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Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities

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ABSTRACT

Modeling impacts of Cooperative Adaptive Cruise Control (CACC) on multi-lane freeway traffic can be challenging. It requires accurate description of the formation and disengagement of CACC vehicle strings when CACC vehicles are mixed with manually driven vehicles in the traffic stream. It also needs to depict the behaviors of CACC vehicles under the influence of CACC operation strategies such as the CACC vehicle managed lane (ML) and implementing the Vehicle Awareness Devices (VAD), which are intended to enhance the CACC string operations. To address these challenges, we extended a state of the art CACC modeling framework to incorporate new algorithms that are essential to describe the interactions among the CACC vehicles and manually driven vehicles in mixed traffic. The updated modeling framework adopts a new vehicle dispatching model to generate the high-volume traffic flow expected to exist due to the CACC string operation. The framework also includes new lane changing rules and automated speed control algorithms that ensure realistic CACC vehicle behaviors at freeway on/off-ramp areas where traffic disturbances might frequently interrupt the CACC string operations. With the model updates, we can further reproduce traffic flow dynamics under the influence of the CACC operation strategies. The modeling capability of the presented framework has been verified via case studies on a simple 4-lane freeway segment with an on-ramp and an off-ramp and a complex 18-kilometer freeway corridor. The case study results indicate that the presented modeling framework not only quantifies the mobility improvements for the study sites under different CACC market penetrations and CACC operation strategies, but also discloses the mechanism that governs the improvement. This study creates a methodology that can estimate detailed kinematics of connected automated vehicles under realistic traffic environments. Findings produced by the methodology are helpful for the future development, implementation and management of the advanced transportation technologies.

1. Introduction

Connected and automated vehicles (CAV) can significantly improve the existing transportation system by reducing congestion, traffic incidents, and vehicle fuel consumption and emissions. While it may take decades to reach a mass market adoption for highly automated vehicles, intermediate steps such as equipping vehicles with Cooperative Adaptive Cruise Control (CACC) can bring considerable improvement. CACC is the combination of Adaptive Cruise Control (ACC), a subset of the broader class of automatic

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speed control systems, with a cooperative element, using Vehicle-to-Vehicle (V2V) communication. The V2V communication can provide information about the subject vehicle and its surrounding vehicles, enabling the subject vehicle to respond almost immediately to speed changes of multiple forward vehicles. This allows for shorter gaps between adjacent vehicles in multi-vehicle strings without jeopardizing safety at higher speeds. CACC strings can operate with 0.6 s inter-vehicle time gap, instead of the longer time gap of 1.4 s when the vehicles are driven manually (Nowakowski et al., 2010), which can significantly increase highway capacity (Chen et al., 2017; Ghiasi et al., 2017).

A few studies have been conducted to develop CACC vehicle behavior models and further quantify the impacts of CACC on the macroscopic traffic flow. Talebpour and Mahmassani (2016) proposed a modeling framework that integrates three different car following models to simulate the interactions of isolated human drivers, connected human drivers, and connected automated vehicles. A stochastic model was adopted for describing the behaviors of the human drivers and the Intelligent Driver Model (IDM) was used for the automated vehicles. In Deng's study (2016), VISSIM's default human driver model and the ACC and CACC models from van Arem et al. (2006) were used to evaluate the impact of heavy-duty vehicle (HDV) platoons on traffic operations. Li et al. (2017a,b) adopted a modified IDM to describe the behaviors of human drivers, ACC vehicles and CACC vehicles, with the purpose of identifying the safety benefits under the CAV environment. The IDM and its modified versions were also utilized by Guériau et al. (2016) for the development of a CAV evaluation platform. In those recent studies, the IDM and its variations were frequently used to model the behaviors of CACC vehicles. However, Milanés and Shladover (2014) argued that the capability of the IDM for realistically representing CACC is debatable. They further developed a CACC vehicle behavior model based on empirical data representing real-world CACC strings. Their test results indicate that the presented model can reproduce the trajectories of CACC vehicles with much higher accuracy.

Although CACC modeling has attracted considerable research efforts in the last few years, there are important model aspects yet to be developed for better CACC behavior representation. Many existing studies analyzed the CACC operations on a one-lane freeway, without considering the lateral interactions of vehicles. Alternatively, some researchers tried to depict the car following and lane changing behaviors of both manually driven vehicles and CACC vehicles by using the same behavior model with different model parameter settings. Such a method failed to consider the differences between the two vehicle classes in terms of their distinct ways of data acquisition, information processing, and driving decision-making. In most of the existing studies, the CACC speed control algorithm was the only model utilized to depict the car following of CACC vehicles. But drivers of the CACC vehicles will take over the vehicle lateral and longitudinal control when they need to make lane changes, yield to other lane changers, and apply emergency braking for the collision avoidance. The above discussion indicates that there is a strong demand to improve the CACC models such that they can describe when a subject driver turns on or off the CACC controller during the car following and lane changing process. The model also needs to explicitly describe the car following behaviors of the CACC controller as it switches among different control modes (e.g., constant time gap regulation or constant speed regulation control) under different roles in a CACC string (e.g., string leader or string follower). Moreover, the realistic modeling of CACC vehicle behavior requires the enhancement of human driver models. The human driver models should be refined to capture a driver's lane changing preparation, gap searching, and lane changing maneuvers as the driver tries to merge into a target lane occupied by CACC vehicle strings.

To address those challenges, this study developed a CACC modeling framework based on the NGSIM oversaturated flow human driver model (Yeo et al., 2008) and the CACC car following model derived from the field CACC tests (Milanés and Shladover, 2014; Milanés et al., 2014). We enhanced these models by developing new algorithms that can reproduce the complicated interactions of CACC vehicles and manually driven vehicles in multi-lane freeway segments. Particularly, the presented anticipatory lane changing algorithm (Section 2.2) and the CACC operation rules (Section 2.3) form a modeling framework to realistically depict the car following and lane changing behaviors of CACC vehicles in mixed traffic under the influence of the CACC management strategies. The lane changing component is important because it considers the complex lateral interactions between the automated vehicles and manually driven vehicles. It makes our models ready to reproduce the traffic dynamics that are likely to appear in multilane highways, while most existing studies only considered CACC operation under hypothetical single lane highway scenarios. In addition, the modeling framework can describe the behaviors of CACC vehicles under the influence of specific CACC operation strategies. The CACC operation strategies are implemented to increase the probability of CACC vehicle string formation under lower CACC market penetrations where the CACC vehicles are usually separated by manually driven vehicles in the traffic stream. Existing studies suggest that providing managed lanes (ML) to CACC vehicles and equipping manually driven vehicles with Vehicle Awareness Devices (VAD) are the most promising strategies (Shladover el al., 2012, 2015). The ML strategy allows the CACC vehicles to exclusively use the leftmost lane(s) of a road segment, thus producing higher local CACC market penetration within the highway facility. With the VAD strategy, the manually driven vehicles are equipped with wireless communication devices that send real-time information about the subject vehicle to nearby CACC vehicles. A CACC vehicle can take a VAD vehicle as the CACC string leader and respond quickly to the leader's speed changes. Modeling the influence of the strategies is made possible because we have developed specific lane changing rules for describing CACC vehicles' maneuvers towards the managed lane and made separate algorithms to depict the behaviors of the CACC string leaders and followers.

In the following section, we first give a detailed description of the proposed modeling framework. Section 3 presents an analysis of the model performance representing homogeneous freeway segments, on/off-ramp bottlenecks, and an extended freeway corridor. The concluding remarks are given in Section 4.

2. Microscopic traffic modeling framework

The presented modeling framework was developed based on the NGSIM oversaturated flow human driver model reported in Yeo

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