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Experimental evaluation of decentralized cooperative cruise control for heavy-duty vehicle platooning

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ABSTRACT

In this paper, we consider the problem of finding decentralized controllers for heavy-duty vehicle (HDV) platooning by establishing empiric results for a qualitative verification of a control design methodology. We present a linear quadratic control framework for the design of a high-level cooperative platooning controller suitable for modern HDVs. A nonlinear low-level dynamical model is utilized, where realistic response delays in certain modes of operation are considered. The controller performance is evaluated through numerical and experimental studies. It is concluded that the proposed controller behaves well in the sense that experiments show that it allows for short time headways to achieve fuel efficiency, without compromising safety. Simulation results indicate that the model mimics real life behavior. Experiment results show that the dynamic behavior of the platooning vehicles depends strongly on the gear switching logic, which is confirmed by the simulation model. Both simulation and experiment results show that the third vehicle never displays a bigger undershoot than its preceding vehicle. The spacing errors stay bounded within 6.8 m in the simulation results and 7.2 m in the experiment results for varying transient responses. Furthermore, a minimum spacing of −0.6 m and −1.9 m during braking is observed in simulations and experiments, respectively. The results indicate that HDV platooning can be conducted at close spacings with standardized sensors and control units that are already present on commercial HDVs today.

1. Introduction

1.1. Motivation

The transport industry faces great challenges. Freight transport demand has escalated and will continue to do so as economies grow. At the same time legislation on engine emissions is becoming increasingly stringent. 2.3 billion tonne-kilometers of inland freight was transported in 2010, of which 76.4% was transported over roads. Overall green house gas emissions was recorded to be reduced by 17% between 1990 and 2009 (Eurostat, 2011). While emissions from other sectors are falling, those from the transport sector have increased by 21%. Road transport alone contributes about 20% of the EU's total emissions of CO_2, the main greenhouse gas. Congestion is a growing problem, being a natural consequence of the increasing need for transport services. Along with challenges regarding congestion and emission policies, the vehicle manufacturers also experience an increase in fuel prices. Transportation is responsible for the main part of the increase in oil consumption during the last three decades, and the growth is expected to continue. As the fuel price increases, the strain on operating costs grows for a heavy-duty vehicle (HDV) fleet provider. This issue has a major impact within the transport industry, since road transport serves as the backbone of the economy in many countries. With the rise in fuel prices, road transportation becomes less economically viable. Hence, the road transport sector has been targeted as a main policy area where further environmental and overall efficiency improvements are critical for a sustainable future of European transport (European Commission, 2014).

The advancements in information and communication technology (ICT) present an opportunity to tackle these problems through novel integrated intelligent transportation system (ITS) solutions. Through improved sensor technology, wireless communication, GPS devices, and digital maps, advanced driver assistance systems are being developed. Key enabling technologies, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, have matured. Furthermore, the number of on-board electronic control units (ECUs) and sensors have increased rapidly over the last decades. They enable additional functionality in terms of smart control logics.

HDV platooning for emission reduction and energy efficiency is intensively studied. It is known that driving at a short inter-vehicle

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spacing to a vehicle ahead results in a reduced fuel consumption and drivers are doing so today with increased stress levels. The reduced fuel consumption occurs due to a lowered air drag when operating in a formation, which in turn creates a coupling of the dynamics between vehicles throughout the platoon. By packing HDVs close to each other, the total road capacity can be increased and emissions can be reduced (De Schutter et al., 1999). Additionally, when governing vehicle platoons by an automated control strategy, accidents can be reduced and the overall traffic flow is expected to improve (Ioannou & Chien, 1993). It is fuel efficient to minimize the relative distance between the vehicles to achieve maximum reduction in air drag (Alam, Gattami, & Johansson, 2010), but, as traffic intensity grows, the complexity of the coupled traffic dynamics increases. The actions of one vehicle may in turn affect all vehicles in a linked chain.

Research projects throughout the world have been conducted to study the challenges and benefits of HDV platooning in practice. In the projects PROMOTE-CHAUFFEUR I & II, needs of intermediate and end users, along with safety and operational requirements, were investigated (Harker, 2001). In KONVOI, experimentally analyzing the use of electronically regulated truck convoys on the road with five vehicles was one of the main focuses (Deutschle et al., 2010). PATH is a vast project that addresses many traffic related research aspects (Bu, Tan, & Huang, 2010). Recently, the focus has been directed towards studying HDV platooning, mainly due to the fuel and congestion reduction potential. The recently concluded ENERGY ITS project evaluated energy efficiency for automated HDV platooning and methods for effectiveness of ITS on energy saving (Tsugawa, 2013). In the SARTRE project, the focuse lied on mixed traffic in highway situations, where fuel efficiency, safety, and comfort were evaluated (Robinson, Chan, & Coelingh, 2010). The aim of the GCDC project was to accelerate the deployment of cooperative driving systems (van Nunen, Kwakkernaat, Ploeg, & Netten, 2012). Several issues, such as communication constraints and erroneous information, were revealed in this project that needs to be solved before platooning can be presented commercially. Finally, in the recent project COMPANION (Adolfson, 2014) a wider perspective is undertaken, where the actual creation, coordination, and operation of platoons are studied. The goal is to identify means of applying the platooning concept in practice for daily transport operations.

There are already commercially available systems that might facilitate platooning, such as the adaptive cruise control (ACC) that uses radar measurements consisting of the relative distance and velocity to a preceding vehicle and adjusts the velocity automatically. The ACC works reasonably well in a two-vehicle platoon. However, a delay arises from measuring the behavior of the preceding vehicle with the radar to producing the actual brake torque at the wheels. Thus, overshoots commonly occur when facing a velocity disturbance. In addition, the follower vehicle might not be able to reduce its speed in time if the preceding vehicle performs an emergency brake. Therefore, it is not suitable for longer vehicle platoons to operate at a short spacing due to safety issues. As an alternative to radar measurements, wireless communication may be utilized to provide information from several preceding vehicles. Even though small delays are still imposed due to data processing, retransmissions, etc., the vehicles should be able to operate at much closer spacing and better performance with a suitable controller, since a wider range of information, e.g., braking events or other actions performed by several vehicles ahead, can be transmitted almost instantaneously.

1.2. Contribution

The main contribution of this paper is to derive a decentralized controller for HDV platooning and establish empiric performance results for the presented control design. Several studies on vehicle platooning have been based on simplified theoretical models. However, as shown in this paper, delays and nonlinear dynamics can significantly influence the closed-loop system. In Alam, Gattami, and Johansson (2011), an early version of the proposed controller design was given, where only one preceding vehicle in the platoon was considered. In this work, we present a method for designing suboptimal decentralized feedback controllers for an arbitrary number of preceding vehicles, with low computational complexity, that also takes dynamic coupling and engine response delays into consideration. The controller performance is evaluated through implementation on commercial HDVs. The design method is scalable in the sense that an additional vehicle can be added at the tail of the platoon without mandating a change in the controllers of the already platooning vehicles. Our proposed vehicle system architecture is shown to be robust to packet losses or short outages in V2V communication. As modern HDVs in general have two separate low-level control systems for governing the longitudinal propulsion and deceleration of the vehicle, the engine management system (EMS) and the brake management system (BMS), we present a simple bumpless transfer scheme to switch between these systems. The proposed platooning controller can be easily implemented on modern HDVs without requiring any changes in the already existing vehicle architecture. It includes three modes, where two modes involve maintaining a suitable distance when facing disturbances during normal operation mode. The third mode incorporates the control strategy derived in Alam, Gattami, Johansson, and Tomlin (2014), which was solely derived for collision avoidance during emergency braking scenarios. We present a suitable vehicle control architecture that also takes existing commercially available speed control strategies into account and we give test procedures for performance evaluation. We show that the controller behaves well even when performing outside the linear region of operation. We also show that the proposed controller attenuates the effect of disturbances downstream in the platoon, when studying scenarios that commonly occur on highways with dynamic operating conditions and physical constraints. Experimental results are given to qualitatively validate the proposed control system behavior. The results show that the controller performance is improved with increasing position index in the platoon, by utilizing additional information from preceding vehicles. However, the effects of unmodeled nonlinearities, such as gear changes, brake blending, and engine dynamics, can cause undesirable behavior in some cases. The experiments have been conducted on a test site south of Stockholm, using HDVs provided by Scania CV AB.

1.3. Related work

A multitude of control strategies for vehicle platooning can be found in the literature since the 1950s. For brevity, we only outline some of the theoretical work on vehicle platooning and more recent literature on implementation and experiments.

1.3.1. Fundamentals of vehicle platooning

Fundamentals of vehicle platooning are well researched and involve stabilizing control based on simple point mass models, string stability, safety, and traffic flow. Early theoretical work on control of vehicular platoons was done by Levine and Athans (1966). Centralized linear quadratic regulator (LQR) design for vehicle platoons was considered in this work, indirectly assuming that computational complexity and V2V communication constraints would not be an issue. In Jovanović and Bamieh (2004), it was shown that even though infinite platoons capture the essence of large platoons, the LQR problem formulation lacks observability and stabilizability in the infinite case. Hence, a well-posed alternative formulation for large vehicle platoons is proposed. Control for chain structures in the context of platoons