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A data fusion approach for real-time traffic state estimation in urban signalized links

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ABSTRACT

Real-time estimation of the traffic state in urban signalized links is valuable information for modern traffic control and management. In recent years, with the development of in-vehicle and communication technologies, connected vehicle data has been increasingly used in literature and practice. In this work, a novel data fusion approach is proposed for the high-resolution (second-by-second) estimation of queue length, vehicle accumulation, and outflow in urban signalized links. Required data includes input flow from a fixed detector at the upstream end of the link as well as location and speed of the connected vehicles. A probability-based approach is derived to compensate the error associated with low penetration rates while estimating the queue tail location, which renders the proposed methodology more robust to varying penetration rates of connected vehicles. A well-defined nonlinear function based on traffic flow theory is developed to attain the number of vehicles inside the queue based on queue tail location and average speed of connected vehicles. The overall scheme is thoroughly tested and demonstrated in a realistic microscopic simulation environment for three types of links with different penetration rates of connected vehicles. In order to test the efficiency of the proposed methodology in case that data are available at higher sampling times, the estimation procedure is also demonstrated for different time resolutions. The results demonstrate the efficiency and accuracy of the approach for high-resolution estimation, even in the presence of measurement noise.

1. Introduction

Real-time traffic information is extensively used by Intelligent Transportation Systems (ITS) and in various Advanced Traffic Management System (ATMS) applications, such as vehicle navigation, incident detection, traffic signal control, traffic surveillance, etc., which require the knowledge of current traffic conditions at various time resolutions and sometimes also short-term predictions of the freeway or urban road traffic states (Rewadkar and Dixit, 2013).

Generally, a road network is defined as an interconnection of links. Typically, the traffic state within a link is inhomogeneous; either due to moving traffic waves, as in long freeway links; or due to the cyclic operation of traffic signals and subsequent queue formation and dissipation, as in urban road links. Thus, at any time, a road link has an overall density or vehicle accumulation, reflecting the total number of vehicles in the link, as well as inhomogeneous partial states in corresponding parts of it (Kwong et al.,

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2010). With regard to urban signalised links, estimating vehicle accumulation is crucial for various applications (Papageorgiou et al., 2003). In addition to vehicle accumulation, high-resolution estimation of queue length or queue profile is also a fundamental requirement of modern traffic control systems, such as, the max-pressure (Varaiya, 2013) or SURTRAC (Smith et al., 2013) algorithms. In summary, accurate and practical real-time estimation of the high-resolution dynamics of queues, vehicle-counts and flows within urban signalised links is of great significance for ITS.

Comprehensive traffic monitoring systems comprising a series of spot sensors, such as loop detectors, radars, video sensors, magnetometers etc., are encountered at some strategic highway infrastructures, which allow for the extraction of accurate real-time information of the traffic state. On the other hand, for urban arterials and road networks, one rarely encounters more than one sensor per link, hence traffic monitoring is noticeably more challenging (Herring et al., 2010). Besides insufficient traffic data collection systems for traffic control or for measuring real-time operational performance in urban networks, another big challenge is that arterial traffic dynamics in signalized urban links are more complicated, owning to the periodic interruptions from traffic signals, than on freeways (Cheng et al., 2012a).

Queue length is one of the most important performance measures of an intersection and has received a lot of attention, as it reflects the delay and travel time at intersections. However, as discussed in more detail later, especially in saturated traffic conditions, the vehicles inside the queue (downstream the queue tail) are not necessarily entirely stationary; hence the number of vehicles inside the queue cannot be estimated merely based on the queue-tail profile. Thus, knowing the exact queue length may not be sufficient for traffic control, estimating the delay at the intersection or other uses. Therefore, apart from the queue length, the number and speed of vehicles inside the queue also plays an important role in traffic surveillance and management. Estimating the real number of vehicles inside the queue with high accuracy at any time may not be straightforward using conventional methods. With recent advances in technology, a growing number of vehicles are now equipped with wireless communication systems and global positioning system (GPS) sensors. Using such vehicles, called probe or connected vehicles, there is a promise of accurate and timely information without large infrastructure and construction expenses.

The scope of the present work is to provide a methodology that fuses high-resolution data from connected vehicles and spot detectors to specially provide second-by-second estimation of the number of vehicles within an urban signalised link without assuming that signal timings are known. The method is designed so as to work properly also in oversaturated traffic conditions. To this end, at a first step, the vehicle queue tail location within an urban link is detected; then, based on this detected location, the link is divided in two varying-length sections, i.e. upstream and downstream of the queue tail. A method is subsequently developed to estimate the number of vehicles in each section separately. Due to the complicated dynamics of traffic flow downstream of the queue tail, knowledge of the queue tail location does not necessary yield the number of vehicles inside the queue section. To address this problem, a well-defined nonlinear function based on physical modeling of traffic flow behavior is developed to obtain the number of vehicles within the queue section based on the queue tail location and average speed of connected vehicles inside this section. On the other hand, inflow from a spot detector, that is placed at the upstream end of the link, together with the queue tail location are used to conclude on the number of vehicles in the upstream section of the link. Consequently, the whole vehicle accumulation of the link is derived as the summation of both link sections accumulations. Another contribution of this paper is to estimate the outflow of the urban link, which is valuable information for queue spillback detection at downstream links and may be exploited for the development of a network-scale estimator, which is the subject of ongoing research. For the simulation procedure, we first assume that all required data, i.e. connected vehicle data and inflow data, are available every one second. Thus the high resolution (second-by-second) estimation is conducted for each traffic states. At the end, we also consider the availability of input data at lower resolutions, i.e. higher sampling times, and test the estimation procedure for such cases as well. The performance of the developed estimation scheme is tested and validated under different conditions and settings through realistic simulations using the AIMSUN (Barceló and Casas, 2005) micro-simulator as ground truth.

The rest of the paper is organised as follows. The literature review addresses relevant research efforts on queue modeling and estimation at signalised intersections and application of connected vehicle data in Section 2. In Section 3, the methodologies for vehicle queue tail, vehicle accumulation (per section and total), and outflow estimation are presented. Some practical considerations are also given in this section. Simulation results are described and presented in Section 4. Finally, conclusions and outline of ongoing work are provided in Section 5.

2. Literature review

There is a vast body of literature on modeling queues at signalised intersections based on appropriate modeling approaches, such as input-output models and shock-wave models. Models based on the cumulative input–output flow, such as (Webster, 1958) which is one of the earliest studies, are often used in research and practice because of their simplicity. However, they are facing two challenges: first, how to address long queues extending beyond the input detector; and, second, how to remove flow measurement errors accumulating over time. Thus, the performance of the input-output techniques is not always satisfactory in practice (Wu et al., 2017). To circumvent this problem, Vigos et al. (2008) employed a Kalman-Filter to produce estimates of vehicle accumulation (or vehicle count) based on real-time measurements of flow and occupancy provided by three loop detectors located at both extreme points and at the middle of the link. This method is further simplified in (Vigos and Papageorgiou, 2010) to allow for estimates on the basis of one single time-occupancy measurement that is typically available in urban signalised links. However, the accuracy of the method was shown to degrade with increasing time resolution. In another recent work (Kwong et al., 2010), a system based on matching vehicle signatures is developed for measuring the vehicle accumulation and travel time in the links of a road network.

Lighthill–Whitham–Richards (LWR) kinematic wave theory (Lighthill and Whitham, 1955; Richards, 1956) provides another