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Microscopic driving theory with oscillatory congested states: Model and empirical verification

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ABSTRACT

The essential distinction between the Fundamental Diagram Approach (FDA) and Kerner's three-phase theory (KTPT) is the existence of a unique gap–speed (or flow–density) relationship in the former class. In order to verify this relationship, empirical data are analyzed with the following findings: (1) linear relationship between the actual space gap and speed can be identified when the speed difference between vehicles approximates zero; (2) vehicles accelerate or decelerate around the desired space gap most of the time. To explain these phenomena, we propose that, in congested traffic flow, the space gap between two vehicles will oscillate around the desired space gap in the deterministic limit. This assumption is formulated in terms of a cellular automaton. In contrast to FDA and KTPT, the new model does not have any congested steady-state solution. Simulations under periodic and open boundary conditions reproduce the empirical findings of KTPT. Calibrating and validating the model to detector data produces results that are better than that of previous studies.

1. Introduction

In order to understand the mechanism of traffic congestion, many traffic flow models have been proposed to explain the empirical findings (see the reviews: Haight, 1963; Whitham, 1974; Leutzbach, 1988; Daganzo, 1997; Chowdhury et al., 2000; Helbing, 2001; Nagatani, 2002; Schreckenberg et al., 2003; Jia et al. 2007; Kerner, 2004, 2009; Treiber and Kesting, 2013; Kerner, 2013). Generally speaking, these models can be classified into the Fundamental Diagram Approach (FDA) and Kerner's three-phase theory (KTPT).

The fundamental diagram (FD) was firstly proposed by Greenshields et al. (1934) who published traffic flow measurements in form of a scatter plot of microscopic distance-speed data and idealized them by a linear distance-speed diagram which can be considered as the first FD. Later, this distinction has been used in many review articles and standard text books. For examples, in Helbing (2001), the name fundamental diagram is used for some fit function of the empirical flow–density relation. In Helbing et al. (2009), the FD is the equilibrium flow–density relationship. In Schreckenberg et al. (2003), the FD represents the homogeneous states lie on a curve in the flow–density plane. Kerner (2004, 2009) defines the FD using the hypothetical limiting case in which all vehicles move at time-independent speeds following each other at single desired (or optimal) space gap. In Ossen (2008), the fundamental diagram represents the equilibrium relation between flow,

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density and space mean speed of a traffic flow. Wu et al. (2011) characterizes the FD as the relationship between traffic flow and density in the steady state. In Shott (2011), the FD is the flow–density relation in steady-state traffic. In Elefteriadou (2013), the FD provides the theoretical relationship between flow, speed, and density. In Treiber and Kesting (2013), the FD describes the theoretical relation between density and flow in stationary homogeneous traffic, i.e., the steady state equilibrium of identical driver-vehicle units. We point out that neither homogeneity nor stationarity is required to define the so-called macroscopic fundamental diagram (MFD, please see Geroliminis and Daganzo (2008)). However, the MFD does not allow to discriminate between two-phase and three-phase models. Therefore, we will use the original formulation and define the FD as the theoretical relationship between density and flow in stationary homogeneous traffic of identical vehicles. Notice that, with this definition, only a small subset of flow–density data (generally representing less restricted situations such as non-homogeneous, non-stationary, or phase-separated traffic flow) lies on the fundamental diagram.

Models within FDA admit the existence of the fundamental diagram that is incorporated into the model explicitly or implicitly. In microscopic models, the FD is linked to the steady states of car-following (CF) or cellular automaton (CA) models. For example, in the Optimal Velocity Model (OV model) by Bando et al. (1995), the FD corresponds to the "optimal flow", i.e., the product of the density and the optimal velocity as a function of density (details can be found in pages 168–171 of Treiber and Kesting (2013)). In the Nagel–Schreckenberg cellular automaton model (abbreviated as the NaSch model (Nagel and Schreckenberg, 1992)), it could be derived in terms of the steady state in the deterministic limit, which means the stochastic randomization of NaSch model is not considered (details can be found in Fig. 10.6(d)) of Kerner (2009) and Kerner et al. (2002)). In macroscopic or mesoscopic models, it has been directly applied (e.g., the LWR theory (Lighthill and Whitham, 1955; Richards, 1956)) or incorporated into the momentum equation (e.g., the PW theory (Payne, 1979)).

Most models within FDA are two-phase models (Lighthill and Whitham, 1955; Richards, 1956; Herman et al., 1959; Payne 1979; Gipps, 1981; Nagel and Schreckenberg, 1992; Daganzo, 1994; Bando et al., 1995; Krauss et al., 1997; Treiber et al., 2000; Aw and Rascle, 2000; Newell, 2002; Tang et al., 2005), which refer to the free flow phase (F) and the jammed phase (J). Phase transitions involved are the transition from free flow to jams (F → J transition) and the transition from jam to free flow (J → F transition). Two-phase models explain the jam formation mainly by the excess demand, i.e., the traffic inflow exceeds the static capacity defined by the maximum point on the FD. Additionally, the instabilities of traffic flow, which are caused by finite speed adaption times (due to finite accelerations) or reaction times, can lead to jam formation even before static capacity is reached, and also to hysteresis effects. For the detailed discussion of stability, one can refer to Treiber and Kesting (2013), Kesting and Treiber (2008).

Based on a long-term empirical analysis, Kerner (2004, 2009) argues that two-phase models could not reproduce the empirical features of traffic breakdown as well as the further development of the related congested region properly. Therefore, he has introduced the KTPT (Kerner and Rehborn 1996, 1997; Kerner 2004, 2009; Rehborn and Klenov 2009; Kerner et al., 2014) distinguishing (1) free traffic flow, (2) synchronized flow, and (3) wide moving jams. The fundamental hypothesis of KPTP is that steady states exist but, in contrast to conventional two-phase models, they are not unique for a given density. Instead, the steady states of synchronized flow cover a two-dimensional region in the flow–density plane. In other words, there is no FD. It should be noted that Kerner's three-phase theory is a qualitative traffic flow theory. There can be a huge number of different mathematical approaches to implement this theory in microscopic and macroscopic models (Kerner et al., 2002, 2011; Kerner, 2012; Kerner and Klenov 2002, 2003, 2006; Lee et al., 2004; Jiang and Wu, 2003, 2005; Tian et al., 2009; Gao et al., 2007, 2009; Davis, 2004; Jiang et al., 2014). In order to improve the readability, we have made a brief introduction of KTPT in the appendix.

It should be noted that there are models within FDA that could reproduce the three-phase theory, such as the Brake Light cellular automaton Model (BLM (Knospe et al., 2000)), the Speed Adaption Models (SAMs (Kerner and Klenov, 2006)) , and the Average Space Gap cellular automaton Model (ASGM (Tian et al., 2012a,b)). However, some models have been criticized by the proponents of three-phase theory. The congested patterns of BLM are inconsistent with the empirical findings of KTPT (Kerner et al., 2002). SAMs are not able to reproduce the observed local synchronized patterns (LSPs) as well as some empirical features of synchronized flow between wide moving jams within general patterns (GPs) (Kerner and Klenov, 2006).

Although this paper is motivated by the inconsistency between FDA and KTPT, the purpose is not to discuss the ensuing controversies. Instead, this paper aims to describe the driver behavior by a novel cellular automaton model containing explicit oscillations around the steady-state in the deterministic limit thereby reproducing the major observational aspects of KTPT. However, this model does not belong to this class since the fundamental hypothesis of KTPT is missing. Moreover, empirical calibration and validation results in a higher accuracy than that of previously investigated models (Brockfeld et al., 2005; Wagner, 2010). To these ends, Section 2 analyses the US-101 trajectory datasets on a single freeway lane, away from lane changes and the influence of bottlenecks. Section 3 proposes a cellular automaton model that incorporates this assumption. Empirical findings of KTPT are simulated and discussed in Section 4. Section 5 is devoted to calibrating and validating the model to the I-80 detector data. The concluding Section 6 gives a summary and a discussion.

2. Empirical data analysis

The essential distinction between the Fundamental Diagram Approach and Kerner's three-phase theory is that the latter assumes the existence of a two-dimensional region of stationary steady states in the density-flow space or, equivalently, in