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A decentralized energy-optimal control framework for connected automated vehicles at signal-free intersections[☆]

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ABSTRACT

We address the problem of optimally controlling connected and automated vehicles (CAVs) crossing an urban intersection without any explicit traffic signaling, so as to minimize energy consumption subject to a throughput maximization requirement. We show that the solution of the throughput maximization problem depends only on the hard safety constraints imposed on CAVs and its structure enables a decentralized optimal control problem formulation for energy minimization. We present a complete analytical solution of these decentralized problems and derive conditions under which feasible solutions satisfying all safety constraints always exist. The effectiveness of the proposed solution is illustrated through simulation which shows substantial dual benefits of the proposed decentralized framework by allowing CAVs to conserve momentum and fuel while also improving travel time.

1. Introduction

Next generation transportation networks are typical cyber–physical systems where event-driven components monitor and control physical entities online. We are currently witnessing an increasing integration of energy, transportation, and cyber networks, which, coupled with human interactions, is giving rise to a new level of complexity in the transportation network and necessitates new control and optimization approaches.

The alarming state of current transportation systems is well documented. In 2014, congestion caused vehicles in urban areas to spend 6.9 billion additional hours on the road at a cost of an extra 3.1 billion gallons of fuel, resulting in a total cost estimated at $160 billion; see Schrank, Eisele, Lomax, and Bak (2015). From a control and optimization standpoint, the challenge is to develop mechanisms that expand capacity *without* affecting the existing road infrastructure, specifically by tighter spacing of vehicles in roadways and better control at the weakest links of a transportation system: the bottleneck points defined by intersections, merging roadways, and speed reduction zones; see Malikopoulos and Aguilar (2013) and Margiotta and Snyder (2011). An automated highway system (AHS) can alleviate congestion, reduce energy use and emissions, and improve safety by significantly increasing traffic flow as a result of closer packing of automatically controlled vehicles. Forming "platoons" of vehicles traveling at high speed is a popular system-level approach to address traffic congestion that gained momentum in the 1990s; see Rajamani, Tan, Law, and Zhang (2000) and Shladover et al. (1991). More recently, a study in Tachet et al. (2016) indicated that transitioning from intersections with traffic lights to autonomous ones has the potential of doubling capacity and reducing delays.

Connected and automated vehicles (CAVs) provide the most intriguing opportunity for enabling users to better monitor transportation network conditions and to improve traffic flow. CAVs can be controlled at different transportation segments, e.g., intersections, merging roadways, roundabouts, speed reduction zones and can assist drivers in making better operating decisions to improve safety and reduce pollution, energy consumption, and travel delays. One of the very early efforts in this direction was proposed in Athans (1969) and Levine and Athans (1966) where the merging problem was formulated as a linear optimal regulator to control a single string of vehicles. Varaiya (1993) has also discussed

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extensively the key features of an automated intelligent vehicle-highway system (IVHS) and proposed a related control system architecture.

In this paper, we address the problem of optimally controlling CAVs crossing an urban intersection without any explicit traffic signaling so as to minimize energy consumption subject to a throughput maximization requirement and to hard safety constraints. The implications of this approach are that vehicles do not have to come to a full stop at the intersection, thereby conserving momentum and fuel while also improving travel time. Moreover, by optimizing each vehicle's acceleration/deceleration, we minimize transient engine operation, thus we have additional benefits in fuel consumption. Several research efforts have been reported in the literature proposing either *centralized* (if there is at least one task in the system that is globally decided for all vehicles by a single central controller) or *decentralized* approaches for coordinating CAVs at intersections. Dresner and Stone (2004) proposed the use of a centralized reservation scheme to control a single intersection of two roads with no turns allowed. Since then, numerous centralized approaches have been reported in the literature, e.g., de La Fortelle (2010), Dresner and Stone (2008) and Huang, Sadek, and Zhao (2012), to achieve safe and efficient control of traffic through intersections. Some approaches have focused on coordinating vehicles to improve the travel time, e.g., Yan, Dridi, and El Moudni (2009), Zhu and Ukkusuri (2015) and Zohdy, Kamalanathsharma, and Rakha (2012). Others have considered minimizing the overlap in the position of vehicles inside the intersection rather than arrival time; see Lee, Park, Malakorn, and So (2013). Kim and Kumar (2014) proposed an approach based on model predictive control that allows each vehicle to optimize its movement locally with respect to any objective of interest. Miculescu and Karaman (2014) used queueing theory and modeled the problem as a polling system that determines the sequence of times assigned to the vehicles on each road.

In decentralized approaches, each vehicle determines its own control policy based on the information received from other vehicles on the road or from a coordinator. Alonso et al. (2011) proposed two conflict resolution schemes in which an autonomous vehicle can make a decision about the appropriate order of crossing the intersection to avoid collision with other manually driven vehicles. Colombo and Del Vecchio (2014) constructed the invariant set for the control inputs that ensure lateral collision avoidance. A detailed discussion of research efforts in this area can be found in Rios-Torres and Malikopoulos (2017a).

The first contribution of the paper is the formulation of an energy minimization optimal control problem for CAVs where the time for each CAV to cross the intersection is first determined as the solution of a throughput maximization problem. We show that the solution structure of the latter problem enables a decentralized energy minimization optimal control problem formulation whose terminal time depends only on a "neighboring" CAV set. An analytical solution of each CAV's optimal control problem without considering state and control constraints was presented in Ntousakis, Nikolos, and Papageorgiou (2016), Rios-Torres and Malikopoulos (2017b) and Rios-Torres, Malikopoulos, and Pisu (2015) for CAVs at highway on-ramps, and in Zhang, Malikopoulos, and Cassandras (2016) for two adjacent intersections. Unlike all these prior formulations, we specify the explicit connection between the energy minimization and throughput maximization problems, do not impose constraints on the terminal CAV speeds, and present a complete analytical solution that includes all state and control constraints. Ensuring that a *feasible* solution to each CAV decentralized optimal control problem exists is nontrivial, as discussed in Zhang, Cassandras, and Malikopoulos (2017). Thus, another contribution is showing that this solution depends on the arrival time of a CAV at a "control zone" defined for the intersection and on its initial speed and then providing a proof (not given in Zhang, Cassandras et al. (2017)) of the existence of a nonempty feasibility region in the space defined by this arrival time and initial speed.

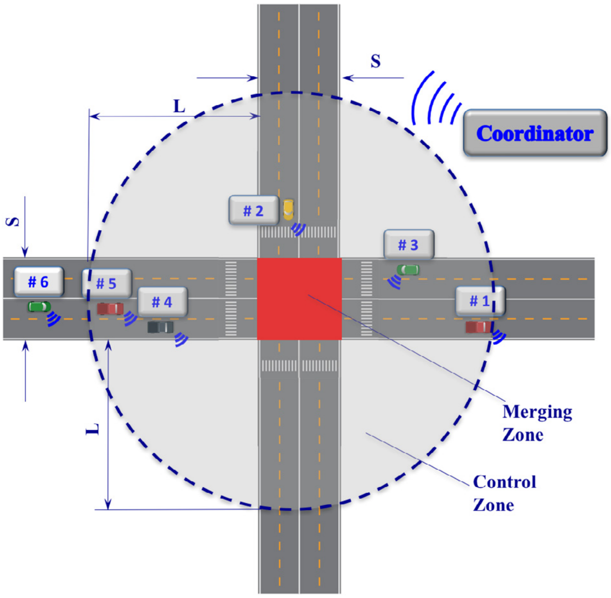

Fig. 1. Intersection with connected and automated vehicles.

The paper is organized as follows. In Section 2, we introduce the modeling framework, formulate the energy-minimization optimal control problem and establish its connection to throughput maximization. In Section 3, we present the decentralized control framework, derive a closed-form analytical solution for each decentralized problem, and show the existence of feasible solutions ensuring that all safety constraints remain inactive. Finally, we provide simulation results in Section 4 illustrating the effectiveness of the proposed solution in terms of significant reductions in both fuel consumption and travel time. Concluding remarks are given in Section 5.

2. Problem formulation

We consider an intersection (Fig. 1) where the region at its center is called *Merging Zone* (MZ) and is the area of potential lateral collision of vehicles. Although this is not restrictive, we consider the MZ to be a square of side S. The intersection has a *Control Zone* (CZ) and a coordinator that can communicate with the vehicles traveling inside the CZ. Note that the coordinator is not involved in any decision for any CAV and only enables communication of appropriate information among CAVs. The distance from the entry of the CZ to the entry of the MZ is L and it is assumed to be the same for all CZ entry points. The value of L depends on the coordinator's communication range capability with the CAVs, while S is the physical length of a typical intersection. In this paper, we limit ourselves to the case of no lane changes and no turns allowed.

Let $N(t) \in \mathbb{N}$ be the number of CAVs inside the CZ at time $t \in \mathbb{R}^+$ and $\mathcal{N}(t) = \{1, \ldots, N(t)\}$ be a queue which designates the order in which these vehicles will be entering the MZ. Thus, letting t_i^m be the assigned time for vehicle i to enter the MZ, we require that

$$t_i^m \geq t_{i-1}^m, \ \forall i \in \mathcal{N}(t), \ i > 1. \tag{1}$$

There is a number of ways to satisfy (1). For example, we may impose a strict first-in-first-out queueing structure, where each vehicle must enter the MZ in the same order it entered the CZ. More