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Stochastic programming model for oversaturated intersection signal timing

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ABSTRACT

In large cities, signalized intersections often become oversaturated in rush hours due to growing traffic demand. If not controlled properly, they may collectively result in serious congestion. How to schedule traffic signals for oversaturated intersections has thus received increasing interests in recent years. Among various factors that may influence control performance, uncertainty in traffic demand remains as an important one that needs to be further studied. In some recent works, e.g., Yin (2008) and Li (2011), robust optimization models have been utilized to address uncertainty in traffic demand and to design fixed-timed signal control for oversaturated intersections. In this paper, we propose a stochastic programming (SP) model to schedule adaptive signal timing plans that minimize the expected vehicle delay. Our numerical experiments show that the proposed SP model better describes the fluctuations of traffic flows and outperforms the deterministic linear programming (LP) model in total vehicle delay, total throughput, and vehicle queue lengths. Moreover, we compare the proposed SP model with the adaptive signal control model proposed in Lin et al. (2011) to provide insights on such improvements from green time utilization and queue balancing perspectives. Furthermore, we study the feasibility of the proposed SP model in practice, with an emphasis on the required sample sizes.

1. Introduction

In large cities, signalized intersections often become oversaturated in rush hours due to growing traffic demand. In such situations, the vehicle inflow rate exceeds the intersection outflow rate at least in one branch (Green, 1967; Carstens, 1971). A number of oversaturated intersections then form oversaturated arterials (Lieberman et al., 2000) and oversaturated networks (Girianna and Benekohal, 2002). As a result, delays of vehicles increase dramatically and lead to congestions, environmental problems, and economic loss (Federal Highway Administration, 2008).

One major cause of oversaturated intersections is improper signal timing plans. Among various factors that may result in improper signal timing plans, failure to appropriately address uncertainty in traffic demand remains as an important one that needs to be further studied. Heydecker (1987) showed that the signal timing plan dedicated to average inflows often fails to yield satisfactory performance, if the fluctuation degree of traffic flows is significant. Yin (2008) used the traffic data collected at Gainesville, Florida to show that the traffic flow varies significantly during 9:00–11:00 am at the studied intersection.

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There were several approaches to handle uncertainties and improve the reliability of traffic control systems (Calvert et al., 2012). We can roughly categorized these approaches into two kinds of schemes.

The first kind of schemes is robust fixed-time signal control, which aims to maintain stable performance under fluctuating traffic conditions. Fixed-time signal control scheme assigns a timing plan with pre-determined cycle length, phase sequences, and phase lengths under certain traffic demands. This scheme mainly uses historical traffic measurements to set the timing plan (Denney et al., 2008). It is world-widely used, especially in developing countries, because of its simplicity and easy maintenance.

Robust fixed-time signal control scheme adopts risk-averse type planning strategy so as to reduce the possible maximum delay under extreme situations. For example, Yin (2008) studied three robust fixed-time signal timing models: mean–variance model, conditional value-at-risk (CVaR) model, and min–max model. It was shown that the performance of an isolated intersection can be improved, if the fluctuations of inflow rates were considered appropriately via these models. The optimization problems for the first two models are easy to solve; while no globally optimal solution can be easily found for the min–max model. In Li (2011), a discretization approach was proposed to solve the min–max model using binary integer programs.

The second kind of schemes is adaptive signal control, which aims to dynamically respond to the fluctuating traffic demands. Adaptive signal control scheme changes the timing plan in every cycle using real-time traffic measurements and usually also real-time prediction of future traffic demands to set the timing plan (Burger et al., 2013; Li et al., 2014). It gains substantially increasing interests nowadays, because of its flexibility and capability to further improve traffic control performance.

For oversaturated intersection, many existing adaptive signal control models adopt greedy algorithms so as to fully utilize the green time (Liu et al., 2008; Zhao et al., 2011; Li et al., 2013). However, some initial tests show that, when the uncertainty of traffic demand cannot be neglected, greedy algorithms may not always be a good choice (Park and Kamarajugadda, 2007; Park et al., 2001).

Recently, Lin et al. (2011) proposed a control model to dynamically update green time allocation so that the proportions of queue lengths in all directions can be well balanced. They showed that the performance of this control model is robust to random fluctuation in traffic demands. More importantly, this model significantly reduces the total vehicle delay compared with the signal timing plan optimized for average inflows, although it does not attempt to minimize total vehicle delay directly. However, their model selects the best alternative from a limited set of predetermined timing plans and thus offers limited flexibility.

In this paper, we consider adaptive signal control against uncertainty in traffic flows from a different viewpoint. Our major contributions can be summarized as follows.

First, we propose a two-stage stochastic programming (SP) model to incorporate uncertainty in traffic flows and to generate efficient signal timing plans. This SP model takes the risk-neutral planning strategy that minimizes the expected total vehicle delay of the intersection, subject to the intersection capacity and other operational constraints. Instead of solving a complex optimization problem of signal timing plans of several consecutive cycles like Han (1996), we recursively solve a series of two-stage stochastic programs, each for the signal timing plan of two consecutive cycles. We choose to use recursive two-stage stochastic programs rather than multistage stochastic programs for several consecutive cycles based on historical traffic statistics. Comparing with multistage stochastic programs, two-stage stochastic programs are significantly less demanding on both computational capability of signal control device and solution time. This makes the proposed signal timing plan strategy easy to implement in practice. Furthermore, by recursively solving two-stage stochastic programs, at the beginning of each cycle, we are able to update the estimates on the traffic demands of the next cycle based on real-time traffic information (Vlahogianni et al., 2014). This strategy not only significantly reduces computational cost but also makes better use of the updated traffic information.

Second, besides considering the inflow rate uncertainty, we also consider uncertainty in the outflows of intersections in the proposed SP model. In most of the aforementioned studies, the outflow rates were assumed to be deterministic and the saturation flow rate is used as the outflow rate for any through direction. However, recent studies reveal that vehicle outflows may also fluctuate because of the uncertainty in driver behaviors (Michael et al., 2000), pedestrian intrusion (see, e.g., Fig. 1), and environmental disturbance.

The most frequently-used measure of stochastic outflows is the departure headway distribution models (Luttinen, 1992; Jin et al., 2009). Departure headway is defined as the elapsed time between two consecutive vehicles departing from the intersection, when the light turns green (Niittymäki and Pursula, 1996). During the last four decades, departure headway distributions have been examined with the aid of the fast developing video analysis methods in many cities worldwide (Al-Ghamdi, 1999; Bonneson, 1994; Hung et al., 2002; Lee and Chen, 1986; Moussavi and Tarawneh, 1990; Zhang et al., 2007).

Notice that the average vehicle departure headway is the reciprocal of the average outflow rate, the outflow rate should therefore be modeled as stochastic rather than deterministic. Our recent paper (Tan et al., 2013) illustrated how to calculate the distributions of outflow rate based on the measured departure headways. It was further revealed that, given a certain green time and assumed no pedestrian/bicycle intrusions, the effective outflow rate roughly follows a certain normal distribution due to stochastic vehicle departure headways. Since pedestrian and bicycle intrusions frequently happen in many developing countries, see Fig. 1 as an example, the variance of empirical outflow rate is often doubled or tripled.