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Data-driven linear decision rule approach for distributionally robust optimization of on-line signal control

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Abstract

We propose a two-stage, on-line signal control strategy for dynamic networks using a linear decision rule (LDR) approach and a distributionally robust optimization (DRO) technique. The first (off-line) stage formulates a LDR that maps real-time traffic data to optimal signal control policies. A DRO problem is then solved to optimize the on-line performance of the LDR in the presence of uncertainties associated with the observed traffic states and ambiguity in their underlying distribution functions. We employ a data-driven calibration of the uncertainty set, which takes into account historical traffic data. The second (on-line) stage implements a very efficient linear decision rule whose performance is guaranteed by the off-line computation. We test the proposed signal control procedure in a simulation environment that is informed by actual traffic data obtained in Glasgow, and demonstrate its full potential in on-line operation and deployability on realistic networks, as well as its effectiveness in improving traffic.

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1. Introduction

Signalized intersections are often the most restrictive bottlenecks in urban traffic networks. For this reason, urban traffic control strategies tend to focus on the operation of individual intersections (e.g., see Miller, 1963; Robertson and Bretherton, 1974; Guler and Cassidy, 2012; Gayah and Daganzo, 2012). And, operations at individual signalized intersections are often used to describe traffic conditions in urban environments (Highway Capacity Manual, 2000).

Optimizing signal timing plans at these locations has been the subject of much research. The optimization procedure employed typically takes on one of two forms: 1) those developed based on historical information, often referred to as fixed timing plans; and, 2) those that are fully responsive to current traffic conditions, often referred to as adaptive (or on-line) signal controls. The former case is less efficient, as signal timings are not able to adapt to naturally occurring variations in traffic flows. This can result in significant periods of queuing and delays during large fluctuations in traffic flows. In the latter case, signal parameters such as cycle lengths and splits between competing movements are determined based on real-time traffic data.

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Real-time signal controls react to unpredicted traffic conditions in a more timely fashion and are more robust to local network disruptions when compared to fixed timing plans. From an optimization point of view, a well-defined function is required to relate the signal parameters to specific objective being optimized. Specific objectives in the literature include the minimization of vehicle delay (Zhang et al., 2010; Sun et al., 2006), minimization of passenger delay (Christofa and Skabardonis, 2011), minimization of number of stops (Lucas et al., 2000), and maximization of total throughput (Chang and Sun, 2004; Han et al., 2014). However, analytical formulations are not always readily available for these objective functions. Furthermore, the objectives often tend to be non-linear functions of the signal parameters and the traffic flow variables, as in the case of traffic delays or vehicle stops. The resulting optimization problem usually becomes a computationally complex non-linear and/or non-convex mathematical program that is difficult to solve exactly. Instead, many real-time signal optimization procedures are developed using heuristic approaches such as genetic algorithm and fuzzy logic (e.g., Foy et al., 1992; Chiu and Chand, 1993; Ceylan and Bell, 2004; Murat and Gedizlioglu, 2005). Unfortunately, solutions obtained in this way are usually inexact and suboptimal.

In this paper, we propose a novel *linear decision rule* (LDR) approach for responsive signal control, which takes into account both historical and real-time traffic data. In addition, we employ a *distributionally robust optimization* (DRO) formulation and a data-driven calibration of the underlying uncertainty set to handle both within-day and day-to-day variations in traffic flow. The proposed methodology involves a two-stage operation of signal control. In the first (off-line) stage, a distributionally robust optimization (DRO) problem is formulated based on a linear decision rule (LDR). The goal of this formulation is to optimize the on-line performance of the decision rule with a range of uncertainties associated with the underlying distribution of the network flows, and to ensure its sound performance even with the worst-case scenario. Adding novelty to the methodology is a data-driven procedure for the calibration of the uncertainty set with arbitrary number of samples and confidence level. Furthermore, we propose two solution schemes for the off-line computation: one based on a mixed integer linear program, and the other based on a metaheuristic search. In the second (on-line) stage, the optimized LDR obtained from the first stage is used to convert real-time information into signal control parameters in a timely fashion. Moreover, the performance of such a simple decision rule is guaranteed by virtue of the DRO performed off line. The proposed signal decision architecture takes into account average traffic pattern while capturing its stochastic component. The proposed method combines solutions obtained from mathematical programs with a practical decision rule that can be fully realized in real time. It also resorts to the theory of distributionally robust optimization and data-driven calibration of the uncertainty set, and thus guarantees optimality under various stochastic circumstances. One of the primary benefits of this approach is that all of the expensive computations are performed off line, making real-time control easily implementable.

Our proposed model significantly differs from existing ones in the literature. First of all, our model incorporates a linear decision rule approach in determining the optimal signal strategy as a response to the real-time traffic states. This approach assumes that the responsive signal control is a linear mapping of the observed traffic states and computes its optimal parameters to improve the system performance. In comparison with the signal strategies based on historical and/or real-time information in the literature, our approach addresses the sophistication of a traffic system with a mathematical program that incorporates the Lighthill-Whitham-Richards traffic flow model (Lighthill and Whitham, 1955; Richards, 1956). This enables the model to capture complex traffic behaviors including physical queuing, shock waves, and spillbacks. Moreover, both the on-and-off signal model and the continuum signal model (Han et al., 2014) are considered and incorporated. [1] In comparison with the current modeling approaches that rigidly preset the signal sequences for an assumed incoming flow, the linear decision rule determines the optimal signal timing plan in response to both real-time and historical traffic states and is, therefore, potentially more flexible, robust, and responsive. Another advantage of this approach is that the computation of the optimal decision rule can be conducted in an off-line environment and thus significantly reduces the real-time computational efforts.

Secondly, the proposed model allows the traffic network flows to be uncertain and mitigates the impacts of uncertainty with a distributionally robust optimization (DRO) procedure. DRO bridges between two popular classes of optimization techniques under uncertainty: *stochastic programming* (SP) and *robust optimization* (RO). The former

[1] The continuum signal model approximates the average effect of the periodic and on-and-off signal controls at an intersection by replacing the binary controls with a continuous parameter (the green ratio). The continuum signal model predicts the aggregate traffic dynamics that exist at signalized intersections and networks without relying on detailed information of vehicle movements and signal phasing plans, and thus entails improved computational efficiency.