Physica A xx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Studies of vehicle lane-changing dynamics and its effect on traffic efficiency, safety and environmental impact

Xiang Li [a], Jian-Qiao Sun [b,*]

[a] Department of Mechanics, Tianjin University, Tianjin, 300072, China

[b] School of Engineering, University of California, Merced, CA 95343, USA

HIGHLIGHTS

- Presented a combined model of vehicle lane-changing with road bottleneck.
- Studied effects of vehicle lane-changing on traffic, safety and energy economy.
- Discovered situations when vehicle lane-changing can be beneficial.
- Studied negative consequences of lane-changing.

ARTICLE INFO

Article history:
Received 27 May 2015
Received in revised form 24 August 2016
Available online xxxx

Keywords:
Traffic system
Vehicle lane-changing
Traffic fuel efficiency
Traffic safety
Lane reduction
Moving bottleneck

ABSTRACT

Drivers often change lanes on the road to maintain desired speed and to avoid slow vehicles, pedestrians, obstacles and lane closure. Understanding the effect of lane-changing on the traffic is an important topic in designing optimal traffic control systems. This paper presents a comprehensive study of this topic. We review the theory of microscopic dynamic car-following models and the lane-changing models, propose additional lane-changing rules to deal with moving bottleneck and lane reduction, and investigate the effects of lane-changing on the traffic efficiency, traffic safety and fuel consumption as a function of different variables including the distance of the emergency sign ahead of the lane closure, speed limit, traffic density, *etc.* Extensive simulations of the traffic system have been carried out in different scenarios. A number of important findings of the effect of various factors on the traffic are reported. These findings provide guidance on the traffic management and are important to the designers and engineers of modern highway or inner city roads to achieve high traffic efficiency and safety with minimum environmental impact.

1. Introduction

Traffic flow includes strong interactions among various participants such as different types of vehicles, bicycles, pedestrians and so on. There have been a large number of theoretical and simulation studies of traffic systems in order to achieve transportation efficiency. The theory of microscopic car-following models has played an important role in helping us understand the vehicle longitudinal in-lane behavior [1–4]. However, the vehicle lateral behavior such as lane-changing received not enough attention in the past, but is important to gain better understanding of the dynamics in multi-lane traffic.

* Corresponding author.
E-mail address: jqsun@ucmerced.edu (J.-Q. Sun).

http://dx.doi.org/10.1016/j.physa.2016.09.022
0378-4371/

This paper presents a comprehensive analysis of the effect of lane-changing on traffic efficiency, safety and environmental impact.

Several lane-changing models have been developed in the literature [5]. Hidas [6,7] proposed an ARTEMiS lane-changing model that takes three drive modes into consideration, i.e. free mode, cooperative mode and forced mode. The intelligent agent concept was described for modeling of vehicle interactions. In this model, the choice of the lag vehicle to provide courtesy or not to the subject vehicle which desires to change lane in the congested traffic is determined by the characters of the drivers involved, and is a result of a checking sequence. The MOBIL (minimizing overall braking induced by lane change) lane-changing model developed by Kesting et al. [8] introduces a politeness factor that makes the interactions of drivers in the lane-changing process more cooperative. This feature allows a driver to prevent lane-changing for a marginal advantage if the subject vehicle will obstruct other drivers, and permits an aggressive driver to take over a slower one ahead. The particle-hopping models of two-lane traffic with a mix of faster and slower vehicles were developed by Chowdhury et al. [9] where both symmetric and asymmetric rules are considered. According to the asymmetric model, fast vehicles are able to avoid being trapped behind slow ones if the drivers of fast vehicles can anticipate such possibilities, which leads to higher traffic flow. Toledo et al. [10] presented a framework of integrated driving behavior based on the concepts of short-term goal and short-term plan. A symmetric two-lane cellular automata model was proposed by Jia et al. [11] to investigate the aggressive lane-changing behavior of fast vehicles and the influence of different lane-changing probability on traffic performance. Naito et al. [12] investigated the safety-collision transition when an oncoming vehicle carries out lane-changing disregard the possible collision with nearby vehicles. It was demonstrated that the dynamic transition depends highly on the headway, vehicle speed, sensitivity, and velocity difference. Kanaris et al. [13] calculated the minimum safety spacing for lane-changing to prevent collision for the rest of the vehicles when a vehicle executes an emergency braking.

In the literature, the duration of lane-changing is usually ignored and the process is regarded as an instantaneous movement in most models [8,14–16]. However, the influence of lane-changing duration on the traffic is significant and cannot be disregarded [17]. Lv and colleagues [18] established a microscopic lane-changing process model and took lane-changing angle and duration into account. The lane-changing process is simplified to longitudinal car-following model by controlling fictitious vehicles.

Road bottlenecks and the resulting vehicle merging are common in multi-lane traffic systems [19–22]. Lane-changing are usually forced to occur near the merging point [23]. Large vehicle density, aggressive lane-changing [24] and lane-squeezing further reduce traffic capacity of the road [25]. The vehicle interactions are complicated in lane-changing due to a road bottleneck such as lane reduction and moving bottleneck. A two-lane traffic model was proposed by Kurata et al. [26] to study traffic congestions due to accidents. Zhang et al. [27] analyzed the traffic characteristics of lane reduction with microscopic simulation approach. The asymmetric lane-changing rules in the slow-down section and the lane-squeezing behaviors near the bottleneck were considered. Macro and microscopic characteristics of the merging before a city road bottleneck was analyzed by Lv et al. [28]. It was pointed out that lane-changing can improve the traffic efficiency in low vehicle density. In high density, it makes the situation worse. The traffic behaviors in the upstream of the lane reduction bottleneck was investigated by Jia et al. [29]. The traffic characteristics at a moving bottleneck was studied by Kerner et al. [30] based on the numerical analysis with a discrete stochastic traffic flow model in the framework of the three-phase traffic theory. It was observed that there is a critical speed of a moving bottleneck where traffic breaks down spontaneously when the upstream flow rate is large enough.

This paper combines the existing well-established lane-changing models to simulate the traffic when the road bottleneck occurs, and presents comprehensive analyses of traffic characteristics in different situations. Three traffic performance measures are considered: transportation efficiency, energy economy and safety. Three types of lane-changing on a two-lane road are studied. (1) Free lane-changing. Vehicles change lane to take over others in order to achieve higher speed. (2) Road bottleneck due to lane reduction where one section of a lane is closed. Vehicles must change lane to merge. (3) Moving bottleneck due to slow moving vehicles. Vehicles change lane to pass slow ones. This paper is focused on the last two types of lane-changing.

Growing number of vehicles in the world consume more energy and impact the environment more severely [31,32]. Traffic congestions caused by road bottlenecks in both urban area and highway significantly worsen the situation with increased energy consumption and air pollution. Hence, we pay an extra attention to vehicle energy consumption in this study.

The paper starts with the review of the microscopic model including both longitudinal and lateral movements in Section 2. The comparison between the presented model and the well established MOBIL lane-changing model is provided in Section 3. Numerical simulations of the effect of road bottlenecks are presented in Section 4. We close the paper with conclusions in Section 5.

2. Model description

Vehicles travel longitudinally in a single lane and move laterally when changing lane. There is a popular car-following model that we can adopt to describe the single-lane movement of vehicles. For the lane-changing movement, we shall present a combined and improved model based on the well-established lane-changing models in the literature.