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Multilane first-order traffic flow model with endogenous representation of lane-flow equilibrium

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ABSTRACT

In this study, we develop a multilane first-order traffic flow model for freeway networks. In the model, lane changing is considered as a stochastic behavior that can decrease an individual driver's disutility or cost, and is represented as dynamics toward the equilibrium of lane-flow distribution along with longitudinal traffic dynamics. The proposed method can be differentiated from those in previous studies because in this study, the motivation of lane changing is explicitly considered and it is treated as a utility defined by the current macroscopic traffic state. In addition, the entire process of lane changing is computed macroscopically by an extension of the kinematic wave theory employing IT principle; moreover, in the model framework, the lane-flow equilibrium curve is endogenously generated because of self-motivated lane changes. Furthermore, the parsimonious representation enables parameter calibration using the data collected from conventional loop detectors. The calibration of the data collected at four different sites, including a sag bottleneck, on the Chugoku expressway in Japan reveals that the proposed method can represent the lane-flow distribution of any observation site with high accuracy, and that the estimated parameters can reasonably explain the multilane traffic dynamics and the bottleneck phenomena uphill of sag sections.

1. Introduction

It is well known that under the condition of high traffic volume lane-flow distribution becomes unbalanced; more traffic tends to use a median lane rather than a middle and outer lane, which results in deteriorated traffic capacity at bottleneck sections (Wu, 2006; Knoop et al., 2010; Duret et al., 2012; Xing et al., 2014). As an intensive development for ITS, active and dynamic lane management has been practically implemented. Balancing lane-flow distribution by employing the technology for ITS is a feasible solution for increasing the throughput of bottleneck flow (Xing et al., 2014). In addition, lane traffic management and control should be considered for improving efficiency and safety in case of lane regulation for road construction or other incidents and at merging, diverging, and weaving sections. For traffic management to be effective, a model-based

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decision support system consisting of traffic state estimation, traffic state prediction and optimization, and traffic control measures are essential (Yuan et al., 2012). However, because of a lack of the methods for computing multilane traffic flow including lane-changing dynamics, a model-based decision support system considering lane-based traffic management has not been realized thus far.

This paper introduces a multilane first-order traffic flow model that depicts the dynamics of lane changing. In this model, we assume that a driver changes a lane to improve utility or decrease disutility. In addition, we assume that the equilibrium for lane-flow distribution is achieved as a condition of stochastic user equilibrium (SUE), in which all drivers believe that they cannot further improve their utilities by changing lanes. In this model, lane changes are represented as dynamics toward lane-flow equilibrium. The utility function for a driver to choose each lane is defined by only two parameters on the basis of lane-changing behavior investigated by Knoop et al. (2012) and Shiomi et al. (2013). The first is a constant value representing cost for breaking the "keep left" (or right) rule, and the second is average speed depending on the fundamental diagram and the density of the lane. Such parsimonious representation enables online calibration using real-time data from conventional loop detectors. To compute the possible solution of multilane traffic under the conservation law of traffic volume, the IT principle (Laval and Daganzo, 2006) is applied. Further, in the present study, the parameters reproducing lane-flow distribution are estimated on the basis of the data collected by the conventional loop detectors. While, on the basis of the estimation results, the cross-sectional characteristics of lane-flow distribution at sag sections are discussed.

The remainder of this paper is organized as follows. Section 2 describes state-of-the-art of multilane traffic. In Section 3, the concept of lane-changing dynamics and the mathematical representation of lane-flow equilibrium are described. In Section 4, the computation methods of multilane traffic flow employing the IT principle is overviewed. In Section 5, the parameter calibration method employing the extended quasi-Newtonian approach is explained, and in Section 6, the application results and discussion are given. Finally, we conclude this paper in Section 7 and mention recommendations for future works.

2. State-of-the-art

During the last two decades, considerable attention has been paid to the science of lane-changing behavior and multilane flow modeling. A change of lanes by a vehicle totally depends on a decision made by the driver and reflects the situation of the subject vehicle. Therefore, because lane changing represents individual driving behavior, it is the most straightforward parameter applied for microscopic modeling (e.g., Gipps, 1986; Kita, 1999; Salvucci and Liu, 2002; Webster et al., 2007; Toledo et al., 2009). This approach can consider various conditions and variables that alter a driver's decision to change lanes. However, because of the computational tasks and complicated model framework involved, this method is not appropriate for online and network-wide freeway traffic evaluation. An additional approach is mesoscopic modeling (Shvestsov and Helbing, 1999; Hoogendoorn and Bovy, 2001), in which an analogue of gas-kinetic modeling is applied to depict longitudinal multilane traffic dynamics and lateral movement. Shvestsov and Helbing (1999) reported that the proportion of lane changers is exogenously determined on the basis of the density. However, the motivations behind lane-changing behavior are not appropriately considered. In Hoogendoorn and Bovy (2001), the probability of a driver changing a lane is estimated by applying discrete choice theory. In this case, however, calibration of various parameters is required, and data with more precision is needed than that for conventional loop detectors. Moreover, it is difficult to employ online and dynamic traffic estimation on the basis of real-time data collection.

From the macroscopic approach, Daganzo (2002a, 2002b) investigated traffic phenomena on multilane freeways and proposed a traffic flow theory based on a kinematic wave model. In his theory, he assumed that there are two types of drivers: slugs, which have lower desired speed and drive in outer lanes, and rabbits, which have higher desired speed and drive in both outer and inner lanes depending on traffic conditions. This slugs and rabbits theory was proven to effectively explain various traffic phenomena. However, a computational method based on this theory has not been developed to depict multilane traffic. Laval and Daganzo (2006) also proposed a method of computing multilane traffic flow on the basis of kinematic wave theory and developed a model to depict the influence of lane changers on traffic flow. This study employed the hybrid approach in which lane changers were computed as particles and were considered as moving bottlenecks. It was assumed that the number of vehicles changing lanes is proportional to the differences in traveling speed among lanes. However, it is apparent that this assumption does not appropriately represent the lane-flow equilibrium curve. Farhi et al. (2013) proposed the logit lane assignment model combined with conservation laws of traffic flow, though the representation of lane-flow equilibrium and a calibration method has never been proposed. Moreover, the hybrid approach combining microscopic and macroscopic models, which was reported by Hong et al. (2010) and Okaue and Okushima (2011), is not feasible for a model-based decision support system. Tang et al. (2009) and Jin (2010, 2013) developed macroscopic models depicting traffic changing lanes that considered disturbances in the traffic flow caused by lane changes. However, the models did not represent lane-specific behavior.

The contribution of the present study can be differentiated from those of previous studies on the basis of the following reasons: (i) In this study, the motivation of lane changing is explicitly considered and is treated as utility defined by the current macroscopic traffic state; (ii) the entire process of lane changing is computed macroscopically in which the extension of the kinematic wave theory employs the IT principle; and (iii) in the model framework, the lane-flow equilibrium curve is endogenously generated as a result of self-motivated lane changes. The proposed model parsimoniously represents