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Platoon based cooperative driving model with consideration of realistic inter-vehicle communication ☆

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ABSTRACT

Recent developments of information and communication technologies (ICT) have enabled vehicles to timely communicate with each other through wireless technologies, which will form future (intelligent) traffic systems (ITS) consisting of so-called connected vehicles. Cooperative driving with the connected vehicles is regarded as a promising driving pattern to significantly improve transportation efficiency and traffic safety. Nevertheless, unreliable vehicular communications also introduce packet loss and transmission delay when vehicular kinetic information or control commands are disseminated among vehicles, which brings more challenges in the system modeling and optimization. Currently, no data has been yet available for the calibration and validation of a model for ITS, and most research has been only conducted for a theoretical point of view. Along this line, this paper focuses on the (theoretical) development of a more general (microscopic) traffic model which enables the cooperative driving behavior via a so-called inter-vehicle communication (IVC). To this end, we design a consensus-based controller for the cooperative driving system (CDS) considering (intelligent) traffic flow that consists of many platoons moving together. More specifically, the IEEE 802.11p, the *de facto* vehicular networking standard required to support ITS applications, is selected as the IVC protocols of the CDS, in order to investigate how the vehicular communications affect the features of intelligent traffic flow. This study essentially explores the relationship between IVC and cooperative driving, which can be exploited as the reference for the CDS optimization and design.

1. Introduction

The emerging vehicular networking technology enables vehicles to timely communicate with each other and exchange important information. These connected vehicles with some common interests can cooperatively drive on the road, e.g., platoon-based driving pattern, which may significantly improve the traffic safety and efficiency (van Arem et al., 2006; Kesting et al., 2008, 2010a; Monteil et al., 2013; Ngoduy, 2013a; Farah and Koutsopoulos, 2014; Sau et al., 2014; Milans et al., 2014).

Basically, in such a Cooperative Driving System (CDS), a vehicle obtains neighboring information via inter-vehicle communication (IVC), and then adopts a suitable control law to achieve certain objective, such as maintaining a constant inter-vehicle spacing within the same platoon. To this end, four major components in CDS are supposed to be considered:

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(1) the vehicle dynamics which inherently characterize vehicle's behavior stemming from manufacture, e.g., actuator lag; (2) the information to be exchanged among vehicles, e.g., the position and velocity of a vehicle; (3) the communication topology describing the connectivity structure of vehicular networks, such as predecessor–follower, leader–follower, and bidirectional; (4) the control law such as sliding-mode control and consensus control to be implemented on each vehicle in order to define the car-following rule in the connected traffic flow.

The issues of CDS have been extensively studied in recent years (Jia et al., 2015; Luo et al., 2016; Liu and Khattak, 2016). For example, some typical control schemes for CDS include the *cooperative adaptive cruise control* (CACC) design (Naus et al., 2010) which adopts the constant time-headway policy with the predecessor–follower information, and the sliding-mode control (Fernandes, 2012) with the leader–follower information. Wan et al. (2016) have investigated how connected vehicles can obtain and utilize upcoming traffic signal information to manage their speed in advance in order to reduce fuel consumption and improve ride comfort by reducing idling at red lights. In terms of information content, Xu et al. (2014) quantified the impact of communication information structures and contents on the platoon safety. The results showed that event data (e.g., drivers braking events) may contain more effective information for platoon management than some traditional information such as distance and vehicle speed. Another important issue is the heterogeneity of vehicle dynamics in CDS, such as the effect of intelligent vehicles on the multi-class traffic flow stability (Ngoduy, 2013a, 2012, 2013b), the mixed operation of the different vehicle classes (e.g. trucks and cars) on the stability of traffic flow (Ngoduy, 2015), and the impact of heterogeneous parasitic time delays and lags on ACC-equipped vehicle longitudinal dynamics (Ling and Gao, 2011). Specifically, due to the natural limitations and uncertainties in practical vehicular networking, such as transmission range, packet loss, and probabilistic transmission delay, substantial work has been concerning how to design the CDS under such communication constraints and uncertainties (Middleton and Braslavsky, 2012; Kesting et al., 2010b; Oncu et al., 2011; Ploeg et al., 2013; Ghasemi et al., 2013; Hao and Barooah, 2012; Wang et al., 2013, 2014; Jin and Orosz, 2014; Monteil et al., 2014). This paper focuses on bridging the gap between traffic flow modeling and communication approaches in order to build up better cooperative systems via a realistic inter-communication design.

In view of communication topology, due to high traffic mobilities, the unreliable vehicular networking with packet loss and transmission error cannot guarantee the fixed topology (e.g., predecessor–follower and leader–follower) among vehicles within the CDS. Therefore, it is imperative to explore a more generic communication structure and control algorithm suitable for cooperative vehicle driving with vehicular networking. To this end, we propose to adopt the *consensus control* approach to build up a model for connected traffic flow. In general, the *consensus control* approach is considered a distributed control law which can efficiently facilitate the convergence of collective behavior among multiple agents and can well adapt to the characteristics of the *time-varying communication topology* of the IVC in the CDS. The related work was initially reported by Fax and Murray (2004), in which dynamical systems as the paradigm are used to model the information exchange within a platoon, and cooperative driving vehicles are formulated as a typical *consensus control* problem. Thereafter, considerable studies were conducted on the issues of cooperative driving and formulated these issues into different consensus problems under various communication assumptions (Ren, 2007; Wang et al., 2012; Bernardo et al., 2015; Santini et al., 2015). In Wang et al. (2012), the cooperative driving vehicles are required to converge the weighted headway spacing to a constant. Moreover, the authors proposed a two-stage stochastic approximation algorithm with post-iterate averaging to mitigate the observation noises. Numerical simulations showed the effectiveness of the vehicle-to-vehicle (V2V) communication in vehicles deployment compared to the sensor-based communication. Later on, Bernardo et al. (2015) considered vehicle platooning in the presence of the time-varying heterogeneous communication delays. They adopted the leader–follower control topology, and calculated the upper bound delay by Lyapunov–Razumikhin theorem which guarantees the stability of the platooning system. Besides, some other studies generalized similar issues as cooperative driving and provided theoretical frameworks for the analysis of the consensus problem in multi-agent networked systems, with an emphasis on the role of the directed information flow, changing network topology due to the impaired communication, as well as the design technologies (Olfati-Saber et al., 2007; Zhang et al., 2012).

Despite the advantage of consensus control design for distributed multi-agent coordination, there still exist some issues unclear about the practical implementation of cooperative driving, especially regarding the communication topology:

(i) The realistic inter-vehicle communication (IVC) has not been fully considered in the cooperative driving model. Most of the previous work only assumed a general IVC condition, regardless of the communication protocols being applied in the CDS. Actually, IVC protocols play a critical role in the CDS and different protocols show system performance at different levels (Fernandes, 2012). Therefore, it is important to clarify and theoretically analyze what the critical metrics (packet delay/loss or other criteria) of the IVC are important to meet the requirement of the consensus-based control for the CDS, and how the communication protocols affect the system performance.

(ii) Most consensus-related work only considered general multi-agent systems in which the relative position of the agents and the direction of the information delivery are barely specified. Actually, due to some practical requirements for the vehicle platooning, such as all vehicle driving in the same direction and collision avoidance, the impact of the communication topology on the platoon-based CDS needs to be further explored.

(iii) The platoon-based CDS has not been comprehensively studied before, where large-scale vehicles are grouped into a series of platoons driving along the road (i.e. connected traffic flow is modeled as many platoons moving together). In this case, not only the vehicles within the same platoon are required to drive cooperatively (intra platoon), but also the cooperation among platoons (inter platoons) should be taken into account.