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Closed-form multiclass cell transmission model enhanced with overtaking, lane-changing, and first-in first-out properties

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ABSTRACT

A novel multiclass macroscopic model is proposed in this article. In order to enhance first-in, first-out property (FIFO) and transmission function in the multiclass traffic modeling, a new multiclass cell transmission model with FIFO property (herein called FM-CTM) is extended from its prior multiclass cell transmission model (M-CTM). Also, to enhance its analytical compactness and resultant computational convenience, FM-CTM is formulated in this paper as a set of closed-form matrix equations. The objective is to improve the accuracy of traffic state estimation by enforcing FIFO property when a fast vehicle cannot overtake a slow vehicle due to a limitation of a single-lane road. Moreover, the proposed model takes into account a different priority for vehicles of each class to move forward through congested road conditions, and that makes the flow calculation independent from their free-flow speeds. Some hypothetical and real-world freeway networks with a constant or varying number of lanes are selected to verify FM-CTM by comparing with M-CTM and the conventional CTM. Observed densities of VISSIM and real-world dataset of I-80 are selected to compare with the simulated densities from the three CTMs. The numerical results show that FM-CTM outperforms the other two models by 15% of accuracy measures in most cases. Therefore, the proposed model is expected to be well applicable to the road network with a mixed traffic and varying number of lanes.

1. Introduction

Traffic state estimation, dynamic traffic assignment, and dynamic traffic flow models have been developed over the years as an important component in real-time traffic management. Since real-time applications require computational efficiency, macroscopic models are essentially applied in those situations. For macroscopic modeling and its extensions, a good review can be seen in the following literature (Mohan and Ramadurai, 2013; Castillo et al., 2015). LWR (Lighthill, Whitham, and Richards) model, (Lighthill and Whitham, 1955; Richards, 1956), is considered the first macroscopic model of this type.

Cell transmission model (CTM) proposed by Daganzo (Daganzo, 1994, 1995) is one of the most well-known discretized versions of LWR model. Since its first inception, CTM has been widely extended and used in a number of transportation

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applications. For instance, to take into account a random fundamental diagram, stochastic CTM was proposed by Alecsandru (2006), Boel and Mihaylova (2006), Zhong and Sumalee (2008), Sumalee et al. (2011). Stochastic CTM for urban networks was proposed by Hadfi et al. (2017). The extension of CTM with variable speed limits was proposed by Han et al. (2017). With the emergence of probe and autonomous vehicles, a velocity-CTM (Work et al., 2008) was studied to estimate time-varying traffic density directly from obtainable speed data. Levin and Boyles (2016a) applied CTM to simulate the overall behavior of autonomous vehicles with dynamic lane reversal. In an attempt to explain lane-changing behavior, CTM was also extended to enable lane-changing property (Laval and Daganzo, 2006; Carey et al., 2015). To emphasize on ramp metering control, Gomes and Horowitz (2006), Gomes et al. (2008) explained and studied ramp metering phenomena with CTM. In addition, Flötteröd and Nagel (2005) extended CTM to simulate more-than-two-upstream and/or -downstream cells directly with a connector.

To track dynamic traffic flow patterns, CTM with a neural network theory or with a fuzzy c-means clustering were proposed by Celikoglu and Silgu (2016), Celikoglu (2014), Silgu and Celikoglu (2015), Celikoglu (2013). Lu et al. (2011) extended the lagged cell-transmission model (Daganzo, 1999) to capture the dynamics of density and the probability distribution of vehicle velocity concurrently. In addition, CTM finds its applications in signal optimization, dynamic traffic assignment, and evacuation planning (Lo et al., 2001; Szeto, 2008; Ukkusuri and Waller, 2008; Kalafatas and Peeta, 2010; Zhang et al., 2013; Zhu et al., 2013; Zhang et al., 2015). Though CTM has the advantages of fast computational time, queue accumulation and spillback prediction accuracy as well as usefulness applicability towards large-scale road networks, CTM assumes that a flow can be captured well by only one velocity average, i.e. a free-flow speed. As a result, CTM in its original forms has still a limitation in abstracting such realistic phenomena as those related to traffic heterogeneities, commonly found in practical urban and highway roads with multiple vehicle types.

In that regard, researchers have in the past tried to address the heterogeneous traffic behavior. To produce platoon dispersion phenomena, LWR was extended to multiclass LWR (Wong and Wong, 2002). The model introduces the notion of classes defined heterogeneous driving on a freeway. In general, as heavy vehicles (HVs) require larger space and have less mobility (free-flow speed) than passenger vehicles (PVs), multiclass models were developed for a freeway with high percentage of HVs with the objective of dynamic traffic assignment or traffic state estimation (Ngoduy and Liu, 2007; Van Lint et al., 2008; Ngoduy, 2011; Szeto et al., 2011; Mesa-Arango and Ukkusuri, 2014; Liu et al., 2015; Qian et al., 2017; Zhan and Ukkusuri, 2017). In addition, an extension was also developed for PVs and buses in an urban area for a bus-rapid transit system (Liu et al., 2015). Freeway and highway multiclass models have been applied to evaluate how HVs can affect overall traffic flow. On the other hand, the distinct behaviors of buses and PVs are of interest to traffic signal control problems considering a bus priority. With the advent of connected and autonomous vehicles, CTM was extended to model a mixed traffic of human and autonomous vehicles (Levin and Boyles, 2016b).

In order to produce platoon dispersion in a general topology, CTM was extended to multiclass CTM by Tuerprasert and Aswakul (2010). The prior multiclass CTM, denoted as M-CTM, was compared with the conventional CTM, denoted as S-CTM, and with a microscopic simulator. Based on the reported results, M-CTM is found be able to produce platoon dispersion well without compromising on the model's computational complexity. As a sequel, in this article, M-CTM is further enhanced and generalized to model the scenario of heterogeneous lanes and with first-in, first-out (FIFO) property. Here, the proposed model is named FM-CTM, standing for the multiclass cell transmission model with FIFO property. FIFO can occur with traffic congestion or in a single lane with or without multiclass traffics. To the best of authors' knowledge, there is no multiclass macroscopic model that can well quantify the impact of the number of lanes on the model performance as most researchers have only verified their traffic flow models with constant-lane homogeneous roads. Moreover, FM-CTM considers that a vehicle with a low free-flow speed could occasionally move ahead of the one with a high free-flow speed during traffic congestion by outmaneuvering aggressiveness or by its movement flexibility due to a compact size (Nair et al., 2011). In overall, FM-CTM in this paper aims to enhance the existing M-CTM by introducing the following newly contributed features;

1 Multiclass traffic state estimation when an overtaking is unavailable and hence the FIFO property of resultant flow.
2 Transmission model enhancement to mimic the behaviors of slow vehicles during free-flow condition.
3 Overtaking model independent of the free-flow speed for a congested road condition.

In addition to these new features, unlike the prior work of M-CTM (Tuerprasert and Aswakul, 2010), FM-CTM is formulated as a set of closed-form matrix equations. This closed-form matrix derivation finds applications in a feedback control theory as desirable observability and controllability are conveniently obtainable. Further, computer programming for the model computability can be numerically facilitated with matrix, instead of scalar, equations. For instance, all the codes of FM-CTM have been developed in Matlab in this research.

This paper is organized as follows: firstly, FM-CTM is proposed along with the closed-form matrix formulation in Section 2. Secondly, the theoretical proof to validate FM-CTM's convergence to the single-class LWR model is elaborated in Section 3. Numerical results comparing the new and old M-CTM are given in Section 4. Finally, Section 5 presents conclusions and future work.