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Constrained optimization and distributed computation based car following control of a connected and autonomous vehicle platoon

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ABSTRACT

Motivated by the advancement in connected and autonomous vehicle technologies, this paper develops a novel car-following control scheme for a platoon of connected and autonomous vehicles on a straight highway. The platoon is modeled as an interconnected multi-agent dynamical system subject to physical and safety constraints, and it uses the global information structure such that each vehicle shares information with all the other vehicles. A constrained optimization based control scheme is proposed to ensure an entire platoon's transient traffic smoothness and asymptotic dynamic performance. By exploiting the solution properties of the underlying optimization problem and using primal-dual formulation, this paper develops dual based distributed algorithms to compute optimal solutions with proven convergence. Furthermore, the asymptotic stability of the unconstrained linear closed-loop system is established. These stability analysis results provide a principle to select penalty weights in the underlying optimization problem to achieve the desired closed-loop performance for both the transient and the asymptotic dynamics. Extensive numerical simulations are conducted to validate the efficiency of the proposed algorithms.

1. Introduction

For traditional human-driven vehicles, drivers determine car-following behaviors, i.e., acceleration or deceleration, speed, and spacing between adjacent vehicles, according to drivers' own sensitivity and reaction time to their leading vehicles' movement variations (May, 1989). Experimental and theoretical results have shown that improper car-following behaviors, e.g., overreacting or timid car-following, are one of the key factors to trigger traffic congestion, oscillations (stop-and-go or slow-and-fast traffic), and accidents (Laval and Leclercq, 2010). However, due to high randomness and inhomogeneity of human drivers' behaviors, few technologies can be implemented to control car-following behaviors of human-driven vehicles and to improve traffic performance. As a result, the current traffic flows often demonstrate low efficiency and have severe environmental impact in many urban areas.

The recent advancement of connected and autonomous vehicle technologies provides tremendous opportunities for developing coordinated car-following control of multiple vehicles that promote driving safety and efficiency and mitigate

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negative environmental impact. In particular, connected vehicle technologies, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-other-digital-facilities (V2X), enable individual vehicles to access online traffic information, accurately view nearby traffic conditions, and further communicate with other vehicles to establish coordinated or cooperative driving. In addition, autonomous vehicle technologies allow modern computation and control techniques to be implemented for advanced vehicle control to achieve neighborhood mobility and safety of individual vehicles as well as desired system performance. Hence, the goal of the present paper is to develop car-following control schemes for a platoon of vehicles by leveraging connected and autonomous technologies to enhance mobility and safety of both individual vehicles and platoon performance, e.g., reduced traffic oscillations and smoother traffic flows, which will potentially improve environmental sustainability significantly.

In the field of transportation engineering, the research of this paper is closely related to the cooperative adaptive cruise control (CACC) technologies. These technologies allow a vehicle to automatically adjust its speed to maintain a safety distance from its preceding vehicle, based on information gathered from stationary or mobile devices, but without platoon performance guarantee. The CACC technologies have been extensively studied in transportation engineering using microscopic traffic flow theory and safety policies under different information structures (Li et al., 2015), e.g., the immediate preceding structure (van Arem et al., 2006; Desjardins and Chaib-draa, 2011; Rajamani and Shladover, 2001; Shladover et al., 2001), the multiple preceding structure (van Arem et al., 2007; Swaroop and Hedrick, 1999; Schakel et al., 2010), and the preceding-and-following structure (Nakayama et al., 2002; Wang et al., 2014; Zheng et al., 2016a). These papers show improved neighborhood driving safety, traffic flow stability and efficiency. The platoon performance of the CACC technologies, e.g., traffic oscillations, also receives considerable interest in the literature. However, such the performance is mainly evaluated by simulations as extra benefits rather than being treated as a direct control objective in CACC algorithm design. Thus this line of research lacks a theoretical foundation and formal justification of effectiveness under general traffic conditions.

Car-following control for connected and autonomous vehicles has also garnered substantial attention in control engineering. From the control systems point of view, a platoon of connected and autonomous vehicles is an interconnected system, and car-following can be treated as a cooperative control problem. Various interconnecting stability issues, e.g., string stability (Swaroop, 1997; Swaroop and Hedrick, 1996), have been studied using frequency-domain methods, linear feedback theory, and Lyapunov theory, and applied to a vehicle platoon (Cook, 2007; Monteil et al., 2014; Naus et al., 2010a,b; Oncu et al., 2014). Linear robust control theory is exploited for performance analysis under different data exchange structures (Hao and Barooah, 2013; Jovanović and Bamieh, 2005; Lin et al., 2012; Middleton and Braslavsky, 2010). Communication delays and other disturbances are also considered (Jin and Orosz, 2014; Qin et al., 2014; Seiler et al., 2004). Most research along this line focuses on asymptotic dynamics and stability; transient traffic dynamics, e.g., traffic oscillations, are not fully addressed.

An ideal car-following control scheme is expected to regulate individual vehicles' car-following behaviors and achieve desired platoon performance. Despite the extensive studies in transportation and control engineering, there remain several unsolved challenges to establish such car-following control. We discuss three major challenges that motivate the research of this paper as follows. (i) Multiple objective are often introduced by desired platoon performance. A vehicle platoon is a complex engineering system, and control design is expected to meet multiple, possibly conflicting, objectives in terms of transient and asymptotic dynamics, including mobility, safety, and traffic dynamic stability. But the transient dynamics issues receive much less attention in the control literature. Furthermore, the conventional CACC technologies mainly focus on individual vehicle's mobility and safety requirements, which may be conflicting to platoon performance. (ii) Achieving desired platoon performance needs to take traffic constraints into account, since connected and autonomous vehicles are subject to various inequality constraints due to physical limitations, safety concerns, and driving comfort consideration. This yields state and control coupled constraints that turn a platoon into a constrained dynamical system and give rise to many difficulties in control design. While certain constraints have been addressed in Cook (2007); Dunbar and Murray (2006); Keviczky et al. (2006); Richards and How (2004), these results often impose restrictive assumptions that are unrealistic to a platoon. (iii) To implement such platoon control, distributed computation is needed. A platoon consists of a large number of vehicles with varying topology. Due to a high computation load and the absence of roadside computing facilities, centralized computation is either inefficient or infeasible. This calls for distributed computation, which takes full advantage of an individual vehicle's computing capability and is more flexible. However, the development of distributed algorithms is rather nontrivial, especially for a system with coupled constraints. Although distributed control schemes are recently proposed in Dunbar and Caveney (2012); Dunbar and Murray (2006); Franco et al. (2008), these schemes focus on stability only, and do not handle state and control coupled constraints.

Inspired by the above-mentioned challenges, this paper develops a novel car-following control scheme based on constrained optimization and distributed computation by exploiting transportation, control and optimization techniques. This control scheme takes vehicle constraints, transient dynamics, and asymptotic dynamics into account, and can be implemented by state-of-art distributed algorithms. We summarize the major contributions of the paper as follows. Throughout the rest of the paper, all vehicles are referred to as connected and autonomous vehicles.

(1) We consider a platoon of connected and autonomous vehicles on a straight roadway, and model the platoon as a multi-agent interconnected dynamic system subject to acceleration, speed, and safety distance constraints. The platoon uses the global information structure such that each vehicle has communication and shares traffic information with all the other vehicles. To handle multiple objectives arising from transient and asymptotic dynamics under the