Transportation Research Part C 83 (2017) 39–60

Contents lists available at ScienceDirect

Transportation Research Part C

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

Scalable stability analysis on large connected vehicle systems subject to stochastic communication delays

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ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 10 July 2017
Accepted 11 July 2017

Keywords:
DSRC
V2V
Stochastic delays
Open chain
Closed ring
Plant stability
String stability
Mean dynamics
Covariance dynamics
Second moment dynamics

ABSTRACT

In this paper large connected vehicle systems are analyzed where vehicles utilize vehicle-to-vehicle (V2V) communication to control their longitudinal motion. It is shown that packet drops in communication channels introduce stochastic delay variations in the feedback loops. Scalable methods are developed to evaluate stability and disturbance attenuation while utilizing the mean, second moment, and covariance dynamics in open chain and closed ring configurations. The stability results are summarized using stability diagrams in the plane of the control parameters while varying the packet delivery ratio and the number of vehicles. Also, the relationship between the stability of different configurations is characterized. The results emphasize the feasibility of V2V communication-based control in improving traffic flow.

1. Introduction

The past decades witnessed a worldwide increase in the number of vehicles on the road, bringing major concerns about traffic congestions (Schrank et al., 2015). The large reaction time and limited perception range of human drivers make them unable to maintain smooth traffic flow and may trigger stop-and-go traffic jams while reacting to unexpected events (Orosz et al., 2009, 2010). On the other hand, advanced driver assistant systems (ADAS) can be used to improve the longitudinal control of vehicles. Although such technologies typically target at the enhancement of safety and driving comfort, they have an enormous potential in improving the efficiency of large scale traffic systems.

For example, adaptive cruise control (ACC) can be used to maintain a velocity-dependent inter-vehicle distance based on range sensors (radar or lidar) (Shladover, 1991; Ioannou and Chien, 1993; Rajamani and Zhu, 2002). It was demonstrated in (Werf et al., 2002; Davis, 2007) that due to faster and more accurate sensing abilities ACC may have a positive impact on traffic flow when the penetration rate of ACC vehicles is high enough. However, due to the high cost of range sensors and the perception limitation within the line of sight, this technology is still not widely available. To overcome the limitations, it was proposed to augment ACC with wireless V2V communication. This can allow vehicles to monitor the kinematic properties of other vehicles, even those beyond the line of sight, and they may utilize such information in their controllers to improve their safety and fuel economy and to mitigate traffic jams. In the US dedicated short range communication (DSRC)

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http://dx.doi.org/10.1016/j.trc.2017.07.005
0968-090X/Published by Elsevier Ltd.

has been standardized (Kenney, 2011; SAE J2735, 2016) for V2V communication to foster this idea. An overview of vehicular control with V2V communication can be found in (Li et al., 2015).

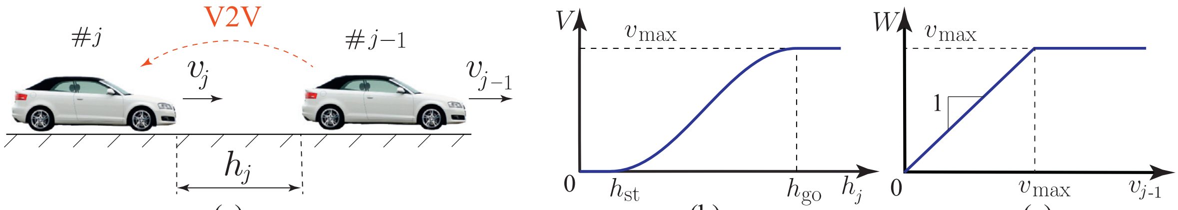
One strategy is called cooperative adaptive cruise control (CACC) (Naus et al., 2010; Desjardins and Chaib-draa, 2011; Milanes et al., 2014; Jia and Ngoduy, 2016) that assigns a fixed communication topology to a group of ACC vehicles: each vehicle monitors the motion of the preceding vehicle using range sensors, as well as the motion of the group leader via V2V communication. This technology was shown to be able to improve traffic throughput with a high enough penetration rate using simulations (van Arem et al., 2006; Milanes et al., 2011; Ploeg et al., 2014b, 2015; di Bernardo et al., 2015; Zheng et al., 2016b; Talebpour and Mahmassani, 2016; Lioris et al., 2017) and fruitful experiments have been conducted in the PATH program (Rajamani and Shladover, 2001), the SARTRE project (Chan et al., 2012), and grand cooperative driving challenge (Ploeg et al., 2012). However, the harsh requirement that all the vehicles must be equipped with range sensors, DSRC devices and controllers hinders the deployment of such strategy.

Alternatively, another control strategy, referred to as connected cruise control (CCC), has been proposed that does not require every vehicle to be equipped with range sensors and DSRC devices. A CCC vehicle utilizes all the available V2V information from vehicles ahead within the communication range (Ge and Orosz, 2014; Zhang and Orosz, 2016; Orosz, 2016). Such flexibility allows controllers to fully exploit the advantages of V2V communication while gathering information from vehicles within and beyond the line of sight. This includes scenarios when the vehicle immediately ahead is hidden by the road geometry and cannot be detected by range sensors (such as radar or lidar). Different aspects of CCC have been studied, such as the influence of communication delays, connectivity topology, nonlinearities and optimal design (Avedisov and Orosz, 2015; Zhang and Orosz, 2017; Ge and Orosz, 2017; Ge et al., 2017), and it was demonstrated that this strategy has a large potential in improving traffic flow.

In Qin et al. (2017), the two major aspects of V2V communication-based control of connected vehicle systems were considered for the simplest CCC system – a predecessor-follower pair; see Fig. 1(a). To incorporate intermittency in communication requires consideration of time delays and digital effects (Qin and Orosz, 2013), while to understand the effects of packet drops requires the characterization of the dynamics in the presence of stochastic delays. The mathematical tools created in (Qin et al., 2017) enabled us to analyze stochastic stability and stochastic disturbance attenuation (often referred to as string stability) in the vicinity of the equilibrium in simple connected vehicle systems. In particular, the concept of $n\sigma$ string stability was established that guarantees the attenuation of velocity fluctuations for trajectories that are within the n times standard deviation about the mean. A natural question to ask is whether such stability results are scalable for large stochastic connected vehicle systems; see (Zheng et al., 2016a) for scalability of stability for deterministic cases.

In this paper, we extend the notion of *$n\sigma$ string stability* to an open chain containing arbitrarily large numbers of connected vehicles (while still keeping the simplification that each vehicle only reacts to the motion of the vehicle immediately ahead). To ensure scalability, a set of decomposition methods is developed to significantly reduce the size of matrices appearing in the mean, second moment, and covariance dynamics. Moreover, the notion of *$n\sigma$ offset string stability* is proposed to characterize stability and disturbance attenuation as the number of vehicles is increased. This way the feasible ranges of control parameters that ensure smooth traffic flow can be characterized analytically as the number of vehicles increases towards infinity. Then, we also study the behavior of a system of arbitrary number of connected vehicles on a ring road. Similar to the open chain system, decomposition methods are developed to make the stability analysis scalable. The stability diagrams obtained unveil the relationships between large systems of connected vehicles of different configurations. Clearly, such comparison is not possible using numerical simulations considering the large system size and the requirement for enormous realizations given by the stochastically varying delays.

This paper is organized as follows. In Section 2, we provide the dynamics of a vehicle model and design a controller based on the information received via wireless communication subject to stochastic packet drops. In Sections 3 and 4, an open chain and a closed ring of connected vehicles are studied and the results are summarized using stability diagrams. In Section 5, the results of the open chain and the closed ring systems are compared to each other. Finally, we arrive at some conclusions in Section 6.



(a) (b) (c)

Fig. 1. (a) Predecessor-follower pair equipped with V2V communication on a single lane. Dashed red arrow indicates the information flow through wireless communication. (b) Range policy function (6). (c) Saturation function (7).