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Review article

Traffic state estimation on highway: A comprehensive survey

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ABSTRACT

Traffic state estimation (TSE) refers to the process of the inference of traffic state variables (i.e., flow, density, speed and other equivalent variables) on road segments using partially observed traffic data. It is a key component of traffic control and operations, because traffic variables are measured not everywhere due to technological and financial limitations, and their measurement is noisy. Therefore, numerous studies have proposed TSE methods relying on various approaches, traffic flow models, and input data. In this review article, we conduct a survey of highway TSE methods, a topic which has gained great attention in the recent decades.

We characterize existing TSE methods based on three fundamental elements: estimation approach, traffic flow model, and input data. Estimation approach encompasses methods that estimate the traffic state, based on partial observation and a priori knowledge (assumptions) on traffic dynamics. Estimation approaches can be roughly classified into three according to their dependency on a priori knowledge and empirical data: model-driven, data-driven, and streaming-data-driven. A traffic flow model usually means a physics-based mathematical model representing traffic dynamics, with various solution methods. Input data can be characterized by using three different properties: collection method (stationary or mobile), data representation (disaggregated or aggregated), and temporal condition (real-time or historical).

Based on our proposed characterization, we present the current state of TSE research and proposed future research directions. Some of the findings of this article are summarized as follows. We present model-driven approaches commonly used. We summarize the recent usage of detailed disaggregated mobile data for the purpose of TSE. The use of these models and data will raise a challenging problem due to the fact that conventional macroscopic models are not always consistent with detailed disaggregated data. Therefore, we show two possibilities in order to solve this problem: improvement of theoretical models, and the use of data-driven or streaming-data-driven approaches, which recent studies have begun to consider. Another open problem is explicit consideration of traffic demand and route-choice in a large-scale network; for this problem, emerging data sources and machine learning would be useful.

1. Introduction

Traffic state estimation (TSE) refers to the process of inference of traffic state variables, namely flow (veh/h), density (veh/km), speed (km/h), and other equivalent variables, on road segments using partially observed and noisy traffic data. TSE plays an important role in traffic operations and planning. For example, traffic control, such as ramp metering, pricing, and information provision, requires precise traffic state information in order to mitigate congestion effectively. Strategic transportation planning such as infrastructure improvements also require traffic state information. These operation and planning tasks can be greatly improved by an efficient and accurate observation of the traffic state. However, the traffic state is not observed everywhere and practical measurements are usually noisy. Thus, the traffic state in unobserved ar-

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Abbreviations: ADAS, advanced driver assistance system; ARZ, Aw–Rascle–Zhang; ASF, adaptive smoothing filter; BVP, boundary balue problem; CDR, call detail record; CL, conservation law; CTM, cell transmission model; EKF, extended Kalman filter; EnKF, ensemble Kalman filter; FD, fundamental diagram; FDM, finite difference method; GPS, global positioning system (and equivalent global navigation satellite systems); HJ, Hamilton–Jacobi; HL, Hopf–Lax; KF, Kalman filter; KFT, Kalman filter-like technique; LWR, Lighthill–Whitham–Richards; ML, machine learning; OBD2, on board diagnostics second generation; PDE, partial differential equaiton; PF, particle filter; PTM, phase transition model; PW, Payne–Whitham; SMM, switching mode model; TSE, traffic state estimation; TTI, travel time information; VT, variatonal theory; xFCD, extended floating car data.

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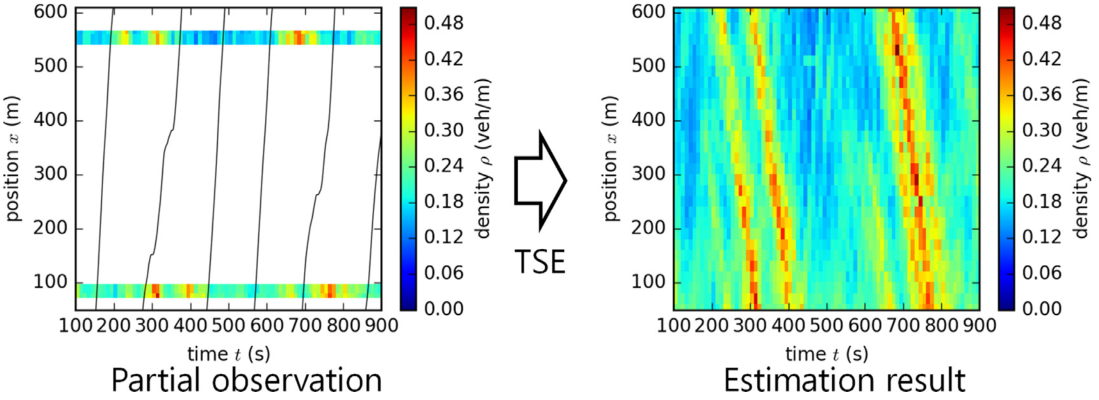

Fig. 1. Illustration of TSE, where entire traffic state (plot color: density) in the time–space domain is reconstructed based on partial observation by stationary (density at specific locations) and mobile (subsets of trajectories of specific vehicles) sensing data. The data is based on US Department of Transportation (2006).

eas needs to be estimated; and that in observed areas needs to be improved (denoised) as well. In this article, TSE is defined as the *simultaneous estimation of flow, density, and speed on road segments with high spatiotemporal resolution,*[1] *based on partially observed traffic data and a priori knowledge of traffic*. Fig. 1 illustrates a conceptual procedure of TSE.

This article focuses on TSE on highways motivated by the following four reasons. First, highways play a significant role in road transportation systems, with high service capability in terms of the volume and speed. Second, they exhibit some controllability (Papageorgiou, Diakaki, Dinopoulou, Kotsialos, & Wang, 2003) because of the nature of vehicular traffic. Third, recent technology developments enable new applications with the use of various and heterogeneous traffic data. Fourth, because of the aforementioned reasons, numerous highway TSE methods with various features have been proposed to date, which are worth considering and summarizing.

For our best knowledge, there is no comprehensive survey on TSE, although more than a decade has passed from the early and influential work on highway TSE by Wang and Papageorgiou (2005) and there have been considerable advances in this field.[2] This makes it difficult to assess available approaches, respective benefits, and potential improvements.

The aims of this article are to provide a comprehensive and systematic summary of highway TSE, to contribute toward a better understanding of state-of-the-art methods, and to identify future research directions. Note that this article does not determine which methodology outperforms others in terms of general performance metrics. Respective advantages or disadvantages of a TSE method need to be discussed separately, by considering the specification of the application. One of the aims of this article is to provide the fundamental materials for such discussion. To achieve these aims, this article characterizes existing TSE methods based on their three fundamental elements: *estimation approaches, traffic flow models*, and *input data*. The following briefly describes these elements (we will discuss the details in the corresponding sections later).

The estimation approach consists of methods that estimate the traffic state, based on a priori knowledge of traffic and partial observation. A priori knowledge (i.e., assumptions) could be physical traffic flow models and data-driven models, which is usually obtained by abstracting actual traffic by employing physical principles and statistical/machine-learning (ML) methods, respectively. In this study, the approaches are grouped into three categories, namely, *model-driven, data-driven*, and *streaming-data-driven*, according to types of a priori knowledge and input data they rely on. In short, model-driven ones rely on physical models of traffic which is characterized by empirical relation. Data-driven ones rely on dependence in historical-data and statistical/ML methods. Streaming-data-driven ones do not rely on these two previous elements. Because the assumptions vary greatly among the approaches, they have different advantages and disadvantages.

Traffic flow models describe the physical and theoretical aspects of traffic dynamics in the spatiotemporal domain. Therefore, they are used by model-driven TSE methods to infer the traffic state in an unobserved time–space region. Various models along with various solution methods have been proposed; and they have totally different advantages and disadvantages in terms of TSE.

The input data for TSE is the partial observation of traffic and is essential for TSE. Because of recent technology advances, the availability of novel data types (e.g., global positioning system (GPS), call detail record (CDR), on board diagnostics second generation (OBD2), etc.) is rapidly increasing in terms of both quality and quantity. This has resulted in the emergence of various TSE methods.

The remainder of this article is organized as follows. In Section 2, we briefly present highway traffic and TSE, along with fundamental terms and definitions. In Section 3, we summarize existing traffic models commonly used for TSE. In Section 4, we describe available measurements and data for traffic. In each sub- and sub-sub-section in Sections 3 and 4, general introduction on the corresponding topic and its application in TSE are discussed sequentially. In Section 5, we review TSE approaches, which mainly use models described in Section 3 and data described in Section 4. In Section 6, we summarize the survey results and propose future research directions.

Note that there are over 100 different methods to the TSE problem; thus, it is not practical to enumerate and explain them all in the core of this article. Therefore, only studies with substantial originality in terms of the aforementioned characteristics (i.e., approach, model, data) are referred in the main text. The remaining studies are summarized in Section 6 together with those explained in the main text. Case studies which did not propose new TSE methods are not reviewed in this article.

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[1] "High spatiotemporal resolution" loosely means spatial discretization on the order of few hundreds meters, and temporal on the order of a few minutes for practical purposes in transportation engineering.

[2] Several review articles from specific perspectives have been provided: a comprehensive review in 2005 (Wang and Papageorgiou, 2005, section 1) (we avoid overlapping with this one), data fusion in generic intelligent transportation system (ITS) research (El Faouzi, Leung, & Kurian, 2011), emerging traffic data collection methods in 2011 (Antoniou, Balakrishna, & Koutsopoulos, 2011), coordinate system in traffic flow models for TSE (Yuan, 2013, chapter 2), TSE for specific ITS applications (Timotheou, Panayiotou, and Polycarpou, 2015b, section 3), and application of vehicular ad hoc networks (Darwish & Abu Bakar, 2015; Song & Lee, 2013).

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