Transportation Research Part D 53 (2017) 440–453

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Traffic state and emission estimation for urban expressways based on heterogeneous data

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ARTICLE INFO

Article history:
Available online 9 May 2017

Keywords:
Urban expressway
Travel time
Data fusion
EGTF
Vehicular emission

ABSTRACT

Urban expressways, as the backbone of a city's transportation network, are critical for reducing traffic congestion and improving transportation efficiency of the whole network. The estimation of traffic states and emissions for urban expressways supports traveler information provision and system-wide traffic management. This paper aims to modify the extended generalized Treiber-Helbing filter (EGTF) to fuse GPS data (probe vehicles) and traditional traffic data (loop detectors), so as to enhance more accurate estimations of traffic states and emissions on urban expressways. The speed field is first reconstructed based on heterogeneous data, and then travel time and emissions are estimated using a virtual trajectory method and the VT-Micro model, respectively. The algorithm is applied to a real-world case study for an urban expressway in Beijing, China. After the parameter tuning, the proposed algorithm is compared with existing algorithms from the literature. Numerical results show that data fusion using the proposed algorithm could make better use of heterogeneous data and increase the accuracy of travel time and emissions estimations.

1. Introduction

The traffic state and emission estimation for urban expressways are often used to guide operational management decisions, while the objectives are to reduce traffic congestion and adverse environmental impacts. With rapid advances of information technologies, it has become possible to use heterogeneous data sources to better monitor and accurately estimate traffic states. Travel time, speed and emissions are often used as indicators of traffic conditions. They can be used to help travelers choose appropriate routes, and help agencies evaluate the efficiency of the transportation system.

Traffic states could be either directly measured or indirectly estimated (Yeon et al., 2008). Treiber and Kesting (2013) summarized a range of travel time estimation methods as follows: methods of trajectories, methods of accumulated vehicle counts, hybrid methods, virtual stationary detections, and virtual trajectory methods. Generally, traffic state estimation is based on either statistical analysis or traffic flow physics. It often requires the use of data collected by fixed detectors or mobile probe sensors. With the development of advanced data collection technologies, multiple data sources (e.g., mobile phone data, floating vehicles, and GPS data) have been used in practice. Several case studies used data from cellular phones to measure traffic speeds and travel times (Westerman et al., 1996; Ygnace et al., 2000; Bar-Gera, 2007). However, such data

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http://dx.doi.org/10.1016/j.trd.2017.04.042
1361-9209/

sources were often less accurate than GPS. Herrera and Bayen (2010) proposed to integrate mobile sensing data, which were considered as a reliable and accurate data source, into macroscopic traffic flow models for estimating freeway traffic states. Zhou et al. (2015) presented a computationally efficient and theoretically rigorous dynamic traffic assignment model DTA-Lite coupled with a computationally efficient emission estimation package MOVES to evaluate traffic dynamics and vehicle emission/fuel consumption impact of different traffic management strategies. Luo et al. (2016) designed a real-time en-route diversion control strategy in a model predictive control framework with objectives of traffic efficiency, emission reduction and fuel economy.

Recently, data fusion models have been widely used in the fields of military operations and natural disaster detection (Bass, 2000; Chen et al., 2013). In the field of intelligent transportation systems (ITS), data fusion has also been widely applied (Berkow et al., 2009; El Faouzi et al., 2009; Qiu et al., 2010; Chen et al., 2012, 2014a,b, 2015; Li et al., 2013, 2014; Li and Chen, 2017). Several data fusion methods were developed to estimate traffic states. For example, some methods developed analytic solution based on the kinematic wave theory. Claudel and Bayen (2010a) included internal boundary conditions into Hamilton-Jacobi equations to model highway traffic. In that research, a semi explicit solution was proposed with a generalized Lax-Hopf formula, which was implemented to improve the accuracy of traffic flow prediction through fusion of Lagrangian data (Claudel and Bayen, 2010b). Claudel and Bayen (2011) proposed a new convex formulation for solving data assimilation and data reconciliation problems in systems modeled by a Hamilton-Jacobi equation with a concave Hamiltonian. The formulated convex optimization programs were implemented in the well-known Mobile Millennium traffic information system (Mobile Millenium Project, 2010; Work et al., 2010; Herrera et al., 2010; Herrera and Bayen, 2010).

Other research focused on the characteristics of different data sources. For example, El Faouzi et al. (2011) summarized the progress and remaining challenges of data fusion in traffic applications, such as ATIS (Advanced Traveler Information Systems), AID (Automatic Incident Detection), ADA (Advanced Driver Assistance), NC (Network Control), and CAP (Crash Analysis and Prevention). Van Lint and Hoogendoorn (2010) claimed that heterogeneous data from multiple sources had the following advantages: higher accuracy, higher robustness, better spatial and temporal coverage, and lower cost. Mazaré et al. (2010) adopted a case study to show that the accuracy of travel time estimation could be improved by fusing data from GPS and loop detectors, especially when the data were very sparse.

Despite its accuracy and effectiveness, traffic data fusion still faces some challenges in practice. Different data sources are likely to bear different characteristics; for example, data from loop detectors may have a non-uniform spatial distribution due to geographical restrictions. Some of the data might be missing or unusable because of sensor failure. Floating-vehicle data might suffer from low accuracy on spatial resolution and potential privacy issues. As a result, simply combing data from different sources may not guarantee accuracy and reliability. Thus, finding an appropriate method to fuse data effectively into reliable forms remains a challenge.

Among those traffic state estimation algorithms, the general adaptive smoothing method (GASM) proposed by Van Lint and Hoogendoorn (2010) has been found able to reconstruct the speed field accurately. That research also proposed an extended generalized Treiber-Helbing filter (EGTF) to fuse data from different sources. Based on the adaptive smoothing method (ASM), Treiber et al. (2011) presented an advanced interpolation method for estimating smooth spatiotemporal profiles for local highway traffic states. The generalized method successfully reproduced state transitions and stop-and-go waves in various field tests. Previous studies mainly focused on traffic state estimation on freeways and only a few studies have been conducted for urban expressways. For example, Li et al. (2016) modified the EGTF algorithm to include more on/off-ramps and weaving areas for urban expressways. This paper further improves the algorithm proposed in Li et al. (2016) to increase the accuracy of the reconstructed speed field. Based on the speed field, travel time can be estimated using the virtual trajectory method. Two parameters of EGTF are then tuned to improve the traffic state estimation.

There have been various applications of reconstructed speed fields over both dimensions of time and space, e.g., traffic flow forecasting, traffic accident prediction, bottleneck detection, and vehicular emissions estimation. There are several microscopic models for emissions estimation, e.g., the comprehensive modal emissions model (CMEM) (Barth et al., 2008) and international vehicle emissions model (IVEM) (Davis et al., 2005). However, these models require inputs such as fleet composition and roadway geometric characteristics, which might not be available in many real-world applications. The VT-Micro model used instantaneous vehicle activity information (e.g., speed and acceleration) as inputs to make an accurate estimation of fuel consumption and emissions (Ahn, 1998; Wang et al., 2015). Several studies on estimating trajectory-based microscopic emissions have been conducted. For instance, Wang et al. (2011) reconstructed traffic state and vehicle trajectories using ASM. Based on microscopic information, the VT-Micro model can be used to estimate emissions. For example, Chen et al. (2014a,b) assumed the vehicle trajectory was a quadratic function of time and improved the trajectory reconstruction method based on the kinematic wave theory (Newell, 1993) and Coifman's method (Coifman, 2002). In their work, CMEM was used to estimate emissions and fuel consumption.

Many of the aforementioned studies are based on data from a single detection source. Hence, the estimation accuracy of traffic states might not be accurate enough because of the sparse distribution of detectors and the unavoidable aggregation of acceleration/deceleration information. It is necessary to develop a method that can fuse heterogeneous traffic flow data to better capture traffic dynamics. Motivated by this limitation, we improve the extended generalized Treiber-Helbing filter to fuse GPS data (probe vehicles) and traditional traffic data (loop detectors), so as to enhance more accurate estimations of traffic states and emissions on urban expressways. This paper aims to apply heterogeneous data to enhance the traffic state and emission estimation for urban expressways. Demonstrated in a field urban expressway in Beijing, China, both loop