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Traffic paradox on a road segment based on a cellular automaton: Impact of lane-changing behavior

Shumin Feng [a], Jinyang Li [a], Ning Ding [b,*], Cen Nie [a]

[a] School of Transportations Science and Engineering, Harbin Institute of Technology, Harbin 150090, People's Republic of China

[b] Department of Automation, Tsinghua University, Beijing, People's Republic of China

HIGHLIGHTS

- Novel cellular automaton is used considering macroscopic characteristics of traffic flow.
- The results are universally applicable for unsignalized and signalized conditions.
- Figures for dual functions of dependent variables are obtained.
- The critical boundaries of the paradox is located.

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ABSTRACT

The traffic paradox "faster is slower" does not always apply. To study when and where it is valid, a simulation for a real road segment is performed using a novel cellular automaton. This simulation is used to analyze the change in global traffic flow status during free lane-changing behavior under general urban traffic conditions. The impact of lane-changing behavior is quantified into two aspects, time and space, and are described by average delay and transitable flow, respectively. Then surfaces are obtained, which adopt the arriving probability of vehicles and the green ratio as dual independent variables. Thus by the comparison of two surfaces, free lane-changing and straight proceeding, the horizontal projection of the intersecting lines is solved. Finally, the range of occurrence and reasons for the paradox are analyzed.

1. Introduction

As the quantity of vehicles grows, urban traffic congestion is becoming an increasingly serious global problem. There are many scholars paying attention to the impact of lane-changing behavior on traffic flow. Generally, we call lane-changing behaviors for speeding up "free lane-changing", while those for avoiding obstacles or to change direction are called "mandatory lane-changing". Scholars used to associate these behaviors with traffic congestion (Fig. 1), and some of them proposed a paradox, "faster is slower" [1]. These scholars pointed out that drivers who frequently change lanes to overtake other drivers actually slow themselves down, resulting in "more haste, less speed".

However, lane-changing behavior is not simply an individual traffic behavior. When traffic becomes congested, individual lane-changing behavior results in macroscopic phenomena such as split-flow, merging, and weaving. This is due to different vehicles trying to occupy the same space at the same time. Lane-changing not only affects traffic individually but also has

* Corresponding author.
E-mail address: ding-n11@mails.tsinghua.edu.cn (N. Ding).

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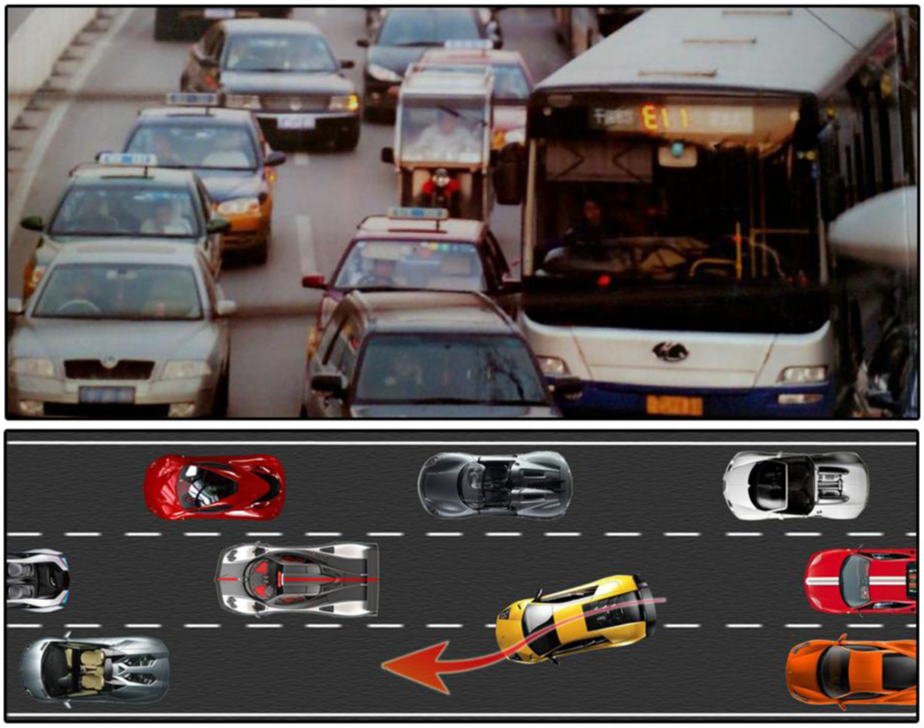

Fig. 1. Lane-changing sketch.

considerable impact on the global traffic flow status, especially when there are a large quantity of lane-changing behaviors. Furthermore, different studies have different opinions on whether the effect of lane-changing is beneficial [1–6]. So far, there are few studies that comprehensively consider the positive and negative effects of lane-changing behavior. The goal of this article is to find the critical point where the effect of lane-changing changes from "good" to "bad", namely the range where the paradox occurs.

In general, the literature on lane-changing phenomenon is regarding traffic behavior of individuals or a particular situation, for example, heavily crowded conditions [7], speed differentials between lanes [1,4], and reduced lanes or transport bottlenecks [2,7,8]. Most of the studies came to a one-sided conclusion that lane-changing behavior is either beneficial [3,6] or harmful [1,2,4,5]. In addition, there has been little discussion on the critical point of the change in traffic flow status caused by permitting drivers to change lanes.

In terms of research methods, models of lane-changing behavior can be summarized as the following categories.

Macroscopic models [2,4,9] can be used to study lane-changing behavior, but they focus on collective integrated average behavior, without regard to the specific interactions between vehicles. Generally, the use of these models requires vast amounts of observation data to acquire parameters, and the results of these models are not very reliable. There are also the disadvantages of large randomness and tedious work. The impact of random error could be eliminated by a vast number of repeated observations, but the system error cannot be eliminated because it is caused by differences of time and region. Therefore, these models require a large amount of effort to acquire data and do not always have universality. Moreover, some assumptions are usually required, and therefore, the models may not conform to the actual situation. This is especially true for macroscopic effect or evaluation models, which are greatly influenced by the researcher's subjective thoughts and have limited reference value.

Microscopic models based on car following Refs. [1,3,5,7,10,11] can accurately simulate lane-changing behavior and track of movement and interactions between vehicles. The law of vehicle motion is described by differential equations, with the advantage of precise calculation but the disadvantages of complex computation and difficulty in obtaining an accurate solution. Sometimes, it is not necessary to accurately calculate the detail and the secondary factors in the process of vehicle movement, but only need to simply solve for the main factors to obtain reliable results. Thus, microscopic models are useful for analyzing the traffic behavior of a few vehicles, but are not sufficiently economical for a large number of vehicles.

Microscopic models based on rules [6,8,12–15] have the advantage of simple, convenient operation and practical application. For example, cellular automata with flexible features and easy simulation of lane-changing behavior are apt for uniquely describing many complicated nonlinear phenomena. However, traditional mathematical methods (both in micro- and macro-models) use continuous functions to explain traffic laws whereas traffic elements are discrete in essence. Thus, it is superior to and more efficient than the car following models that use cellular automata theory to study traffic without the discrete–continuous–discrete approximation [16].