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Simultaneous estimation of states and parameters in Newell's simplified kinematic wave model with Eulerian and Lagrangian traffic data

Zhe Sun[a], Wen-Long Jin[b,*], Stephen G. Ritchie[a]

[a] Department of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Irvine, CA, 92697, USA
[b] Department of Civil and Environmental Engineering, California Institute for Telecommunications and Information Technology,Institute of Transportation Studies Irvine, CA, 92697-3600, USA

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ABSTRACT

The traffic state estimation process estimates various traffic states from available data in a road network and provides valuable information for travelers and decision makers to improve both travel experience and system performance. In many existing methods, model parameters and initial states have to be given in order to estimate traffic states, which limits the accuracy of the results as well as their transferability to different locations and times. In this paper, we propose a new framework to simultaneously estimate model parameters and traffic states for a congested road segment based on Newell's simplified kinematic wave model (Newell, 1993). Given both Eulerian traffic count data and Lagrangian vehicle reidentification data, we formulate a single optimization problem in terms of the initial number of vehicles and model parameters. Then we decouple the optimization problem such that the initial number of vehicles can be analytically solved with a closed-form formula, and the model parameters, including the jam density and the shock wave speed in congested traffic, can be computed with the Gauss-Newton method. Based on Newell's model, we can calculate individual vehicles' trajectories as well as the average densities, speeds, and flow-rates inside the road segment. We also theoretically show that the optimization problem can have multiple solutions under absolutely steady traffic conditions. We apply the proposed method to the NGSIM datasets, verifying the validity of the method and showing that this method yields better results in the estimation of average densities than existing methods.

1. Introduction

Traffic information is essential for travelers and decision makers to improve both travel experience and system performance. The traffic estimation process estimates various traffic states, e.g. density, flow rate, from available data in a road network. Ideally, an estimation method should provide a complete picture of the traffic states based on limited available data (Wang and Papageorgiou, 2005).

* Corresponding author.
E-mail address: wjin@uci.edu (W.-L. Jin).

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Two types of traffic data can be collected through various sensors. The first one is the Eulerian data collected at fixed locations. The inductive loop detector system is the most commonly used sensing system to collect Eulerian data. These detectors collect traffic counts and occupancy, and aggregate them at certain sampling intervals (usually 30 s) for each lane. This type of data has been used for many traffic applications and studies, including traffic management and control and traffic state estimation. The second type is the Lagrangian data collected for individual vehicles. This type of data can be generated by a vehicle reidentification system, which matches vehicles passing different locations (Sun et al., 1999). A vehicle reidentification system can be implemented based upon different sensing technologies, such as video cameras, AVI (automatic vehicle identification) tags, and loop detectors (Jeng, 2007). This type of data has been used for travel time estimation (Coifman and Cassidy, 2002), performance evaluation (Jeng, 2007; Oh et al., 2005), and O/D trip estimation (Oh et al., 2002).

Traditionally, traffic states are estimated with Eulerian traffic data. Coifman (2002) proposed a method to reconstruct vehicle trajectories from speed measurements of dual loop detectors. This method exploits the propagation of characteristic waves based on the Lighthill–Whitham–Richard (LWR) model (Lighthill and Whitham, 1955; Richards, 1956). Sun et al. (2003) developed a mixture Kalman filter to estimate traffic states based on the Switching-Mode Model (SMM) and tested it with Eulerian traffic counts and occupancy data through the PeMS database. Wang and Papageorgiou (2005) described traffic dynamics with a second-order continuum model, and estimated traffic densities and speeds with Kalman filters from Eulerian flow and occupancy measurements of loop detectors.

Recently, there has been increased interest in assimilating both Eulerian and Lagrangian data for traffic state estimation. Nanthawichit et al. (2003) adopted Payne's traffic flow model (Payne, 1971) for traffic state estimation, and a Kalman filtering estimation framework was implemented to combine data from both loop detectors and probe vehicles. Herrera and Bayen (2008) developed a similar Kalman filtering framework to estimate traffic states from both mobile sensor and loop detector data, but with the SMM (Muñoz et al., 2003). In addition, the study also introduced the nudging method (Newtonian relaxation) for data fusion. The two methods were evaluated with real-world traffic data, and it was found that Kalman filtering slightly outperformed the nudging method at the cost of being more complicated to tune and implement. The study by Claudel and Bayen (2010a, 2010b) reformulated the traffic state estimation problem using the Hamilton–Jacobi formula of the LWR model. This approach guarantees an exact solution with piece-wise linear initial and boundary data. In the study by Tossavainen and Work (2013), the Markov chain Monte Carlo (MCMC) method is used to estimate parameters in the fundamental diagram from GPS data. Using synthetic data, the authors verified the accuracy of parameter estimation and examined the absolute error of the velocity field obtained using the parameters. The study by Deng et al. (2013) proposed a stochastic three-detector (STD) method to incorporate heterogeneous data sources and formulated the estimation problem as an optimization problem. In a recent study by Bekiaris-Liberis et al. (2016), a "linear parameter-varying system", which is closely related to SMM, is proposed for traffic state estimation with both Eulerian and Lagrangian data in the Kalman filter framework. Nantes et al. (2016) proposed the incremental Extended Kalman filter for traffic estimation on arterial corridors using data from multiple sensors. Most existing studies support that probe sensor data, complementary to fixed location sensor data, improve data availability and enhance estimation accuracy. It is worth noting that Kalman filter (and its extensions) is a widely used technique for data assimilation in most of the traffic estimation literatures. It provides a natural and principal way of combining difference data sources with the error models, within a solid decision framework. However, misleading results can be generated if the prior distribution and error models are misspecified. Also, the computational cost is usually quite high, especially for traffic networks with large number of parameters.

Almost all traffic flow models used by existing methods involve a number of model parameters, especially those in the fundamental diagram (Cassidy, 1998), including the free-flow speed, jam density, and shock wave speed. In addition, traffic states at a time also depend on the initial conditions. Despite the substantial progress made in traffic estimation, existing estimation methods are limited since either the model parameters or the initial states have to be predetermined. In most existing studies,[1] the fundamental diagram is assumed to be given, or calibrated before estimating the initial and other traffic states. In other studies the initial states are to assumed be empty (Deng et al., 2013) or known (Sun et al., 2003) in advance. Such assumptions can limit the accuracy of the results as well as their transferability to different locations and times.

In this paper, we attempt to fill the gap by proposing a new framework to simultaneously estimate model parameters and traffic states for a homogeneous road segment with no internal ramps based on Newell's simplified kinematic wave model (Newell, 1993). Note that, by simultaneous estimation, we mean that model parameters in the fundamental diagram, the initial states, and later traffic states can all be estimated within the same framework, but calculations can still be sequentially ordered. This is substantially different from existing methods where model parameters and initial states have to be observed or estimated separately with other frameworks. The simultaneous estimation of both parameters and states is achieved by formulating a single optimization problem in terms of the initial number of vehicles and model parameters. Here we assume that both Eulerian traffic count data and a portion of Lagrangian vehicle trajectory data are available through loop detectors and vehicle reidentification systems or GPS devices, respectively. We then decouple the optimization problem such that the initial number of vehicles can be calculated with a closed-form formula, and the model parameters, including the jam density and shock wave speed in congested traffic, can be computed with the Gauss-Newton method. Further, based on

[1] There are exceptions. e.g. Canepa and Claudel (2012).