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Highway traffic state estimation with mixed connected and conventional vehicles: Microscopic simulation-based testing ☆

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ABSTRACT

This paper presents a thorough microscopic simulation investigation of a recently proposed methodology for highway traffic estimation with mixed traffic, i.e., traffic comprising both connected and conventional vehicles, which employs only speed measurements stemming from connected vehicles and a limited number (sufficient to guarantee observability) of flow measurements from spot sensors. The estimation scheme is tested using the commercial traffic simulator Aimsun under various penetration rates of connected vehicles, employing a traffic scenario that features congested as well as free-flow conditions. The case of mixed traffic comprising conventional and connected vehicles equipped with adaptive cruise control, which feature a systematically different car-following behavior than regular vehicles, is also considered. In both cases, it is demonstrated that the estimation results are satisfactory, even for low penetration rates.

1. Introduction

Traffic congestion is a significant problem for the majority of large cities in the modern world (Papageorgiou et al., 2007). While the number of vehicles has been increasing steadily during the past decades (Dargay et al., 2007), a corresponding expansion of road networks is not deemed feasible for various reasons. On the other hand, traffic management represents a valid alternative allowing to improve the performance of traffic systems with fairly moderate effort. For this reason, traffic authorities and automobile industries are currently focusing on the development of innovative methods for traffic monitoring (Bishop, 2005).

Real-time traffic state estimation utilizing limited traffic data is of major importance, not only for traffic monitoring but also for traffic control. In conventional traffic, real-time traffic data are provided by spot sensors positioned at appropriate locations on the highway. Since the cost of installation and maintenance of a sufficient number of spot sensors that guarantees accurate traffic monitoring is high, several studies deal with the development of traffic estimation algorithms employing a limited amount of sensors, such as, for example, Muñoz et al. (2003), Alvarez-Icaza et al. (2004), Wang and Papageorgiou (2005), Hegyi et al. (2006), Mihaylova et al. (2007), Morbidi et al. (2014), to name only a few.

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The eminent need for improvement of traffic conditions, for enhancement of driver safety and comfort, and for reduced operation cost of traffic systems has led to the introduction of various Vehicle Automation and Communication Systems (VACS). VACS capabilities can be exploited for the development of novel traffic estimation and control methodologies (Diakaki et al., 2015). Traffic control in the presence of VACS is the subject of numerous papers, such as, for example, Varaiya (1993), Rao and Varaiya (1994), Rajamani and Shladover (2001), Bose and Ioannou (2003), Kesting et al. (2008), Shladover et al. (2012), Ge and Orosz (2014), Wang et al. (2014), Roncoli et al. (2015, 2016).

The problem of traffic estimation in the presence of VACS is addressed in numerous studies, such as, for example, Work et al. (2008), De Fabritiis et al. (2008), Herrera et al. (2010), Rahmani et al. (2010), Treiber et al. (2011), Gayah and Dixit (2013), Yuan et al. (2012), Ramezani and Geroliminis (2012), Yuan et al. (2014), Piccoli et al. (2015), Seo et al. (2015), Bekiaris-Liberis et al. (2016), Roncoli et al. (in press) to name only a few. Note that in Yuan et al. (2012, 2014) an extended Kalman filter that utilizes both Eulerian and Lagrangian measurements is employed, based on the Lagrangian coordinates model (where state variables move with the traffic stream) proposed by Leclercq et al. (2007). Typically, such traffic state estimation algorithms employ data stemming from connected vehicles, i.e., vehicles that can provide real-time information to a central or local authority (Turksma, 2000). Connected vehicle data can be utilized as a low-cost and efficient, complementary or primary, source of traffic information towards traffic state estimation (Treiber and Kesting, 2013).

In addition to vehicle communication systems, automated vehicle systems play an important role in modern intelligent transportation systems. While fully automated highways, an innovation that would affect traffic conditions significantly (Kesting et al., 2007), are unlikely to come into existence in the near future, partially automated highways are already part of reality. One of the crucial components of such automated systems is Adaptive Cruise Control (ACC), which was already introduced into modern vehicles by the automobile industry (Darbha and Rajagopal, 1999; Wang et al., 2014). ACC-equipped vehicles aim at increased driver safety and improved comfort (Dragutinovic et al., 2005) and may have a different car-following behavior than manually driven cars, thus changing the traffic flow characteristics accordingly. Since a high penetration rate of ACC-equipped vehicles is not yet a reality, the effect of various percentages of such vehicles on traffic conditions is typically examined utilizing microscopic simulation platforms, see, e.g., Treiber and Helbing (2001), Marsden et al. (2001), VanderWerf et al. (2001), Rajamani et al. (2005), van Arem et al. (2006), Kesting et al. (2007), Ntousakis et al. (2015).

In this paper, we continue and extend our research on the validation of the scheme developed in Bekiaris-Liberis et al. (2016) for estimation of densities and ramp flows, which is based on a simple but exact macroscopic model for traffic density and employs mainly speed measurements obtained from connected vehicles (equipped with ACC or not). The distinguishing characteristic of this estimation scheme, compared to virtually all previous related developments, is that it is only based on the conservation-of-vehicles equation, without the resort of fundamental diagrams or other empirical relationships, which would call for appropriate and tedious model validation procedures, before field application. We test the performance of the estimation scheme under mixed traffic conditions, where connected vehicles, equipped with ACC or not, are present at various penetration rates. We utilize for our testing the microscopic simulation software Aimsun (Transport Simulation Systems, 2014) in which we build a highway stretch that includes several on-ramps and off-ramps, and employ a scenario in which both congested and free-flow traffic conditions occur. We also evaluate the performance of the estimation scheme when, for some instances, a very limited (or literally zero) number of speed measurements from connected vehicles are available, and propose simple algorithms for resolving the problem of lack of reliable segment speed measurements. Moreover, it is demonstrated that density estimation is highly insensitive to the choice of the filter parameters, while ramp flow estimation is more sensitive.

The rest of the paper is structured as follows. Section 2 presents the estimation scheme employed. Section 3 describes the details of the microscopic simulation configuration as well as the traffic network and scenario employed. Section 4 presents the results of the estimation in mixed traffic, i.e., traffic comprising conventional and connected vehicles. Section 5 presents the results of the estimation in mixed traffic comprising conventional and ACC-equipped connected vehicles. Finally, Section 6 concludes the paper.

2. Traffic state estimation exploiting VACS capabilities

2.1. Innovative features of VACS

2.1.1. Connected vehicles

Data stemming from connected vehicles may contain a wide variety of traffic information, but the most commonly used are vehicle position (longitude, latitude, and altitude) and vehicle speed. The most popular way of acquiring a vehicle's position is via the Global Positioning Systems (GPS), see, e.g., De Fabritiis et al. (2008), Rahmani et al. (2010), Herrera et al. (2010), although cellular positioning is also utilized, usually with less accurate results, see, e.g., Yim and Cayford (2001), Bar-Gera (2007). GPS is a low-cost, efficient solution to gather traffic data, with a reported position error of 5–15 m in older studies (Zito et al., 1995; Turksma, 2000), whereas recently, with the employment of Differential GPS (DGPS) and map-matching algorithms, position accuracy up to 1–5 m can be achieved (Waterson and Box, 2012). Speed measurement error is mostly reported to be as low as 1 km/h (Zito et al., 1995), reaching 5 km/h in some studies (Zhao et al., 2011). Data from connected vehicles are mainly transmitted to a central traffic authority, which reflects the so called Vehicle to Infrastructure (V2I) com-