relevant for the next few seconds of the driver's route. Each application fills in some aspect of the driver's mental picture with potential hazards and traffic flow changes in the immediate future, leading to a more informed decision. The applications typically do not tell the driver what to do. Relevance, in this context, is in terms of the driver's current position and predicted trajectory. The time window is relatively short, up to perhaps 10 seconds, because of the difficulty in predicting the trajectory beyond that point, especially in an urban environment.

The situational awareness applications are organized as a suite of programs whose inputs are infrastructure map databases and the real-time dynamics of the vehicle and whose outputs are sounds and images on a dashboard-mounted cell phone. By depending on vehicle dynamic state, including position, heading, and speed, the output can be tuned to the current situation of the driver. Different applications make use of speed and heading in different ways.

The applications in the suite are as follows:

1. stop sign
2. work zone
3. speed limit notification
4. pedestrian crossing
5. railroad crossing
6. trucks entering
7. street closure
8. school zone
9. right turn

Each case has its own geometry and logic for interacting with the driver's trajectory. For example, pedestrian and railroad crossings are defined by a line segment across a roadway, and relevance is determined by comparing the vehicle's position and heading with this line segment. Speed is used for the timing and sometimes for the priority of the message.

3.3.3.2 ***Integration of applications and scheduling of display resource usage***

With so many applications running simultaneously, there is the danger of contention for the display (including sound): while one application is using the display, another application may attempt to do so as well. Without resolving the conflicts, the display and sound are likely to degenerate into chaos.

These conflicts are resolved by an arbitrator program which is responsible for tracking which applications need access to the display, which applications have had recent access, current unresolved requests for the display, and the current access granted to the display. The algorithm by which the arbitrator and the other processes interact is as follows:

Time is discretized at a fixed granularity, such as 10 Hz. Even if the GPS updates only at 1Hz or more, a finer time scale is needed to support the arbitration algorithm. Also, this better supports messages that are based on elapsed time, not just GPS input.

At any point on this discretized time line, a situational awareness process (for example, the speed limit application) may request use of the display. Typically, the request was reissued repeatedly as long as the situation is relevant (for example, as long as the vehicle is in the speed zone) The request is sent to the arbitrator and includes the priority level of the message, which is a number between 0 (low priority) and 10 (high). The priority level may (and usually does) vary each time the request is made.

The arbitrator considers all outstanding requests. If there is only one request, it is granted access to the display. If there are two or more requests, access is granted to the one with the highest priority, with one special case: the application that currently has access to the display is given a priority boost. The degree of the priority boost depends on the duration for which that application has had access to the display. The function has a value of (2 – duration) for any duration less than 2 seconds, and a value of 0 for any duration greater that 2 seconds. The effect of this function is to reduce flickering between messages that have similar priority levels, but avoiding starvation of processes that do not currently have access.

3.3.3.3 ***Application logic***

Each application searches its own database and decides for itself which data point is most relevant, and how it is relevant, in order to decide what (if anything) to present to the driver. The arbitrator makes the final decision, as described above, about what to display among all requests from all applications.

Application logic varies, but typically has these stages:

1. Relevance check by comparing the vehicle's position and heading against each item in the application's infrastructure database. The latter may include one or more position/heading vectors. For example, a speed zone includes at least two vectors corresponding to the entry and exit of the zone, whereas a stop sign has a single vector of position and heading

representing the location of the sign and the angle of approach that the sign faces. This stage involves searching all nearby entries in the database and results in a primary entry being selected for further filtering.

2. Timing check using speed and position to estimate arrival time at the area of interest. Very low speeds or long arrival times suppress most messages.
3. Classification of the vehicle's relationship to the area of interest (e.g., whether the vehicle is approaching or is in the area; how fast the vehicle is approaching; whether the vehicle is decelerating appropriately; etc). This step varies more than steps 1 and 2 do among applications and is further described below for each application. This step also helps determine the content and priority of the message, and not just whether a message needs to be shown or not.

The applications have the following specializations in their logic, in addition to the relevance and timing checks described above.

1. The stop sign application classifies in two dimensions: arrival time at the stop sign and deceleration needed to stop safely (given vehicle's current position and speed). Lower arrival time and higher deceleration result in a higher priority message. The two dimensions are represented independently in the visual display as shown below. Note that the sign looms larger as the vehicle approaches, and the STOP content is displayed only when the driver seems not to be decelerating appropriately.

<table>
<tr><th></th><th>High arrival time</th><th>Medium arrival time</th><th>Low arrival time</th></tr>
<tr><td>Current braking sufficient to stop</td><td colspan="3"></td></tr>
<tr><td>Harder braking needed</td><td colspan="3">
</td></tr>
</table>

10. The work zone and school zone applications are similar. Each one classifies the situation as follows:
    1. The vehicle is approaching (but not yet in) the zone (estimated using current speed and distance to zone).
    2. The vehicle is in the zone (between the two endpoints, more or less, and with an appropriate heading).

The priority is higher for the latter. For the former, priority is decreased for higher arrival times.

2. The speed limit application classifies into three cases, each with its own display message and priority:
    1. The vehicle is approaching (but not yet in) the speed zone (estimated using current speed and distance to zone).
    2. The vehicle is in the speed zone, but not violating the limit.
    3. The vehicle is in the speed zone, and violating the limit.

The priority is higher for 2 and even higher for 3. For 1, priority is decreased for higher arrival times.

For 1, the icon is smaller than for 2 and 3. In the case of violation (3), a red violation message is added to the display text. The speed limit application also detects *changes* in speed limits between two successive zones. As the vehicle approaches such a change and as it enters the new zone, the message is modified to indicate that the speed limit decreases (or increases) ahead or that it has decreased (or increased), respectively.

3. The pedestrian and railroad crossing applications define the crossing area by two points—the endpoints of the crossing. The relevance determination is unlike in the other applications. We check first that the bearings from the vehicle to each of the two endpoints differs by at least a certain small threshold, so that a crossing in a side street does not trigger the message. Next we require that the GPS heading of the vehicle is more or less between the two points, to select only crossings on the vehicles predicted path. We use distance and time of arrival to decide on the icon size and the priority of the message.

4. The street closure application is similar to the work zone application, but simpler. When the vehicle is in the defined zone with the correct heading, a message is generated. There is no separate approach classification as there is in the work zone application.

5. The right turn ahead application is similar to the work zone application. The approach classification works the same way, but with different display content and priority reflecting the immediacy of the turn.

Application logic was validated using both simulation and on-the-road testing as described in the sections on testing.

3.3.3.4 ***Database Development***

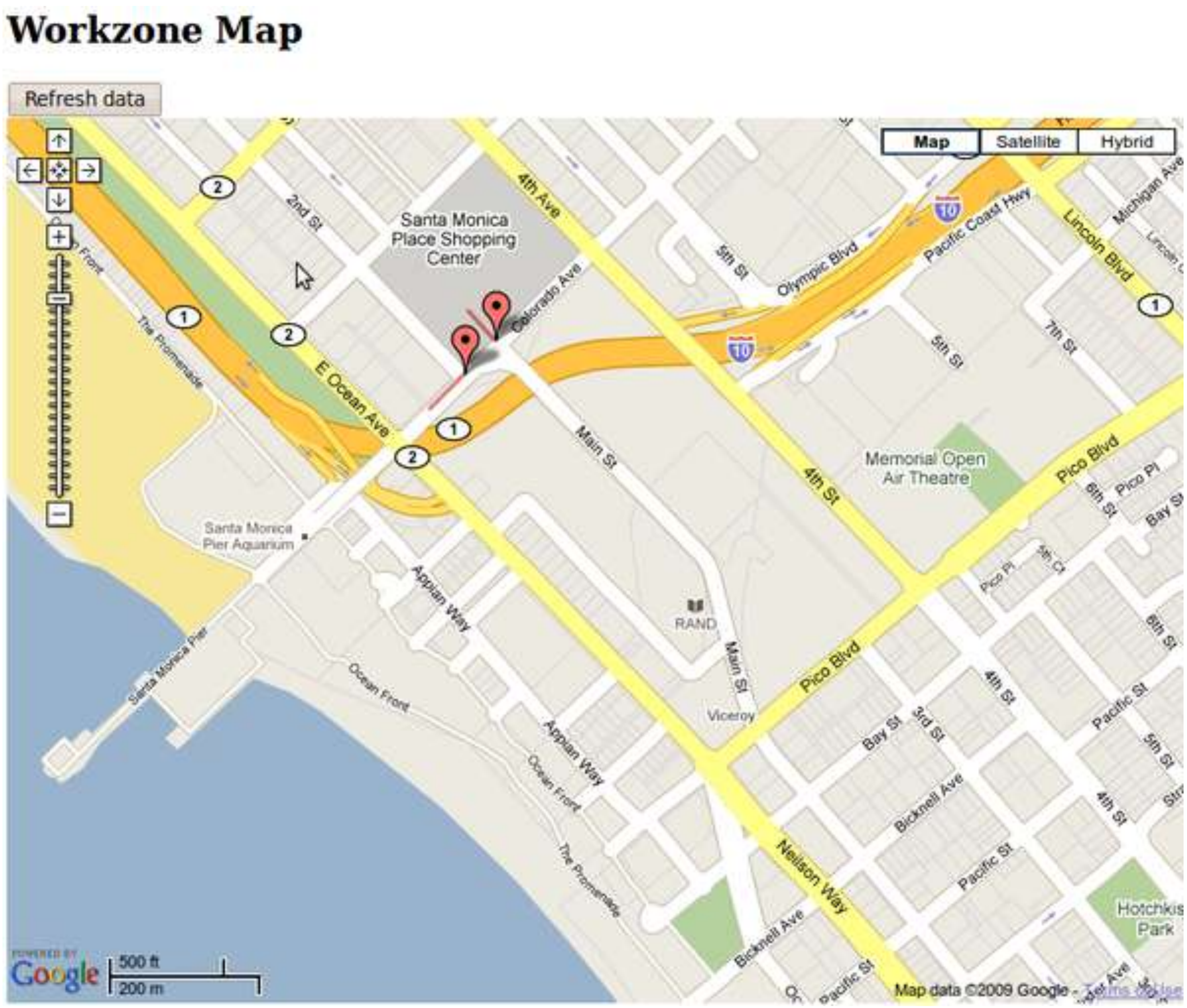
We developed infrastructure databases for three geographic regions, as needed for our demonstrations:

1. El Cerrito, CA, and Richmond, CA.
2. Santa Monica, CA.
3. New York, NY, around the Javits Center.

Maps of these areas showing all of the data elements are available on-line. Within the demonstration area, each of these data sets contains relatively complete data for each of the applications.

We collected the data using survey vehicles that recorded GPS coordinates correlated with operator annotations. We further refined the data using web-based mapping services. Validation was performed using both simulation and on-the-road testing as described in the sections on testing.

One sample map is included below. This shows work zones in the area of the Santa Monica demonstrations in January, 2009. As it happened, there was a real work zone in effect on Colorado Ave., which was along our bus demo route. The red lines in this case show the heading of relevance for the work zone application; the heading attribute is used to prevent nuisance alerts. The red line does not show the actual road work area.



3.3.3.5 ***System Architecture***

The system architecture consists of three components:

1. Web server, which provides maps, infrastructure data, software (javascript and HTML), and image and sound files.
2. Savari on-board unit (Sobu).
3. Smartphone, which provides cellular backhaul and user interface (web browser).

In practice, components 1 and 2 were combined in the Sobu, and we did not use cellular backhaul. Communication between the Sobu and phone was by wifi or bluetooth. The Sobu also provides GPS data to the phone as a web service. The phone side of the application software was simply a web browser, displaying HTML and executing javascript code downloaded on demand from the web server (on the sobu). No native mobile development was needed. The user interface for the applications consisted of graphics and sound. The graphics was typically an image of a MUTCD sign with explanatory text below. The sound was a brief version of the same information, in spoken English.

3.3.3.6 <u>Data Provisioning</u>

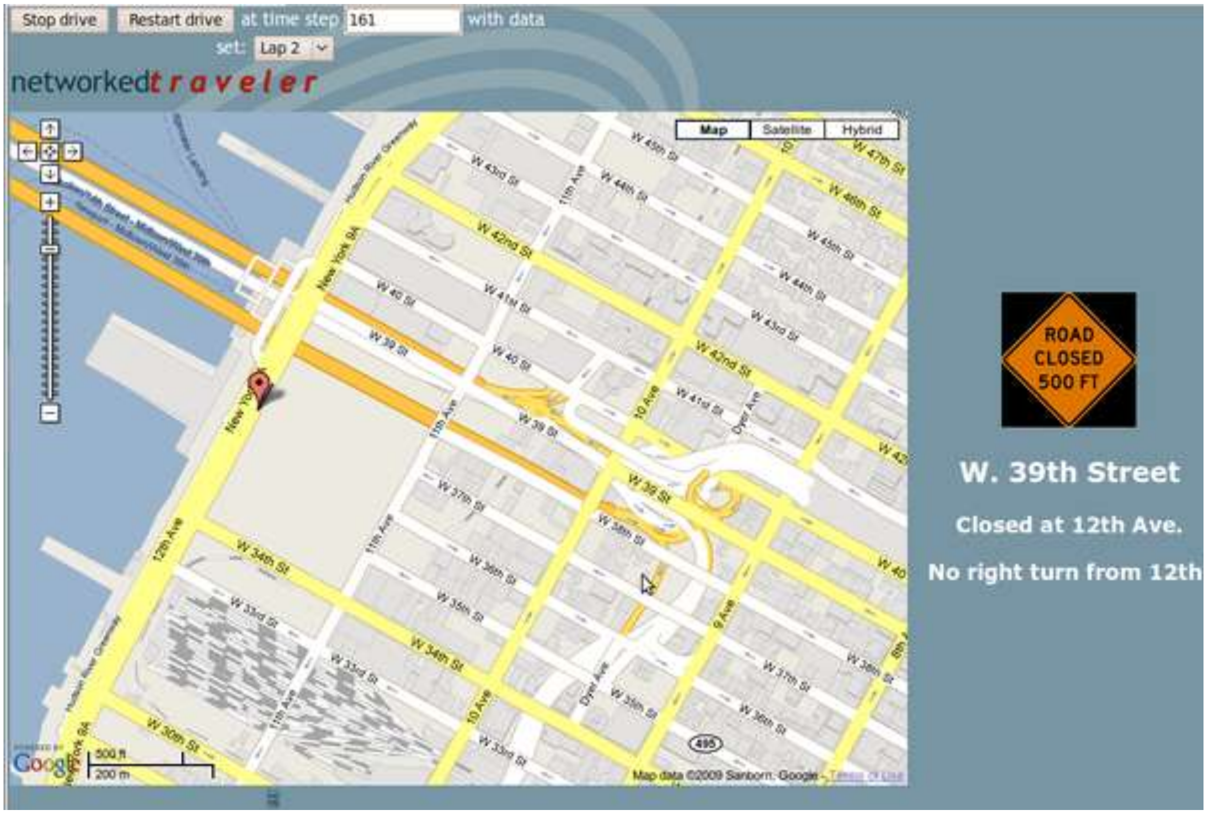
For our demonstrations, we did not rely on backhaul communication to provision our mobile devices. Rather, we pre-loaded all map elements into the Sobu units, from which they were served to handheld clients. This difference was not visible to the application, however, and we could have used dsrc-to-RSE or cellular backhaul to provision the database.

3.3.3.7 <u>Simulation Testing</u>

We developed a web-based simulation tool to assist both in the database development task and in the development of application logic. It also served as a communication tool at the 2008 World Congress booth. The simulation plays back recorded GPS traces and displays the corresponding situational awareness messages, along with the position and speed/heading vector superimposed on a map.

The code to generate the messages is identical to the code running on handsets in the real-world application, which makes it easier to desk-test the application. Playback is in real time with the same sound and graphics as well (on certain browsers), so the look and feel of the application can also be tested. The user may select among several GPS traces, and it is possible to install new traces from data recorded on test drives.

The simulation tool is available at http://vii.path.berkeley.edu:8081. Two screen shots are shown below. The area on the right side of the screen shows the handset display, typically including both a MUTCD-based icon and a supplementary informational message. The map area on the left shows the vehicle as a red marker with a blue line (visible in the second screen shot) indicating speed (length of line) and heading (angle of line). The map scrolls as the vehicle moves off the edge. The controls at the top of the window let the user select the dataset and start or stop playback at a specified time.


Stop drive
Restart drive
at time step 161
with data
set: Lap 2
networkedtraveler
Map
Satellite
Hybrid
ROAD
CLOSED
500 FT
W. 39th Street
Closed at 12th Ave.
No right turn from 12th


Stop drive
Restart drive
at time step 23
with data set: June 17
Map
Satellite
Hybrid
Speed limit
SPEED
LIMIT
25

3.3.3.8 ***On-the-road testing***

In addition to the simulation testing, we tested extensively in both cars and buses by driving several routes through the covered areas. This validated that the application logic was not too badly degraded by variations in vehicle position, speed, and heading, nor by inaccuracy in the gps data.

3.3.4 Transit Applications

3.3.4.1 ***Premises***

If travelers are better informed of the travel options in real-time, including driving, transit and mixed mode, they was more likely taking transit.

Transit has become increasingly viable for travelers as a result of gas price hike. APTA reported a 4.36 % increase in ridership nationwide in 2008 compared with a year ago due to the gas price hike. For similar reasons, the ridership increase for rail is about 12%. The ridership data provided by transit agencies in the Bay Area is consistent with national statistics and, promisingly, ridership continues to grow despite the fact that gas prices have become lower. While the gas price is the key factor in causing a mode shift for many, the fact that riders stay with the transit mode indicates that most travelers may not know their transit mode option as an alternative before being ‘triggered’ (in this case, by the pocketbook) for mode transfer. Once triggered, these former drivers have stayed with the transit. It appears that the mode shift ‘experiment’ due to gas price hikes is due to knowledge and information about the transit alternatives. It is therefore hypothesized that this is such knowledge will help attract riders and that transit can be a viable, realistic mode for commute corridors where travel time for transit is competitive.

The GEMS infrastructure enables a “connected” environment for the transit users, both pre-trip and en-route. Via the GEMS infrastructure, travelers was able to get the real-time transit information using web browser, and even via cell phone while they are on the move. The information available via the cell phone also becomes personalized in the sense that the bus arrival time, the estimated remaining time of the trip can be calculated based on the specific trip of the traveler.

3.3.4.2 The transit applications—En route transit information

Figure 3-13: Dynamic Personalized Passenger Information System

The dynamic personalized passenger information is generated by integrating into GEMS the Automatic Vehicle Location (AVL) system and its real-time bus arrival time prediction and processing system. Real-time updates of the bus schedules are updated. At the server side, passenger trip information is saved and combined together with this real-time transit information to make the information personalized for the trip.

While the traveler is on the bus, it shows the traveler information of the “time to transfer point” update in real-time.

Figure 3-14: Time to Transfer point update

The AVL equipped bus has frequent GPS update so that GEMS travelers could get an alert for the upcoming events such as “your stop next”.

Figure 3-15: Your stop next alert

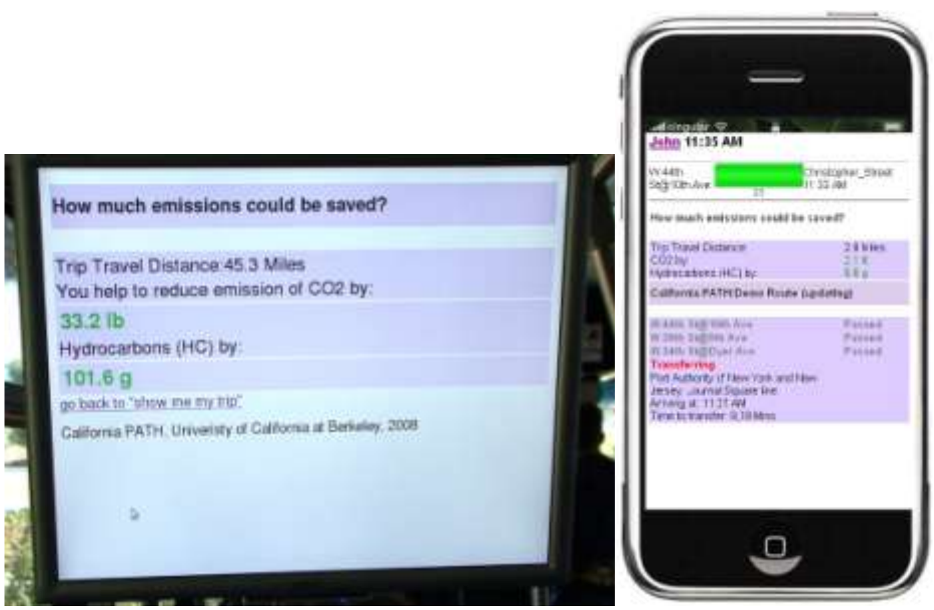


Figure 3-16: Carbon emissions saving of a transit trip

3.3.4.3 The transit applications—Improving the transit operations

The GEMS connected environment also provides opportunities for the transit agencies to improve the transit operations. Two GEMS transit applications are introduced in the GEMS system and have been demonstrated at New York World congress are the driver advisory application and the adaptive transit signal priority application using DSRC.

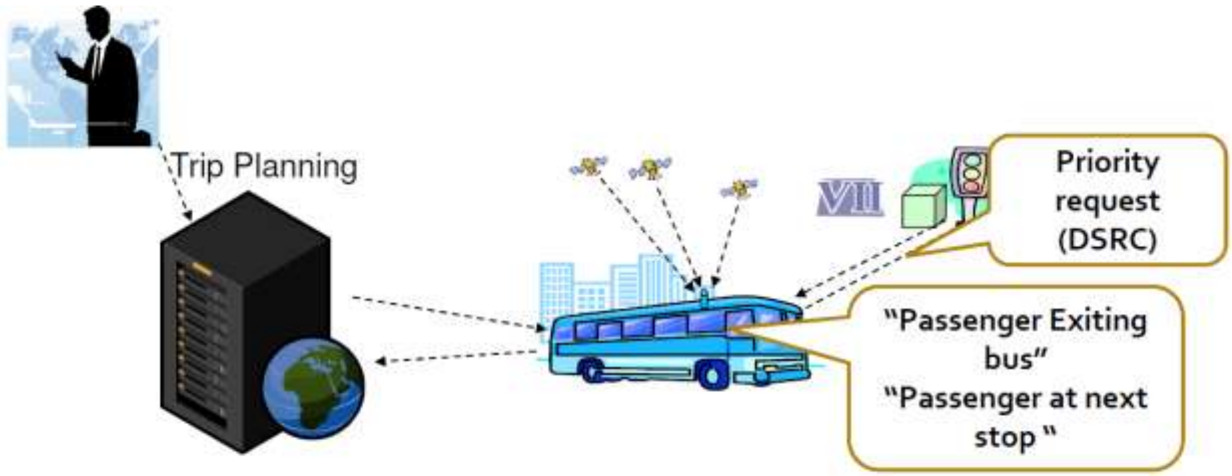


Figure 3-17: GEMS transit apps for transit operations

The trip information of a traveler can be sent to a trip planning server, which is connected to the transit agencies bus operational center. The travel's cell phone, when connected with the bus via GEMS environment, could get the personalized information for the trip as has been shown in the previous section. And at the same time, the connection information of the user on board the bus is also processed to generate the Driver advisory information, which alerts the driver about "passenger exiting bus" or "passenger waiting at bus stop". The information could further be processed to coordinate the operation of the buses and make the transit services more demand responsive.

The GEMS environment also features a real-time vehicle-roadside connectivity which could be used to enable the high resolution adaptive transit signal priority. Bus, in real-time, sends the GPS location in sub-second level to road-side GEMS receiver, which is in turn connected to the signal controller. Enabled by the standard DSRC messages, the signal controller could grant the buses extra green time or earlier green onset.

3.3.5 Shuttle traffic probes:

In July 2008, PATH and Stanford University cooperatively instrumented part of the Marguerite Shuttle fleet to collect probe data. The installation has since collected 16 months of data and is still operating, as of November 2009, with data available on interactive maps and as a web service.

The application is designed to gather information relevant to travel time estimation. Since the shuttle routes include bus stops and intersections, the bus speed is frequently low or zero at certain locations. We avoid those locations when reporting speed by basing the data collection on mid-block points. A mid-block point consists of latitude, longitude, and heading. It is selected (manually) to be at a point where the bus achieves its maximum speed for that block, which indicates traffic speed. We selected 44 such points around the campus. All three coordinates are used as matching criteria for incoming GPS data on the server. The bus records GPS data only at these points. Conceptually, a mid-block point defines the location of a virtual loop detector. The heading defines the road direction (which side of the road the virtual sensor is on). The system collects on average about 100 of these data points (speed at a mid-block location) per day.

3.3.5.1 Marguerite Shuttle system

The Marguerite Shuttle (http://transportation.stanford.edu/marguerite/MargueriteShuttle.shtml) is the primary transit system on the Stanford University campus. There are several routes which pass at least one of the VII California testbed RSE sites along El Camino Real, which permits periodic (though not continuous) contact with our roadside network. Furthermore, some routes coincide for several blocks with urban arterials such as Page Mill Road, Sand Hill Road, Junipero Serra Blvd, and El Camino Real, allowing us to gather traffic data on some roads of interest to non-campus users.

3.3.5.2 VII California Testbed

The testbed is described elsewhere in this document. The region relevant to the shuttle instrumentation is shown below.

The shuttle routes that we instrumented pass by one or more of the following RSE locations, designated by cross street on El Camino Real: California Ave., Page Mill Rd., Stanford Ave., and Quarry Rd.

3.3.5.3 *System architecture – Hardware*

The installed equipment consists of a Savari OBU (SOBU) with DSRC and WIFI antennas and an external (USB connected) GPS receiver/antenna.

The system was installed in 20 vehicles: 11 vans and 9 buses. These vehicles serve 6 of the Marguerite routes. The SOBU units installed in the vans draw power from the cigarette lighter. The bus installations use an inverter for power supply. In either case, the SOBU powers up and down synchronously with the vehicle ignition.

The roadside equipment is described elsewhere in the VII California reports. Each RSE installation consists of a MCNU computer with DSRC and one of several backhaul options (land line or wireless), connecting the RSE by Internet to a server at PATH.

3.3.5.4 *System architecture – Software*

The probe application consists of several software components:

1. The probe client running on the SOBU.
2. The probe server running at PATH.
3. A middleware process running on the RSE computer.
4. A public web server running at PATH.

The probe client (1) has a database of mid-block points, as defined above and manually selected for the area. As each GPS data point is received, the client process compares the latitude, longitude, and heading with the mid-block points. If one of them is a close match, then the current speed, time, heading, and GPS diagnostics are recorded, along with the ID of the matching mid-block point, in a local buffer (since there is usually no network to send them out on).

The probe client is also listening for beacons from the RSE on DSRC. When it hears one, all observed data that has been stored in the buffer is sent to the RSE over DSRC. Then, if the transmission succeeds, the buffer is cleared.

The middleware (3) brokers asynchronous requests between 1 and 2. It is in general impossible to communicate synchronously between 1 and 2 because of (a) the sporadic, short, and unpredictable wireless access of the OBU to the RSE and (b) the possibility of delay and network outages in the backhaul network. In fact, the middleware is a HTTP proxy that operates over DSRC, and all the data transmissions use standard HTTP rather than custom protocols. The second step of the upload (from RSE to server) can be performed even if the client goes out of range during the upload.

The probe server (2) receives the uploads from the four RSEs, and stores them in a database.

The public web server (4) uses this database to provide both interactive maps and a web service API (application program interface) for programs that consume the data. This is described in the next sections.

An experimental feature of the software is remote updates. We have no direct network access to the Marguerite shuttles, and site visits are expensive and time consuming. So we developed software to perform remote asynchronous software updates brokered by the RSE. The RSE acts as a repository for the software updates and also for diagnostic scripts from the the server. The client downloads them when in DSRC range, and executes them if needed to update to the latest software version; diagnostic scripts may prepare diagnostic data for future upload, when next in range. This feature was tested at the RFS site, but not at the remote Stanford site.

3.3.5.5 Map interface

The following image shows a sample query and its results. This interface is available at: http://vii.path.berkeley.edu:8080/speed-map.html

The “Start time” and “Finish time” text boxes let the user enter the time range for the query. The results are overlaid on the Google map. The results show average speed for each mid-block point over the time interval. Red indicates speed is less than 10 meters per second. In addition, the length of the stripe is proportional to speed.

3.3.5.6 Web service interface

A richer but less visual interface to the data is by the web API. This interface allows access to other aspects of the data including GPS diagnostics: HDOP and satellite count.

The query structure is documented on-line at:

http://vii.path.berkeley.edu:8080/marguerite-readme.html and below:

```
Sample query:
/marguerite?n=10&mid=41&t0=1217264400&t1=Mon Jul 28 15:07:43
These params are accepted:
```

- `mid - value is a string that references a midblock location (e.g. midblock?mid=4)`
- `t0 - starting time (lower bound for query)`

- t1 – finishing time (upper bound for query)
- n – limit on number of rows returned (returns most recent n rows).

All params are optional, and if omitted the constraint is absent in the query and all relevant matches are returned.
The time can be specified in two ways:

- As an integer number of seconds since the epoch, namely Thu Jan 01 00:00:00 UTC 1970 (as t0 in above example).
- As a human readable date string with underscores instead of spaces (as in t1 in above example). Most conventional date formats are accepted, including:
    - Jan_23,_2008
    - 10_aM_14_Aug_2007_EDT
    - 2:31_PM *(interpreted as today)*

Precision is in seconds. Anything smaller is ignored.

The database containing the mid-block points can be queried at this url: http://vii.path.berkeley.edu:8080/midblock?mid=4. The last number is the ID of the mid-block point.

4 Integrate Applications with User Devices

4.1 WiFi Device Integration

Three kinds of WiFi devices were used:

1. WiFi Radio on the handhelds (Cell phones and PNDs)
2. WiFi Radio on the SOBU
3. WiFi Radio on the Technocom (Now Kapsch) MCNU

The applications developed required a combination of communication among these devices. Of the two radios available in the MCNU one was configured to be in the 2.4GHz WiFi frequency. It was programmed to boot up in a specific channel with a specific SSID. The fixed SSID made it easier for the handheld client to associate with it while the fixed SSID allows for a quicker association. A program was developed to reside in the MCNU and broadcast relevant information (e.g. map data etc) and unicast pedestrian related information to a specific pedestrian. The available WiFi radio on the cell phone was tuned to talk with the other GEMS components using WiFi (viz. MCNU, SOBU). The WiFi radio on the SOBU acted as a communication bridge with the handhelds. The SOBU was programmed to boot up in a specific WiFi channel much in the same way as the MCNU, the only difference is that it was for dedicated use for communication with the handhelds.

4.2 Cell Phone Integration

A browser based integration was chosen for the cell phone integration of the applications. The main program resided on the SOBU. A proxy was used to serve the necessary information in HTML format to the cell phone. Extensive use of Sqlite3 was used as a data hub. The applications were also tested for IP over Bluetooth and audio over Bluetooth functionality. The cell phone interface gave included a browser based audio visual display. Various techniques including innovative use of Javascript were used to refresh the display with current information on the mobile browser. Being a browser based approach it worked on a broad range of cell phones and PNDs. The programming was done in a way to make it useable in a variety of mobile browsers.

4.3 Personal Navigation Device (PND) Integration

Same as cell phone integration.

4.4 Provide Roadside GEMS Elements

4.4.1 Develop Multiband RSE Components

Initially Ad-hoc DSRC was used on the road side units. Technocom (Now Kapsch) Multiband Configurable Units (MCNU) were used as RSE. One of the two radios available was configured to be in the DSRC frequency range. We chose Channel 172, also known as the control channel, for the project. Tests were done in various other channels also (Channels 174, 176 etc.). The transmit power used was 17dBm and the coverage was tested and found enough for our applications. Natively compiled communication programs were used in the MCNU for DSRC based communication. The pedestrian application depends on the MCNU alerting vehicle driver via almost real time WAVE/ DSRC communication.

4.4.2 Install Multiband RSE

A couple of MCNUs were installed outdoors at RFS for demo purposes.

5 Provide Data Integration and Display Elements

5.1 Develop Generic Display Format and Data

Work in this subtask will provide a software component able to receive probe data in the SAE J2735 format from the vehicle and transform it into data representing a color coded speed map and link travel times. This data was decoded by the in-vehicle or on-user device software components to produce the display. This component was delivered by the University of Utah, which will include server design, system design and prototyping, and importantly, offline data mining for historical and web-based data.

It is a given that there must be a 511 interface and a PeMS interface. The University of Utah PI (Prof Xeusong Zhou) is a well-regarded investigator in integrating and putting into a common display arterial data. Among his past efforts are work sponsored by FHWA for his NEXTA tool; this and his private sector experience, was leveraged into this task. Additionally, PATH human factors engineers will work with the University of Utah team to provide an human-factored messaging components, suitable to effectively and safety provide application information.

5.2 Provide MTC 511 Interface

Work in this subtask will provide a software component able to receive probe data in the SAE J2735 format from the vehicle and feed it to MTC's 511 system. The basis of this work has already been done, e.g., the early December 2007 VII California demonstration to the RITA Administrator and the VII Working Group. Hence, the incremental contribution from MTC and their contractors is presumed to be small; moreover, the incremental contribution from PATH researchers will likewise be relatively modest, comprising mainly of interface and formatting details necessary to make the generic display to work.

5.2.1 Provide PEMS Interface

Work in this subtask will provide a software component able to receive probe data in the SAE J2735 format from the vehicle and feed it to PeMS. This task was executed by the University of Utah and PATH team, with a BTS principal and PeMS co-inventor (Dr. Karl Petty) providing consultation hours. We anticipate this to be straightforward, partly based on the qualifications and experience of the team, and we anticipate also that this could have lasting value to Caltrans as this would bootstrap PeMS development to display arterial data, regardless of source (probe or other surveillance instrument).

5.2.2 Develop VII California Internet Server

Work in this subtask will provide a software component that will receive all the data from the vehicles in the system and check it for correct format and integrity before passing it on to the application components. This component is only required for the GEM demonstrations as a redundant and therefore risk-minimization effort and will eventually be phased out once the system is operating robustly.

6 Make GEMS Testbed Operational

To make GEMS operational requires a successive series of milestones to minimize the risk to the culminating demonstration and proof of concept. ***The integration between RSE, OBE, applications, and, importantly, users was successively addressed in this task.*** The GEM deliverables was three first wave applications drawn to cover safety, mobility, and transit, and the future application development environment (software and hardware). These deliverables was released in two phases:

6.1 Internal demonstration of GEMS proof-of-concept

The purpose of the proof of concept is to provide the GEMS outreach task with a credible showcase used to attract partners. Potential partners include traffic information providers, telecommunication companies, automotive companies, telematics companies, Internet search and service provider companies, etc.

6.2 GEMS demonstration with partners to SSOM in mid-August 2008.

This demonstration will improve GEMS software, hardware, and applications to be robust enough to covers up to 100s of users over multiple devices, networks, OBE and RSE. The demonstrated applications was adapted based on the feedback received at deliver the first test. Our overall objective was instantiated here: that this will indeed be the starting point in Statewide and national deployment and open the door for significant research thereafter.
We will implement this task in three subtasks:

6.3 Install, Shakedown and Test

There was an install-test paradigm implemented throughout the OBE and RSE installation tasks. ***Applications was developed and put into the field in subscale expeditiously***. This ongoing and almost parallel activity was conducted through the duration of the effort.

6.4 Scale to GEMS Trial

Scalability was the result of Task 1 (Outreach) success, as the user base recruitment and means to address scalability will conducted in this subtask. To facilitate this, we have budgeted temporary recruitment financial incentives to 200 drivers and up to 100 additional mobile devices (e.g., iPod Touch). While we aim for voluntary recruits who will receive value from the GEMS services on their own devices, we add this investment toward scalability as a means to reduce the risk in a successful GEMS demonstration. The GEMS Demonstration Readiness Documentation is Written Deliverable #3.

6.5 Conduct GEMS Testbed Trials

Trials 1 and 2 described in Task 5 work statement was conducted in this subtask.

6.6 Management and Reporting

We will provide written quarterly status reports, along with the written deliverables described\ below. Due to the short nature of this project, we do not focus on the quantity of written deliverables; however, we will focus on the quality, and very much so on the final deliverable: final report, open users guide and development kit. The Comprehensive Final Report and Technology Transfer Documentation is the final Written Deliverable. ***We note that besides the written deliverables, we will provide the following:***

- ***Demonstrations, at a minimum the June small-scale demonstration to DRI and the culminating SSOM GEMS demonstration; however, observation and checkout of in progress experiments was provided as necessary and required.***
- ***Real applications, which was demonstrated and delivered with the final report.***

Due to the complexity and importance, the project management was proactive, and is budgeted to include Jim Misener, Raja Sengupta and a day-to-day project engineer to provide high-quality assistance (as well as a program assistant).

Per TO 6217 precedent, we will also schedule approximately bi-monthly meetings with VII California representatives and stakeholders to discuss progress. We was available for more frequent teleconferences, calls and status updates. The final report was accompanied with briefings to DRI and briefing material was prepared for DRI, also.

7 Schedule, Milestones, and Deliverables

The schedule for this project is aggressive, as the target – research and experiments culminating with the AASHTO SSOM meeting in the San Francisco Bay Area in mid-August, coincident with a demonstration of the companion CCIT-Nokia cell phone probe project, is aggressive. Hence, at some level, six major tasks – outreach, OBE provision, RSE provision, data integration and making the VII California-GEMS testbed operational, not to mention the complexity of management – must begin at some level immediately with contract award. (Staffing and subcontract plan per budget submitted in this project.) After the SSOM demonstration, a report and ancillary but very important and tangible product of hardware and software design, users guides and software development kits as necessary was produced for reuse for other applications and for other regions, both within and outside of California.

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9 Appendices:

9.1 Appendix: VII DSRC/NTRIP DGPS Setup Manual

This guide details the setup of a purpose built GPS/IMU receiver and NTRIP messaging for transmission of DGPS corrections from a local base station. The configuration is detailed for the NTRIP broadcaster located at UC Riverside. NTRIP server locations in the VII California testbed area can be routed through the NTRIP broadcaster through configuration and settings of the base station. The selection of the GPS correction stream would be modified in Step 8 to reference the VII tested source.

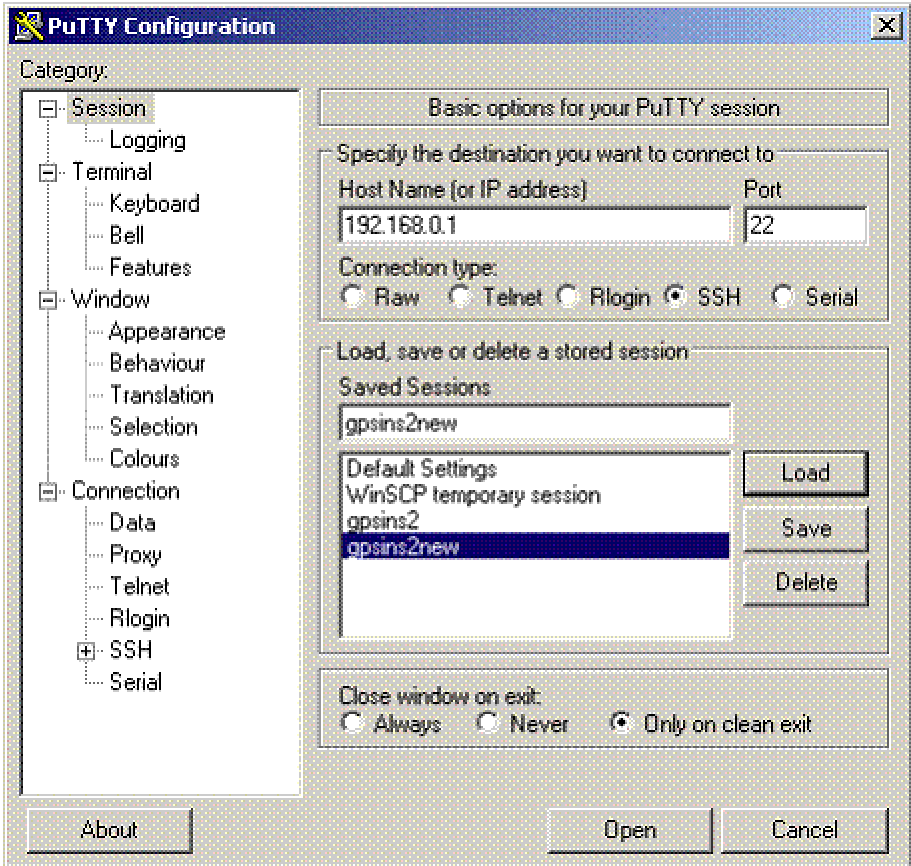
Using the NTRIP program, this unit is configured to start logging a GPGGA sentence to a new file on boot. The refresh rate is 1 Hz. The fix flag in the GPGGA sentence tells whether or not the GPS is receiving differential corrections via NTRIP.

9.1.1 *To set up unit and begin logging data:*

1. Turn on computer and plug in GPS unit; also plug serial/USB cable with brown tape into rearmost USB port on right side of a laptop.

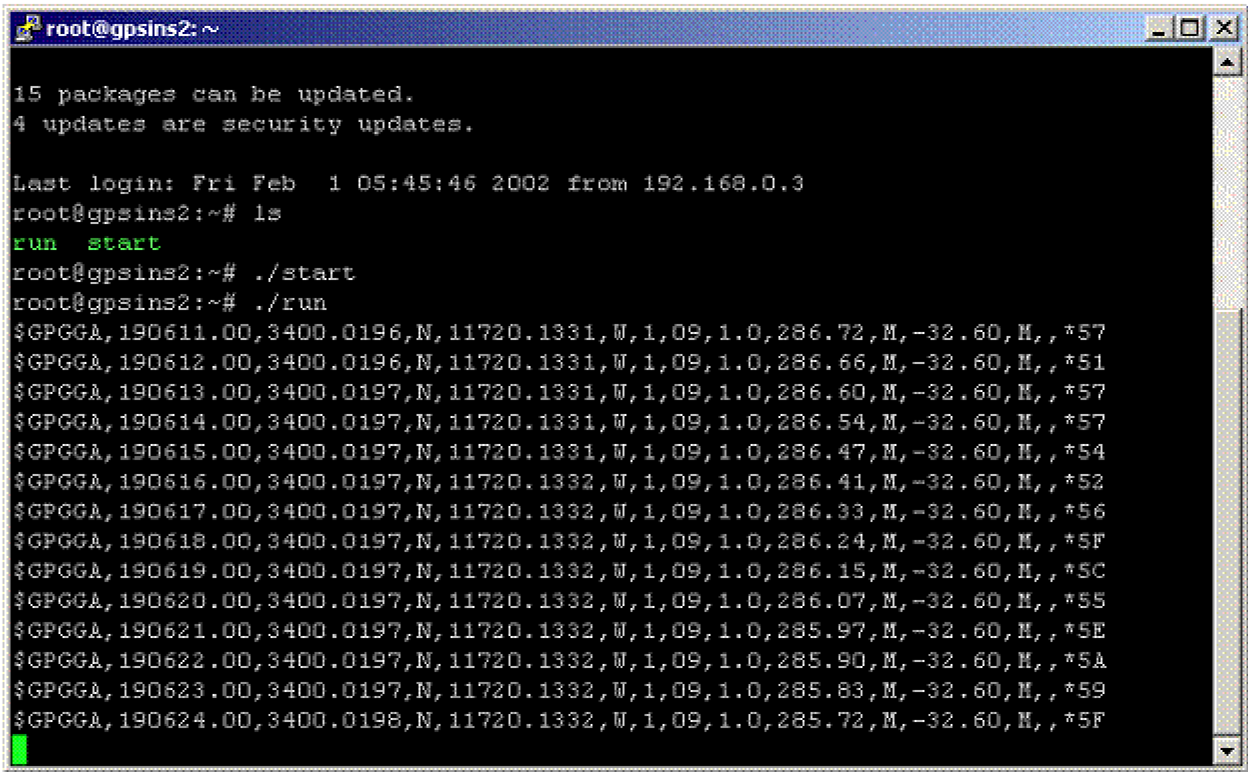
2. After waiting about a minute for the GPS to warm up, plug in Ethernet cable between unit and computer.

3. Open PuTTY and click "Open" (the host name should already be entered [192.168.0.1] port 22).

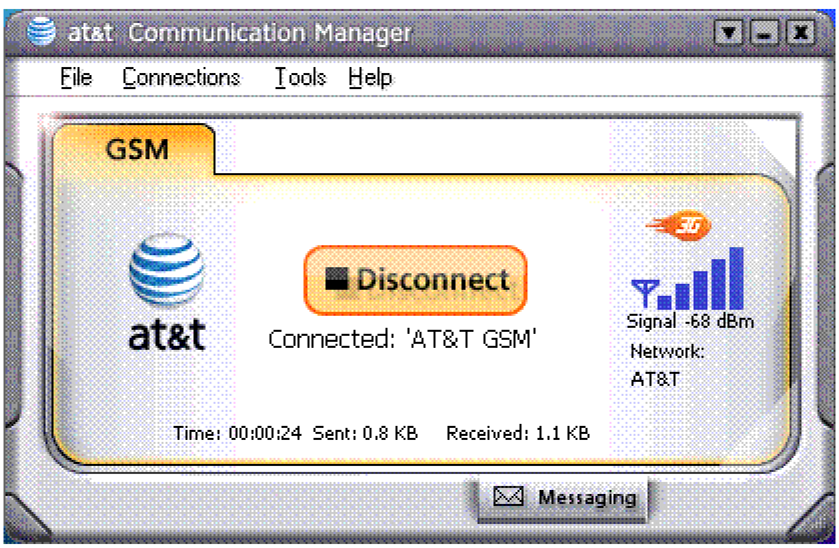


4. When prompted for password, enter "gpsins"

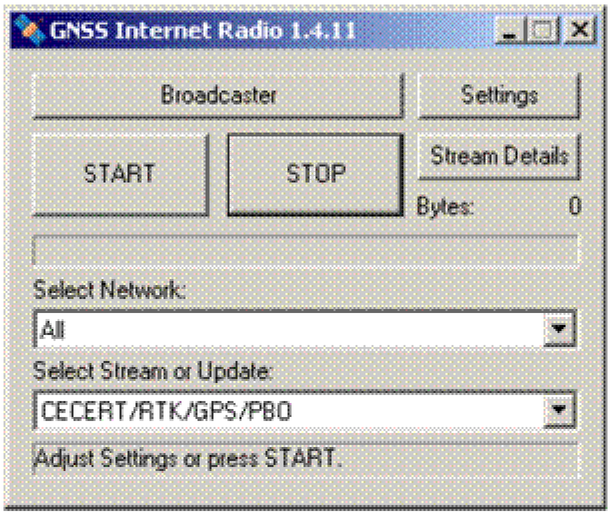
5. Once logged in, at the command prompt, type "./start" (without quotes) the press enter. Next type "./run" (without quotes) then press enter, if all is working properly, this will display the GPGGA sentence in real time on the screen.

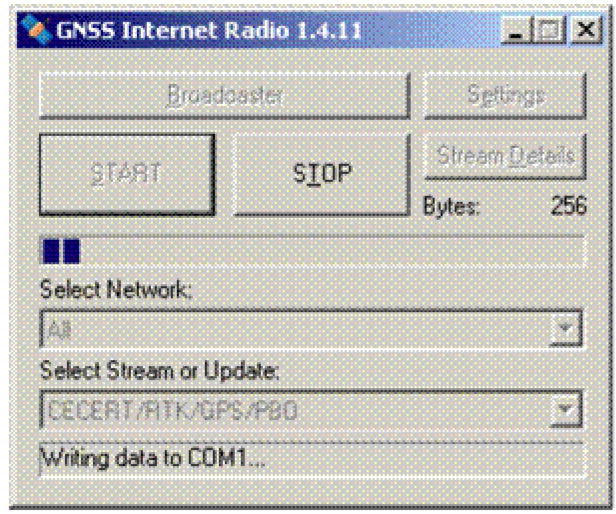


6. Close the PuTTY window, and disconnect the Ethernet cable.
7. Open the ATT Communication Manager and click “Connect” when it is ready.



8. Once connected to ATT, open GNSS Internet Radio, and click “Start” to start sending differential corrections to the GPS via COM Port 1 (rearmost USB port on right side of ASUS laptop) (be sure that the “Select Stream” pull-down menu is set to CECERT/RTK/GPS/PBO)





9. Everything is now configured and logging GPS data with NTRIP corrections.

9.1.2 In order to make sure that GPS is receiving NTRIP corrections

1. After logging data for 1-2 minutes via the above setup, click “Stop” in GNSS Internet Radio.

2. Click “Disconnect” in ATT Communication Manager, and plug in Ethernet cable again.

3. Wait for about a minute, then SSH into the unit and output the GPGGA sentence by repeating steps 3-5 from above.

4. If the GPS unit is indeed receiving differential GPS corrections, the fix flag in the GPGGA sentence will read “2” (if it is not receiving differential GPS corrections, the fix flag will read “1”, if no fix “0”)