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Modeling the effect of microscopic driving behaviors on Kerner's time-delayed traffic breakdown at traffic signal using cellular automata

Wang Yang, Chen Yan-Yan *

Beijing Key Lab of Traffic Engineering, Beijing University of Technology, Beijing 100124, China
College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China

HIGHLIGHTS

- A novel cellular automaton was developed by incorporating the driving behaviors induced by traffic signals.
- Two sets of rules were developed for the sections where the effect of traffic signals is considered or not in driving.
- The anticipatory behavior incorporates a perception factor considering the vehicle speed implicitly and the gap to the preceding vehicle explicitly.
- The driving behaviors were examined on formation and dissolution of spontaneous traffic breakdown.
- The driving behaviors were investigated for the formation of platoon.

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ABSTRACT

The signalized traffic is considerably complex due to the fact that various driving behaviors have emerged to respond to traffic signals. However, the existing cellular automaton models take the signal–vehicle interactions into account inadequately, resulting in a potential risk that vehicular traffic flow dynamics may not be completely explored. To remedy this defect, this paper proposes a more realistic cellular automaton model by incorporating a number of the driving behaviors typically observed when the vehicles are approaching a traffic light. In particular, the anticipatory behavior proposed in this paper is realized with a perception factor designed by considering the vehicle speed implicitly and the gap to its preceding vehicle explicitly. Numerical simulations have been performed based on a signal controlled road which is partitioned into three sections according to the different reactions of drivers. The effects of microscopic driving behaviors on Kerner's time-delayed traffic breakdown at signal (Kerner 2011, 2013) have been investigated with the assistance of spatiotemporal pattern and trajectory analysis. Furthermore, the contributions of the driving behaviors on the traffic breakdown have been statistically examined. Finally, with the activation of the anticipatory behavior, the influences of the other driving behaviors on the formation of platoon have been investigated in terms of the number of platoons, the averaged platoon size, and the averaged flow rate.

1. Introduction

In cities, traffic congestion frequently occurs at intersections, resulting in significant travel delays. To improve the traffic efficiency, various signal control strategies have been proposed mainly based on the classical theory of city traffic assuming

* Corresponding author at: College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China.
E-mail address: cdyan@bjut.edu.cn (Y.-Y. Chen).

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that no queue growth and no traffic breakdown can occur in under-saturated traffic. However, recent findings by Kerner et al. [1–3] have shown that, in under-saturated, spontaneous traffic breakdown can occur at a signal after a random delay, which is named as Kerner's traffic breakdown in this paper. To better understand the work presented in this paper, this section will firstly give a brief review on the classical theory of traffic breakdown and Kerner's time-delayed traffic breakdown theory, and then traffic flow cellular automation models before describing the objectives of this paper.

1.1. Classical theory of traffic breakdown versus Kerner's time-delayed traffic breakdown at a signal

The classical theory of city traffic assumes that instabilities and self-organization phenomena can be suppressed by the massive deterministic perturbations due to the presence of traffic signal [4,5]. In over-saturated traffic, the queue formed during the red phase cannot be fully dissolved during the green phase and therefore promotes the growth of queue over time, eventually leading to traffic gridlock. However, such growth on the number of vehicles queuing at a traffic light should not be expected in under-saturated traffic.

On the other hand, the three-phase theory for city traffic proposed recently by Kerner [1–3] has revealed that traffic breakdown at a signal exhibits complex phenomena of self-organization. It has been shown that the queue at traffic light begins to self-grow non-reversibly after a random time delay in under-saturated traffic, resulting in traffic gridlock. Furthermore, it has been found that such traffic breakdown has been significantly affected by the occurrence of a moving synchronized flow pattern (MSP). In particular, the time-delayed traffic breakdown is stimulated from the occurrence of a critical disturbance in metastable under-saturated traffic. For more details on Kerner's time-delayed traffic breakdown theory, please refer to Refs. [1–3].

1.2. A brief overview of traffic flow cellular automation models

The research practices over the last decades have shown simulation is an effective tool to study the essential properties of traffic dynamics. Since the seminal work of Nagel and Schreckenberg (the NaSch model) [6], a series of improvements have been made by incorporating various influencing behaviors, such as aggressive acceleration [7], velocity-dependent randomization [8], comfortable driving [9,10], anticipation behavior [11], brake light effect [12], decelerating damping effect [13], etc. However, the NaSch model has been frequently used to investigate city traffic at signal. Huang and Huang employed the NaSch model to investigate the synchronization effects among a set of traffic signals [14]. Neumann and Wagner modified the NaSch model by introducing deceleration probability and analyzed the impact of traffic lights on travel time [15]. Jiang and Wu introduced a stopped time dependent randomization mechanism into the original NaSch model for the signal controlled intersection [16]. Varas et al. examined two control strategies for a sequence of traffic lights with a simple CA in which the velocity of vehicles are limited to two values of 0 or 1 [17]. Mhirech and Ismaili employed the NaSch model to investigate the dependence of the formation of the queue behind traffic lights and the dependence of car accident on the duration of green light, injecting and extracting probabilities [18]. Gier, et al. developed a CA model for generic urban road networks and applied it to compare the effects of non-adaptive versus adaptive traffic signals for the vehicles obeying NaSch dynamics [19]. Chowdhury and Schadschneider developed a CA model for traffic flows in cities by combining the Biham–Middleton–Levine (BML) model and the NaSch model [20].

Although various CA models have been successively developed, many (such as those mentioned above) can only reflect the phase transition from free flow to the jam ($F \to J$ transition). Different from those two-phase CA models, three-phase CA models can capture the phase transition from free flow to synchronized flow ($F \to S$ transition). In 2002, the first version of Kerner–Klenov model [21] was proposed with the introduction of over-acceleration occurring in car-following. Apart from its complexity, it is a continuum model which cannot reflect lane changing and fluctuations and therefore unable to be used to investigate spontaneous phase transitions on multi-lane roads. Consequently, a number of discrete versions of Kerner–Klenov model have been developed with different emphases, such as variety of driver behavioral characteristics and types of vehicles [22], and the relation between over-acceleration and lane changing [23]. In 2013, a new three-phase model was presented in Ref. [24] by combining two qualitatively different mechanisms of over-acceleration (i.e., over-acceleration occurring in car-following without lane changing and over-acceleration due to lane changing to a faster lane).

However, this paper is not intended to review all two-phase and three-phase models and those models briefly described above are only some of the representative ones. Additionally, it should be aware that to obtain Kerner's time-delayed traffic breakdown at signal does not require a specific description of synchronized flow. This means that both two-phase models and three-phase models can be used to generate Kerner's time-delayed traffic breakdown. The detailed explanations can be found in Refs. [1,2].

1.3. Objectives of this paper

The above review on the existing CA models indicates that the NaSch model and its variations have been widely used to exam traffic flows under various traffic signal control strategies. It may not be appropriate to directly employ these models, originally developed for highway traffic, to investigate the signal controlled traffic where the vehicular movement is affected by not only the vehicles but also traffic lights. Due to the lack of adequate modeling for the signal–vehicle interaction, there