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Real-time energy-efficient traffic control via convex optimization

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ABSTRACT

This article proposes a macroscopic traffic control strategy to reduce fuel consumption of vehicles on highways. By implementing Greenshields fundamental diagram, the solution to Moskowitz equations is expressed as linear functions with respect to vehicle inflow and outflow, which leads to generation of a linear traffic flow model. In addition, we build a quadratic cost function in terms of vehicle volume to estimate fuel consumption rate based on COPERT model. A convex quadratic optimization problem is then formulated to generate energy-efficient traffic control decisions in real-time. Simulation results demonstrate significant reduction of fuel consumption on testing highway sections under peak traffic demands of busy hours.

1. Introduction

Large scale complex transportation system is one of the indispensable infrastructures in urban and rural areas. The dramatically increasing demands of transportation service leads to traffic congestion, energy wasting and pollution, as well as safety issues. To deal with these issues, intelligent traffic management strategies relying on advanced sensing, communication, and high performance computation techniques are attracting researchers' attention. Recent work in areas of intelligent transportation systems mostly focuses on modeling and reducing travel time (Daganzo, 1995; Lu et al., 2008), minimizing delay (Sims and Dobinson, 1980; Guler et al., 2014; Li et al., 2016), or controling traffic density (Verghese et al., 2016). If fuel consumption is considered in evaluating the transportation system performance, it is necessary to analyze the effectiveness of current traffic control systems in terms of energy efficiency while guaranteeing the accomplishment of transportation tasks in desired time.

Existing traffic control strategies are categorized into two application areas, i.e., urban roads and freeways. For traffic control of urban roads, developed work mainly focuses on signal-timing optimization. For example, a signal control system, named RHODES, aims to improve throughput and reduce the delay (Mirchandani and Head, 2001). Another example (Putha et al., 2012) employs the ant colony optimization algorithm to solve large scale traffic network problems. In areas of freeway traffic control, typical approaches include ramp metering control, such as ALINEA (Papageorgiou et al., 1991) and METALINE (Messner and Papageorgiou, 1990), and dynamic speed limits control, e.g. the SPECIALIST proposed in Hegyi et al. (2008) for shockwave elimination. Furthermore, some of these work combine ramp metering and dynamic speed limits control to generate hybrid control commands. For example, in order to prevent traffic breakdown and relieve congestion, work in Hegyi et al. (2005) presents a predictive control approach for coordination of both ramp metering and dynamic speed limits.

An energy-efficient transportation system aims to reduce fuel consumption and emissions, e.g. CO, NO, CH_4, through eco-driving guidance. Existing eco-driving strategies for individual driving guidance focuses on training drivers behaviors, i.e., smooth acceleration, maintaining steady speeds, avoiding too fast speed, etc., which has been verified to improve fuel economy on the order of

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5–20% (Barkenbus, 2010). However, changing drivers' behaviors is a long-term effort and static driving advices may not guarantee prominent effects in dynamic traffic environments. Instead, recent studies concentrate on traffic control and management strategies. For example, work in Liu et al. (2017) uses model predictive control (MPC) for traffic network based on a multi-class macroscopic traffic flow and emission model. Incorporated with end-point penalties, total time spent and emissions are further reduced. Another MPC-based method descibes an efficient en-route diversion strategy for real-time traffic flow control in Luo et al. (2016). More energy-efficient traffic control approaches can be found in Pasquale et al. (2015), Jamshidnejad et al. (2018), and Han et al. (2016), where the authors present nonlinear optimal control and gradient-based method in a MPC framework. However, although macroscopic traffic flow model, e.g. FASTLANE and METANET, have been adopted in energy-efficient traffic management, it is time consuming to find a convergent solution when a highly nonlinear traffic flow model is considered (Zegeye, 2011). Speed intervals have been used to obtain an approximate solution without solving highly nonlinear dynamics, which results in accumulative errors over time (Dai et al., 2015).

This work focuses on managing one type of highway infrastructure, dynamic speed limit signs, to control traffic flow speeds in order to reduce total fuel consumption during a specific time period. We adopt Lighthill-Whitham-Richard (LWR) macroscopic traffic flow model, introduced by Ligthhill and Whitham in the 1950s (Lighthill and Whitham, 1955), and COPERT fuel consumption estimation model (Ntziachristos et al., 2000). Inspired by Barron-Jensen/Frankowska (B-J/F) solution for Hamilton-Jacobi (HJ) PDEs (Barron and Jensen, 1990), we use B-J/F solution to Moskowitz HJ PDEs to obtain exact solutions without approximation (Mazaré et al., 2011). It generates an explicit expression of solution based on a pre-specified fundamental diagram associated with initial and boundary conditions (Greenshields et al., 1935; Claudel and Bayen, 2010a). Those analytical solutions are handled as model constraints incorporated in the optimization problem formulation. Furthermore, the solutions to Moskowitz HJ PDEs are simplified based on roadway decomposition and traffic status. Combing the simplified solution to Mozkowitz HJ PDEs with the quadratic formulation of COPERT, we formulate the energy-efficient traffic control problem as a convex quadratic optimization problem (CQOP). The convex nature of the problem formulation guarantees convergence to a global optimal solution within polynomial computational time, which makes the approach feasible for real-time traffic control.

The contribution of this article include the following aspects. (1) Different from previous work that adopt triangular fundamental diagram for the derivation of explicit solution to Moskowitz HJ PDEs, new solution expressions are developed and simplified based on a parabolic shaped fundamental diagram associated with initial and boundary conditions. (2) By incorporating simplified solutions in model constraints, an energy-efficient traffic control problem is formulated as CQOP and embedded in a real-time traffic management scheme to efficiently search for optimal commands. (3) Beyond the theoretical development in earlier work (Zu and Dong, 2016), we implement CQOP in VISSIM based on microscopic traffic simulation environment and real-world collected data. By constructing a Component Object Model (COM) interface, the MATLAB generated control commands are connected with VISSIM simulation environments. The simulation based on a more general model and real-world collected data plays a critical role in demonstrating the feasibility and effectiveness of our proposed traffic control strategy in practical scenarios using existing highway facilities.

The rest of this article is organized as follows. We first introduce the problem and traffic flow model in Section 2. The general solution of Moskowitz HJ PDEs and its simplified solution are described in Section 3. Section 4 depicts the fuel consumption problem using COPERT fuel consumption estimation model and formulation of the energy-efficient traffic control problem. Simulation examples are demonstrated in Section 5 to verify efficiency and improved performance of the proposed method. We address the concluding remarks and summary in Section 6.

2. Problem statement and traffic flow dynamics

2.1. Problem statement

A one-dimensional, uniform highway section considered in this article is represented by $[\xi,\chi]$, where ξ and χ are upstream and downstream boundaries. We denote the vehicle density as $\rho(t,x)$ per unit length for local position $x \in [\xi,\chi]$ at time $t \in [0,t_M]$. The inflow and outflow are denoted as Q_ξ and Q_χ, respectively. The vehicle velocity is a function of ρ and is denoted as $v = v(\rho(t,x))$. The goal of the proposed traffic control strategy is to minimize the fuel consumption of vehicles on the concerned highway section for a desired time interval based on current traffic status by controlling dynamic speed limit signals, shown as an example in Fig. 1, where

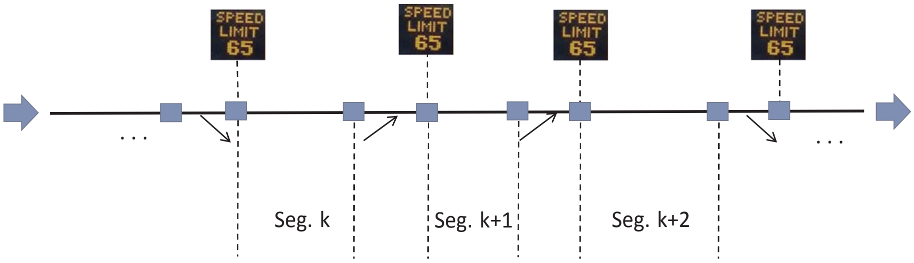

Fig. 1. Example of a traffic control scenario. Arrows at upstream and downstream boundaries refer to the vehicle flow directions. Arrows along main road section represent on-ramps and off-ramps. Rectangles indicate installed sensors for measuring traffic volume. Dynamic speed limit signs are located at the starting point of each road segment.