Dynamic programming-based multi-vehicle longitudinal trajectory optimization with simplified car following models

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\section*{A R T I C L E   I N F O}

Article history:
Received 6 February 2017
Revised 25 October 2017
Accepted 25 October 2017
Available online xxx

Keywords:
Traffic flow management
Autonomous vehicle
Vehicle trajectory optimization
Car-following model

\section*{A B S T R A C T}

Jointly optimizing multi-vehicle trajectories is a critical task in the next-generation transportation system with autonomous and connected vehicles. Based on a space-time lattice, we present a set of integer programming and dynamic programming models for scheduling longitudinal trajectories, where the goal is to consider both system-wide safety and throughput requirements under supports of various communication technologies. Newell’s simplified linear car following model is used to characterize interactions and collision avoidance between vehicles, and a control variable of time-dependent platoon-level reaction time is introduced in this study to reflect various degrees of vehicle-to-vehicle or vehicle-to-infrastructure communication connectivity. By adjusting the lead vehicle’s speed and platoon-level reaction time at each time step, the proposed optimization models could effectively control the complete set of trajectories in a platoon, along traffic backward propagation waves. This parsimonious multi-vehicle state representation sheds new lights on forming tight and adaptive vehicle platoons at a capacity bottleneck. We examine the principle of optimality conditions and resulting computational complexity under different coupling conditions.

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\section{1. Introduction}

As population, economic growth and personal travel activities continue to increase, traffic congestion remains as an extremely challenging problem due to limited road capacity and limited budgets for expanding infrastructure. A recently emerging technology, autonomous vehicles or automated vehicles (AV) are likely to create a revolutionary paradigm shift in the near future for real-time traffic system automation and control. AV technology is expected to provide a wide range of new opportunities for managing transportation networks, and also redefines what is tractable regarding full system-wide optimization through a tight integration among vehicles and system managers.

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https://doi.org/10.1016/j.trb.2017.10.012
0191-2615/© 2017 Published by Elsevier Ltd.

Please cite this article as: Y. Wei et al., Dynamic programming-based multi-vehicle longitudinal trajectory optimization with simplified car following models, Transportation Research Part B (2017), https://doi.org/10.1016/j.trb.2017.10.012
Varaiya (1993) outlined an automated highway systems (AHS) to significantly improve highway capacity and safety, in which a hierarchical control mechanism for AVs is provided at different spatial scales, ranging from a network, routes, freeway corridors, to dedicated lanes. In a recent review from the perspective of traffic flow theory and operations, Mahmassani (2016) highlighted many unique features and challenges in the next-generation transportation systems of optimizing and controlling automated and connected vehicles. In the connected environment with different degrees of automation and connectivity supports, we need to not only fully recognize the changing driver/vehicle behavior (including car following and lane-changing), but also design a system-optimal scheduling and control architecture to achieve robust, stable and effective traffic flow management.

In our research, we focus on a longitude vehicle trajectory optimization problem, which is fundamental to many AV applications, such as vehicle platooning or adaptive cruise control. We briefly review the related research topics, including car following models and traffic-flow oriented trajectory optimization.

1.1. Review of car-following models and AVs’ impact on traffic flow characteristics

Since the 1950s, there are a wide range of car following models proposed for vehicles driven by humans. After the earliest car-following models developed by Reuschel (1950) and Pipes (1953), many car-following models were developed based on the response-stimulus mechanism between a lead vehicle and a following vehicle. As examples, Kometani and Sasaki (1958, 1959, 1961), Forbes et al. (1958), Forbes (1963), and Chandler et al. (1958) had developed nonlinear car-following models, respectively. To overcome the complexity of those nonlinear models, Newell (1993, 2002) first presented a simplified car-following theory which is consistent with the macroscopic triangular flow-density relationship. Due to its simplicity without loss of flexibility, the Newell’s simplified car-following models have been calibrated in many locations using real-world trajectory data. For example, Ahn et al. (2004) calibrated the Newell’s car-following model using real-world vehicle trajectory data at signalized intersections. Taylor et al. (2015) applied the time-warping approach to investigate drivers’ situation-dependent perception and reaction to external impetus. In parallel, there are also many studies focusing on calibrating various stochastic and situation-dependent car-following models, to name a few, Hamdar et al. (2009), Laval and Leclercq (2010), Hoogendoorn et al. (2011) and Kim and Mahmassani (2011).

While most car-following models focus on human-operated vehicles, researchers in automated control and artificial intelligence started characterizing the driving behaviors of AVs and their potential impact on road capacity in the 1990s. Reliable actuators and sensors in AVs, as summarized by Ward (1997), have made AVs more available and ready for field tests. There are two types of research efforts in parallel along this research line: one focusing on the interactions between AVs based on vehicle dynamics to derive possible changes to traffic characteristics; the other focusing on overall changes to the performance of road capacities brought by AVs under various conditions. As examples of the first type of research, Horowitz and Varaiya (2000) described the findings from the automated highway system (AHS) development in the 1990s at the California PATH program. In general, the actuators make AVs react much faster than a normal or even sensitive human driver. Sensitive drivers can have a short perception-reaction time of 1.0 s to 1.5 s, as reported by NAHSC (1996), compared to a typical perception-reaction time of 2.0–2.5 s. Further shorter AV reaction times, such as 0.7 s reported by Bose and Ioannou (1999), can lead to closer spacing between cars and a higher roadway capacity. Another important aspect that motivates the development of AHS is based on optimal flow control through reducing or smoothing random errors in human drivers via the deterministic and possibly optimized vehicle trajectory planning/control. An early prototype for single-lane vehicle platooning on automated highways was reported by Alvarez and Horowitz (1999). They designed a safe zone between two platoons according to the distance, relative speed and maximum acceleration and deceleration rates. Horowitz and Varaiya (2000) also evaluated many platooning methods in simulation as well as in the physical test beds. Recently, Lioris et al. (2017) demonstrate that platoons of connected vehicles can double throughput in urban roads based on the analysis of three queuing models and by the simulation of a road network with 16 intersections and 73 links.

A set of adaptive cruise controller (ACC) and the intelligent driver model controller (IDM) by Treiber et al. (2000) were tested by Milanés and Shladover (2014) in different traffic situations in order to measure the actual responses of the vehicles. Talebpour and Mahmassani (2015) proposed a non-linear acceleration framework for autonomous vehicles and evaluated the possible changes to traffic flow stability. Roncoli et al. (2015a, b) proposed a linear lane-based traffic flow model and discussed how to calibrate the model and optimize the traffic flow in the presence of autonomous vehicles. Using the relaxed Pontryagin’s minimum principle, Hu et al. (2016) proposed an optimal controller to improve fuel efficiency for a vehicle equipped with automatic transmission traveling on rolling terrain. Recently, by applying the Improved Intelligent Driver Model (IIDM) in a road traffic simulation package named SUMO, Askari et al. (2017) assess the impact of the maximum vehicle acceleration and variable proportions of adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) vehicles on the throughput of an intersection. The results show that (C)ACC vehicles can obviously increase the urban mobility with little or no cost in infrastructure.

1.2. Review of vehicle trajectory optimization models

Vehicle trajectory optimization and control has been extensively studied in a broader domain, including surface vehicles, aircraft and Unmanned Aerial Vehicles (UAV). As summarized by Betts (1998), nonlinear programming, optimal control, and dynamic programming are classical modeling approaches to describe vehicle dynamics with various constraints and...
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