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Effect of driver over-acceleration on traffic breakdown in three-phase cellular automaton traffic flow models

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HIGHLIGHTS

- The importance of driver over-acceleration effect in a road lane has been revealed.
- This effect is a generic physical feature of three-phase cellular automaton models.
- This result leads to a new cellular automaton (CA) model for traffic flow.
- This KKSW CA model overcomes drawbacks of previous KKS and KKW models.

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ABSTRACT

Based on simulations with cellular automaton (CA) traffic flow models, a generic physical feature of the three-phase models studied in the paper is disclosed. The generic feature is a discontinuous character of driver over-acceleration caused by a combination of two qualitatively different mechanisms of over-acceleration: (i) Over-acceleration through lane changing to a faster lane, (ii) over-acceleration occurring in car-following without lane changing. Based on this generic feature a new three-phase CA traffic flow model is developed. This CA model explains the set of the fundamental empirical features of traffic breakdown in real heterogeneous traffic flow consisting of passenger vehicles and trucks. The model simulates also quantitative traffic pattern characteristics as measured in real heterogeneous flow.

1. Introduction. Description of over-acceleration effect of three-phase traffic theory with cellular automaton models

In 1958–1961, Herman, Gazis et al. introduced a car-following model (called General Motors (GM) model), in which an instability of vehicular traffic flow has been explained by a finite driver reaction time leading to a driver's over-deceleration effect (called also as a driver's over-reaction) [1,2]: If a vehicle begins to decelerate unexpectedly, then due to the finite driver reaction time the following vehicle starts deceleration with a delay. When the time delay is long enough, the driver of the following vehicle decelerates stronger than needed to avoid a collision. As a result, the speed of the following vehicle becomes lower than the speed of the preceding vehicle. If this over-deceleration effect is realized for all following drivers, a wave of vehicle speed reduction appears and increases in amplitude over time. This classical traffic flow instability, which has been incorporated in a huge number of traffic flow models (see reviews and books [3]), should explain traffic breakdown

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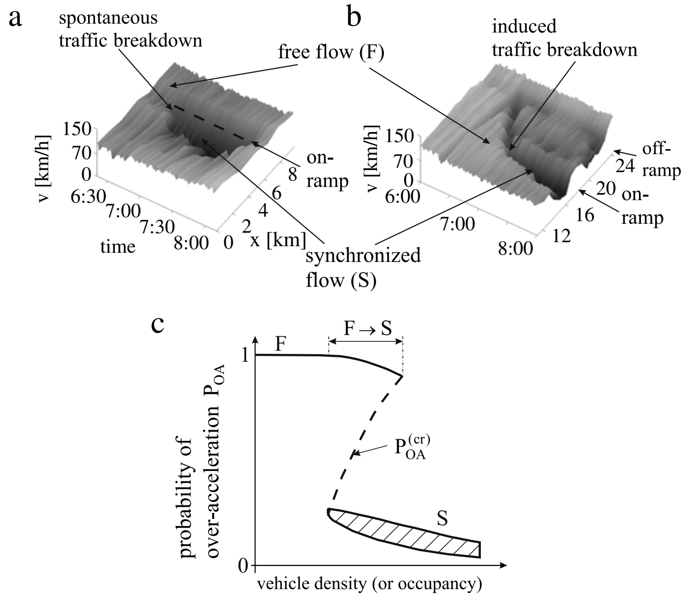

Fig. 1. Empirical traffic breakdown and its explanation with three-phase traffic theory [9,10]: (a), (b) empirical speed in space and time showing spontaneous (a) and induced traffic breakdown (b). (c) Hypothesis of three-phase theory about a discontinuous character of probability of over-acceleration; arrow $F \to S$ shows density region of free flow in which traffic breakdown can occur; $P_{OA}^{(cr)}$ denotes a critical branch of Z-characteristic for over-acceleration probability P_{OA}; F—free flow, S—synchronized flow.

observed in real traffic flow. Microscopic, macroscopic as well as all other traffic flow models in which this traffic flow instability has been incorporated based on sometimes very different mathematical approaches can be considered as related to the GM model class. This is because all these traffic flow models as known now exhibit the same feature first found by Kerner and Konhäuser from their study of a version of Payne's macroscopic traffic flow model that belongs to the GM model class [4]: The model instability due to driver reaction time of the GM model class leads to a phase transition from free flow to a wide moving jam ($F \to J$ transition).

An effective mathematical approach for the description of this traffic flow instability has been introduced by Nagel and Schreckenberg in their cellular automaton (CA) model for traffic flow (NaSch CA model) [5]. The main idea of the NaSch CA model is the description of the driver's delay through "randomization" of vehicle motion associated with a random driver deceleration. Since the discovering of the NaSch CA model there has been developed a huge number of different CA models for traffic flow. In particular, to describe the $F \to J$ transition and the resulting wide moving jam, Barlović et al. [6] have incorporated in the NaSch CA model a slow-to-start rule first introduced by Takayasu and Takayasu [7] (see for review the book [8]).

However, rather than an $F \to J$ transition of the GM model class, in real data traffic breakdown is a phase transition from free flow to synchronized flow ($F \to S$ transition) (Fig. 1(a), (b)) [9]. In three-phase theory introduced by Kerner [9,10], both a wide moving jam and synchronized flow belong to congested traffic. The fundamental difference between these two phases in measured data of congested traffic is as follows: While the downstream front of a wide moving jam propagates through a highway bottleneck upstream with a characteristic mean velocity, the downstream front of synchronized flow does not exhibit this jam characteristic feature and this synchronized flow front is usually fixed at the bottleneck (Fig. 1(a), (b)).

The essence of traffic flow modeling based on the three-phase traffic theory is that three-phase theory explains the set of the fundamental empirical features of traffic breakdown that is as follows [9,10]: (i) Traffic breakdown at a highway bottleneck is an $F \to S$ transition (Fig. 1(a)). (ii) At the same bottleneck, traffic breakdown can be either spontaneous (Fig. 1(a)) or induced (Fig. 1(b)). (iii) The probability of traffic breakdown is an increasing flow rate function. (iv) There is a well-known hysteresis phenomenon associated with traffic breakdown: When the breakdown has occurred at some flow rates, then a return transition to free flow at the bottleneck ($S \to F$ transition) is usually observed at smaller flow rates.

None of the two-phase traffic flow theories and models can explain this set of the fundamental empirical features of traffic breakdown (see explanations in Chapter 10 of Ref. [10] as well as in Ref. [11]). In particular, rather than over-deceleration effect (driver's over-reaction) of two-phase traffic flow theories reviewed in Ref. [3], in three-phase traffic theory traffic breakdown ($F \to S$ transition) has been explained by a competition between opposing tendencies occurring within a random local disturbance in which the speed is lower and vehicle density is greater than in an initial free flow [9,10]:

(i) A tendency towards synchronized flow due to vehicle deceleration associated with a speed adaptation effect. The term *speed adaptation* is related to car-following behavior in which the following vehicle should decelerate while approaching a slower moving preceding vehicle.

(ii) A tendency towards the initial free flow due to vehicle acceleration associated with an over-acceleration effect.