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Estimating traffic volumes for signalized intersections using connected vehicle data

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ABSTRACT

Recently connected vehicle (CV) technology has received significant attention thanks to active pilot deployments supported by the US Department of Transportation (USDOT). At signalized intersections, CVs may serve as mobile sensors, providing opportunities of reducing dependencies on conventional vehicle detectors for signal operation. However, most of the existing studies mainly focus on scenarios that penetration rates of CVs reach certain level, e.g., 25%, which may not be feasible in the near future. How to utilize data from a small number of CVs to improve traffic signal operation remains an open question. In this work, we develop an approach to estimate traffic volume, a key input to many signal optimization algorithms, using GPS trajectory data from CV or navigation devices under low market penetration rates. To estimate traffic volumes, we model vehicle arrivals at signalized intersections as a time-dependent Poisson process, which can account for signal coordination. The estimation problem is formulated as a maximum likelihood problem given multiple observed trajectories from CVs approaching to the intersection. An expectation maximization (EM) procedure is derived to solve the estimation problem. Two case studies were conducted to validate our estimation algorithm. One uses the CV data from the Safety Pilot Model Deployment (SPMD) project, in which around 2800 CVs were deployed in the City of Ann Arbor, MI. The other uses vehicle trajectory data from users of a commercial navigation service in China. Mean absolute percentage error (MAPE) of the estimation is found to be 9–12%, based on benchmark data manually collected and data from loop detectors. Considering the existing scale of CV deployments, the proposed approach could be of significant help to traffic management agencies for evaluating and operating traffic signals, paving the way of using CVs for detector-free signal operation in the future.

1. Introduction

Signalized intersections are indispensable parts of urban traffic networks. Currently, over 300,000 traffic signals exist in the U.S., accounting for $82.7 billion public investments (NTOC, 2012). With two-thirds of urban vehicle miles traveled on signal controlled roads (McCracken, 1996), signalized intersections have often become hot-spots of traffic congestion, causing 295 million vehicle-hours of delay annually.[1] Considering the amount of traffic signals and their impact to the traffic

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[1] Congestion Reduction Toolbox. U.S. DOT FHWA. http://www.fhwa.dot.gov/congestion/toolbox.

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network, it is critical to operate traffic signals efficiently. However, the majority of signals in the U.S. are only re-timed once every 2–5 years, despite of a high benefit-cost ratio for signal re-timing (Sunkari, 2004). This is primarily due to the labor costs for the retiming process. With tightening budgets and resources nowadays, maintaining efficient signal operation has become a challenging task for many traffic management agencies.

Recent advent of connected vehicle (CV) introduces great opportunities of reforming the conventional traffic signal operation. Currently, many traffic signals in the U.S. are still fixed-time signals, which are not responsive to fluctuated traffic demands. For traffic signals to accommodate varying demands, vehicle detectors, e.g., inductance loop detectors or video detectors, need to be installed and maintained properly. This inevitably incurs significant cost for the public agencies. With the vehicle-to-infrastructure (V2I) communication, CVs can continuously report their status to roadside equipment (RSE) at intersections, working as mobile sensors. Therefore, CVs hold great potential to reduce or even eliminate the needs for fixed-location detectors in the existing signal systems. When penetration rates are low, the CV data could be used to generate performance measures for fine-tuning traffic signals periodically. When penetration rates are high, it becomes viable to operate adaptive signal control that solely depends on CV input.

Considering these potentials, deploying V2I systems at signalized intersections has been an important part of CV pilot deployment, exemplified by the installation of RSEs at intersections in the Safety Pilot Model Deployment (SPMD) project (Gay and Kniss, 2015), the upcoming CV pilot deployment (Masters, 2016), as well as in the Smart City development supported by the US Department of Transportation (USDOT). Along with the deployment efforts, a number of CV-based signal control algorithms have also been proposed. However, the signal control algorithms proposed in the previous studies mainly focus on scenarios that penetration rates of CVs reach certain levels, e.g., 25%, which may not be feasible in the near future. In addition, most of the existing studies rely on simulated data which may not capture real-world characteristics of CVs, e.g. communication performance or GPS accuracy. Therefore, the proposed algorithms may not be transferable to the practice. How to utilize real-world CV data under low penetration rate environment to improve traffic signal operation remains as an open question.

Aiming to answer this question, this work develops an innovative approach that uses data from CVs to estimate traffic volumes at signalized intersections, particularly under low penetration rate environment. It has been well known that traffic volumes are the very key inputs to designing and optimizing traffic signal operation. In conventional signal systems, vehicle arrival information can only be obtained from detectors at fixed locations. Different from the detector data, CV data provide detailed trajectories, albeit from a small percentage of vehicles. The comparison is illustrated in Fig. 1. The challenge here is to estimate overall arrival information using limited CV trajectories. (For example, about 3–12% traffic in the City of Ann Arbor, MI, are CVs because of the SPMD Project.)

In this work, the above challenge will be addressed through leveraging historical CV data and the repetitive patterns of vehicle arrivals at signalized intersections. In the proposed algorithm, vehicle arrivals at intersections are modeled as a time-dependent Poisson process with a time dependent factor characterizing arrival types. For volume estimation, an expectation maximization (EM) procedure is derived that can incorporate different types of CV trajectories. To evaluate the performance of the proposed algorithm, two case studies were conducted: the first case study utilized real-world CV data received by a RSE in the SPMD project; the second case study utilized vehicle trajectory data from users of a route navigation service. To the best of our knowledge, this research is the first attempt of exploring real-world CV or GPS trajectory data under low penetration rate environment for volume estimation at signalized intersections. Our ultimate goal is to use CV data to develop a detector-free signal control system in the future.

The rest of this paper is organized as follows. Section 2 presents a review of relevant work for traffic signal control with CVs, as well as traffic state estimation at intersections with probe vehicle. Section 3 briefly introduces the SPMD project and CV data. Section 4 describes the methodology for estimating traffic arrivals. Section 5 presents the two case studies using vehicle trajectory data. Conclusions and future research are discussed in Section 6.

2. Relevant work

Traffic signal control with CVs has captured substantial attention in the past several years. Many existing studies focus on developing real-time traffic signal control with CVs, through either extending signal actuation mechanism or minimizing vehicle delay based on a traffic model (Agbolosu-Amison et al., 2008; Milanés et al., 2012; He et al., 2012, 2014; Lee et al., 2013b,a; Guler et al., 2014; Feng et al., 2015; Goodall et al., 2016). However, most of the proposed adaptive signal control algorithms require high penetration rates of CVs, e.g., 25%. Such high penetration rates may not be achievable in the near future. A notable exception is Day and Bullock (2016) which conducted a proof-of-concept study using CV data in a low penetration rate environment for optimizing signal coordination. However, the data used in Day and Bullock (2016) were sampled from fixed location vehicle detectors so vehicle trajectories were not used in their study. The problem of estimating traffic volume from vehicle trajectories, which is a fundamental input for signal operation, is also not tackled.

On the other hand, with increasing availability of GPS data from cell phones and navigation units, substantial efforts have been carried out for traffic state estimation using vehicle trajectory data. Exemplified by the Mobile Century project (Hoh et al., 2008; Work et al., 2008; Herrera et al., 2010), a large group of existing studies used GPS data to estimate traffic speed and travel time (Turner and Holdener, 1995; Chen and Chien, 2001; Long Cheu et al., 2002; Hellinga and Fu, 2002; Nanthawichit et al., 2003; Bhaskar et al., 2011; Jenelius and Koutsopoulos, 2013; Zheng and Van Zuylen, 2013).