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Long queue estimation for signalized intersections using mobile data

Peng Hao[a,1], Xuegang Ban[b,*]

[a] Center for Environmental Research & Technology, University of California, Riverside, 1084 Columbia Avenue, Riverside, CA 92507, USA
[b] Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, 110 Eighth Street, 4034 Jonsson Engineering Center, Troy, NY 12180-3590, USA

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ABSTRACT

Queue length is one of the key measures in assessing arterial performances. Under heavy congestion, queues are difficult to estimate from either fixed-location sensors (such as loop detectors) or mobile sensors since they may exceed the region of detection, which is defined as long queue in the literature. While the long queue problem has been successfully addressed in the past using fixed-location sensors, whether this can be done using mobile traffic sensors remains unclear. In this paper, a queue length estimation method is proposed to solve this long queue problem using short vehicle trajectories obtained from mobile sensors. The method contains vehicle trajectory reconstruction models to estimate the missing deceleration or acceleration process of a vehicle. Long queue estimation models are then developed using the reconstructed vehicle trajectories. The proposed method can provide estimates of the queue profile and the maximum queue length of a cycle. The method is tested in a field experiment with reasonable results.

1. Introduction and motivation

Arterial performance measures such as queue lengths at signalized intersections and route travel times are crucial means to quantify the performance of arterial systems, and thus have attracted much attention in the literature. For example, there are many applications that would benefit from detailed travel time information through an urban traffic network, such as traffic navigation and fleet management. Arterial traffic flow however is challenging to model or measure. One of the reasons is that intersections bring disruptions to arterial traffic flow, which results in complex traffic evolution over time and space in queues close to intersections and due to traffic signals. Meanwhile, arterial traffic data are increasingly available today. Third party traffic data collectors already started to gather traffic information in real time (Brindle, 2014), e.g., vehicle locations and speeds updated in seconds or a minute, or vehicle travel times for specific routes. This research seeks to gain a deeper understanding using such data to estimate signalized intersection queuing, which can lead to better estimation of arterial performances in real time (and potentially for very large areas).

In the past, queue length estimation for signalized intersections mostly concentrated on the static or average queue lengths using statistical methods (Webster, 1958; Newell, 1965) or shockwave-based methods (Lighthill and Whitham, 1955; Richards, 1956; Stephanopoulos et al., 1979). With the growing demand of live traffic information and the development of new sensing

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[*] Corresponding author. Tel.: +1 518 276 8043; fax: +1 518 276 4833.
E-mail addresses: haop@cert.ucr.edu (P. Hao), banx@rpi.edu (X. Ban).
[1] Tel.: +1 951 781 5777; fax: +1 951 781 5790.

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technologies, real time arterial performance, such as the cycle-by-cycle (or real time) queue length, has gained much attention. Such real time traffic studies have been conducted using (i) 30-s loop detector data with fine-grained signal timing (Skabardonis and Geroliminis, 2008); (ii) event-based signal and loop detector data (Balke et al., 2005; Smaglik et al., 2007; Liu and Ma, 2008; Liu et al., 2009); and (iii) other techniques (such as video-based) that have not been seen as widespread use. Mobile traffic sensors, such as global position system (GPS), cellular phones, connected vehicles, and other tracking devices, provide a supplement or alternative to fixed-location sensors in arterial performance measurement. Mobile data have shown great potential for real time queue length estimation (Ban et al., 2011; Hao et al., 2014a, 2014b; Cheng et al., 2012; Comert and Cetin, 2009; Comert, 2013), along with new challenges (e.g., privacy protection; see Sun et al., 2013).

We note here that fixed-location sensor data and mobile data are complementary to each other. They both have their own advantages and disadvantages. In some areas, there may be only fixed-location sensors so that previous methods based on fixed-location data (Skabardonis and Geroliminis, 2008; Liu et al., 2009) can be used. In some other areas, there may be only mobile sensing data (e.g., from smart phones or probe/fleet vehicles), for which the method proposed here may be applied. In other areas, both data elements may exist, for which one can fuse them to extract more useful information (e.g., see Sun et al., 2015). Even when new technologies such as Connected Vehicles are widely deployed, fixed-location sensors may be needed for security or reliable monitoring purposes. In this case, the fixed-location data, especially the event-based data will also be useful sources for measuring the performances of traffic systems such as queue lengths of signalized intersections. In addition, fixed-location sensors have inherent advantages in real time traffic control as they are able to acquire the lane-by-lane incoming flow efficiently. Therefore, the proposed methods here do not imply that that mobile sensors are superior and will replace fixed-location sensors (such as loops) in the future; rather they provide alternative ways to assess arterial performance measures using mobile data.

In this paper, we focus on mobile sensing data only, and aim to answer the question of what one can do to estimate signalized intersection queue length using mobile data especially when the queue is long. Here we are concerned with queue length *estimation*, not prediction. Estimation means one infers something (e.g., queue lengths) after the fact, e.g., to infer queue information of a cycle when a vehicle in the cycle passes the downstream location (VTL2; see below) or more practically, to estimate the queue length profile of a cycle when the cycle finishes. One may possibly build prediction models using the estimated results, by modeling how the queues likely change over time. This however is not a trivial task, and not the focus of the paper. Also “queue length” here is defined as the number of vehicles that have been queued in a cycle, which describes how far upstream the queue reaches. This definition was adopted from previous studies (Liu et al., 2009; Ban et al., 2011; Hao et al., 2014b), which was shown to better represent the impact of the queue to the upcoming vehicles (even during the green time period).

For queue length estimation (using either fixed-location sensors or mobile sensors), there is the so-called “long queue” problem (Liu et al., 2009) when the queue exceeds the area of detection (the advanced detector if fixed-location sensors are concerned or the upstream virtual detector, i.e., VTL1 as will be shown later in this paper, if mobile sensors are concerned). Recently such problem was addressed successfully using fixed-location sensors. For example, Skabardonis and Geroliminis (2008) used flow and occupancy as the key measures to estimate the time when long queue or spillover happens. Some adjustments were then applied to estimate the queue length. Liu et al. (2009) identified a long queue by searching the “break points” from the detector occupancies and vehicle gaps. A shockwave-based model was then developed to reconstruct the shockwave propagation beyond the advance detector to recover the length of a possible long queue.

Mobile sensors can collect sample trajectories from vehicles equipped with such sensors. The long queue problem may not be that severe for mobile-data-based models: the queue far from the intersection could still be detected by mobile sensors if one assumes the entire trajectories in the upstream link (defined as *long* trajectories in this paper) of sample vehicles are available for traffic analysis. Some intersection models were built upon those long trajectory data. Izadpanah et al. (2009) proposed a trajectory based shockwave detection model, and tested their model in simulation using long trajectories of all passing vehicles. Cheng et al (2012) developed a cycle-by-cycle queue length estimation method using long vehicle trajectories. Critical points were extracted from the trajectories which indicate when vehicles change their dynamics (such as slow down, speed up, or stop). A shockwave-based model was then proposed to estimate the real time queue length and signal timing using measures at the critical points. Collecting long trajectory data however may violate privacy because the continuous trace of a vehicle may indicate the home and work place of the driver. This may be true even if the entire trajectory is divided into multiple pieces (e.g., one for each of the links between two intersections) since there are methods that can effectively connect those partial, short traces even when they are anonymously collected (Sun et al., 2013).

To protect privacy while still preserving the needed data for traffic modeling applications, Hoh et al. (2008) introduced the concept of virtual trip lines (VTLs). VTLs are “virtual loop detectors” that receive the locations, times, and speeds of passing vehicles. For arterial performance measurement, a pair of VTLs is installed at the upstream and downstream of an intersection (called VTL1 and VTL2 respectively) so that only sample travel times and/or *short* trajectories within the VTL zone (the region between the pair of VTLs) can be collected. It was shown that those short trajectories can protect privacy to a reasonable level if VTLs are appropriately deployed and the collected traces are filtered using proper filtering algorithms (Zan et al., 2011; Sun et al., 2013). Ban et al. (2011) showed that travel times collected via the arterial VTL system can be used to estimate real time queue lengths. Hao et al. (2014a) developed a kinematic equation based method to investigate the queue location of each sample vehicle, which also provides a lower bound to the queue length in a cycle. Hao et al. (2014b) also proposed a Bayesian Network based algorithm to evaluate the cycle-by-cycle queue length distribution using sample travel times based on the vehicle index estimation model in Hao et al. (2013). Those methods were all developed upon the assumption that queues never spill back to VTL1. If queue spillback does happen (i.e., the long queue problem), however, such methods cannot be applied directly to estimate long queues, for two reasons.