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Parsimonious shooting heuristic for trajectory design of connected automated traffic part II: Computational issues and optimization

Jiaqi Ma[a], Xiaopeng Li[b,*], Fang Zhou[a], Jia Hu[c], B. Brian Park[d]

[a] Transportation Solutions and Technology Applications Division, Leidos, Inc., Reston, VA 20190, United States
[b] Department of Civil and Environmental Engineering, University of South Florida, FL 33620, United States
[c] Turner Fairbank Highway Research Center, Federal Highway Administration, VA 22101, United States
[d] Department of Civil and Environmental Engineering, University of Virginia, VA 22904, United States

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ABSTRACT

Advanced connected and automated vehicle technologies enable us to modify driving behavior and control vehicle trajectories, which have been greatly constrained by human limits in existing manually-driven highway traffic. In order to maximize benefits from these technologies on highway traffic management, vehicle trajectories need to be not only controlled at the individual level but also coordinated collectively for a stream of traffic. As one of the pioneering attempts to highway traffic trajectory control, Part I of this study (Zhou et al., 2016) proposed a parsimonious shooting heuristic (SH) algorithm for constructing feasible trajectories for a stream of vehicles considering realistic constraints including vehicle kinematic limits, traffic arrival patterns, car-following safety, and signal operations. Based on the algorithmic and theoretical developments in the preceding paper, this paper proposes a holistic optimization framework for identifying a stream of vehicle trajectories that yield the optimum traffic performance measures on mobility, environment and safety. The computational complexity and mobility optimality of SH is theoretically analyzed, and verifies superior computational performance and high solution quality of SH. A numerical sub-gradient-based algorithm with SH as a subroutine (NG-SH) is proposed to simultaneously optimize travel time, a surrogate safety measure, and fuel consumption for a stream of vehicles on a signalized highway section. Numerical examples are conducted to illustrate computational and theoretical findings. They show that vehicle trajectories generated from NG-SH significantly outperform the benchmark case with all human drivers at all measures for all experimental scenarios. This study reveals a great potential of transformative trajectory optimization approaches in transportation engineering applications. It lays a solid foundation for developing holistic cooperative control strategies on a general transportation network with emerging technologies.

* Corresponding author.
E-mail address: xiaopengli@usf.edu (X. Li).

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1. Introduction

Highway traffic is frequently forced to decelerate and accelerate (or stop and go), particularly along signalized arterials due to alternating green and red lights. Vehicles engaged in repeated stop-and-go movements are exposed to high crash risks (Hoffmann and Mortimer, 1994), extra driver discomfort (Beard and Griffin, 2013), and excessive fuel consumption and emissions (Li et al., 2014). Further, when vehicles slow down or stop, traffic throughput decreases and capacity drops (Cassidy and Bertini, 1999), causing excessive travel delay.

In recent years, increasing research efforts have been on vehicle smoothing using advanced vehicle-based technologies on both freeways and arterials. See Part I of this study (Zhou et al., 2016) for a thorough review on this topic. One approach to smooth vehicle trajectories is variable speed limits (VSL) to dynamically regulate traffic speed based on real-time information of traffic states. On freeways, VSL is applied to mitigate sudden brakes that may trigger stop-and-go traffic, and this strategy is also referred to as speed harmonization (see Lu and Shladover (2014); Ma et al. (2016) for reviews on this topic). On signalized arterials, VSL is applied to guide a vehicle to arrive at the intersection during a green phase to avoid a full stop (e.g., Sanchez et al. (2006); Trayford et al. (1984a; 1984b); Wu et al. (2015)). These VSL-based approaches are relatively easy to implement on the existing infrastructure and have been widely deployed around the world (Robinson, 2000). However, VSL can only regulate traffic in an aggregated manner without much control of each individual vehicle's acceleration profile, and its performance is largely dependent on driver compliance (Brinckerhoff, 2010).

The other traffic smoothing approach, the focus of this study, is based on advanced connected and automated vehicle (CAV) technologies that enable precise control of individual vehicle trajectories (e.g., Ahn et al. (2013); Wang et al. (2014a); 2014b)). In addition to freeway speed harmonization, CAV brings opportunities for new paradigms of arterial intersection traffic control. With precise trajectory control, vehicles can either adjust their driving according to existing traffic signal timing plans to smoothly pass the intersection during green phases (e.g., Kamalanathsharma et al. (2013)), or coordinate with each other such that they can cross the intersection without an explicit traffic light like a school of fish (e.g., Dresner and Stone (2008); Lee and Park (2012)).

However, most existing studies mainly address individual trajectory control instead of coordinating a stream of vehicles that interact with each other. Most control methods developed so far either seek algorithm efficiency by ignoring detailed acceleration tuning (e.g., allowing speed jumps) or rely on complex algorithms that may impede real-time applications. Further, the integration of traffic signal timing and vehicle trajectory control is yet to be investigated. To address these research gaps, Part I of this study (Zhou et al., 2016) proposed a parsimonious Shooting Heuristic (SH) algorithm that can efficiently smooth trajectories of a stream of vehicles approaching a signalized intersection by controling detailed acceleration profiles. The SH algorithm represent each infinite-dimensional vehicle trajectory with a few segments of analytical quadratic curves, and therefore efficiently construct a large number of vehicle trajectories subject to physical limits, car-following safety and traffic signal timing. Further, this algorithm uses only a few parameters (i.e., acceleration levels) to control overall smoothness of the stream of vehicle trajectories, and thus it is suitable for real-time traffic smoothing optimization. The Part I paper describes this SH algorithm and reveals its elegant theoretical properties. To complete the entire study, this Part II paper proposes to embed SH into an efficient optimization framework that aims at finding the optimum vehicle trajectories on a signalized highway segment in order to minimize a number of traffic performance measures simultaneously, including travel time, fuel consumption, and safety risks. This paper also discusses properties of SH on optimality and computational complexity. Overall, this paper makes contributions to the literature from the following three perspectives: (1) simplifying the complex multi-trajectory optimization problem and consider only a few control variables, dealing with a small number of analytical trajectory segments; (2) theoretically showing the appealing properties of the SH algorithm on computational complexity and optimality; and (3) conducting numerical experiments to verify efficiency of this proposed optimization framework and draw managerial insights. Note that in this paper, we assume all vehicles are connected automated vehicles that are subject to centralized control. Although this assumption is somewhat utopian and cannot exactly match the reality in the near future when highway traffic is composed of both automated and manual vehicles, the results from this utopian scenario provide insights into the best CAV technologies can achieve and set an ultimate goal for using CAV technologies to improve existing traffic systems.

This paper is organized as follows. Section 2 states the studied CAV trajectory optimization problem, including problem settings, constraints and system objectives. Section 3 briefly reviews the SH algorithm developed in the Part I paper (Zhou et al., 2016), and analyzes its computational complexity and optimality properties. Efficient methods of evaluating the system objectives are also discussed. Section 4 demonstrates the proposed optimization framework, and tests its solution efficiency and related properties with numerical examples. Section 5 concludes this paper.

2. Problem statement

2.1. Trajectory construction problem

This section briefly reviews the problem of constructing a stream of feasible vehicle trajectories on a signalized one-lane highway segment as illustrated in Fig. 1. The details are presented in the Part I paper.

As illustrated in Fig. 1, we consider a highway segment of length L. The set of locations of this segment is $[0, L]$. There is a traffic signal at Location L. The signal timing is fixed with a green phase time of G and a red phase time of R. The signal