Transportation Research Part C 75 (2017) 136–167

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

A flexible traffic stream model and its three representations of traffic flow

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A R T I C L E I N F O

Article history:
Received 13 September 2016
Received in revised form 22 November 2016
Accepted 14 December 2016

Keywords:
Traffic stream model
Car-following model
Fundamental diagram
Lagrangian coordinate

A B S T R A C T

To connect microscopic driving behaviors with the macro-correspondence (i.e., the fundamental diagram), this study proposes a flexible traffic stream model, which is derived from a novel car-following model under steady-state conditions. Its four driving behavior-related parameters, i.e., reaction time, calmness parameter, speed- and spacing-related sensitivities, have an apparent effect in shaping the fundamental diagram. Its boundary conditions and homogenous case are also analyzed in detail and compared with other two models (i.e., Longitudinal Control Model and Intelligent Driver Model). Especially, these model formulations and properties under Lagrangian coordinates provide a new perspective to revisit the traffic flow and complement with those under Eulerian coordinate. One calibration methodology that incorporates the monkey algorithm with dynamic adaptation is employed to calibrate this model, based on real-field data from a wide range of locations. Results show that this model exhibits the well flexibility to fit these traffic data and performs better than other nine models. Finally, a concrete example of transportation application is designed, in which the impact of three critical parameters on vehicle trajectories and shock waves with three representations (i.e., respectively defined in *x*-*t*, *n*-*t* and *x*-*n* coordinates) is tested, and macro- and micro-solutions on shock waves well agree with each other. In summary, this traffic stream model with the advantages of flexibility and efficiency has the good potential in level of service analysis and transportation planning.

1. Introduction

In the field of traffic flow theory, it is always desirable to bridge microscopic car-following (CF) behaviors and macroscopic traffic flow. A simple yet flexible traffic flow model, which not only describes vehicle longitudinal operational control satisfactorily under various scenarios, but also characterizes the basic relationships between macro-traffic variables, is the interest for world-wide researchers. Usually, the relations between macro-traffic variables can be presented as continuum traffic flow models or fundamental diagrams. As for the connection between CF rules and corresponding macroscopic traffic flow models, a large number of related researches can be traced. Berg et al. (2000) developed a continuum model from the optimal velocity model using a series expansion of headway in terms of the density, which enables predictions of global impact and characteristics of any car-following model using the analogous continuum model. Later, Gupta and Katiyar

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http://dx.doi.org/10.1016/j.trc.2016.12.006
0968-090X/

(2006) employed this series expansion method to derive a new anisotropic continuum model based upon an improved car-following model and obtained some important and realistic model properties. On the other hand, Lee et al. (2001) presented a coarse-graining procedure to derive macroscopic fluid-dynamic models from microscopic car-following models, and took the optimal velocity model as an example for demonstration, in which properties of macro- and micro-models have a reasonable agreement. Specially, this derivation method can be extended to general car-following models. Zhou and Lü (2011) also utilized this coarse graining method to develop a macroscopic model from the generalized optimal velocity model. Besides, Zhang (2002) derived an anisotropic continuum model from a GM (General Motors) car-following model (Chandler et al., 1958), with the transformation method between micro- and macro-variables proposed by Liu et al. (1998). Jiang et al. (2002) applied the same transformation method to obtain an anisotropic continuum model from fully velocity difference (FVD) model (Jiang et al., 2001). Afterwards, Tang et al. (2009) also utilized this transformation method to put forward a new dynamic model for heterogeneous traffic flow consisting of buses and cars from a vehicle type-dependent heterogeneous car-following model. Zheng et al. (2015) employed this method to get an anisotropic continuum model, considering bi-directional information impact from a bi-directional car-following model based on Helly's framework (Helly, 1959). What attracts our attention is that Helbing (2009) compared several different approaches allowing one to derive macroscopic traffic equations directly from microscopic car-following models. Those approaches included a gradient expansion approach, a linear interpolation approach and an approach reminding of smoothed particle hydrodynamics.

On the other hand, fundamental relations of traffic flow have been established either empirically or derived from car-following models. Early derivations of the fundamental diagrams from car-following were carried out in order to study the aggregate-level behavior of proposed car-following rules and validate such rules against real-world data (e.g., Edie, 1963; Gazis et al., 1959; Newell, 1961; Pipes, 1965). It was not long, however, before the fundamental diagram induced by car-following theory itself began to attract the interest (Pipes, 1967). Later, Treiber et al. (2000) put forward the well-known intelligent driver model (IDM) and gave out the macro-correspondence under steady-state conditions, i.e., speed-gap equilibrium relation, which help understand the traffic phenomena and their correlation with car-following rules. Zhang and Kim (2005) proposed car-following rules that result in the fundamental diagrams with capacity drops and hysteresis loops; empirical investigation was carried out in Kim and Zhang (2004). Furthermore, Kim and Zhang (2008) demonstrated how heterogeneity in the driver population alone can be used to explain the observed scatter in flow-density plots. Rakha and Arafeh (2010) carried out the transformation between Van Aerde's car-following model (i.e., Van Aerde, 1995) and the macro-correspondence (i.e., speed-density relationship), and utilized a heuristic automated tool named SPD_CAL to calibrate them using loop detector data. Jabari et al. (2014) presented the derivation of probabilistic stationary speed-density relation from Newell's simplified car-following model, whose probabilistic nature allows for investigating the impact of driver heterogeneity on the heavy scatter in flow-density data in congested traffic. Recently, Ni et al. (2015) proposed a longitudinal control model (LCM) and derived the corresponding traffic stream model under steady-state conditions, which had good capability of fitting empirical traffic data. LCM was also proved to be consistent at the microscopic and macroscopic levels.

This work attempts to put forward a traffic stream model with an excellent flexibility, even better than LCM. In LCM, its flexibility mainly depends on the calmness parameter, which is defined in an emergency and related to the emergency decelerations of two successive vehicles. However, driving behavior-related parameters that play an important role in normal driving regimes (e.g., free flow, approaching, stopping, etc.) would also influence the macroscopic traffic behaviors. Intuitively, the driver's sensitivity to speed- and spacing-related traffic information would definitely influence his/her operations in both normal and emergency situations (c.f., IDM), which aggregately makes the fundamental diagrams exhibit various shapes. Therefore, a novel car-following model, that incorporates the reaction time, calmness parameter, speed- and spacing-related sensitivities, will be proposed to describe the vehicle longitudinal motion. Obviously, it inherits the advantages LCM and IDM, and is more flexible and general. Then, its macro-correspondence will be derived to include these four critical driving behavior-related parameters, which help guarantee the excellent flexibility. Because of the micro-macro coupling relationship, i.e., the microscopic equation to its macroscopic equivalent, the macroscopic traffic behavior illustrated by the fundamental diagram can be explained or predicted by traffic flow modeling and simulation based on the microscopic CF model.

Traditional fundamental diagrams (i.e., flux-speed-density relations) are usually developed based on the spatial-temporal (x-t) coordinate, i.e., Eulerian coordinate, and corresponding traffic variables are measured by fixed-point detectors, e.g., inductive loop detectors. Lagrangian coordinate n, in hydrodynamics, is a physical coordinate that moves along with the flow and can be considered as the continuous version of accumulative number of vehicles (ANV) in traffic flow (Leclercq et al., 2007; Herrera and Bayen, 2010; Claudel and Bayen, 2010; Laval and Leclercq, 2013). The traffic states in Lagrangian coordinates can be detected by new vehicle detection technologies, e.g., GPS probe vehicle technologies, Video-Detection technologies, Automatic Vehicle Identification (AVI) technologies and Cellular probe vehicle technologies. To better understand micro- and macro-traffic phenomena from a completely new perspective, vehicular trajectories, macro-traffic variables and fundamental relations will be also defined in Lagrangian coordinates (i.e., n-t and x-n coordinates). From the micro-perspective, the vehicular trajectory can be inspected and defined from three possible 2-dimensional coordinate systems (Makigami et al., 1971; Jin and Ran, 2011), i.e., Eulerian coordinate x-t, and Lagrangian coordinates n-t and x-n. These three kinds of vehicular trajectory provide completely various physical meanings for vehicular flow and correspond to different ways of traffic data detection aforementioned (Jin and Ran, 2011). Meanwhile, at the macro-aspect, the fundamental relation (in x-t coordinate) can also be re-formulated with traffic variables defined in Lagrangian coordinates, based on which LWR