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An extended car-following model incorporating the effects of lateral gap and gradient

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HIGHLIGHTS

- A more generialized CF model is proposed by incorporating the effects of both lateral gap and gradient on a road without lane discipline.
- Stability of the proposed model is analyzed using the perturbation method to obtain the stability condition.
- With the increase of the slope, the stability region of the proposed model is enlarged in uphill scenario, while it will be reduced in downhill scenario.
- The dynamic performance associated with the perturbation rejection of the proposed model is improved.

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ABSTRACT

This study proposes a new car-following (CF) model to capture the effects of road geometry characteristics on traffic flow behavior. In particular, an extended CF model is proposed incorporating the effects of both lateral gap and gradient. Stability of the proposed model is analyzed using the perturbation method to obtain the stability condition. Numerical experiments are performed for comparisons among the full velocity difference (FVD) model, two-sided lateral gaps based full velocity difference (TSFVD) model, and the proposed model. Results from numerical experiments demonstrate that, with the increase of the slope, the stability region of the proposed model will be enlarged in uphill scenario, while it will be reduced in downhill scenario, respectively. Also, the proposed model is effective to rapidly dissipate the effect of a perturbation such as a sudden acceleration or deceleration from the lead vehicle. In addition, the CF behavior of traffic flow can be characterized by the proposed model in terms of the space headway profile in uphill and downhill scenarios. That is, with the increase of the slope, the average space headway of the traffic flow will be decreased in uphill scenario, while it will be increased in downhill scenario, respectively. These findings can be generalized to the scenario of traffic system with gradient and lateral gap.

1. Introduction

To develop effective control and management strategies to relieve traffic congestion, enhance road capacity and improve transportation service level, a lot of focus has placed on traffic flow models [1–9]. Traffic flow models aim to capture the complex characteristics of vehicle dynamics in traffic. Past studies [10,11] suggest that the effect of gradient will impact

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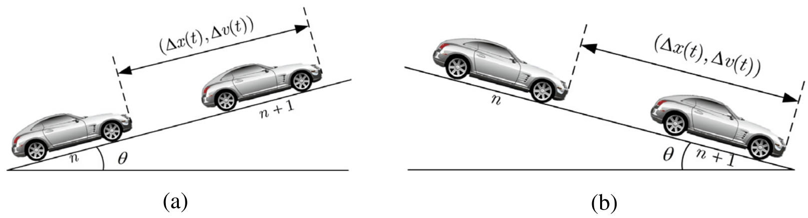

Fig. 1. Illustration of the traffic flow with the slope: (a) the uphill scenario; (b) the downhill scenario.

the car-following (CF) behavior of traffic flow. Recently, studies [12,13] illustrate that incorporation of the lateral gap into the traffic flow model will improve the steady and dynamic performance of traffic flow in terms of the stability and smoothness. However, to the best of our knowledge, no study on traffic flow incorporates the effects of lateral gap and gradient simultaneously. This motivates the construction of a theoretical traffic flow model to investigate the effects of both lateral gap and gradient on CF behavior of traffic flow.

In the literature, various CF models have been proposed to characterize the complex traffic conditions by considering the factors of vehicle states (i.e., velocity and position), vehicle dynamics (i.e., electronic throttle opening angle) and road geometry (i.e., gradient and curvature) [14–23]. CF models can be mainly divided into lane-discipline and non-lane-discipline based models [20–36]. Lane-discipline based CF models restrict the limitation to the assumption that vehicles follow the lane discipline and travel in the middle of the lane. In this research line, Bando et al. [20] proposed the optimal velocity (OV) model based on vehicle state variables such as velocity and position. Henceforth, considerable variants of OV-based models have been developed [21–28], such as the full velocity difference (FVD) model [21]. In addition, Li et al. [22] incorporated the electronic throttle opening angle of vehicle into the model and thus improved the steady and dynamic performance. Also, Zhou et al. [23] factored the gradient into the model to capture the CF behavior of traffic flow. However, the aforementioned CF models will be invalid in the context of a road without lane discipline.

Non-lane-discipline CF models allow that multiple vehicles move in parallel on a road with lateral gaps. In this context, lateral gap is focused on to investigate the CF behavior of traffic flow. To address this scenario, Jin et al. [29] proposed a non-lane-based full velocity difference CF (NLBCF) model considering the unilateral gap. Later, Li et al. [30,31] proposed a two-sided lateral gaps full velocity difference (TSFVD) model and investigated the energy consumption based on the bilateral gaps. In addition, Li et al. [32] further proposed an extended model by considering the effects of visual angle and lateral gap. Recently, Li et al. [33] proposed a new model incorporating the roadside device communication and lateral gap. More recently, Li et al. [34] proposed a model based on the electronic throttle opening angle and lateral gap. These models characterize the non-lane-discipline traffic flow with a focus on lateral gap and therefore the performance associated with the stability and smoothness is improved accordingly.

The literature review heretofore illustrates the significance of incorporating the road geometry characteristics for modeling the traffic flow. The primary objective of this study is to develop a new CF model to capture the CF behavior of traffic flow under the non-lane-discipline road system with gradient. Specifically, a new CF model is proposed by considering the effects of two-sided lateral gaps and gradient in a road system without lane discipline. Stability of the proposed model is analyzed using the perturbation method to obtain the stability condition. Theoretical analyses demonstrate that the lane-discipline-based FVD, the non-lane-discipline-based NLBCF model and non-lane-discipline-based TSFVD model are special cases of the proposed model. Simulation-based numerical are performed based on the FVD model without lateral gap, TSFVD model with two-sided lateral gaps and the proposed model with both two-sided lateral gaps and gradient. Results from numerical experiments show that, with the increase of the slope, the stability region of the proposed model will be enlarged in uphill scenario, while it will be reduced in downhill scenario, respectively. In addition, the CF behavior of traffic flow can be characterized by the proposed model in terms of the space headway profile in uphill and downhill scenarios. That is, with the increase of the slope, the average space headway of the traffic flow will be decreased in uphill scenario, while it will be increased in downhill scenario, respectively.

The study contributes to the literature in three aspects. First, a more general CF model is proposed by incorporating the effects of both lateral gap and gradient on a road without lane discipline. Second, with the increase of the slope, compared with the FVD and TSFVD models, the stability region of the proposed model is enlarged in uphill scenario, while it will be reduced in downhill scenario, respectively. Third, the dynamic performance associated with the perturbation rejection of the proposed model is improved, and the CF behavior of the road with gradient can be characterized by the proposed model in terms of the space headway profile.

The rest of the paper is organized as follows. Section 2 proposes the new CF model considering the effects of both two-side lateral gap and gradient. Section 3 performs the stability analysis of the proposed model. Section 4 conducts the numerical experiments and comparisons. The final section concludes this study.