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The effects of vehicular gap changes with memory on traffic flow in cooperative adaptive cruise control strategy

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HIGHLIGHTS

- To evaluate the impacts of new influence factor in cooperative adaptive cruise control strategy on traffic flow.
- An improved car-following model considering multiple vehicular gap changes is developed.
- The new strategy can improve the stability of traffic flow and enhance traffic safety.

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ABSTRACT

To evaluate the impacts of new influence factor in cooperative adaptive cruise control strategy on the dynamic characteristics of traffic flow, an improved cooperative car-following model considering multiple vehicular gap changes with memory is developed to study the influences of multiple vehicular gap changes with memory on each car's speed, acceleration and relative distance. Some numerical simulations are carried out and the results show that considering multiple vehicular gap changes with memory in designing the cooperative adaptive cruise control strategy can improve the stability of traffic flow and reduce the accidental probability.

1. Introduction

The improvement of traffic efficiency and safety are becoming two crucial priorities for the world society. Traffic congestion in the US caused about 5.5 billion hours of traveling time delay and 2.9 billion gallons of extra fuel consumptions in 2011 [1] and it has become an economically important problem everywhere. Effective technologies to reduce the cost of road mobility by cars are of first order importance. Some projects focus on providing traffic information about the road traffic conditions for drivers to reroute, other projects work on developing intelligent systems like Adaptive Cruise Control systems [2] to help drivers form an eco-driving style as much as possible.

In the past decades, Adaptive Cruise Control systems have been actively developed and introduced into the consumer market by vehicle manufacturers by extending earlier Conventional Cruise Control systems [3]. Nowadays, Adaptive Cruise Control systems are primarily installed on premium vehicles besides a few introductions on middle-class vehicles. The effects of Adaptive Cruise Control systems on traffic flow have been deeply and widely studied. Brackstone et al. [4] conducted

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an extensive review about different car-following models for traffic flow analysis. Besides those car-following models mentioned by Brackstone, there are some others in the literatures [5–25]. Helbing et al. [26] proposed the Intelligent Driver Model based on the generalized force model [6]. Treiber et al. [27] used the Intelligent Driver Model to model ACC car-following behavior in traffic flow simulations. D. Ngoduy [28] carried out analytical studies on the instabilities of heterogeneous intelligent traffic flow simulated by the Intelligent Driver Model. Jerath and Brennan [29] used the General Motors car-following model to analyze traffic flow and found that highway capacity drastically increases when the percentage of ACC-equipped vehicles approaches 100%. Swaroop and Rajagopal [30] studied the intelligent cruise control system and the traffic flow stability. Li and Shrivastava [31] analyzed the traffic flow stability induced by constant time headway policy for adaptive cruise control vehicles. Davis [32] has shown that traffic jams can be suppressed in a mixed traffic of human-driven but the adaptive cruise control cars constituting at least 20% of the traffic flow. Davis [33] analyzed the stability of adaptive cruise control systems taking account of vehicle response time and delay.

The next generation of longitudinal control systems is so-called Cooperative Adaptive Cruise Control systems, which can receive more extensive preceding vehicle information with reduced delays from multiple preceding vehicles. Integrating the adaptive cruise control system and wireless communication was experimented on a closed highway in the PATH program in 1997 [34]. The SARTRE project has been experimenting with car platoons since 2009 [35]. In 2011, the grand cooperative driving challenge in the Netherlands carried out the idea of feedback from the car immediately ahead and the platoon leader [36–38] and proved the benefits of using information received from cars farther ahead, which is in accordance with the ideas in the following *literatures* [39–46]. Ge et al. [39] presented a two velocity difference model considering navigation in modern traffic in the light of the optimal velocity model. Wang et al. [40] presented a multiple velocity difference model by considering multiple preceding cars' velocity differences. Peng and Sun [41] took the effects of multiple preceding cars' velocity differences and headways into account and proposed a multiple car-following model considering multiple preceding cars' information. Li et al. [42] proposed a new car-following model termed as multiple headway, velocity, and acceleration difference, which is a further extension of the existing models of full velocity difference and full velocity and acceleration difference. Yu and Shi [43] put forward an extended car-following model considering multiple preceding cars' accelerations. Ge and Orosz [44] modeled the car-following dynamics of the connected cruise control vehicle with appropriately designed gains and delays by considering a platoon of cars traveling on a single lane. Kesting et al. [45] studied connectivity statistics of store-and-forward inter-vehicle communication by using the Intelligent Driver Model in the simulator. Li et al. [46] extended the Intelligent Driver Model and conducted its numerical simulation under open boundary condition.

First of all, the above-mentioned cooperative car-following models [39–42,44,46] focus on studying the traffic phenomena from the analytical perspectives by assuming a range of market penetrations, which did not use the empirical data to extract the useful information to seek the endogenous variables with higher information as the input variables of car-following model. In essential, it needs a lot of field observations and deep data mining analysis on the real traffic flow before modeling.

Secondly, velocity, velocity difference, the relative distance and vehicular gap changes with memory are easier to be obtained. Considering accurate vehicular gap changes with memory information from multiple cars ahead may enable the following cars to better respond to the front traffic conditions.

And lastly, a driver has memory if his speed at a later time depends on his speed at a previous time. Zhang [47] developed a continuum macroscopic model arising from a car-following model with driver memory and found that driver memory in car-following behaviors can lead to viscous effects in continuum traffic flow dynamics. Tang et al. [48] proposed an extended OV model with consideration of driver's memory and found that considering driver's memory in modeling car-following behaviors can improve the stability of traffic flow.

In light of the above-mentioned three perspectives, an improved car-following model considering multiple preceding vehicular gap changes with memory is proposed for evaluating the effects of the cooperative cruise control strategy on traffic flow, where assumes that the following cars are actuated using multiple vehicular gap changes with memory information from other preceding cars and local headway, velocity difference, velocity information and vehicular gap changes with memory monitored by sensors. Numerical simulations are carried out to test whether the new proposed cooperative car-following model can describe the effects of multiple preceding vehicular gap changes with memory on cooperative car-following behaviors and explore how multiple preceding vehicular gap changes with memory affect the stability of traffic flow and road driving safety.

2. Modeling

In this section, we consider a platoon of $n+m$ successive interacting cars running on a signal lane as shown in Fig. 1.

All cars are supposed to be equipped with the cooperative adaptive cruise control system and the new proposed car-following model considering multiple vehicular gap changes with memory based on the full velocity difference model is constructed, which can be formulated as follows:

$$\ddot{x}_n(t) = \kappa\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda \Delta v_n(t) + \sum_{j=1}^{m} \gamma_j \left[\Delta x_{n+j-1}(t) - \Delta x_{n+j-1}(t-\eta)\right] \quad (1)$$

where $x_n(t)$ is the position of car n at the time t; $V(.)$ is the optimal velocity function; $\Delta x_n(t)$ and $\Delta v_n(t)$ are respectively the headway and the velocity difference between car $n+1$ and car$n$ at the time t; $\left[\Delta x_{n+j-1}(t) - \Delta x_{n+j-1}(t-\eta)\right]$ is vehic-