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Modelling of lane-changing behaviour integrating with merging effect before a city road bottleneck

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HIGHLIGHTS

- Merging behaviour was distinguished from generic lane-changing behaviour.
- An integrative lane-changing model with merging effect was proposed.
- A simulation scenario derived from real life was investigated.
- A calculation method for merging distance was given.

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ABSTRACT

Merging behaviour is a compulsive action in a discretionary lane-changing traffic system, especially in a system with a bottleneck. This paper aims to investigate the generic lane-changing behaviour considering the merging effect before a city road bottleneck. Thus firstly the merging behaviour is distinguished from other generic lane-changing behaviour. Combining discretionary lane-changing and compulsive merging, we developed an integrative traffic model, in which a method to calculate the lane-changing probability and the merging probability was proposed. A simulation scenario derived from real life was conducted to validate the proposed programming algorithm. Finally, a discussion on the simulation findings shows that the merging influence can be expanded and the merging behaviour can increase the probability of local traffic jamming in its affected area of the adjacent lane. The distribution of the merging distance provides fundamental insights for actual traffic management. The result of the clearance time implies the position of the incident point has a significant effect on the clearing time and it is important to ensure the end (exit) of the road is unimpeded in traffic evacuation.

1. Introduction

In recent years, research on traffic flow has become more and more attractive for its potential economical and social values in modern cities. Most researchers treat vehicular traffic as a multiparticle system in which diverse individuals interact with each other under certain restrictions. Based on these physical or psychological restrictions, simulation models [1–18] have presented various kinds of characteristics about realistic traffic and thus have been proved to be a good way to study traffic dynamics. For the scenario of a multi-lane traffic system, the lane-changing behaviour, i.e., a vehicle

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driver will choose to change lanes according to his/her neighbouring environment, should be taken into account to describe the dynamics of a traffic system more accurately. In addition, when there is a traffic accident or road construction in one lane, the vehicles in this lane must merge into the adjacent lane before reaching the accident or construction location, of which the influence on lane-changing behaviour also needs consideration.

There are considerable studies on modelling lane-changing behaviour [19–33]. The main idea of these studies is to extend the single lane car-following models (such as the NaSch model [2], and the Bando model [16]) to multi-lane lane-changeable models by introducing specific lane-changing rules. Nagatani et al. [34] presented a deterministic cellular automation model and found that lane-changing has an important effect on phase transition. Richert et al. [20] investigated related parameters to the fundamental diagram with a two-lane cellular automaton based on the NaSch model. Chowdhury et al. [21] considered the anticipation of the driver and proposed a symmetric model. Nagel et al. [24] summarized different lane-changing rules for freeway traffic and reproduced the density inversion at a density somewhat below the maximum flow density corresponding with empirical data of a German freeway. Lv et al. [35] simulated the lane-changing behaviour on the road with different speed limits and found the nature of density inversion. Kesting et al. [32] presented a general lane-changing model MOBIL for car-following models, which is applicable for both a continuous model such as the optimal velocity model and a discrete model such as the NaSch model. Toledo et al. [36] gave an integrated lane-changing model which allows drivers to jointly consider mandatory and discretionary considerations. These studies could well reflect realistic normal traffic flow, however, they may not be applicable for some sudden scenarios due to the lack of considering the influencing factors of lane-changing behaviour. As a consequence, there is a critical need to investigate lane-changing behaviour under sudden scenarios, for which we concentrate on the merging effect.

Strictly speaking, merging behaviour is a special lane-changing behaviour. The lane-changing behaviour describes the situation that a driver may discretionarily change lanes for better driving conditions, while the merging behaviour describes the situation that the driver must compulsively merge into another lane no matter what the traffic condition on that lane is. Recent studies on merging behaviour focused on the desired merging location and the merging probability. Chowdhury et al. [21] and Nassab et al. [37] determined the merging location using several lane-changing rules. Louisell et al. [38] determined the desired merging location using a Fuzzy Inference System (FIS). Kanaris et al. [39] calculated the inter-vehicle spacing that the vehicles should maintain during a merging in the case of an emergency braking manoeuvre. Weng et al. [40] proposed a desired merging location model and a binary logit model to determine where drivers start to consider merging and the merging probabilities respectively. Another important point is that the merge lane length should be long enough to ensure most vehicles are able to complete their merging manoeuvres, and research has identified the distance for 85% accomplishment of merging behaviours can be used as a reference for traffic engineers designing the merge lane length [41]. Many studies had also been conducted to determine this factor. Nonetheless, most of above studies did not distinguish the merging behaviour with the lane-changing behaviour, while in fact merging behaviour is a compulsive action in a discretionary lane-changing traffic system. In addition, in order to keep relatively good driving conditions the driver must take the merging earlier, or he will have to decelerate or even stop to wait for the right time to merge. We consider the influence of this kind of merging behaviour on lane-changing as the merging effect.

This paper aims to distinguish merging behaviour from generic lane-changing behaviour and introduces the merging effect into the lane-changing model. Thus an improved lane-changing model will be developed to investigate the influence of the merging effect on traffic flow. Relevant simulating results will be given and discussed. We hope this study would be helpful for traffic management and evaluation of sudden or emergency traffic evacuation.

2. Model

2.1. Basic model

A basic lane-changing model consists of two essential processes: car-following and lane-changing. In the past decades, car-following theory and car-following models had been fully developed and extensively applied to describe traffic systems. In order to accord with the actual traffic status on the road, we choose the full velocity difference model (FVDM), which is a space–time-continuous car-following model proposed by Jiang [42], to simulate the car-following process:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = \kappa[V(\Delta x_n(t)) - v_n(t)] + \lambda \Delta v_n \tag{1}$$

where κ is a sensitive coefficient that represents the time delay of a driver's reaction, $\Delta x_n(t)$ is the headway of car n (the distance between car n and its adjacent front car $n+1$), $v_n(t)$ is the velocity of car n at time t. λ is a constant. Δv_n, is the velocity difference between the car n and the adjacent car in front $n+1$. $V(\cdot)$ is an optimal velocity function related to the headway $(\Delta x_n(t))$, which has the following formation [43]:

$$V(\Delta x_n) = V_1 + V_2 \tanh[C_1(\Delta x_n - l_c) - C_2] \tag{2}$$

where V_1, V_2 are two speed constants, C_1, C_2 are two corrected parameters, l_c is the safe distance.

In addition, a comprehensive lane-changing rule set, which may include headway difference, velocity difference, safety distance, the probability of lane-changing intention, is also needed to judge lane-changing behaviour. In this study, we use a similar rule set as our previous works [35,44], nonetheless, considering the merging effect we need to improve the rule set, which will be illustrated in the next section.