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Microscopic simulation-based validation of a per-lane traffic state estimation scheme for highways with connected vehicles

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ABSTRACT

This study presents a thorough microscopic simulation investigation of a recently developed model-based approach for per-lane density estimation, as well as on-ramp and off-ramp flow estimation, for highways in the presence of connected vehicles. The estimation methodology is mainly based on the assumption that a certain percentage of vehicles is equipped with Vehicle Automation and Communication Systems (VACS), which provide the necessary measurements used by the estimator, namely vehicle speed and position measurements. In addition, a minimum number of conventional flow detectors is needed. In the investigation, a calibrated and validated, with real data, microscopic multi-lane model is employed, which concerns a stretch of motorway A20 from Rotterdam to Gouda in the Netherlands. It is demonstrated that the proposed methodology provides satisfactory estimation performance even for low penetration rates of connected vehicles, while it is also shown that the method is little sensitive to the parameters (two in total) of the model utilized by the estimator.

1. Introduction

Most cities around the world experience ever-growing traffic congestion in urban areas and motorway networks. Congestion may be mitigated by optimizing the performance of the traffic infrastructure through traffic management and operational strategies. Real-time traffic information is a prerequisite for traffic operations, such as freeway ramp metering control, dynamic route guidance, incident detection, and variable message sign operations. In recent years, VACS are all the more receiving considerable attention since they may create new principles in traffic management, as they are capable of communicating real-time information and execute novel control tasks (Papageorgiou et al., 2015). Considering that density distribution may be highly heterogeneous among the different lanes of a highway, real-time lane assignment strategies may have significant advantages in traffic management. Lane policies and lane advice may be achieved if real-time traffic state information per lane is available (Roncoli et al., 2016b, 2017).

Recently, research on exploiting the innovative characteristics of VACS as a source of traffic data in traffic state estimation has drawn some attention, primarily due to the low cost, wide coverage and high accuracy of the extracted data. In this work, we consider that connected vehicles are vehicles capable of reporting information (i.e., position and speed) to an infrastructure-based system, which may be achieved via different technologies and communication paradigms. A basic scenario may simply consist of vehicles

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equipped with a GPS (Global Positioning System) and a system for mobile communication. However, more complex scenarios, for example, scenarios that incorporate communication among vehicles or between vehicles and roadside units, are also possible. Connected vehicles use localization technologies that can provide these data such as Dedicated Short-Range Communications (DSRC), as well as Global Positioning Systems (GPS), cellular and Bluetooth. Data stemming from connected vehicles may contain a variety of essential dynamic transportation information, while the most commonly used are vehicle position (longitude, latitude, and altitude) and vehicle speed. Global Positioning System (GPS) receivers are stated as the most popular communication system because they are low-cost, efficient and are already commonplace in many vehicles, in use for navigation. GPS systems have stated accuracy ranging from 5 to 15 m in geographical positioning Zito et al. (1995), Turksma (2000), and Liu et al. (2006). But most modern methods adopt a hybrid positioning system, combining differential GPS (DGPS) with map-matching and dead-reckoning, which improved vehicle position data up to 1–5 m accuracy Waterson and Box (2012), sufficient for lane-based applications. Speed measurements are mostly reported to be quite accurate with a precision error lower than 1 km/h Chalko (2007) and Zito et al. (1995), while some studies claim a tendency of underestimation in speed measurements and a reported error around 5 km/h Zhao et al. (2014).

Traffic state estimation utilizing floating car data has been investigated in numerous studies, such as, for example, Work et al. (2008), Fabritiis et al. (2008), Herrera et al. (2010), Herrera and Bayen (2010), Rahmani et al. (2010), Qiu et al. (2010), Schreiter et al. (2010), Treiber et al. (2011), Yuan et al. (2012), van Hinsbergen et al. (2012), Deng et al. (2013), Anand et al. (2014), Piccoli et al. (2015), Seo et al. (2015), Seo and Kusakabe (2015), Rempe et al. (2016), Wang et al. (2016), Wright and Horowitz (2016), Bekiaris-Liberis et al. (2016), Roncoli et al. (2016a), Seo et al. (2017), and Fountoulakis et al. (2017). While multi-lane traffic flow modeling has been the subject of several works (Laval and Daganzo, 2006; Roncoli et al., 2015; Carey et al., 2015; Du et al., 2016), the existing studies that deal with lane-based traffic state estimation are rare in the traffic literature, while they mainly assume data obtained from conventional detectors (Chang and Gazis, 1975; Coifman, 2003; Singh and Li, 2012; Yılan, 2016) with the exception of Zhou and Mirchandani (2015).

This paper presents several novelties with respect to our previous works and to other approaches published in the last decade. Existing works in literature dealing with the problem of lane-based traffic state estimation mainly assume data obtained from conventional detectors. Thus, the available measurement information as well as the measurement configurations employed in the present paper are different from those required in almost all other lane-based estimation approaches. Previous works (Bekiaris-Liberis et al., 2016; Roncoli et al., 2016a; Fountoulakis et al., 2017) employed connected vehicle data to estimate only cross-lane densities and on-ramp flows. In contrast, in the present paper, we implement a different model and we use a different measurement configuration to enable per-lane density estimation. Nevertheless, the distinguishing feature of our previous works, namely the lack of the need for any empirical modeling approach, such as fundamental diagrams, that would call for tedious calibration procedures, is present here as well.

The main contribution of this paper is the thorough evaluation of a per-lane density and ramp flow estimation methodology via microscopic simulation, including different penetration rates of connected vehicles. The estimation scheme uses a data-driven macroscopic model for per-lane traffic density and employs real-time measurements obtained from connected vehicles, namely vehicles which transmit information about their position and speed. A minimum number of spot flow measurements from detectors is also needed to guarantee the observability property of the underlying model, see Bekiaris-Liberis et al. (2017) for details. Density estimation is performed via the employment of a Kalman filter. The performance of the estimation scheme is examined under various penetration rates of connected vehicles, using data retrieved from a microscopic multi-lane model, which has been calibrated and validated by Perraki et al. (2017) with real data from a stretch of motorway A20 from Rotterdam to Gouda in The Netherlands. The case-study highway stretch includes several on-ramps, off-ramps, and a lane-drop, while the employed simulation scenario is characterized by both congested and free-flow traffic conditions. Thus, the effectiveness of the proposed methodology is examined in carefully designed experiments for a real highway stretch with real demand scenarios. It is worth mentioning that, in the investigation, simple algorithms are employed in case of inconsistencies in the probe vehicle data (such as, for instance, in case there are temporarily no measurements available from connected vehicles). The performance of the tested estimation scheme is shown to be satisfactory even for low penetration rates. Finally, it is demonstrated that estimation performance is little sensitive to the choice of the model parameters (two in total).

The remainder of the paper is organized as follows. The model for the per-lane density dynamics and the proposed estimation scheme are presented in Section 2. The description of the microscopic simulation configuration as well as the highway network under study and the traffic conditions are presented in Section 3, which includes also the details of the computation of the data employed by the estimator. Subsequently, the results of the estimation and a sensitivity analysis of the estimation performance with regard to the model parameters are presented in Section 4. Finally, in Section 5 the main findings of this study are summarized.

2. Per-lane traffic state estimation using a data-driven model

2.1. General set-up

We consider a highway stretch consisting of M lanes, indexed by $j = 1,\ldots,M$, subdivided into N segments, indexed by $i = 1,\ldots,N$. We define a cell (i,j) to be the highway part that corresponds to lane j of segment i. The length of each segment is denoted by $\Delta_i, i = 1,\ldots,N$.

The following variables are extensively used in the paper: