Mobile Century
Using GPS Mobile Phones as Traffic Sensors: A Field Experiment

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abstract

This article presents the *Mobile Century* field experiment, performed on February 8, 2008, to demonstrate the feasibility of a prototype location-based service: real-time traffic estimation using GPS data from cellular phones only. *Mobile Century* consisted of 100 vehicles carrying a GPS-equipped Nokia N95 cell phone driving loops on a 10-mile stretch of I-880 between Hayward and Fremont, California. The data obtained in the experiment was processed in real-time and broadcasted on the internet for 8 hours. Travel time and velocity contour estimates were shown in real-time using a privacy-preserving architecture developed to provide this new service in an environment acceptable to users and participants. The quality of the data proves to be accurate against data obtained independently from the experiment. The experiment also shows that it is not necessary to have a high proportion of equipped vehicles to obtain accurate results, confirming that GPS-enabled cell phones can realistically be used as traffic sensors, while preserving individuals' privacy.

1. Background

The convergence of sensing, communication and multi-media platforms has enabled a key capability: mobility tracking using GPS. Major cellular phone manufacturers plan to embed GPS receivers in most of their phones in the near future. This trend has major implications for the traffic engineering community. Currently, traffic monitoring is most commonly based on fixed detectors, which provide vehicle counts, roadway occupancy, and often speed. Unfortunately, their high installation and maintenance costs prohibit more widespread deployments, particularly in developing countries. Moreover, the reliability and accuracy of this type of detectors vary.

GPS-equipped mobile phones can provide speed and position measurements to the transportation engineering community by leveraging infrastructure deployed by phone manufacturing companies and network providers. Because this technology is market driven, it will penetrate transportation networks at a very rapid pace, soon covering rural areas with a significant impact in developing countries where there is a lack of public traffic monitoring infrastructure.

The present study describes a field experiment to assess the feasibility of this new traffic monitoring system based on GPS equipped phones.

2. System architecture

A prototype system architecture was created to gather probe vehicle data in a privacy preserving environment. The architecture uses the concept of *virtual trip lines* (VTLs). Virtual trip lines are geographical markers stored in the client (i.e. the mobile handset), which trigger a position and speed update whenever a probe vehicle crosses them. Sampling in space through VTLs, rather than in time leads to increased privacy by facilitating a distributed monitoring architecture that processes only anonymous location updates (i.e. no single infrastructure entity possesses identity and accurate location information [1]). A privacy-aware placement algorithm that generates the VTL database was designed and used for this study. We demonstrated the validity of the implementation of the virtual trip line concept through a preliminary 20-vehicle experiment on a highway segment on November 2, 2007.

The system architecture comprises four entities: the probes (i.e. GPS-equipped cell phones traveling onboard vehicles), a cellular network operator, an ID proxy server, and a traffic monitoring and reconstruction system. Standard encryption techniques secure the data transmissions. To further address the privacy concern, the VTL concept can be associated with a cloaking technique whereby several speed updates are aggregated based on trip line identifiers, without collecting the geographic locations of individual trip lines.

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Thus, VTLs facilitate the design of a distributed architecture, where no single entity has complete knowledge of probe identity and fine-grained location information.

The data collected is used to estimate the state of the system (in this case, velocity and travel time on the highway). It is sent to a server, which runs traffic flow reconstruction algorithms using this data. The algorithms rely on nonlinear flow models, which describe evolution of the traffic velocity, and can accurately reproduce shockwaves created from accidents or bottlenecks on the highway. These flow models are embedded into an inverse modeling estimation algorithm. This algorithm employs Ensemble Kalman filtering, which enables the use of the discretized nonlinear flow models. The estimates produced by the algorithm are sent back to a visualization server, which broadcasts traffic state through the internet (see interface in Figure 2).

3. *Mobile Century*: A FIELD EXPERIMENT

The *Mobile Century* experiment took place on February 8th, 2008. It consisted in deploying 100 GPS-equipped Nokia N95 cell phones on a freeway during 8 hours. The experiment was conducted on Highway I-880, near Union City, CA, between Winton Ave. to the North and Stevenson Blvd. to the South (Figure 1). This 10-mile long section was selected for its traffic properties (in particular the known existence of a recurrent bottleneck between Tennyson Rd. and CA92 in the northbound (NB) direction), and a high loop detector density useful for validation purposes. 165 UC Berkeley students drove loops on the section of interest between 10am and 6pm. This period encompasses free flow and congested conditions, and the transition between the two of them. The loop structure was implemented in order to achieve a desirable penetration rate of 3%-5% of the total flow. Different ramps were used by different vehicles and at different times of the day (AM and PM loops in Figure 1) for experimental reasons.

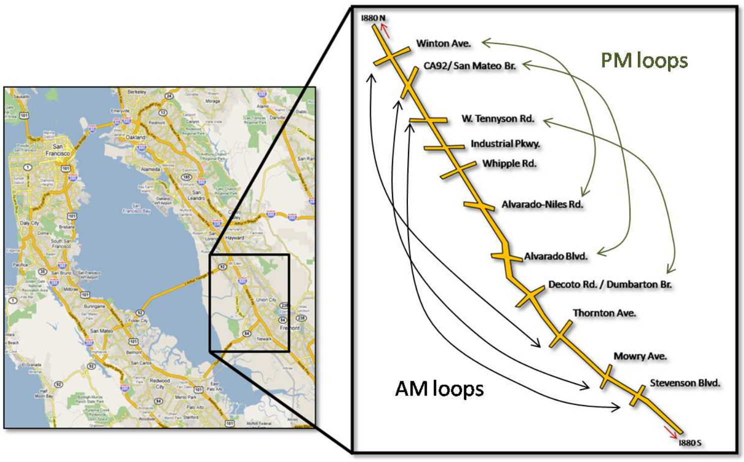

FIGURE 1. Deployment section on highway I-880, CA, for the *Mobile Century* experiment.

The data was collected in two ways during the experiment. First, the privacy preserving architecture described earlier collected data from the 45 VTLs deployed in the section of interest (each VTL covers both travel directions). This data was used to produce real-time travel time and speed estimates on the section of interest. In addition, each cell phone was storing its position and velocity every 3 seconds. This data (*trajectory* data) becomes available only once the experiment is finished, and is used a posteriori to evaluate the quality and accuracy of traffic data. This data is only generated for experimental purposes, and would never be collected in an operational system.

VTL data. The data obtained in the experiment was processed in real-time, and used to produce real-time travel time and velocity estimates, which were broadcasted for 8 hours. Figure 2 illustrates the interface used to broadcast travel time and speed during the day. The figure shows traffic at a time after an accident occurred in the NB direction between Tennyson Rd. and CA92. The figure also shows the 511.org traffic display at the same time.

The quality and accuracy of the VTL data depends on the proportion of equipped vehicles that cross them. To evaluate this, VTLs were placed on existing loop detector locations to compare the speed measurement provided by each one of them. A loop detector can be thought of as a VTL that collects data not from a subset, but from all vehicles. Figure 3 shows this comparison for two locations. The first location – part a) of the figure– is between Whipple Rd. and Industrial Pkwy. in the NB direction and has an average penetration rate of 3%-4%, while the second location is between CA92 and Winton Ave. in the NB direction and penetration rate rarely exceeds the 2% of the total flow. As expected, accuracy of the measurements increases with the proportion of equipped vehicles crossing the VTL. Notably, high penetration rates are not needed to provided reasonable speed measurements.

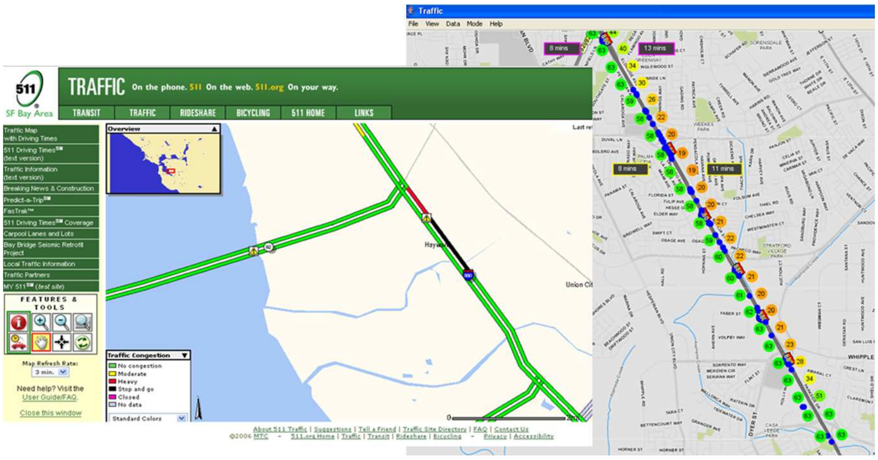

FIGURE 2. Traffic report provided by 511.org and our system at 10:52am on February 8, 2008, after an accident on the NB direction of I880 ocurred.

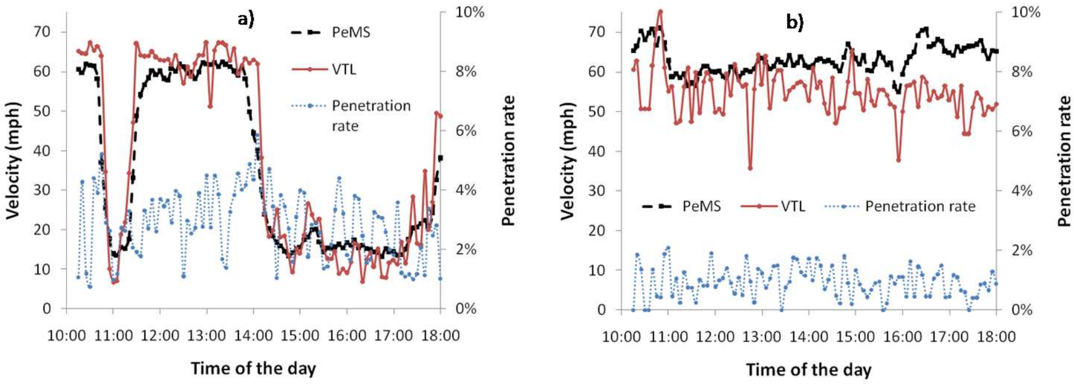

FIGURE 3. Loop detector velocity data versus VTL data with different levels of penetration rates.

Trajectory data. Data stored by every cell phone was processed after the experiment, in order to conduct more detailed analysis on the quality of the data. Trajectory of every vehicle can be reconstructed using this data. Figure 4 shows 50% of the collected trajectories in the NB direction. The transition from the AM loops to the PM loops occurs at 1:30pm and can be clearly seen in the figure, as well as the fact that different vehicles were using different ramps to get in and out of the highway. The propagation of the shockwave generated by the accident is clearly identified in this plot as well.

Using these trajectories, a velocity map can be constructed and compared with the one provided by PeMS (Figure 5). The velocity map computed from the trajectories uses Edie's speed definition [2]. The section chosen for this plot is between Decoto Rd. and Winton Ave. in the NB direction, from 10am to 6pm. This 6.5-mile section of highway is covered by 17 loop detector stations, providing a very good estimate of the actual speed contour.

Blank spots in part a) of the figure mean no equipped vehicle was at that time at that location. The agreement between the two plots in Figure 5 is evident, considering that less than 5% of the trajectories are known. The discrepancies at the ends of this section can be explained by the low penetration rate at these locations (especially at the north end, where the penetration rate is less than 2% as shown previously in Figure 3).

4. Final comments

The Mobile Century experiment has demonstrated that GPS-enabled cell phones can be used as sensors for traffic monitoring purposes, while preserving individuals' privacy when collecting data. The experiment shows the possibility of reconstructing traffic using a penetration rate of equipped vehicles less than 5%. The results show the accuracy of the reconstructed speeds and their correlation with the loop detector data available throughout the experiment.

This prototype system is in the process of being scaled up so it can handle up to 10,000 vehicles for a pilot deployment of six months, in a project called the *Mobile Millennium*. The *Mobile Millennium* project

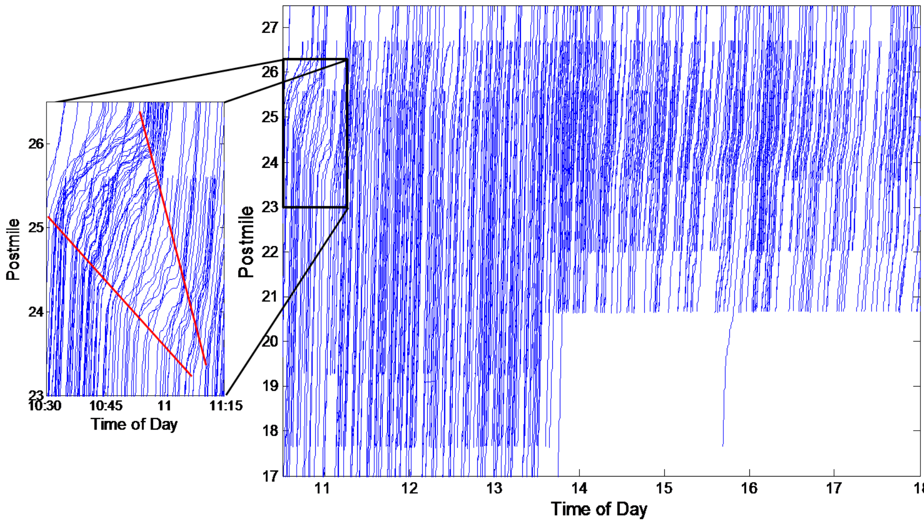

FIGURE 4. Vehicle trajectories in NB direction extracted from the data stored by 50% of the cell phones. The shockwave propagation can be seen during the accident in the morning.

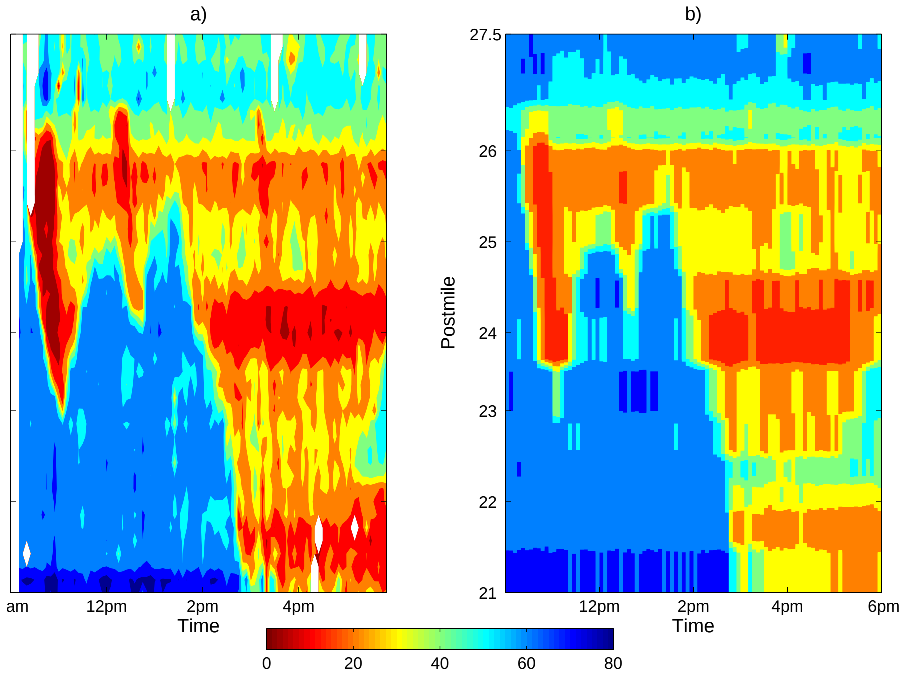

FIGURE 5. Velocity contour map (in mph) using a) vehicle trajectories and Edie's speed definition, b) 17 loop detector stations.

in its early phase will span some of the major highways in California, and provide similar levels of service as demonstrated during the *Mobile Century* experiment.

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