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Dynamics of connected cruise control systems considering velocity changes with memory feedback

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ABSTRACT

In this paper, a new connected cruise control strategy considering multiple preceding cars' velocity changes with memory is designed to improve roadway traffic mobility, enhance traffic safety and reduce fuel consumptions and exhaust emissions. The linkage between multiple preceding cars' velocity changes with memory and the following car's acceleration or deceleration is explored by using the empirical car-following data and the gray correlation analysis method, and then an improved car-following model considering multiple preceding cars' velocity changes with memory in the connected cruise control strategy is put forward to investigate the effects of multiple preceding cars' velocity changes with memory on each car's speed and acceleration, the relative distance, fuel consumptions, CO, HC and NO_X emissions. The new connected cruise control strategy is designed to be able to receive signals of velocity changes with memory from multiple cars ahead through wireless vehicle-to-vehicle communication and the immediately ahead car's relative distance and velocity difference by radar. The results of numerical simulations prove that multiple preceding cars' velocity changes with memory have significant effects on car-following behaviors and that using multiple preceding cars' velocity changes with memory feedback in designing a connected cruise control system can improve roadway traffic mobility, enhance traffic safety and reduce fuel consumptions and exhaust emissions.

1. Introduction

Nowadays the improvement of road traffic safety and traffic efficiency are two crucial priorities for the world society. As for road traffic safety, about 1.3 million people died and fifty million people were injured each year in road crashes all over the world reported by the World Health Organization [1] and it was also estimated that the rear-end collision was one of the most frequent among all the road accidents [2]. As for road traffic efficiency, congestion in the US caused around 5.5 billion hours of travel delay and 2.9 billion gallons of extra fuel consumption with a total cost of 121 billion dollars in 2011 [3], which has become an economically important problem affecting large and medium-sized cities. Thus, effective policies and technologies to reduce the cost of road mobility and safety by cars are of first order importance. This paper primarily focuses on the possibility of using technologies rather than policies to ease traffic congestion and enhance road traffic safety.

In the past decades, researchers and manufacturers experimented several in-vehicle technologies to assist various aspects of driving, such as Advanced Driver Assistance Systems, which are supposed to improve road traffic safety as well as traffic efficiency. The adaptive cruise control

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system is one of the most famous and deployed Advanced Driver Assistance Systems. Davis [4] 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. To overcome the limitation, integrating the adaptive cruise control system and wireless communication was experimented with the help of inter-vehicle communication on a closed highway in the PATH program in 1997 [5], which is often referred to as cooperative adaptive cruise control system. The SARTRE project has been experimented with car platoons since 2009 [6]. 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 [7–9]. This experiment pointed out the benefits of using signals received from multiple cars farther ahead, which is in accordance with the ideas in the literatures [10–15].

Good traffic properties of the adaptive cruise control system, the cooperative adaptive cruise control system or the connected cruise control system depend on good control strategies, and good control strategies depend on the properties of individual vehicles as well as on their interactions.

Many car-following models have been developed to describe interacting driver–car units on a single lane without overtaking, which include the early linear models proposed by Chandler et al. [16], the early nonlinear models presented by Pipes [17], Gazis et al. [18] and Newell [19], the recent remarkable works of Bando et al. [20], Helbing and Tilch [21] and Jiang et al. [22] and some other related car-following models in the literatures [23–40]. The optimal velocity model taking the following car's velocity and the relative distance into account proposed by Bando et al. [20] is one of favorable car-following models, which can be used to describe many properties of the real traffic flow, such as the instability of traffic flow, the evolution of traffic congestion and the formation of stop-and-go waves. Subsequently, many efforts have been made based on the optimal velocity model by taking into account both headway and velocity difference in different ways. Helbing and Tilch [21] took the negative velocity difference into account and put forward the generalized force model. Jiang et al. [22] took both negative and positive velocity differences into account and proposed the full velocity difference model. Gong et al. [41] considered the asymmetric characteristic of the velocity differences of the vehicles in a traffic stream and presented a new car-following model. Zhu and Zhang [42] introduced a speed feedback control mechanism into the system to improve the dynamical performance of traffic flow.

Cars with human drivers or autonomous controllers can receive various signals from multiple cars ahead by using vehicle-to-vehicle communication and radars. Many experts have conducted a lot of research on them. Tang et al. [10] put forward an extended car-following model considering inter-vehicle communication. Ge et al. [11] presented the two velocity difference model in the light of the optimal velocity model. Wang et al. [12] presented the multiple velocity difference model by considering multiple preceding cars' velocity differences. Peng and Sun [13] took the effects of multiple preceding cars' velocity differences and headways into account and proposed the multiple car-following model considering multiple preceding cars' information. Yu and Shi [14] put forward an extended car-following model considering multiple preceding cars' accelerations. Ge and Orosz [15] 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.

However, the above-mentioned car-following models [10–13,15] focus on studying the traffic phenomena from the analytical and numerical perspective, 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. It is necessary to test whether the results obtained by the above car-following models are quantitatively accordant with the real traffic phenomena. In essential, it needs a lot of field observations and deep data mining analysis on the real traffic flow before modeling car-following behaviors.

One hand, distance, velocity, velocity difference and velocity changes with memory are easier to be obtained. Using multiple preceding cars' velocity changes with memory information may enable the host car to better respond to the front traffic conditions. On the other hand, a driver has memory if his speed at a later time depends on his speed at a previous time. Zhang [43] 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. [44] proposed an extended OV model considering driver's memory and found that driver's memory in car-following behaviors can improve the stability of traffic flow.

Under the above perspective, a new connected cruise control strategy with consideration of multiple preceding cars' velocity changes with memory is designed, where the host car is actuated using velocity changes with memory information from other cars and local headway, velocity difference and velocity information monitored by sensors. Several numerical simulations are carried out to explore how velocity changes with memory feedback used in the connected cruise control strategy affects road driving safety, roadway traffic mobility, fuel consumptions, CO, HC and NO_X emissions.

2. The related data

The empirical car-following data used to analyze the linkage between multiple preceding cars' velocity changes with memory and the following car's acceleration or deceleration come from the survey of our Traffic Control Research Group.

2.1. The field data collection site

The Jingshi Road/Shanshi East Road intersection of Jinan in China was selected for the field data collection