Transportation Research Part C 46 (2014) 46–64

Contents lists available at ScienceDirect

Transportation Research Part C

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

Dynamics of connected vehicle systems with delayed acceleration feedback

Jin I. Ge *, Gábor Orosz

Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

A R T I C L E I N F O

Article history:
Received 4 March 2014
Received in revised form 28 April 2014
Accepted 28 April 2014

Keywords:
Connected cruise control (CCC)
Head-to-tail string stability
Acceleration feedback
Time delay
Robustness
DSRC

A B S T R A C T

In this paper, acceleration-based connected cruise control (CCC) is proposed to increase roadway traffic mobility. CCC is designed to be able to use acceleration signals received from multiple vehicles ahead through wireless vehicle-to-vehicle (V2V) communication. We consider various connectivity structures in heterogeneous platoons comprised of human-driven and CCC vehicles. We show that inserting a few CCC vehicles with appropriately designed gains and delays into the flow, one can stabilize otherwise string unstable vehicle platoons. Exploiting the flexibility of ad-hoc connectivity, CCC can be applied in a large variety of traffic scenarios. Moreover, using acceleration feedback in a selective manner, CCC provides robust performance and remains scalable for large systems of connected vehicles. Our conclusions are verified by simulations at the nonlinear level.

1. Introduction

Advanced driver assistance systems (ADAS) have been developing rapidly in the last decade, leading to significantly improved passenger comfort and active safety of road vehicles. However, mobility of road traffic has not experienced similar transformation, as traffic jams still plague highways and major cities in the United States and around the world (Schrank et al., 2012). Mobility depends on the properties of individual vehicles as well as on their interactions, i.e., on the control strategies used to react to the motion of other vehicles. A control strategy that is based solely on local traffic information has limited ability to change the dynamics at the system level, which is necessary if one wishes to eliminate traffic congestion.

Past research has shown that maintaining smooth traffic flow is closely related to the so-called string stability of the local controllers that represents their ability to attenuate velocity fluctuations coming from the vehicles in front (Orosz et al., 2010). Human drivers who rely on distance and velocity information are typically unable to maintain string stability in the entire velocity range due to their reaction time (Zhang and Orosz, 2013). A possible solution may be to use adaptive cruise control (ACC) where the distance and the velocity difference between the vehicle and its predecessor is measured by radar and the vehicle is actuated accordingly. Since the delay in these systems is smaller than the human reaction time, controllers may be designed to ensure attenuation of velocity fluctuations, which results in string stable platoons if all vehicles are controlled by the same ACC algorithm. A past study (Davis, 2004) has shown that traffic jams can be suppressed in a mixed traffic of human-driven and ACC vehicles, when ACC vehicles constitute at least 20% of the traffic flow. However, the

* Corresponding author. Tel.: +7346479732.
E-mail address: gejin@umich.edu (J.I. Ge).

http://dx.doi.org/10.1016/j.trc.2014.04.014
0968-090X/

current ratio of ACC vehicles on the road is estimated to be orders of magnitude smaller than this. Consequently, the improvement of traffic efficiency through ACC systems is very limited.

In order to overcome the limitations of ACC systems, one may use information about the motion of more than one preceding vehicles that can be obtained through wireless vehicle-to-vehicle (V2V) communication, such as dedicated short range communication (DSRC). In this way, the performance of ACC controllers, particularly the string stability, may be improved. Such augmented ACC systems are often referred to as cooperative adaptive cruise control (CACC) (van Arem et al., 2006). Experimental work in integrating ACC systems and wireless communication dates back to the PATH program in 1997, when a platoon of eight cars performed longitudinal motion control with the help of inter-vehicle communication on a closed highway (Rajamani and Shladover, 2001). Since 2009, the SARTRE project has been experimenting with vehicle platoons where each following vehicle is driven automatically using signals sensed by radars and transmitted from a designated platoon leader (the first vehicle in the platoon) that is equipped with high-quality sensors and driven by a professional driver (Chan et al., 2012). In 2011, the grand cooperative driving challenge (GCDC) in the Netherlands implemented the idea of feedback from the vehicle immediately ahead and the platoon leader (van Nunen et al., 2012; Geiger et al., 2012; Lidström et al., 2012). These experiments pointed out the benefits of using signals received from vehicles farther ahead. However, it was required that all vehicles in the platoon were equipped with ACC and the connectivity structures were fixed relying on a prescribed platoon leader. Such assumptions not only restrict the application of CACC in real traffic but also limit the feedback design to a particular connectivity structure. Considering the low penetration of ACC vehicles and the additional requirements to create CACC systems, the chance that three or more of these vehicles get close to each other in traffic is extremely low. Two recent papers (Wang et al., 2014a,b) discuss different control setups and heterogeneity for CACC platoons by lowering the requirement on penetration rate. However, specific repetitive connectivity patterns are assumed where vehicles only monitor the motion of the vehicles ahead and immediately behind. Therefore, the benefits of using information from distant vehicles are not exploited and requiring fixed connectivity may limit modularity in the entire transportation system.

Connected cruise control (CCC) is proposed to resolve these problems, where ad hoc platoons can be formed based on the available communication and platoons may be heterogeneous, i.e., include human-driven vehicles that only transmit data or do not participate in the communication at all. In this scenario, the leader is considered to be the furthest vehicle ahead that transmits signals to the CCC vehicle, and this may be different for each CCC vehicle. Since this framework neither requires a designated platoon leader nor a fixed communication structure, it allows modular design that is scalable for large systems. Moreover, the flexibility in the connectivity structure permits CCC design that is robust against the uncertainties in the parameters of human drivers. In fact, even a CCC vehicle may be human-driven in which case the communication-based control acts as a driver assistance system. Indeed, CCC can also be used to supplement ACC, or even to substitute sensors like radars with communication.

CCC can be designed based on the various signals received via V2V communication, including distance, velocity, and acceleration. Distance and velocity information has been used frequently when designing ACC controllers, but acceleration is seldom used since it requires taking derivatives of (noisy) velocity signals generated by the sensors. On the other hand, human drivers often use acceleration signals provided by the taillights, but they cannot determine the exact deceleration value, and can only observe the taillight of the vehicle immediately ahead. Using accurate acceleration information from multiple vehicles ahead may enable the host vehicle to better respond to traffic conditions. In this paper, we consider an acceleration-based CCC design, where the host vehicle is actuated using acceleration information broadcasted by other vehicles and local headway and velocity information monitored by sensors or human drivers. Moreover, we propose a delay-based control design where both the gains and the delays are tuned in the feedback loop. We show that this design is robust against variations of human parameters (driver gains and driver reaction time) and we derive the ranges of feasible acceleration gains and delays that ensure string stability. It has been shown that acceleration feedback can be effective in other applications involving human reaction time, e.g., human balancing (Insperger et al., 2013).

The layout of the paper is the following. In Section 2, we introduce a general class of the nonlinear car-following models that can be used to describe CCC as well as conventional vehicles. This general class of models allow us to consider a large variety of communication structures where a few CCC vehicles are inserted into the platoon to exploit V2V information. In Section 3, we linearize the system about the uniform flow equilibrium and analyze the head-to-tail string stability for different communication structures. The linear stability results are summarized using stability charts and the results are verified at the nonlinear level using numerical simulations. We conclude our results in Section 4.

2. Connected car-following models with acceleration feedback

We consider a platoon of $n+m+1$ vehicles traveling on a single lane as shown in Fig. 1(a). The preceding $n+m$ vehicles are not equipped with CCC and are assumed to be human-driven. The tail vehicle (the last vehicle of the platoon) implements acceleration-based CCC using acceleration signals received through V2V communication from n preceding vehicles. The car-following dynamics of the CCC vehicle is modeled by

$$\begin{aligned}\dot{h}(t) &= v_1(t) - v(t),\\ \dot{v}(t) &= \alpha\Big(V(h(t-\tau)) - v(t-\tau)\Big) + \beta\,\dot{h}(t-\tau) + \sum_{k=1}^{n}\gamma_k\,\dot{v}_k(t-\sigma_k),\end{aligned} \tag{1}$$