Dynamic sensing policies for monitoring arterial road traffic

Aude Hofleitner*
Department of Electrical Engineering and Computer Science
University of California, Berkeley, CA
aude.hofleitner@polytechnique.edu

Saurabh Amin
Department of Civil and Environmental Engineering, Systems Engineering
University of California, Berkeley, CA

Ryan Herring
Department of Industrial Engineering and Operations Research,
University of California, Berkeley, CA

Pieter Abbeel
Department of Electrical Engineering and Computer Science
University of California, Berkeley, CA

Alexandre Bayen
Department of Civil and Environmental Engineering, Systems Engineering
University of California, Berkeley, CA

1 Introduction

In the United States and numerous other parts of the world, road traffic for a critical part of economic activity. Numerous measures are being taken to address problems arising from traffic congestion. An essential step in this direction is the creation of a traffic monitoring system with capabilities to estimate traffic with significant accuracy and reliability. Historically, dedicated infrastructure has been used for collecting traffic data, however, the corresponding sensors have limited coverage, high installation and maintenance costs, and their fixed position does not enable optimized and adaptive sampling as traffic conditions change. An alternative to using dedicated sensing infrastructure is to leverage an existing communication system such as the cellular phone network.

The mobile internet and web 2.0 are the underlying technology and paradigm that have enabled the development of traffic estimation systems based on GPS enabled phones, as illustrated by the *Mobile Millennium* project [1], as well as numerous other cellular device-based traffic monitoring systems. User-generated content (in the present case, traffic data measured by the smartphone) is sent to a central system, which provides information back to the cell phone owner for personal use. This web 2.0 user generated content based location based service is commonly referred to as "participatory sensing," which refers to the ad hoc process of voluntarily providing sensing data to a system. GPS-equipped vehicles transmit data upon traversing the virtual geographical sensors, thus offering a promising alternative to estimating traffic statistics using fixed point-sensors. This sensing technique leverages market driven telecommunication infrastructure, thus limiting cost for society and the users. Moreover, these virtual sensors, by definition, are not embedded in the

*Corresponding Author

physical infrastructure, and their location can be optimized dynamically (adaptively) as traffic conditions change. The location of the sensors can be dictated by the central system to optimize the value of each traffic sensor measurement sent to the system.

Besides the value of the data for traffic estimation, ensuring location privacy of the users is an important consideration for the deployment of mobile traffic sensing methods. A GPS-enabled smartphone is capable of recording and transmitting its GPS location every few seconds. While this level of detail can be useful for traffic estimation [2], it can be privacy invasive without the proper safeguards, since the device is ultimately carried by a single user.

Virtual Trip Lines (VTLs) provide a mobile sensing framework that preserves the privacy of users [3]. VTLs are geographical markers embedded in the map, that trigger probabilistic measurement updates. Each VTL consists of two GPS coordinates which make a virtual line drawn across a roadway of interest. Instead of time-based periodic sampling, VTLs trigger disclosure of speed and location updates by spatial sampling, creating updates at predefined geographic locations on roadways of interest. Additionally, the travel time between pairs of VTLs can be extracted and this type of travel time data will be considered the primary data source used in our approach. This sensing paradigm of virtual trip lines has emerged as a viable solution for real-time traffic monitoring based on large-scale traveler participation.

However, standard VTL deployment is static and does not take advantage of the mobility of probes. It acts as fixed sensors but only senses a small portion of all the vehicles. A dynamic placement of VTLs based on an interaction between the phone client and the the backend server increases the value of the information sensed by the phone, by adapting it to the current traffic conditions. *Our main contribution is to design privacy aware sensing strategies that are adaptive to the traffic conditions, thereby enabling the sensing infrastructure to take full advantage of the mobility of probes*.

2 Related Work

In the machine learning community, optimized sensors placement with privacy and availability guarantees has been done by modeling traffic as a Gaussian process [4]. However, the modeling of traffic as a Gaussian process has limitations for traffic flow on arterial roads due to restrictions and constraints imposed by traffic lights. We argue that traffic estimation can be improved with the use of physical models of traffic.

Historically, in the transportation community, arterial traffic modeling queuing theory has been studied. However, these queuing models usually require extensive data measurements (which usually include the knowledge of vehicle counts, in addition to signal timing). In practice, these traffic parameters are highly variable and are hard to estimate, or even obtain from public sources. Furthermore, these models hardly generalize to arbitrary networks with several intersection, due to sometimes restrictive assumptions [5].

3 Our Contributions

We model traffic flow on arterial roads as a random process and derive probability distribution of traffic statistics such as travel time, queue length, etc. using queuing theoretic arguments. For ideal conditions such as uniform arrivals and cyclically operated intersections, we compute the theoretical travel time probability distribution on a route with n intersections. We then generalize our probability model to accommodate for more realistic scenarios such as nonuniform arrival rates, varying signal timings, and changing traffic regimes.

We parameterize the probability distributions in terms of VTL location to formulate and solve the problem of optimal VTL placement for route travel time estimation under two regimes: under-saturated and congested. Using the optimal spatial placement scheme for each traffic regime, we use sequential change-detection methods to identify the change in the defined traffic conditions, for example, under-saturated to congested or vice-versa. When we detect a congestion change, the VTL placement is modified dynamically according to the new traffic conditions. Thus, our dynamic sensing strategies are *adaptive* to changing traffic conditions. We study the effects of the number of measurements used to detect the regime change on the accuracy of our prediction.

The robustness of our estimation scheme is tested by arguing its resistance towards missed detection and false alarm. The change of sensing strategy due to a false alarm still provides reasonably accurate estimation and clears the false alarm poster to regime-change detection. Similarly, an outdated sensing strategy due to a missed detection detects the regime-change as more data becomes available. This dynamic sensing scheme relies on an interaction between the phone and the back-end server. We also propose the enhancement of the sensing strategies when the phone has some information on its environment and can directly sense valuable information such as queue lengths.

The advantage of our proposed sensing policies is demonstrated using probe data collected on a stretch of arterial roads in Berkeley, CA. We also validate our model by estimating travel time distributions as a function of the VTL placement and show that our change-detection scheme for traffic regimes represent the traffic pattern observed on the data. We compare our results of route travel time estimation to the ones obtained with a baseline placement of VTLs.

Finally, we consider the privacy issues related to probe sensing in arterial roads. Given the average length of roads between intersection, we argue that the main privacy intrusive information is the disclosure of direction movements throughout an intersection. We show that our estimation scheme does not need this information and provide optimal sensing strategies that do not disclose turn information.

References

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