Project Millennium

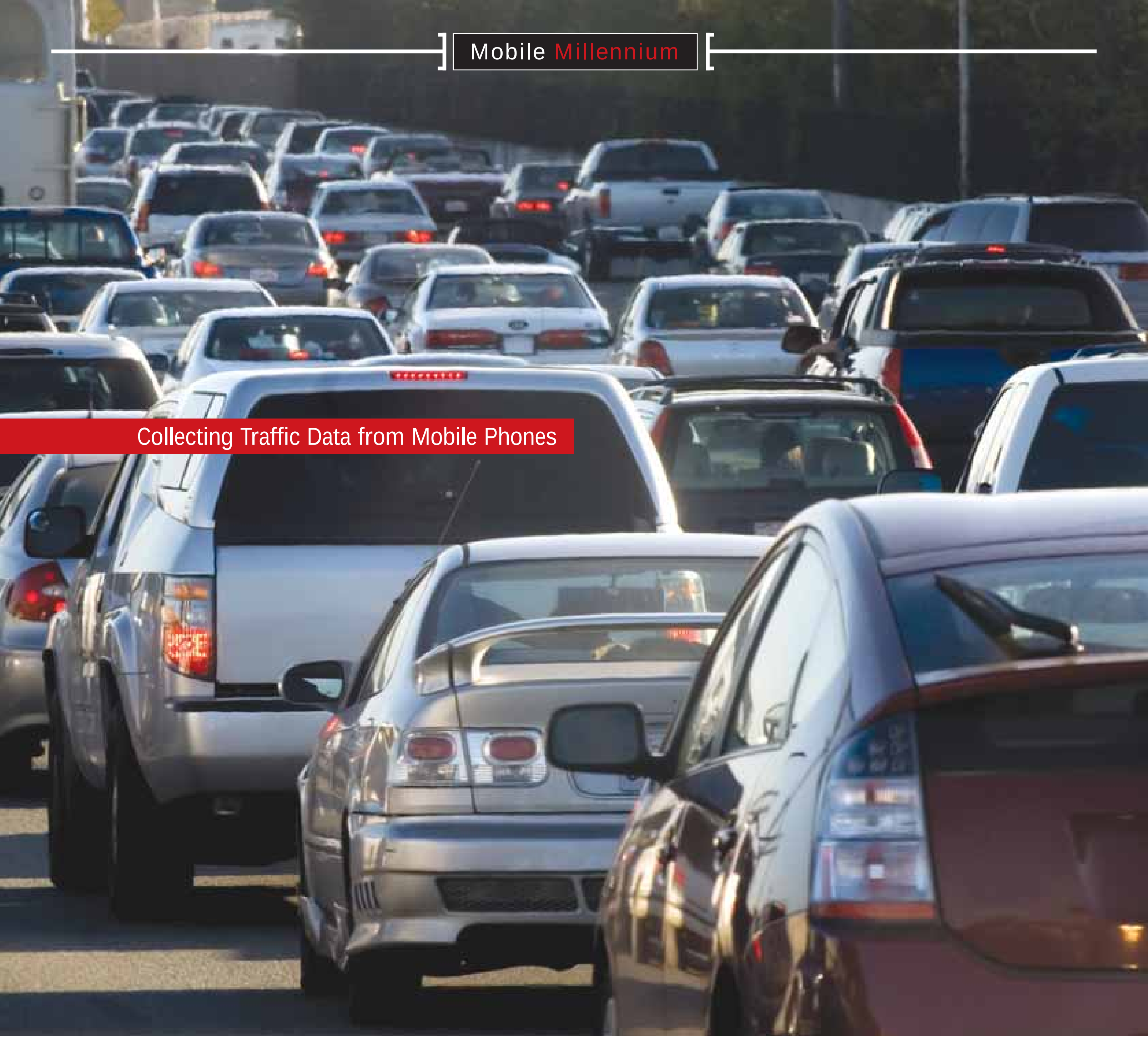
The potential of cell phones to operate as traffic data collection devices has been considered by the Intelligent Transportation Systems (ITS) community for several years. Government agencies currently deploy networks of infrastructure-based traffic sensors that are expensive to install and maintain. Leveraging the existing infrastructure of commercial cellular networks could drastically cut the ongoing costs of traffic monitoring and expand coverage to thousands of miles of highways and urban arterials for which sensors are not currently a viable option.

On February 8, 2008, Nokia and the University of California, Berkeley demonstrated the real-time reconstruction of traffic on highways using cell phones by running an experiment, nicknamed Mobile Century for its 100 cars traveling in 10-mile loops on Hwy 880 in the San Francisco East Bay for 8 hours, which amounted to 2%-5% of traffic. During the experiment, GPS equipped Nokia N95 phones sent traffic information in a privacy aware environment which was processed in real-time and broadcast to the internet. The successful experiment, funded by the California Department of Transportation (Caltrans), led to the development of a pilot system, Mobile Millennium, to make this technology available to the public.

The project is a partnership between Nokia, NAVTEQ, and UC Berkeley, based at the California Center for Innovative Transportation (CCIT) and supported by the U.S. and California Departments of Transportation.

Researchers have constructed an unprecedented traffic monitoring system capable of fusing GPS data from cell phones with data from existing traffic sensors. The research and development phase of this project was dubbed Mobile Millennium for the potential thousands of Early Adopters who downloaded the pilot software, launched November 10, 2008 and still running at the time of this publication.

Left: A Nokia E71 smartphone shows Mobile Millennium traffic pilot



Collecting Traffic Data from Mobile Phones

Mobile Millennium covers not only highways, but also the arterial network, where there is currently almost no sensing infrastructure. The software works on Nokia and non-Nokia phones, and the public can download it free of charge from an UC Berkeley website http://traffic.berkeley.edu.

Mobile Millennium gathers data in a privacy aware environment, relying on "Virtual Trip Lines" technology, a spatially data-sampling paradigm, the system anonymizes the GPS-based position information and aggregates it into a single data stream.

The transmissions of the data are encrypted. A computer system blends it with other sources of traffic data and broadcasts this real-time, data-rich information back to the phones and to the internet through a user-friendly interface.

This Special IQ Section contains the following articles on the Mobile Millennium Project:

The convergence of sensing, communication and computation on multi-media platforms has enabled a key capability: mobility tracking using GPS.

Using GPS Mobile Phones as Traffic Sensors: A Field Experiment

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 broadcast on the internet for 8 hours. Travel time and velocity estimates were shown in real-time using a privacy aware architecture developed to provide this new service in an environment acceptable to users and participants.

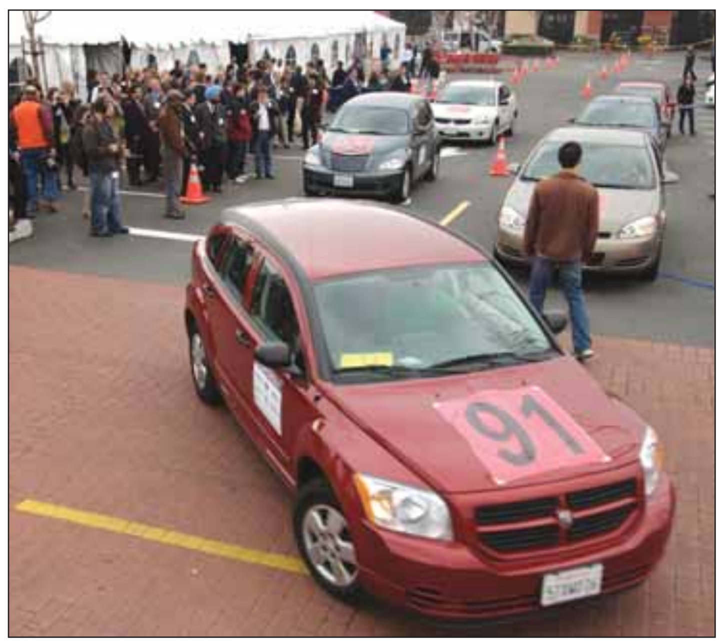
The quality of the data proved to be accurate against video data obtained independently during the experiment. The experiment also shows that it is not necessary to have a high proportion of equipped vehicles to obtain accurate results, confirming that GPS-enabled cell phones can realistically be used as traffic sensors, while maintaining individuals' privacy.

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 speed. Unfortunately, their high installation and maintenance costs prohibit more widespread deployments. Moreover, the reliability and accuracy of these types 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 the technology is market driven, it has the potentional to penetrate the transportation network at a very rapid pace, and could have significant impact in developing countries lacking existing 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.

System Architecture A prototype system architecture was created to gather probe vehicle data in a privacy aware 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 probabilistically trigger a position and speed update whenever a probe vehicle crosses them. By anonymously sampling phones in space using VTLs, the system is better suited to maintain the privacy of users compared to temporal based sampling strategies [1]. A privacy aware placement algorithm that generates the VTL database was designed and used for this study.



Staging area for the experiment. (Photo by Paul Kirchner Studios)

The validity of the implementation of the virtual trip line concept was demonstrated 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.

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 nonsmooth flow models. The estimates produced by the algorithm are sent back to a visualization server, which broadcasts traffic state through the internet.

A Google Earth rendering of collected GPS data. Virtual trip lines (shown in red) trigger measurement updates to the server.

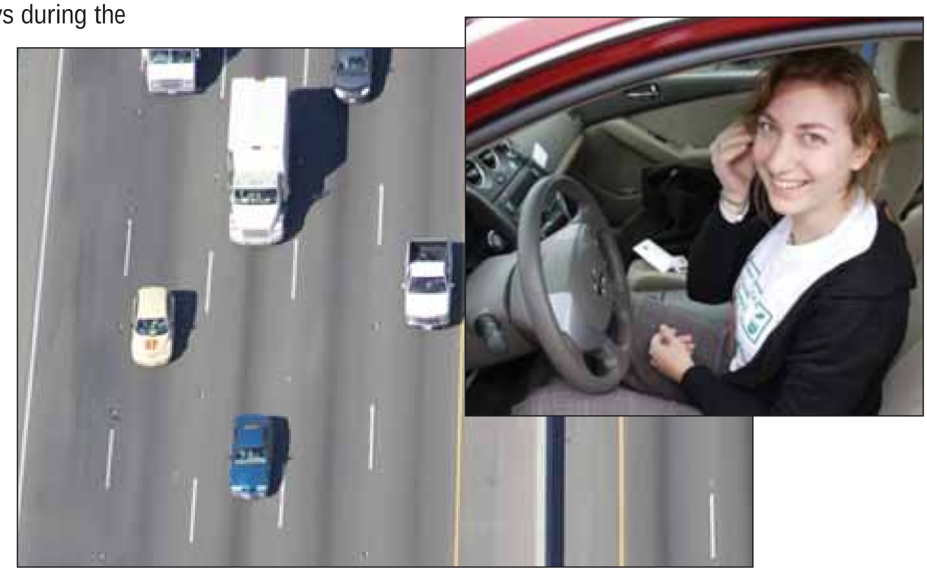
Mobile Century: A Field Experiment

The Mobile Century experiment took place on February 8th, 2008. It consisted of 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. 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 2%-5% of the total flow. Different ramps were used by different vehicles and at different times of the day for experimental reasons. 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 is not 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.

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 1 (next page) 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.



Aerial photo of the experiment in progress, and (inset) a participant. (Photo by Paul Kirchner Studios)

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 2 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 identifed in this plot as well. Using these trajectories, a velocity map can be constructed and compared with the one provided by PeMS (Figure 3). 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 3 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 in Figure 1).

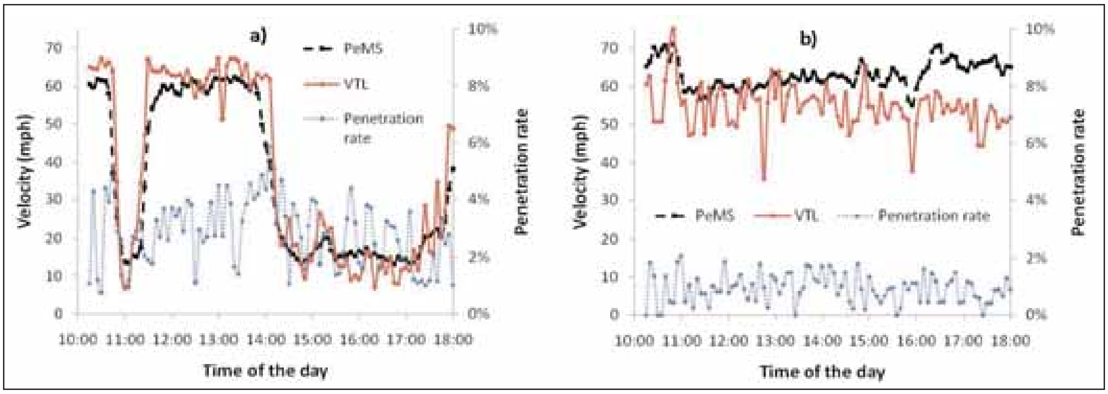


Figure 1. Loop detector velocity data versus VTL data with different levels of penetration rates.

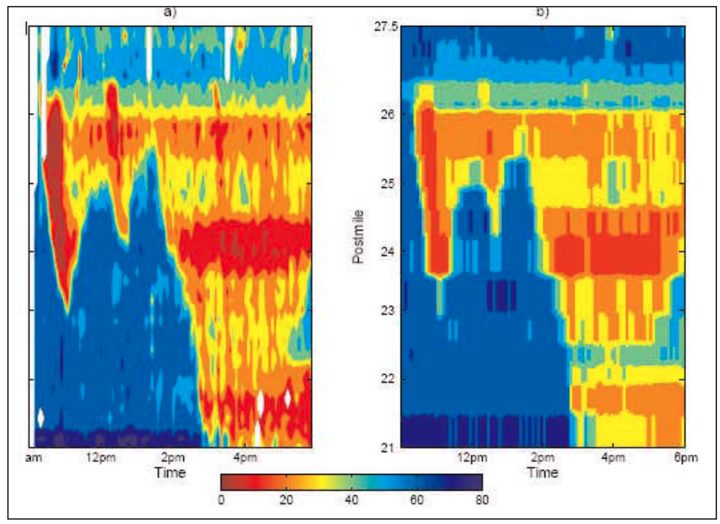


Figure 3 . Velocity contour map (in mph) using (a) vehicle trajectories and Edie's speed definition, left, and (b) 17 loop detector stations, right.

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.

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

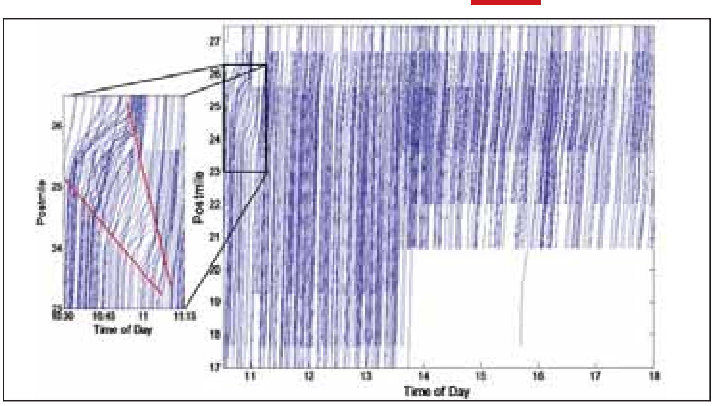


Figure 2. Vehicle trajectories in NB direction extracted from the data stored by 50% of the cell phones. The shockwave propagation can be seen during the accident in the morning.

Participants

The following Engineers, Directors and Administrators were involved:
Saurabh Amin[2], Steve Andrews[6], Saneesh Apte[6], Jed Arnold[6], Jeff Ban[6], Marika Benko[6], Alexandre M. Bayen[2], Benson Chiou[6], Christian Claudel[4], Coralie Claudel[2], Tia Dodson[6], Osama Elhamshary[6], Chris Flens-Batina[6], Marco Gruteser[8], Juan-Carlos Herrera[1], Ryan Herring[3], Baik Hoh[8], Quinn Jacobson[7], Manju Kumar[6], Toch Iwuchukwu7, James Lew[2], Xavier Litrico[9], Lori Luddington[6], JD Margulici[6], Ali Mortazavi[6], Xiaohong Pan[6], Tarek Rabbani[5], Tim Racine[2], Erica Sherlock-Thomas[6], Dave Sutter[7], Andrew Tinka[2], KenTracton[7], Olli-Pekka Tossavainen[2], Tom West[6], Arthur Wiedmer[10], Daniel B. Work[2], Qingfang Wu[9]

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[1] B. Hoh, M. Gruteser, R. Herring, J. Ban, D. Work, J. Herrera, A. M. Bayen, M. Annavaram, and Q. Jacobson. Virtual trip lines for distributed privacy-preserving traffic monitoring. In MobiSys 2008, Breckenridge, CO, June 17-20 2008.
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CCIT: The Key to Accelerating Innovation

How does innovation happen on the Mobile Millennium scale? How do you get the most cutting-edge ideas out of the minds of society's best thinkers and into the real world, where they can serve people, industries, and communities that will benefit most?

The California Center for Innovative Transportation (CCIT), a research center at UC Berkeley's Institute of Transportation Studies, was formed to address just these questions in the field of the transportation. CCIT's mission is to accelerate technological advances that will enable a safer, cleaner, and more efficient surface transportation system for California and beyond.

To achieve these goals, CCIT focuses on the critical "deployment" phase of the research cycle--getting the most promising ideas out of the lab and into the real world. Their team of experts is equipped to handle the myriad aspects of bringing large-scale technical projects to life, and to partner with behemoths like the California Department of Transportation (Caltrans), the largest state DOT in the U.S., and Nokia, a world leader in mobility services.

CCIT director Thomas West, himself a veteran of Caltrans senior management, says having a single organization at the center of largescale technical projects is the key to successful, expeditious deployment, and, “The full range of expertise that the CCIT team brings to a project includes solving complex engineering problems, navigating the change-management process in large organizations, and managing highly detailed logistical and communications operations, West said. “Having all those skills in our organization means projects can keep moving forward on every front."

Engineering is at the core of CCIT's work. On Mobile Century, for example, a team of six CCIT researchers, comprising both staff and graduate students, were responsible for much of the technical work that made the science come alive in early field-testing and troubleshooting, and again on February 8, 2008, when they kept accurate data flowing to the command center during the all-day field test operation.

CCIT engineers worked closely with UC Berkeley and Nokia researchers, making technological advances in an aggressive timeframe West calls astounding, and added: “At CCIT, relevant findings don't get lost in a report collecting dust on a shelf. With our deployment focus, our engineers study the real-world performance of the technologies they are developing or reviewing--they observe, correct, then advance expeditiously.”

UC Berkeley professors and their cadres of student researchers are also at the heart of the CCIT engineering team. When Berkeley professors receive funding for research projects, they can't go it alone; they turn to campus research units like CCIT to help turn award dollars into the technical support, materials, people, and administration needed to run an operation.

Alexandre Bayen, assistant professor of civil and environmental engineering, was the principal investigator for both Mobile Century and Mobile Millennium, overseeing all the engineering work on both projects.

Thomas West says having Berkeley's world-renowned brainpower on its team keeps the performance bar persistently high. "Berkeley engineering faculty and students are simply the best in the world," West said. "Having them on our team translates to excellence at every level."

But engineering alone can't make transportation projects come to life. In addition to the technical experts, CCIT's staff includes specialists in technical project management, communications, and logistics.

"The public is essentially a partner in anything related to the transportation network," West said. "So professional communication is a key function of our work." CCIT develops its own marketing materials, press materials, and other communications according to the needs of each project, keeping funders, partners, transportation colleagues, and the public informed about new opportunities.

On both Mobile Century and Mobile Millennium, for example, he remarks that extensive media preparations led to local, national, and international coverage that did a good job of telling a multifaceted technology story comprising several high-profile partners. In addition to standard marketing and media collateral publicizing the project, the communications team has also made a website, a video, and even an interactive museum exhibit.

Logistics are also a big part of moving theoretical research from the lab to the field. For Mobile Century, a logistics and operations team dealt with everything from fleet car rentals, to hiring and training drivers, to managing more than 100 smart phones getting regular software updates.

On event day, the command center timing was orchestrated to coordinate power and computer access for the CCIT engineers and students tracking the traffic events; information, rest, and food for the student drivers; monitors, a PA system, and other services for high-ranking observers from the transportation sector; and media support for the extensive press presence. Talk about details…and those are just a few.

Innovations can raise new and complex issues, and within large organizations, change-management can be a full-time job. CCIT's experienced project managers keep partners and funders informed of relevant issues, and managed institutional, state, and federal policies and regulations that pertain to each project. In Mobile Century, for example, driver safety was paramount, and compliance issues included adhering to UC Berkeley's "human subjects" policies and working with various law-enforcement jurisdictions where the experiment passed through.

With all these moving parts, it's easy to see all the effort involved in keeping acceleration at the heart of CCIT's mission. Thomas West thinks CCIT is unique: "As Mobile Century and other high-visibility projects like travel times on Changeable Message Signs show, CCIT has created a new model for getting cutting-edge technology out into the transportation network, with a one-stop-shop that brings top engineers together with a talented team of professionals. Our fantastic people allow to develop the most promising ideas coming out of UC Berkeley, so we can create better, smarter tools to help the traveling public make

Impacts of the Mobile Internet on Transportation Cyber Physical Systems

Traffic Monitoring Using Smartphones

By Daniel B. Work and Alexandre M. Bayen

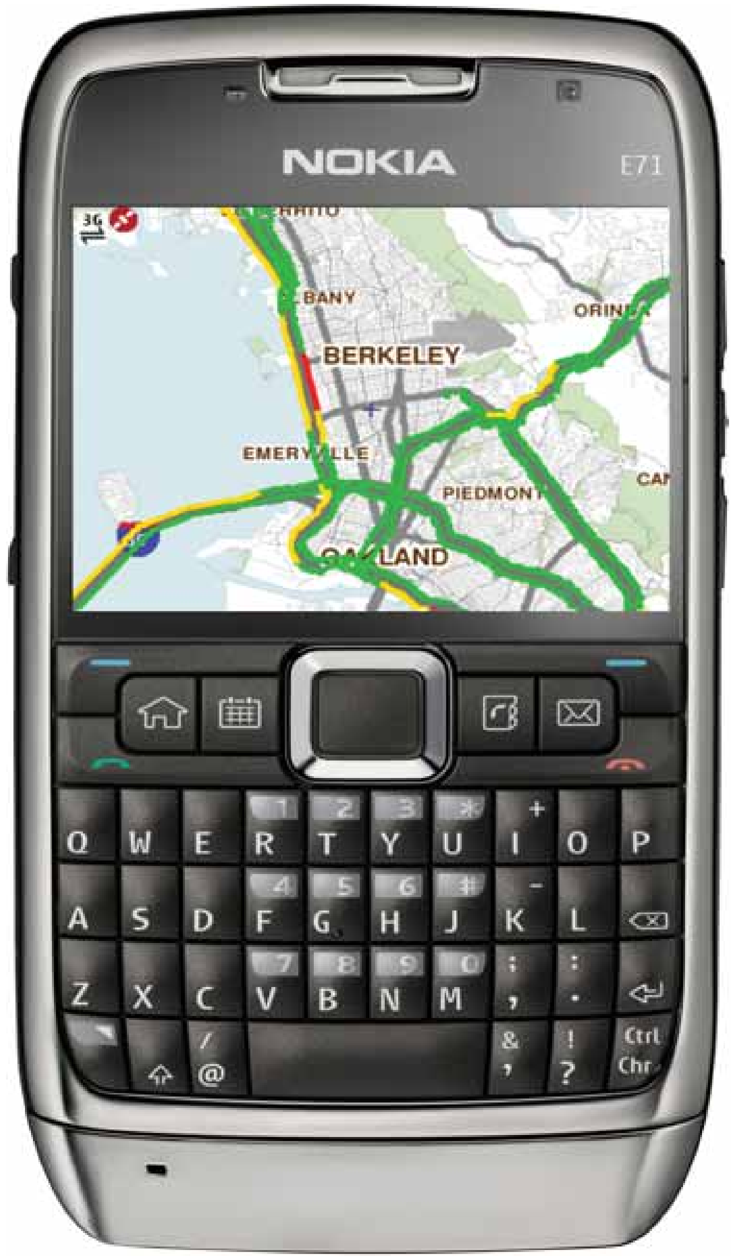
The mobile internet is changing the face of the transportation cyber physical system at a rapid pace. In the last five years, cellular phone technology has leapfrogged several attempts to construct dedicated infrastructure systems to monitor traffic. Today, GPS-equipped smartphones are progressively morphing into an ubiquitous traffic monitoring system, with the potential to provide traffic information in real-time for the entire transportation network. Traffic information systems are one of the first instantiations of the potential of participatory sensing for large scale cyber physical infrastructure systems. While mobile device technology is very promising, fundamental challenges remain to be solved, in particular in the fields of modelling and data assimilation.

Traffic Monitoring at the Era of Mobile Internet Devices

Smartphones as sensors of the built environment.
The convergence of communication and sensing on multimedia platforms such as smartphones provides the engineering community with unprecedented monitoring capabilities.

Smartphones such as the Nokia N97 now include a video camera, numerous sensors (accelerometers, light sensors, GPS, microphone), wireless communication outlets (GSM, GPRS, WiFi, Bluetooth, infrared), computational power and memory. This phone can be used to listen to the radio, to watch digital TV, to browse the internet, to do video conferencing, to scan barcodes, to read pdfs, etc. The rapid penetration of GPS in smartphones is enabling device geopositioning and context awareness, which in turn is causing an explosion of Location Based Services (heavily relying on mapping) on the devices. For example, Nokia Maps display theaters and museums near the phone, Google Mobile provides driving directions from the phone location, and the iPhone Travelocity shows hotels near the phone.

Because of their portability, computation, and communication capabilities, smartphones are becoming useful for numerous applications in which they act as sensors moving with humans embedded in the built infrastructure. Large scale applications include everything from population migration tracking and traffic flow estimation to physical activity monitoring for assisted living.



A Nokia E71 Smartphone shows Mobile Millennium Traffic Pilot software displaying real-time freeway traffic in Berkeley, CA.

The competition for probe traffic data collection as a proxy for the larger war to conquer the mobile internet.
In recent months, there have been increased levels of competition between cell phone manufacturers, network providers, internet service providers, computer and software manufacturers, and mapping companies. Following the transition from desktops to laptops to smaller and more portable devices, top companies in these industries are redefining themselves to remain relevant as the internet goes mobile. In the context of traffic monitoring, the examples below are eloquent and show the importance of information technology for transportation systems. In late 2007, Google made a move towards the phone industry with the launch of the Open Handset Alliance and the Linux-based Android platform (leading to the T-Mobile G1 Google phone). In turn Nokia, who manufactures more than 40% of the cell phones in the world, purchased Symbian, which licenses the operating system running on more than half of the smartphones in the world.

Nokia then established the Symbian Foundation, with the intention of unifying the platform and making it open-source (Apple also partially opened its iPhone OS to software developers with the release of a software development kit). To strengthen its own mapping capabilities, Nokia bought Navteq, which is the largest mapping company in the world, following personal navigation device manufacturer TomTom's purchase of Tele Atlas, Navteq's chief competitor. Navteq in turn owns Traffic.com, one of the leading traffic data collection and broadcast companies. Its competitors include Inrix, which provides traffic data to Microsoft's web, desktop, and mobile applications.

New sources of traffic data for the transportation network.
Highways have traditionally been monitored using static sensors, which include loop detectors built in the pavement, radars and cameras along the road, and more recently toll tag readers (such as FasTrak or EZ-pass), which can serve as probes wherever such infrastructure exists. While this infrastructure has proved to be efficient for highways, the costs of deployment, communication, and maintenance for such an infrastructure in the arterial network make it prohibitive for public agencies or companies to deploy on a global scale.

To alleviate possible communication bottlenecks, on October 21, 1999, the Federal Communications Commission allocated 75MHz of spectrum as part of the US Department of Transportation's (DOT) Intelligent Transportation Systems (ITS) US-wide program, with mostly traveler safety, fuel efficiency and pollution in mind.

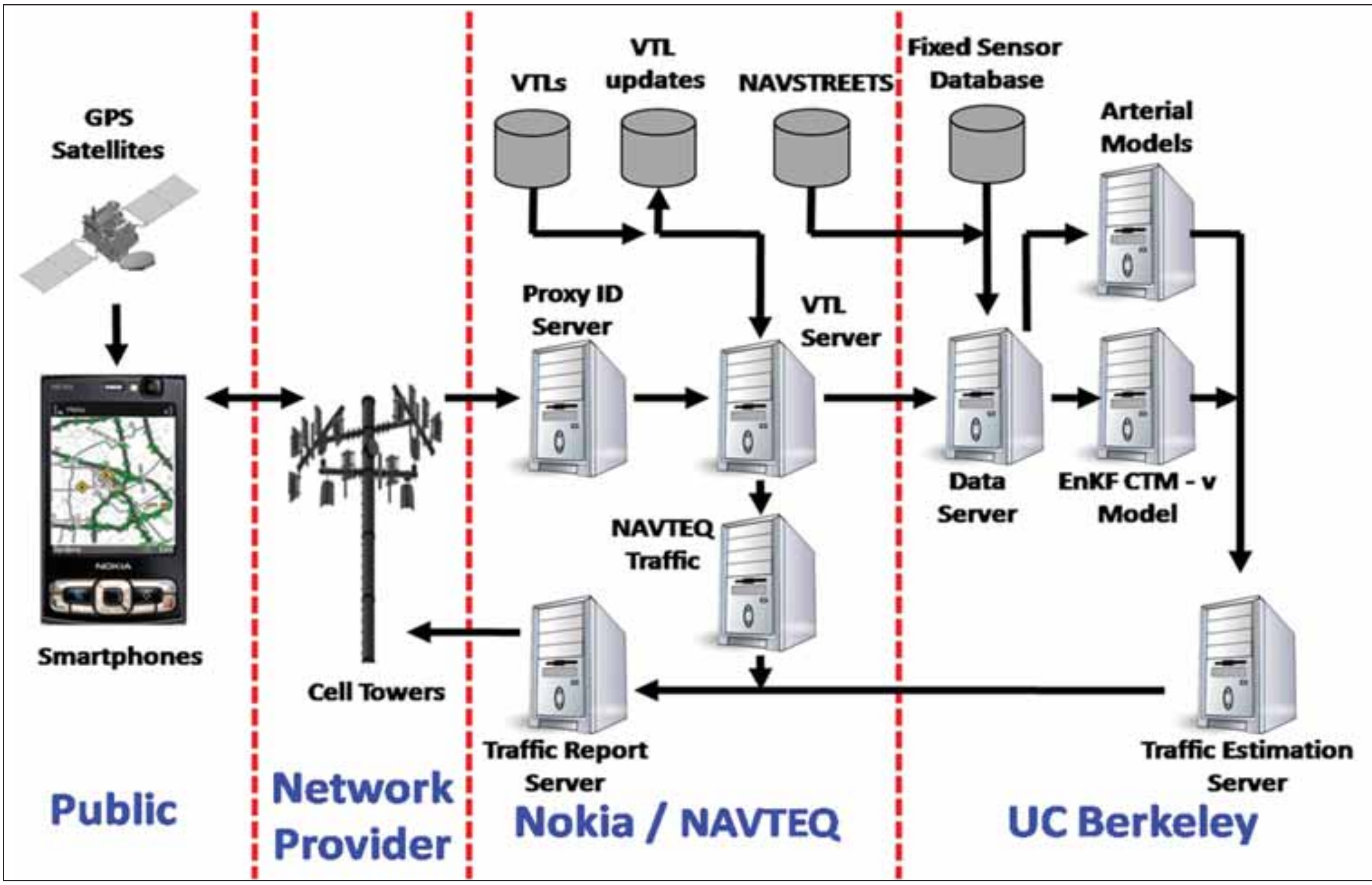
The first industry-government supported standard followed on August 24, 2001, when ASTM's E17.51 Standards Committee voted 20-2 to base Dedicated Short Range Communication (DSRC) on a modification of the IEEE 802.11a specification now named IEEE 802.11p. At the same time, the US DOT launched a plan which included the deployment of around 250,000 road side DSRC radios, but only led to around 100 radios deployed for the entire US to this day.

This example highlights the difficulty of creating a dedicated system for the transportation network. At the same time, the need of monitoring traffic remains unsolved: if traffic information was available at a global scale including the arterial network, several problems could potentially be solved: (1) real-time congestion estimation of the arterial network; (2) re-routing of the highway traffic into arterial networks where beneficial; (3) optimized travel time, fuel efficient or emission optimal routes for commuters.

Impact of the Mobile Internet on the Transportation Cyber Physical Systems

Smartphones: a transformation from dedicated infrastructure to market-driven technology.
The scale at which cell phones are produced, and the rate at which they integrate new technology is dramatic. The total number of cell phones worldwide exceeds three billion, with some European countries with a penetration of more than 150% (150 cell phones for 100 people). Nokia alone produces more than 15 phones a second, at the time the present article was written, which means with the increasing penetration of GPS in the cellular phone fleet, cell phones will soon constitute one of the major traffic information sources available to the public. In North America and Europe, the overwhelming majority of commuters have a cell phone, potentially populating the entire arterial network with probe traffic sensors. Obviously, the use of cellular devices as traffic sensors has numerous benefits. (1) It is possible to leverage the market driven communication infrastructure already in place. (2) The spatio-temporal penetration of cell phones in the transportation network is increasing at an extremely fast pace. (3) The use of cell phones as traffic probes is device and carrier agnostic, leading to faster penetrations. (4) Major car manufacturing companies already have cradles and interfaces with cell phones (for example BMW and the iPhone) in their new cars so the sensing information gathered by modern cars can also be sent to such monitoring system.

Lagrangian vs. Eulerian Information.
While cellular phones provide an ideal bridge between the physical world (vehicle flows and dynamics on the road) and the information world (software systems monitoring the network), there is one major difference between the data collected by cell phones and traditional data, commonly used to estimate traffic in real-time: the data collected by phones in cars is Lagrangian, i.e. gathered along cars trajectories, and not Eulerian, i.e. control volume-based. This poses major challenges in building an information system for a cyber physical infrastructure such as the transportation network. While a static loop detector or a camera (both Eulerian) can easily capture all vehicles going through the space monitored by the sensor, and therefore infer from it exhaustive quantities (flows, counts, local speed), a Lagrangian sensor can only monitor quantities following the vehicle, which does not give direct access to flows, counts, etc. In addition, measurements are only available where participating vehicles / phones are located. These are not predictable, and the local penetration of devices in the network might vary. These problems open many research avenues with direct impact on technology development for traffic monitoring.



Architecture of the Mobile Millennium System: (1) client software on the phones; (2) operators; (3) Nokia/Navteq data gathering privacy preserving architecture; (4) UC Berkeley real-time traffic modeling engine.

Modeling and computational challenges for monitoring the transportation Cyber Physical Systems.

As indicated in the name cyberphysical, the two key components of cyber physical systems are "information" (cyber) and "constitutive laws" (modeling the physics of the system). Monitoring cyber physical systems such as the transportation network poses two major challenges:

• Distributed models for the transportation network. Because GPS enabled phones sense velocity, or travel time between two consecutive GPS readings, constitutive models used to describe the evolution of the system need to incorporate these reading and bypass quantities which cannot be measured (density, flows, counts). The development of such flow models, for highways and arterials is still at its infancy. Techniques used for this include partial differential equations, queuing systems, and hybrid systems models of flow equations.

• Machine learning models to circumvent lack of geographical information. Mapping the entire US with an automated traffic monitoring system prevents the use of accurate knowledge of signage and traffic light presence, let alone cycle information. The presence of stops, lights, and their effect on traffic is not available from databases on a US-wide scale. Furthermore, they change too often to be incorporated in flow models. This difficulty has to be circumvented by machine learning algorithms capable of learning the flow features without knowledge of the detailed infrastructure, using for example, clustering analysis.

Spatially aware sampling and privacy.

At the heart of such a system, privacy by design sampling tecniques must be used to prevent privacy invasion. In addition to proper anonymous data collection and encryption, sampling the vehicles at locations which are privacy safe is key to ensuring ongoing participation of the public which is needed for such a system. One possible architecture for preserving privacy is to collect data using a concept known as Virtual Trip Lines (VTLs), which are virtual geographic line segments deployed across roadways in the transportation network, triggering phones to collect and transmit data to the system. Defining optimal sampling strategies, which are privacy preserving is still a relatively unexplored field.

Real-time, online and robust availability.

Unlike the more permanent Eulerian detectors, to which data quality, reliability and performance indices can be easily attributed, the penetration of cell phones at a given location and time is highly variable.

Furthermore, in the coming few years before this type of monitoring becomes the standard, the participation of the public will be spatially and temporally varying. This means that the algorithms used for estimating the traffic must be robust to variability in penetration.

Inverse modeling and data assimilation.
At the age of massive data collection, one of the most fundamental theoretical challenges associated with the reconstruction of traffic using mobile data will be the proper use of techniques to incorporate data into flow models or statistical models. The development of these techniques in fields such as oceanography or meteorology is relatively mature. For cyber physical systems, in particular large scale infrastructure systems, the state of modeling, model inversion and computation is still at its infancy and promises significant break-throughs in the near future. **END**

Article Sources

Impacts of the Mobile Internet on Transportation Cyber-Physical Systems: Traffic Monitoring using Smartphones.
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J. C. Herrera et al. ITS World Congress, New York, NY, November 16-20, 2008.

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He is the recipient of the Ballhaus Award from Stanford University, 2004. The project Mobile Century for which he serves as the Principal Investigator received the 2008 Best of ITS Award for ‘Best Innovative Practice’, at the ITS World Congress. He is the recipient of the CAREER award from the National Science Foundation, 2009.

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Limitations of the current automotive Cyberphysical System: Its vehical-centric view only provides partial information about the surrounding environment.

Automotive Cyber Physical Systems in the Context of Human Mobility

By Daniel B. Work, Alexandre M. Bayen and Quinn Jacobson

FFor the past century, the primary function of the automobile has been to move people efficiently. The main challenge has been to build vehicles which are safe and dependable, and meet the intrinsic societal need for mobility. The automobile has enjoyed dominance in meeting this need, which has been characterized at a fundamental level as getting people and goods where they need to be. As the demands for mobility have increased in complexity, from simply enabling people to reach destinations that were previously impractical, to getting people to their destination safely and reliably, technology developed in the automobile sector has also increased in complexity. The vehicle has developed from a purely physical system based on the laws of mechanics and chemistry, to a more sophisticated Cyber Physical System (CPS) which embeds electronic components and control systems to improve performance and safety.

The demand for mobility over this time has continued to increase, creating a new set of challenges which cannot be addressed by simply improving the technology of a single vehicle. In California alone, there are 280 billion vehicle miles traveled each year, and the need for human mobility is now a lifeline of the economy. But California commuters spend more than 500,000 hours delayed in traffic each day, with an annual estimated cost of $21 billion per year, and the problem is not isolated to this state. These problems suggest a new Human Mobility CPS (HMCPS) will be required to answer the problems which are faced by all commuters independent of the vehicle. This HM-CPS will emphasize the coupling of the physical movements of people both at an individual and aggregate scale with the cyber communication, computation, and sensing needed to monitor and efficiently enable mobility in the surrounding physical environment.

Fundamental Limitations of the Existing Automotive CPS

A. Limited Information

Automobiles are well suited to collect information about the local physical world, but they lack the capability to collect global information about the environment in which they evolve.

Most automobile sensors are specifically designed to monitor infrastructure within the vehicle itself, such as the engine temperature or the fatigue of some components. Localized sensing is effective at managing issues such as vehicle reliability, but it can only provide limited solutions for larger scale aspects of the CPS such as safety, route planning, and context aware location based services.

As an example of the limitation of the current automotive CPS framework, most safety critical sensing is aimed at minimizing the severity of accidents. While this has undoubtedly saved the lives of several commuters, it does not provide sufficient monitoring to prevent accidents from occurring. Although sensors can be added to the outside of the vehicle to determine where neighboring vehicles are located, better information can be provided if vehicles or surrounding infrastructure share information in cyberspace.

While near misses or car crashes on a very short timescale are hard to avoid using automation, new soft safety concepts such as warning of upcoming slowdowns are achievable with today's wireless technology (in particular mobile phones). More advanced safety applications will evolve only when the existing sensing and communication limitations are removed. Another challenge in collecting information is the timeliness in which it must arrive to be useful to the embedded human. Information about the level of use of the immediate surrounding infrastructure can be obtained locally by the vehicle, but this information must be collected before the vehicle arrives for important navigation decisions to be made. Even if a vehicle has a navigation device on-board, it must get traffic information from a global aggregator. Due to the expense of installation of sensing equipment such as inductive loop detectors (ILDs) or radio frequency identification (RFID) transponders, this information is limited at best. Interestingly, although no single vehicle has complete information about the current state of the transportation network, it can easily be inferred from the data that each vehicle is collecting locally, such as speed and acceleration. The problem of limited information in this case is manifested as a problem of communication.

B. Inadequacy to Address Human-Centric Needs

Another category of limitations arises from the local/ global interaction because the current automotive CPS largely ignores a defining feature of the HM-CPS: embedded humans. Embedded humans in the CPS are important because they are the primary consumer for traditional transportation infrastructure information, such as travel times and route navigation. They will also triggered the development of a new breed of mobility services which have previously been outside the domain of the automotive CPS.

Following a trend similar to that found in the mobile phone, context aware location-based services will play an increasingly important role in the HM-CPS. The information which ultimately creates the demand for trips will need to be more closely integrated with the vehicle to address the human-centric mobility needs. Ultimately, embedded humans perform three tasks: (i) they can sense, (ii) decide, and (iii) assess. A poorly designed CPS will require the human to actively participate in information acquisition instead of allowing the system to automatically integrate sensed information into the infrastructure. Instead of requiring the user to integrate driving directions and historic traffic patterns collected from experience, a human-centric system should leverage infrastructure to gather information, leaving the embedded human free to make higher level decisions such as preference for the fastest route or the shortest route.

The most important aspect of the impact of human-centric needs with respect to the automotive CPS is that embedded humans make the overall assessment of how well the system performs. This creates new challenges because humans are exposed to a wide variety of human-centric systems with which the automotive CPS must compete. As new human-centric features appear in other CPSs ranging from mass transit to mobile devices such as cell phones, the utility of the automotive CPS will depend on its ability to adapt and integrate similar features.

C. Pace of Adaptation

As the automobile CPS is forced to interact with other cyber infrastructure systems for data collection and to address human-centric needs, the rate at which it integrates new technology will become critical to its utility. This poses a significant problem because the automotive CPS inherently moves at three timescales.

Changes in the transportation infrastructure may take decades to become fully implemented. Vehicle scale changes may take years. The virtual infrastructure, led by high tech innovation, evolves on Internet timescales of a few months. The automotive CPS simply moves too slow to evolve with cutting edge products and services in an integrated way. The rapid changes of the virtual infrastructure makes it very difficult for the physical components of vehicles to even integrate themselves at a fundamental level. As communication protocols and ports change, in-vehicle infrastructure runs the risk of almost immediate obsolescence. This problem cannot be ignored: the embedded human which generates the need for mobility is also driving the need for integration with the virtual infrastructure.

Research Challenges

A. Openness

The constraints of the existing automotive CPS suggest that it must be opened to access the surrounding environment, both physical and virtual (cyber). The availability of new data sources will enable the automobile to better navigate the surrounding environment, as well as provide a higher quality commuter experience. When the system is opened, it will force it to directly confront the need to remain dynamic and relevant in the human mobility CPS.

Designing a platform with an open architecture for automobiles will not be easy. The design must be sufficiently flexible to meet the demands both today and decades from now. The key will be to create a platform with which hardware and software are upgradable and replaceable. Interfaces can be built to collect and interact with the vehicle's infrastructure, while leaving core CPS components to be developed through aftermarket devices.

Determining how to verify the safety of applications developed on an open platform presents additional barriers beyond the simple transition to an open platform. In the phone industry, Apple has attempted to walk this delicate line by providing a publicly available software development kit for the iPhone, but all applications must be approved by Apple before they can be widely distributed. Others, such as the Nokia Maemo platform and the Google Android platform provide less centralized control, because such a structure provides more freedom for the open source communities to create innovative products. The ongoing move to open devices in the mobile phone industry should be viewed as an early indicator of how an open platform increases the functionality of the product, and a similar leap could be expected for the automotive CPS.

B. Data Processing and Analysis

One advantage the automobile has over other technologies such as the phone is that it can be used to enable a powerful and energy demanding sensing platform that physically moves one though the infrastructure. Although automobile location-based applications and services have not yet become mainstream, the vast amount of useful data which could be collected from the vehicle is encouraging for their development. This data becomes even more rich when it is put in context with other geo-referenced databases obtained online or from other infrastructure systems. Even vehicle specific data may begin to serve expanded functions when integrated with other services on computers and mobile devices. It would not be difficult to imagine a future mapping service which recognizes your vehicle has insufficient fuel to arrive at your destination to automatically route you to the cheapest gas station. Other potential applications might range from new forms social networking to environmental quality sensing. The challenge of such cyber-information systems is the transmission, processing, and analysis of the data. The quality and volume of the potential data sources is phenomenal. Because of the mobile aspect of the vehicle, most communications with the vehicle and the virtual environment will need to be made wirelessly.

Mobile Millennium internet traffic display. Mobile Millennium provides real-time traffic information for highway and arterial networks.

The Federal Communications Commission (FCC) has dedicated a portion of the wireless spectrum for this communication, but there has not been sufficient momentum to develop standards which are meaningful outside the immediate context of the vehicle. The Dedicated Short Range Communication (DSRC) standard is problematic because the lack of usage of this technology outside the domain of the vehicle limits connectivity with the vast majority of devices in the virtual infrastructure. One of the biggest research opportunities in this field will be to create large scale distributed CPS models to assimilate the data into useful information. Human mobility modeling is at its infancy, and fundamental questions still exist such as (i) the correct characterization of human mobility at local and global scales; (ii) multi-modal trip modeling; and (iii) transportation in urban networks. The current state of our knowledge still leaves open the debate over the correct model to understand automobile traffic on highways, which is an area which has received a significant amount of attention in the transportation modeling community. Clearly, a new class of models and abstractions will be necessary to interpret the vast amount of data generated by an open automotive CPS correctly and efficiently in the context of human mobility.

C. Privacy

The openness of a networked automotive CPS, and large volumes of data coupled with an embedded human create opportunities for abuse. Specifically, geo-referenced data contains information which is particularly sensitive. Attacks on this data range from direct privacy intrusions such as being able to identify a speeding vehicle, to more sophisticated attacks such as inferences gained from trips taken.

A non-direct trip from work to home may reveal personal affairs the driver wishes to remain private. Recent research has shown that simply anonomizing data is insufficient to prevent privacy intrusion. A non-direct trip from work to home may reveal personal affairs the driver wishes to remain private. Recent research has shown that simply anonomizing data is insufficient to prevent privacy intrusion.

Worse yet, economic incentives exist for companies (insurance, for example) who can successfully infer information from the data streams collected. The data collected from a HM-CPS could potentially be as sensitive as personal health records, since many health related exposure risks may be determined from location based information. Determining how to structure data collection and communication in a privacy preserving environment is an area of research that must be developed quickly to enable a functioning human-centric CPS. Ultimately, the success of the HM-CPS system depends on it, since the human-in-the-loop will otherwise make choices to avoid these types of services all together. **END**