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Distributed optimization and coordination algorithms for dynamic speed optimization of connected and autonomous vehicles in urban street networks

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A B S T R A C T

Dynamic speed harmonization has shown great potential to smoothen the flow of traffic and reduce travel time in urban street networks. The existing methods, while providing great insights, are neither scalable nor real-time. This paper develops Distributed Optimization and Coordination Algorithms (DOCA) for dynamic speed optimization of connected and autonomous vehicles in urban street networks to address this gap. DOCA decomposes the nonlinear network-level speed optimization problem into several sub-network-level nonlinear problems thus, it significantly reduces the problem complexity and ensures scalability and real-time runtime constraints. DOCA creates effective coordination in decision making between each two sub-network-level nonlinear problems to push solutions towards optimality and guarantee attaining near-optimal solutions. DOCA is incorporated into a model predictive control approach to allow for additional consensus between sub-network-level problems and reduce the computational complexity further. We applied the proposed solution technique to a real-world network in downtown Springfield, Illinois and observed that it was scalable and real-time while finding solutions that were at most 2.7% different from the optimal solution of the problem. We found significant improvements in network operations and considerable reductions in speed variance as a result of dynamic speed harmonization.

1. Introduction

Connected vehicle technology has provided highly granular traffic information that can be used to enhance traffic management methods. For instance, Feng et al. (2015) and He et al. (2014) developed strategies to control the timing of signalized intersections using connected vehicle information and technology. Letter and Elefteriadou (2017), Ntousakis et al. (2016), and Mohebifard and Hajbabaie (2018) developed metering strategies based on connected vehicle information. Moreover, Levin and Boyles (2016) and Zhu and Ukkusuri (2015) developed dynamic traffic assignment methods for connected vehicle environments, and Zhu and Ukkusuri (2014) developed a method for speed harmonization for connected vehicles.

Speed harmonization provides a great potential to control traffic congestion on freeways and arterial streets by changing vehicles' speed to regulate the traffic. Speed harmonization often activates upstream of active bottlenecks to reduce the speed of vehicles arriving the bottlenecks. Therefore, it improves safety by lowering the speeds, and improves operations by controlling the number of vehicles arriving the bottlenecks. Similarly, speed optimization can regulate the speed and number of vehicles that arrive at signalized intersections. Previous studies have shown that speed harmonization improves traffic safety (Abdel-Aty et al., 2006; Lee et al., 2006) and helps reduce the emission of environmental pollutants (MacDonald, 2008). Moreover, from the operations perspective, it is shown that speed harmonization decreases the travel time (Khondaker and Kattan, 2015) and in general smoothens the flow of traffic (Ghiasi et al., 2017).

Tajalli and Hajbabaie (2018) presented a Dynamic Speed Harmonization (DSH) formulation in a connected urban street network and showed that DSH decreased the network travel time, speed variance, and the total number of stops. Moreover, DSH increased the

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total number of completed trips and average speed under different demand patterns. The approach utilized the Cell Transmission Model (CTM) as a dynamic traffic flow model with a nonlinear objective function aimed at harmonizing speed over the network both spatially and temporally. While this approach could find the optimal speed in medium-sized urban street networks, it was computationally complex, not scalable to large-sized transportation networks, and not real-time. The present paper builds upon the previous work and develops a scalable and real-time solution technique for Dynamic Speed Optimization (DSO) for Connected and Autonomous Vehicles (CAVs) in urban street networks.

This paper develops Distributed Optimization and Coordination Algorithms (DOCA) to solve the DSO problem for CAVs in urban street networks. DOCA decomposes the network-level nonlinear DSO problem into several subnetwork-level (a.k.a. computation node level) nonlinear problems. As a result of this decomposition, the computational complexity of the problem is reduced significantly, and solutions can be found in real-time. Note that the problem will be scalable as long as one computation core is allocated to each subnetwork. DOCA creates effective coordination between each pair of neighboring subnetworks by sharing information on the number of vehicles traveling from one subnetwork to another, the available capacity, and the average speed of the receiving subnetwork. Besides, the signal status of the downstream subnetwork is shared between the controllers. Information from all neighboring subnetworks will be implemented in the nonlinear DSO program of each subnetwork. The coordination pushes the solution toward optimality and ensures finding near-optimal solutions. Finally, DOCA is integrated into a Model Predictive Control (MPC) approach to reduce problem complexity further and account for adaptive transportation demand and capacity.

In the remainder of this paper, a review of the relevant literature is presented. Then, the problem formulation and solution technique are detailed. The case study and the results of the DSO problem will be discussed next, and finally, concluding remarks are presented.

2. Background

2.1. Speed harmonization

Speed harmonization strategies are utilized to improve traffic performance on freeway facilities, arterial streets, and urban street networks. Abdel-Aty et al. (2006), Ha et al. (2003), Robinson (2000) and Smulders (1990) have shown that speed harmonization helps reduce the number of crashes in freeways by adjusting the speeds of vehicles. Besides, Aziz and Ukkusuri (2012) and MacDonald (2008) have shown that speed harmonization reduces emission rates. In a connected vehicle environment, Khondaker and Kattan (2015) showed that Variable Speed Limit (VSL) strategies reduced total travel time and fuel consumption on freeway facilities by 20% and 16%, respectively. Moreover, Grumert et al. (2015) and Ghiasi et al. (2017) showed that speed harmonization smoothened traffic flow on freeway facilities.

In arterial streets, advisory speed strategies help reduce fuel consumption by preventing excessive number of stops at signalized intersections (Kamalanathsharma et al., 2015; Wan et al., 2016; Xia et al., 2013; He et al., 2015). Advisory speed strategies can be applied to individual vehicles (Almqvist et al., 1991) or the platoon leader (Sanchez et al., 2006). Second ordered traffic flow models are mostly utilized to find the optimal acceleration and deceleration rates for finding advisory speeds on arterial streets (Mandava et al., 2009).

Most network-level studies considered speed limit optimization as a static mathematical problem (Wang, 2013; Yang et al., 2012, 2013; Yan et al., 2015). Wang (2013), Yang et al. (2013), and Yan et al. (2015) proposed bi-level speed limit design problems, where the speed limits were calculated in the upper level and the static user equilibrium link flows were found in the lower level under the predefined speed limits. A study by Zhu and Ukkusuri (2014) has addressed dynamic speed limit control problem in a connected vehicle environment. This study aimed to minimize travel time and environmental emissions and found speed at each network link over the study period using Markov Decision processes. This approach did not guarantee the optimality of the solutions as it was a reinforcement learning process, where the optimal actions might not be found. The results of this study showed that dynamic speed limit control in a connected vehicle environment reduced network travel time and emissions by 18% and 20%, respectively.

Tajalli and Hajbabaie (2018) showed that dynamic speed harmonization in connected urban street networks improved traffic operations significantly. They formulated the DSH as a nonlinear mathematical program and converted it to a linear program utilizing characteristics of fundamental traffic flow diagram. The study showed that the DSH reduces average speed in links upstream to intersections, increases the average speed in the neighborhood of intersections, and significantly reduces the number of stops. For instance, in a network with saturated demand pattern, the travel time, speed variance, and number of stops were reduced by 5.4%, 20.2%, and 16.8%, respectively. Moreover, the average speed and the total number of completed trips increased by 5.9% and 4.0%, respectively.

2.2. Strategies to reduce the computational complexity of optimization problems

The complexity of traffic control problems is often reduced in the literature by decomposing the network to several subnetworks and optimizing them individually. More explanations on two classes of these approaches follow:

2.2.1. Decomposition approaches for traffic control

Tettamanti and Varga (2010) solved the signal timing problem using Lagrangian Relaxation (LR) utilizing an MPC solution technique. The quadratic objective function of this problem aimed at minimizing queue length at intersections. They found the dual of this problem and solved it iteratively such that each intersection found its corresponding Lagrangian multipliers. Determining the