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Vehicle trajectory reconstruction for signalized intersections using mobile traffic sensors

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ABSTRACT

Mobile traffic sensors – those move with the flow they are monitoring – have quickly emerged as an important means for traffic monitoring and data collection. In this paper, we propose methods to reconstruct short vehicle trajectories for the entire traffic flow at arterial intersections using sample vehicle trajectories obtained from mobile traffic sensors. The motivation for this work is that once the trajectories for all vehicles are available, a complete picture of the traffic flow will be obtained. Such information can then be applied for arterial performance measurement and other related applications. This paper presents optimization-based and delay-based models to estimate shockwave boundaries at signalized intersections, which are used to reconstruct short vehicle trajectories by applying the variation formulation (VF) of traffic flow. The models are tested using the NGSIM data and micro-simulation data. The results indicate that the proposed models are not very sensitive to penetration rates. In general, the optimization-based model outperforms the delay-based model.

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1. Introduction and motivation

Mobile traffic sensors – those that move with the flow they are monitoring such as Global Positioning System (GPS) enabled devices and smart phones – have quickly emerged as an important means for traffic data collection and monitoring (Herrera et al., 2010). Mobile sensors provide new forms of data such as vehicle trajectories that may transform how traffic data are collected and used in the future. Mobile traffic data are fundamentally different from data collected from traditional means (e.g., fixed location sensors such as loop detectors). This is shown in Fig. 1 that depicts a signalized intersection at location *B*. Two sets of loop detectors are installed at *B* and an upstream location *A* respectively. Fixed-location sensors can provide information at spatially discrete locations (i.e., where they are deployed) for the entire traffic flow: regular loop detectors can provide flow and occupancy aggregated for 30-s or 5-min; high-resolution detector data also include the time when a vehicle passes a detector (the short thin lines at *A* and *B* in Fig. 1) and the duration the vehicle occupies the detector (Balke et al., 2005). Mobile sensors, on the other hand, provide spatially (almost) continuous information but for a sample of traffic flow, e.g., the vehicle trajectories between *A* and *B* as shown by the bold lines in Fig. 1. They are direct samples of what happens between the two locations. Such difference implies that the standard modeling techniques based on traditional data sources may not be directly applied to mobile data. New modeling methods for traffic states and performance estimation using mobile data have been recently developed for both freeways (Herrera and Bayen, 2009; Izadpanah et al., 2009; Lu and Skabardonis, 2007; Goodall et al., 2012) and arterials (Ban et al., 2009a, 2011a; Herring et al., 2010; Hao et al., 2012; Comert and Cetin, 2008; Li et al., 2013; Hao and Ban, 2013; Hofleitner et al., 2012).

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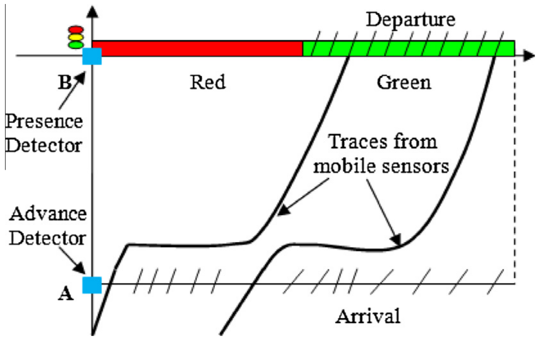

Fig. 1. Mobile sensor data vs. loop data.

While these new methods aim at exploiting how to best utilize the special forms of mobile data (e.g., intersection travel times are used in Ban et al. (2009a, 2011a)), as shown in Fig. 1, one may wonder whether information regarding the *entire* traffic population can be inferred from mobile data that are just samples of the traffic flow. Answer to such question is not only scientifically intriguing but also useful in practice. Indeed, if such information is available, a complete picture of the entire traffic flow can be obtained. Such information can be applied for arterial performance measurement and other related applications using either traditional methods (that need the entire traffic flow information) or new methods (that exploits the special forms of mobile data; see Ban et al. (2009a, 2011a) and Hao et al. (2012)). For example, as showed in Section 6, the estimated vehicle trajectories can be used to estimate queue length of the intersection, which is crucial to signal optimization and control. In this paper, we show that the answer to such a question is affirmative at least under specific situations, e.g., we can reconstruct *short* trajectories of the entire traffic flow using sample vehicle trajectories around a signalized intersection.

Here we notice that tracking the trajectories of vehicles for extended times or distances may severely violate privacy even after anonymization or obfuscation techniques are applied (Hoh et al., 2007). To balance privacy protection and data needs for traffic modeling, Hoh et al. (2008) proposed the idea of the Virtual Trip Lines (VTLs). VTLs are geographic markers that indicate where vehicles should provide speed and location updates. Hoh et al. (2008) showed that by using VTLs to regulate location and speed reports, the privacy issues can be alleviated. Sun et al. (2013) further proposed the VTL-zone (which is the region between the upstream and downstream VTLs of an intersection) based system and associated filtering algorithms to protect privacy for arterial traffic modeling, which allows the collection of short vehicle trajectories within a VTL zone. It was showed that such system can balance privacy protection and data needs for arterial modeling (Ban and Gruteser, 2012). Since only short trajectories around an intersection are required for the methods proposed in this paper, we expect that privacy is not a major concern; in the conclusion section, brief discussions of the privacy implication will also be presented.

Reconstruction of vehicle trajectories using mobile sensing data has received attention recently. Goodall et al. (2012) proposed *microscopic-based* methods for vehicle trajectory estimation on freeways. The methods we propose in this paper for short vehicle trajectory reconstruction are based on the variational formulation (VF) of kinematic waves developed by Daganzo (2005a, 2005b). In this sense, they can be considered as *macroscopic-based* methods. Daganzo (2005a) proved that the solution of every well-posed kinematic wave traffic problem with a concave flow-density relation is a set of least-cost (shortest) paths in the space–time domain, and a VF model is further proposed for this. The VF can be solved in a discrete intra-link time–space mesh, which is referred to as the "solution network". Complex boundary conditions and constraints were also discussed in Daganzo (2005a). Daganzo (2005b) developed more detailed solution methods for VF. Daganzo and Menendez (2005) examined the special case where the fundamental diagram is triangular. Blumberg and Bar-Gera (2009) applied the VF model in the dynamic network location procedure in order to maintain the consistency between the results of traffic flow models and those via the network loading process.

In order to properly apply the VF method, the shockwave boundaries of traffic flow have to be known. While these boundaries are relatively straightforward to be constructed if flow and density information is available (e.g., from loop detectors), doing so using mobile data is not trivial since flow or density is not directly available. Therefore, *the key challenge* in reconstructing vehicle short trajectories around a signalized intersection is how to estimate accurate shockwave boundaries from mobile data. In Sun and Ban (2011), the cumulative vehicle numbers are assumed to be given. Based on these numbers, the arrival flow rate can be estimated; shockwave boundary can then be reconstructed. The cumulative vehicle numbers, however, are generally not available directly from mobile data.

In this paper, we propose two methods, namely the optimization-based and delay-based models, to estimate shockwave boundaries, based on which to reconstruct short vehicle trajectories. We first propose the optimization-based model and show that such model is hard to solve because it involves not only potentially large dimension binary variables, but also a complicated objective function evaluation process. A simplified optimization-based model is then proposed, which targets on estimating the combination of the boundary points (where vehicle stops and joins the queue) for different sample vehicles such that the overall difference between the ground-truth vehicle trajectories and the estimated ones is minimized. The

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