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Study on traffic characteristics for a typical expressway on-ramp bottleneck considering various merging behaviors

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HIGHLIGHTS

- A novel set of rules is proposed to model the various merging behaviors at the on-ramp bottleneck.
- Traffic volume features are studied under different upstream arrival rates within numerical simulations.
- The merging ratio at the bottleneck and its influencing factors are investigated.
- The effect of lane changing probability and merging section length are studied.

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ABSTRACT

Recurring bottlenecks at freeway/expressway are considered as the main cause of traffic congestion in urban traffic system while on-ramp bottlenecks are the most significant sites that may result in congestion. In this paper, the traffic bottleneck characteristics for a simple and typical expressway on-ramp are investigated by the means of simulation modeling under the open boundary condition. In simulations, the running behaviors of each vehicle are described by a car-following model with a calibrated optimal velocity function, and lane changing actions at the merging section are modeled by a novel set of rules. We numerically derive the traffic volume of on-ramp bottleneck under different upstream arrival rates of mainline and ramp flows. It is found that the vehicles from the ramp strongly affect the pass of mainline vehicles and the merging ratio changes with the increasing of ramp vehicle, when the arrival rate of mainline flow is greater than a critical value. In addition, we clarify the dependence of the merging ratio of on-ramp bottleneck on the probability of lane changing and the length of the merging section, and some corresponding intelligent control strategies are proposed in actual traffic application.

1. Introduction

Urban traffic problems have increasingly become concern issues all over the world with the rapid growing urban population and traffic demand. Especially on urban expressways, while the capacity of expressways cannot be further improved, the

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increasing traffic congestion may also affect the traffic safety and traffic delays which lead to a great waste of social costs. In urban transport system, bottlenecks are the major cause of traffic congestion while that can be non-recurring (e.g. incident, road work or slow moving vehicle) or recurring (e.g. lane drop, ramp junction, or weaving section). Different with stochastic non-recurring bottlenecks, recurring bottlenecks as the outcome of road facilities bring about more traffic congestion. According to the Federal Highway Administration (FHWA) [1], 40% of traffic congestion on the US highway system is caused by recurring bottlenecks. Of various recurring bottlenecks, on-ramp bottlenecks on urban expressways are the significant one that usually results in traffic jams during peak hours. The competition relationship of mainline and ramp flow at the merging section of on-ramp make the traffic flow characteristic distinctive. Therefore, it is essential to analyze the characteristics of on-ramp bottlenecks on urban expressways in order to propose control strategies to alleviate traffic congestion.

Regarding on-ramp bottlenecks, numerous studies based on empirical data on expressways have been conducted to investigate the traffic flow features around merging area [2–6]. The bottleneck capacity is one of major research directions while several definitions of capacity have been proposed [2,3]. Some traffic phenomena such as breakdown, capacity drop, and traffic oscillations were also been investigated by previous researchers [4,5]. Additionally, the specific lane changing behavior at on-ramp bottlenecks and its relationship with macroscopic traffic flow characteristics were analyzed [6–8]. In general, at on-ramp bottlenecks, it is suggested that a large amount of vehicles come from mainline lanes and ramps will lead to congestion and low passing efficiency due to the competition of mainline flow and ramp flow. Thus it is essential to understand the competition at the bottleneck. The merging ratio which denotes the proportion of ramp vehicles in the traffic flow passing through the bottleneck could be considered as an indicator of the competition of two streams of traffic flow. Therefore, this paper concentrates on the merging ratio to study the competitive relationship of mainline flow and ramp flow. Furthermore, the merging ratio is a parameter about traffic volume. The traffic volume characteristics at the bottleneck are accordingly studied first. As the arrival rates of mainline and ramp flow are the most directly influencing factors of traffic volume, traffic volume under different upstream arrival rates are investigated in this paper.

On the other side, regardless of empirical researches, traffic simulation modeling can be an alternative effective approach to study the traffic system. Various important traffic characteristics have been described and some important results have been obtained by use of a variety of traffic flow model [9–34] while several previous researches apply traffic flow models to study the traffic features of bottlenecks [31–34]. Therefore this study also adopts simulation models to investigate the characteristics of on-ramp bottleneck. The traffic flow models were proposed to explore intrinsic and inherent operation law in traffic system where two kinds of models are the most important. The car following model can describe the inner rules of vehicles' moving forward behaviors with another vehicle ahead or not. Of various car following models, the optimal velocity model (OVM) proposed by Bando et al. [10] has been studied widely while many extended versions have been developed. Helbing and Tilch calibrated the OVM with empirical car-following data and built a generalized force model (GFM) [11]. Jiang et al. [12] found that the GFM showed poor delay time of car motion and kinematic wave speed at high density and presented a full velocity difference model. Li et al. [13] also developed a velocity-difference-separation model (VDSM) to remove the unpractical negative speed in traffic simulation. Thus, the VDSM is adopted as the car following model in this study.

The other one is the lane changing model which is used for modeling the lane changing behaviors on a multi-lane road. Numerous models have been proposed in previous researches [14–21]. However, the present models are always used on common highways is not suitable for that at the on-ramp bottleneck, as the lane changing behaviors at the on-ramp bottleneck are distinct from others. First, it is impractical to only consider the space headway on the target lane without the speed of vehicles when modeling the lane changing, because drivers always think ahead about the condition comprehensively when changing lanes. Hence, the time headway which exhibits the relationship of space headway and vehicle speed is proposed as the criterion of lane changing. Second, at different region of merging section of the bottleneck, the lane changing criterions show much difference. Moreover, since drivers may choose to change lane or not when facing a possible gap on the target lane, there can be a probability of vehicles' lane changes when the lane changing criterions are satisfied. With these considerations, a novel lane changing model is proposed with a set of lane changing rules.

In this paper, with regard to a simple and typical on-ramp bottleneck, simulations are conducted with an extended OVM car following model and a novel lane changing model under the open boundary condition. The traffic flow characteristics at the on-ramp bottleneck are studied to obtain the relationship of the traffic volume and merging ratio with upstream arrival rates. Besides, driving behavior factors like the probability of lane changing, and road design factors like the length of merging section may also have an influence on the traffic volume and merging ratio at the bottleneck. Consequently, the effects of these parameters are researched in this study.

This paper is organized as follows: The detailed simulation modeling of the on-ramp bottleneck is proposed in Section 2. In Section 3, the numerical simulations are performed to study the relationship of traffic volume at the on-ramp bottleneck with various factors changing. Then Section 4 concludes the paper and provides suggestions for future research.

2. Modeling of on-ramp bottleneck

2.1. Structure of on-ramp bottleneck

As the focus of this study is the on-ramp bottleneck on urban expressway, a simple and typical structure of on-ramp bottleneck is adopted for modeling as shown in Fig. 1. The bottleneck is similar to a two-lane lane reduction bottleneck