Vehicular Cyber-Physical Systems

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Road transportation is a "grand challenge" problem for cyber-physical systems (CPS). With close to a billion vehicles on the road today, and a doubling projected over the next 20 years, we face pressing challenges to the efficiency and the safety of this critical infrastructure. Location-based vehicular services that use a combination of embedded ("on-board") automotive computers, in-car devices, and roadside monitoring and surveillance systems can reduce travel times with smart routing, save fuel and reduce carbon emissions by determining "greener" routes and finding the best times to commute, improve safety by detecting road hazards using collaborative processing amongst cars, change driving behavior using smart tolling, and enable measurement-based insurance plans that incentivize good driving, among other benefits.

Under the NSF CPS program, the **CarTel** project has made contributions to the following areas:

1. Methods for embedded collaborative processing: Many interesting vehicular services use raw data and processed information from multiple cars and other information sources, rather than each car in isolation. The development of distributed algorithms for various tasks, such as accurate road delay prediction, traffic-aware routing, hazard assessment, and smart tolling will be useful not just as stand-alone applications, but to other vehicular services too.

We have developed **VTrack** (SenSys 2009) and **CTrack** (NSDI 2011), two systems that can process large amounts of inaccurate position information to produce accurate map-matched trajectories and traffic delay estimates. CTrack is able to process a sequence of cellular RF fingerprints and produce trajectories 75%-80% as accurate gathering GPS every second, but consuming *more than an order-of-magnitude less energy*.

We have developed a new practical stochastic routing algorithm that computes credible routes that maximize the probability of reaching a destination by a deadline, computing the route over delay distributions on the links (IJRR 2011). We investigated the multi-user version of stochastic routing (SAGT 2011). We also conducted a traffic analysis with data gathered from 16,000 taxis in Singapore, with some members of our team spending several months there.

We have developed a classification-based machine learning algorithm to predict travel delays from *sparse* historical data, finding that it has a modest median error rate in predicting times of only 6.75%, and with a small error variance.

Finally, we developed a scalable method to compute dynamic routes in a transportation network (ICDE 2011), a problem made difficult because the costs change (so precomputing is not easy).

2. Privacy-preserving protocols. Vehicular services involve human users, and the rampant gathering and sharing of data poses huge privacy problems. It is important to develop protocols that enable these services without compromising location privacy.

We have developed **VPriv** (Usenix Security 2009), which enables tolling, speeding, and insurance computations that involve additive functions over time-position samples to be computed by an untrusted server *without* revealing any user location information. The protocol is robust to malicious client behavior.

We have developed **PrivStats** (ACM CCS 2011), which provides strict location privacy to compute aggregate traffic and other statistics over location tracks.

3. A secure macro-tasking run-time substrate. Rather than programming each car or node in isolation, it is better to think of them as components of a larger system and program them as a collection. In addition, the programs that run on the nodes must not compromise the safety of the on-board automotive computing infrastructure or adversely interfere with it. We have been developing *Code In The Air*, a platform for such programming (preliminary demo at SenSys).

Broader impact: The CarTel project has partnerships with Ford (vehicular networking), PlanetTran (deployment), and a large insurance company (secure and private telematics). We have developed iCartel, an iPhone application that embeds the traffic-aware routing methods developed in the project and available on the app store. A personal commute portal web site is also available at icartel.net. We have presented our technologies in a series of meetings to the World Bank and assisted in their efforts to develop cost-effective methods to gather traffic data in developing countries. We have worked with local agencies in Singapore on traffic analysis.