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Cellular automaton model simulating spatiotemporal patterns, phase transitions and concave growth pattern of oscillations in traffic flow

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ABSTRACT

This paper firstly shows that a recent model (Tian et al., Transpn. Res. B 71, 138–157, 2015) is not able to replicate well the concave growth pattern of traffic oscillations (i.e., the standard deviation of speed is a concave function of the vehicle number in the platoon) observed from car following experiments. We propose an improved model by introducing a safe speed and the logistic function for the randomization probability. Simulations show that the improved model can reproduce well the metastable state, the spatiotemporal patterns, and the phase transitions of traffic flow. Calibration and validation results show that the concave growth pattern of oscillations and the empirical detector data can be simulated with a quantitative agreement.

1. Introduction

The formation and evolution of traffic congestion has been investigated for decades (see e.g., Brackstone and McDonald, 1999; Chowdhury et al., 2000; Helbing, 2001; Nagatani, 2002; Treiber and Kesting, 2013; Kerner, 2004, 2009, 2013, 2016; Saifuzzaman and Zheng, 2014; Zheng, 2014; Jin et al., 2015). Various traffic flow data have been collected to clarify the nature of traffic flow dynamics (Ranjitkar et al., 2003; Kerner, 2004; Bertini and Monica, 2005; NGSIM, 2006; Laval and Daganzo, 2006; Ahn and Cassidy, 2007; Wagner, 2006, 2010, 2012; Sugiyama et al., 2008; Nakayama et al., 2009; Zheng et al. 2011; Shott, 2011; Tadaki et al., 2013; Laval et al., 2014; Jiang et al. 2014, 2015). In order to simulate traffic flow, different kinds of models have been proposed, such as the car-following models (Chandler et al. 1958; Newell, 2002; Rakha and Crowther, 2003; Kesting and Treiber, 2008; Laval and Leclercq, 2010;Chen et al. 2012a, 2012b; Aghabayk et al. 2013; He et al. 2015), the cellular automata models (Nagel and Schreckenberg, 1992; Knospe et al., 2000; Kerner et al., 2002, B.S. 2011) and hydrodynamic models (Lighthill and Whitham, 1955; Papageorgiou 1998; Wong and Wong 2002).

Many traditional models, such as the General Motor models (GMs, Chandler et al., 1958; Gazis et al. 1961; Edie, 1961), Gipps' Model (Gipps, 1981), Optimal Velocity Model (OVM, Bando et al., 1995), Full Velocity Difference Model (FVDM, Jiang et al., 2001), Intelligent Driver Model (IDM, Treiber et al., 2000) and so on, are classified as two-phase models

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(Kerner, 2013). In two-phase models, only free flow (F) and congested flow states are distinguished, and the formation of traffic jams is explained via linear instability.

However, by analyzing the long-term detector data, Kerner (1998) further distinguished congested traffic into wide moving jams (J) and synchronized traffic flow (S). The wide moving jam is a moving structure in which vehicles stop completely or nearly. The downstream front of a jam moves upstream with a characteristic speed about 15 km/h. In contrast, synchronized flow is usually fixed at traffic bottlenecks and the flow rate in the synchronized flow is much larger than that in jam. For the synchronized flow that moves upstream, the propagating speed of its downstream front is not necessarily the characteristic speed. Based on these observations, Kerner proposed the three-phase traffic theory, in which it is hypothesized that the steady states of synchronized flow should cover a two-dimensional region in the flow–density plane. Based on Kerner's three-phase traffic theory, many models have been developed, such as the Kerner-Klenov-Wolf model (KKW, Kerner et al., 2002) that considers the speed adaptation effect, the model that considers mechanical restriction versus human overreaction (Lee et al., 2004), the Brake Light Model (BLM, Knospe et al., 2000) and its variants (Jiang and Wu, 2003, 2005; Tian et al., 2014, 2016b) that consider the influence of brake light on driving behaviors, the model that assumes that randomization depends on speed difference (the model of Gao, Gao et al. 2007, K. 2009), and so on. These models have been claimed to be able to simulate the observed spatiotemporal patterns of traffic flow.

Kerner (2004, 2009, 2013, 2016) claimed that traffic breakdown corresponds to a phase transition from free flow to synchronized flow (F→S) while wide moving jams usually emerge from the synchronized flow (S→J). As a result, the transition from free flow to jams corresponds to a F→S→J process. In an open road section with an isolated bottleneck, two types of spatiotemporal traffic patterns can be observed: the general pattern (GP) and the synchronized pattern (SP). In SP, no traffic jam occurs. In contrast, in GP, jams will eventually develop in the synchronized flow. The associated self-compression effect that initiates jams is named as pinch effect and this self-compression of synchronized flow means that the average density increases and average speed decreases considerably in the synchronized flow (Kerner, 2009).

Spontaneous formations of jams have been observed in the absence of any bottleneck as well. For example, Treiterer and Myers (1974) have shown the trajectories of a phantom jam. Coifman (1997) also presented the trajectories of thirteen shockwaves in platoons, where a small disturbance grows as it propagates upstream until vehicles come to a stop. Sugiyama et al. (2008), Nakayama et al. (2009), and Tadaki et al. (2013) performed traffic experiments on a circuit to investigate the emergence of a jam without bottleneck. The experiments showed that when the density is below a critical value, traffic flow is unconditionally stable and no jam emerges. However, above another critical density, traffic flow always becomes unstable and jam always occurs spontaneously. Between the two critical densities, traffic flow is metastable and the spontaneous formation of jam can be observed probabilistically.

Recently, Tian et al. (2015) have proposed a Two-state cellular automaton model to simulate these empirical features, in which the defensive state and the normal state of drivers have been considered. In the Two-state model, the space gap between two vehicles will oscillate around the (speed dependent) desired value rather than maintaining this value in the deterministic limit in congested traffic flow. It was shown that the model is able to simulate above-mentioned spatiotemporal patterns and phase transitions very well.

In the meantime, however, another important feature of traffic flow concerning the propagation of oscillations in platoons has been reported. Jiang et al. (2014, 2015) carried out a car following experiment on a 3.2 km-long open road section, in which a platoon of 25 passenger cars has been studied. The leading vehicle was asked to move with constant speed. The formation and development of oscillations have been observed. It has been found that standard deviations of speed increase in a concave or linear way along the 25-car-platoon. For the latter case, due to the physical limits of speeds, unconditional concavity, i.e., a decreasing increment of the amplitude from car to car is expected for sufficiently large platoons. Later, the concave growth pattern of oscillations is also validated by the empirical NGSIM data (Tian, et al., 2016a).

Moreover, Jiang et al. (2014, 2015) have shown that (i) the simulation results of the two-phase models with additional reasonable acceleration noise, such as GMs, Gipps' Model, OVM, FVDM and IDM etc., run against the experimental finding since the standard deviation initially increases in a convex way in the unstable density range; (ii) by removing the fundamental diagram in two-phase models and allowing the traffic state to span a two-dimensional region in velocity-spacing plane, the growth pattern of disturbances has changed and becomes qualitatively in accordance with the observations. In particular, the two-dimensional Intelligent Driver Model (2D-IDM) considering variable desired time headway can fit the experimental results quantitatively well.

The importance of the concave growth of traffic oscillations lies in that it indicates that the instability mechanism of traditional two-phase models is debatable. In traditional models, the unstable traffic flow is generated due to linear instability of the steady state solution. As proved by Li et al. (2014), the linear instability in a class of car-following models leads to initial convex growth of oscillations. We further demonstrate that the linear instability in general two-phase models leads to initial convex growth of oscillations (Tian et al., 2016a). Thus, the initial convex growth pattern in Two-phase models contradicts with the observed concave growth pattern, which implies that the mechanism triggering traffic jams in two-phase models is questionable.

Motivated by the new experimental finding, we examine whether the Two-state model is able to reproduce the concave growth pattern of oscillations or not. Unfortunately, as shown in Section 2.1, simulation results of the two-state model significantly deviate from the experimental data. To overcome the deficiency of the two-state model, this paper proposes an improved model which is simultaneously able to reproduce the spatiotemporal patterns, the phase transitions, and the concave growth pattern of oscillations.