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Probe vehicle based real-time traffic monitoring on urban roadways

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ABSTRACT

Travel time estimation and prediction on urban arterials is an important component of Active Traffic and Demand Management Systems (ATDMS). This paper aims in using the information of GPS probes to augment less dynamic but available information describing arterial travel times. The direction followed in this paper chooses a cooperative approach in travel time estimation using static information describing arterial geometry and signal timing, semi-dynamic information of historical travel time distributions per time of day, and utilizes GPS probe information to augment and improve the latter. First, arterial travel times are classified by identifying different travel time states, then link travel time distributions are approximated using mixtures of normal distributions. If prior travel time data is available, travel time distributions can be estimated empirically. Otherwise, travel time distribution can be estimated based on signal timing and arterial geometry. Real-time GPS travel time data is then used to identify the current traffic condition based on Bayes Theorem. Moreover, these GPS data can also be used to update the parameters of the travel time distributions using a Bayesian update. The iterative update process makes the posterior distributions more and more accurate. Finally, two comprehensive case studies using the NGSIM Peachtree Street dataset, and GPS data of Washington Avenue in Minneapolis, were conducted. The first case study estimated prior travel time distributions based on signal timing and arterial geometry under different traffic conditions. Travel time data were classified and corresponding distributions were updated. In addition, results from the Bayesian update and EM algorithm were compared. The second case study first tested the methodologies based on real GPS data and showed the importance of sample size. In addition, a methodology was proposed to distinguish new traffic conditions in the second case study.

1. Introduction

Travel time is a crucial variable both in traffic demand modeling and network performance measurement. Today, travel time estimation and prediction on urban arterials is an important component of Active Traffic and Demand Management Systems (ATDMS). Although great progress has been achieved in ATDMS, reliable and efficient estimation of travel time is still not a wide spread accomplishment especially on arterials since it requires extensive sensor infrastructure normally found only on freeways.

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Several analytical models (Spiess, 1990; Xie et al., 2001; Skabardonis and Dowling, 1997; National Research Council, 2010; Bureau of Public Roads, 1964) have been proposed to relate arterial link travel time to traffic volume. Even with signal timing and volume information, these models can only provide the average travel time for all vehicles and are generally used in planning applications. In reality, different cluster of vehicles' travel time behave very differently. The average value couldn't reflect different components of travel time. Therefore, a travel time distribution, from which performance measures such as the mean travel time, or the standard deviation can be derived, is preferred.

In order to estimate the arterial travel time distribution, travel time information for individual vehicles is required. One feasible way to collect travel time data is from the monitoring systems. In the United States, most urban freeways are now equipped with sensor systems that allow real time monitoring of traffic conditions as well as estimating travel times. For urban arterial systems however the ability to monitor traffic conditions and estimate travel times has lagged behind. This is in large part due to the complexity of urban traffic environment.

These difficulties have led to an active interest in monitoring urban arterials using already-deployed sensors. One interesting possibility is to use probe vehicles. Certain types of vehicles, such as taxies or buses, which are easier to monitor, have been suggested as probe vehicles (Daily and Cathey, 2002). However, using special purpose vehicles has disadvantages. Buses have to stop at each bus stop, which overestimates travel times, while taxis behave differently when they are empty or full. Recently, the increasing availability of vehicles which can access the Global Positioning System (GPS) and the development of wireless telecommunication technologies, have permitted general road users to serve as probes. In principle, a steadily increasing number of GPS-equipped vehicles could lead to reliable, accurate travel time. Information transmitted from those GPS probe vehicles not only can help calculate travel time distributions on arterials, but also provides real-time traffic condition information.

The main difficulty with reliance on GPS probes is that the travel time provided by a single probe is essentially a sample, of size one, from the prevailing distribution of travel times. This leads to questions regarding the density of probes needed to produce useful sample sizes. Current, GPS equipped vehicle density is quite low and moreover one GPS vehicle could only provide information regarding one component of travel time at each link. Therefore, rather than attempt to estimate the travel time distribution from scratch, it may be possible to combine limited information from GPS probes with prior knowledge from signal timing and arterial geometry information to reconstruct the travel time distribution.

In this paper, a cooperative approach is chosen for travel time estimation using static information describing arterial geometry and signal timing information, semi-dynamic information of historical travel time distributions per time of day, and utilizes GPS probe information to augment and improve the latter. The objectives of this study focused on developing a methodology to characterize arterial travel time patterns by travel time distributions, propose methods for estimating such distributions from static information and refining them with the use of historical GPS probe information, and given such time and location based distribution use real-time GPS probe information to monitor arterial traffic conditions.

The rest of the paper is organized as follows: Section 2 provides a brief literature review in travel time estimation models. Section 3 introduces the NGSIM data used in this study and characterizes the travel time patterns on signalized arterial links by travel time states. Section 4 presents two approaches to estimate travel time distributions. In Section 5, two applications that combine travel time distributions with GPS data are illustrated. Sections 6 and 7 provide two comprehensive case studies using the NGSIM Peachtree Street (Atlanta, GA) dataset and Washington Avenue (Minneapolis, MN) GPS data. Section 8 concludes this paper and lays out the directions for further research.

2. Literature review

Estimation and prediction of arterial travel time has been one of the most popular topics in transportation engineering for decades. Zhang et al. (1997) summarized the early arterial travel time estimation models. He divided them into five different categories: Regression-type link travel time models (Gault, 1981; Young, 1988), Dynamic input–output link travel time models (Strobel, 1977), Sandglass link travel time models (Usami et al., 1986; Geroliminis and Skabardonis, 2006), Link travel time estimation based on pattern matching (Boehnke and Pfannerstill, 1986) and BPR-type model (Bureau of Public Roads, 1964; National Research Council, 2010). However, these BPR types of models tend to produce unreliable estimation under oversaturation conditions.

Probe vehicles are also used widely in travel time estimation. Daily and Cathey (2002) used a mass transit system as a speed sensor. This approach requires a "transit database" which contains the schedule times and geographical layout of every route and time point. In addition, all the transit vehicles used as probes should be equipped with a transmitter such as GPS receiver, and report back to control center periodically. Liu and Ma (2009) proposed a virtual probe vehicle method for arterial travel time estimation. A virtual probe is a simulated vehicle that is released from the origin to the destination at certain time point. This approach actually used data from loop detectors rather than real probe vehicles. Bluetooth devices were also equipped in vehicles to acquire individual travel times (Hainen et al., 2011). When the Bluetooth equipped vehicle passes the upstream/downstream detection points, the MAC address of the Bluetooth device is recorded. The travel times were then collected by matching the MAC addresses. Herrera et al. (2010) collected data from GPS-enabled Nokia N95 phones to estimate travel time. They claimed that a 2–3% penetration of cell phones in the driver population was enough to provide accurate measurement. In the following research (Hunter et al., 2009), travel time distributions were extracted from raw GPS measurements and presented the arterial network by a probabilistic model with expectation maximization