Transportation Research Part C 40 (2014) 290–311

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Rolling horizon control framework for driver assistance systems. Part II: Cooperative sensing and cooperative control

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ARTICLE INFO

Article history:
Received 18 June 2013
Received in revised form 22 November 2013
Accepted 22 November 2013

Keywords:
Cooperative Systems
Car-following
Cooperative Adaptive Cruise Control (CACC)
Cooperative sensing
Cooperative control

ABSTRACT

This contribution furthers the control framework for driver assistance systems in Part I to cooperative systems, where equipped vehicles can exchange relevant information via vehicle-to-vehicle communication to improve the awareness of the ambient situation (*cooperative sensing*) and to manoeuvre together under a common goal (*cooperative control*). To operationalize the *cooperative sensing* strategy, the framework is applied to the development of a multi-anticipative controller, where an equipped vehicle uses information from its direct predecessor to predict the behaviour of its pre-predecessor. To operationalize the *cooperative control* strategy, we design cooperative controllers for sequential equipped vehicles in a platoon, where they collaborate to optimise a joint objective. The *cooperative control* strategy is not restricted to cooperation between equipped vehicles. When followed by a human-driven vehicle, equipped vehicles can still exhibit cooperative behaviour by predicting the behaviour of the human-driven follower, even if the prediction is not perfect.

The performance of the proposed controllers are assessed by simulating a platoon of 11 vehicles with reference to the non-cooperative controller proposed in Part I. Evaluations show that the multi-anticipative controller generates smoother behaviour in accelerating phase. By a careful choice of the running cost specification, cooperative controllers lead to smoother decelerating behaviour and more responsive and agile accelerating behaviour compared to the non-cooperative controller. The dynamic characteristics of the proposed controllers provide new insights into the potential impact of cooperative systems on traffic flow operations, particularly at the congestion head and tail.

1. Introduction

Fast developments in information and communication technologies (ICT) lead to the emergence of cooperative systems, where equipped vehicles can ‘talk’ with each other through Vehicle-to-Vehicle (V2V) communication and with the infrastructure through Vehicle-to-Infrastructure (V2I) communication, and hence may exhibit different behaviour compared to vehicles that do not communicate (Keller, 1994; Varaiya and Shladover, 1991). The debut of cooperative systems dates back some two decades ago in the Intelligent Vehicle Highway System (IVHS) programme in the United States (Varaiya and Shladover, 1991), the PROMETHEUS programme in Europe (Williams, 1990) and the smart vehicle initiatives in Japan (Nakamura et al., 1994). Several conceptual models have been developed and demonstrations have been deployed to show feasibility and potential of cooperative systems aiming at the compatibility of traffic safety and efficiency (Kato et al., 2002; Kovacs et al., 2006; Richter, 2006). In this paper, we focus on cooperative systems using V2V communication.

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0968-090X/$ - see front matter
http://dx.doi.org/10.1016/j.trc.2013.11.024

In general, conceptual models regarding cooperative systems can be categorised into *cooperative sensing* and *cooperative control*. *Cooperative sensing* entails equipped vehicles communicate with other equipped vehicles via V2V communication to improve the awareness of the ambient situation (Kovacs et al., 2006; Richter, 2006). *Cooperative control* pertains to the collaboration process of exchanging information, negotiation, task distribution and manoeuvring under a common goal using V2V communication (Kovacs et al., 2006; Richter, 2006). Although many initiatives have been launched, the development of cooperative systems remains at conceptual level. Few studies have been reported on the operational models for *cooperative sensing* (VanderWerf et al., 2001; Van Arem et al., 2006; Wilmink et al., 2007), and knowledge gaps exist on how equipped vehicles interact and collaborate at the manoeuvre level.

This contribution operationalizes several conceptual models of cooperative systems and provides insights into the platoon behaviour consisting of equipped vehicles, building upon the generic control framework introduced in Part I of this study (Wang et al., 2014). While Part I focused on the methodology and controller design for *non-cooperative* Advanced Driver Assistance Systems (ADAS), i.e the equipped vehicles only optimise their *own* situation using the information from their *own* on-board sensors, this contribution extends the control framework to *cooperative systems*, where an equipped vehicle *receives and uses* information from other equipped vehicles and *collaborate* under a joint objective. Several control strategies and algorithms are proposed under the *cooperative sensing* and *cooperative control* concept and the performances of the controllers employing the proposed algorithms are examined through simulation of a vehicle platoon.

The paper is organised as follows. Section 2 reviews the relevant work on cooperative systems. Section 3 formalises the receding horizon control framework for cooperative systems. Several control strategies and the experimental design to assess the controller performance are discussed in Section 4. Section 5 presents the controller development for cooperative sensing systems, where an equipped vehicle is capable to react on multi-predecessors. The cooperation between two equipped vehicles is presented in Section 6, while Section 7 pertains to the cooperation between an equipped vehicle and a human-driven vehicle. Conclusions and future work are presented in Section 8.

2. Related work on cooperative systems using V2V communication

In this section, we revisit the most relevant work on control strategy and algorithms for cooperative systems, which aim to describe the controllers or models for equipped vehicles with V2V communication.

Several authors developed Cooperative Adaptive Cruise Control (CACC) systems under the concept of *cooperative sensing*. These CACC systems take advantage of the V2V communication to make a better estimation of the situation around the vehicle, and hence can improve vehicle-following behaviour and enable a CACC vehicle to look further ahead than its direct predecessor.

In Rajamani and Shladover (2001), a constant spacing controller for a closely-coordinated platoon of automated vehicles was proposed. V2V communication is used to transmit speeds and accelerations of the platoon leader and the direct predecessor in the homogeneous vehicle platoon. In doing so, the following gaps in the platoon can be substantially reduced, resulting in a capacity of 6300 veh/h on a dedicated lane. Although this improvement in capacity is remarkable compared to the capacity of around 2000 veh/h with the human-driven vehicles, the prerequisite of implementing a dedicated lane hampers the applications of the system in the very near future.

In VanderWerf et al. (2001), V2V communication is used to transmit not only predecessor speed, but the acceleration and braking capabilities of the predecessor as well. The controller proposed in VanderWerf et al. (2001) is a linear feedback controller:

$$a_i = K_v \dot{s}_i + K_s(s_i - v_i t^* - s_0) + K_a a_{i-1} \tag{1}$$

where a_i and a_{i-1} are the accelerations of vehicle i and its predecessor $i-1$ respectively. s_i and v_i denote the gap and speed of vehicle i respectively. K_a, K_v and K_s are positive feedback gains. t^* is the desired time gap and s_0 denotes the minimum gap at standstill conditions. The first two terms in the right-hand side of the CACC controller in Eq. (1) is the Constant Time Gap (CTG) policy for ACC controller (Godbole et al., 1999; VanderWerf et al., 2001). The third term in Eq. (1) distinguishes the CACC controller from the ACC controller, which implies that an CACC vehicle tends to accelerate when the predecessor is increasing speeds and tends to decelerate when vice versa. By using more information about the leading vehicle, the CACC system permit closer vehicle following (with a time gap of 0.5 s) compared to ACC systems.

In Wilmink et al. (2007), a similar concept of CACC systems was proposed by looking ahead beyond the direct predecessor of the controlled vehicle to the pre-predecessors. This multi-anticipation CACC system entails equipped vehicles further downstream transmitting information (i.e. position and speed) to the controlled vehicle. The controller is formulated as:

$$a_i = K_v \dot{s}_i + K_s(s_i - v_i t^* - s_0) + \frac{K_v}{n-1} \sum_{k=i-n+1}^{i-1} \dot{s}_k \tag{2}$$

where n denotes the number of vehicle the CACC vehicle i looks downstream. Other notations are the same as in Eq. (1). Similar to Eq. (1), the fist two terms in the right-hand side of Eq. (2) is also the CTG policy for ACC systems. The third term is the multi-anticipation terms, implying that the CACC vehicles tends to accelerate when the pre-predecessors are driving at a higher speeds.