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Multi-stage stochastic program to optimize signal timings under coordinated adaptive control

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ABSTRACT

In the wake of traffic congestion at intersections, it is imperative to shorten delays in corridors with stochastic arrivals. Coordinated adaptive control can adjust green time flexibly to deal with a stochastic demand, while maintaining a minimum through-band for coordinated intersections. In this paper, a multi-stage stochastic program based on phase clearance reliability (PCR) is proposed to optimize base timing plans and green split adjustments of coordinated intersections under adaptive control. The objective is to minimize the expected intersection delay and overflow of the coordinated approach. The overflow or oversaturated effect is explicitly addressed in the delay calculation, which greatly increases the modeling complexity due to the interaction of overflow delays across cycles. The notion of PCR separates the otherwise related green time settings of consecutive cycles into a number of stages, in which the base timing plan and actual timing plan in different cycles are handled sequentially. We then develop a PCR based solution algorithm to solve the problem, and apply the model and the solution algorithm to actual intersections in Shanghai to investigate its performance as compared with Allsop's method and Webster's method. Preliminary results show the PCR-based method can significantly shorten delays and almost eliminates overflow for the coordinated approaches, with acceptable delay increases of the non-coordinated approaches. A comparison between the proposed coordinated adaptive logic and a coordinated actuated logic is also conducted in the case study to show the advantages and disadvantages.

1. Introduction

Signal control can be broadly classified into three categories: pre-timed control, actuated control, and adaptive control (Wilshire et al., 1985; Shenoda and Machemehl, 2006). Pre-timed signals are the most widely implemented control methods, despite their limited ability to handle varying traffic conditions. Actuated signals can extend or cut off green splits based on real traffic conditions detected (Newell and Osuna, 1969). The changes in cycle length or green splits, however, are still subject to a set of predefined, fixed control parameters such as minimum green, maximum green and gap-out interval that are not responsive to changing traffic patterns (Zheng et al., 2010). Adaptive control is a relatively new method, which adjusts

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green splits continuously, based on the anticipated arrivals in each cycle. Adaptive control has received increasing interest recently due to its additional flexibility to respond to demand fluctuations and its capability of distributing green time equally for all approaches (Wolshon and Taylor, 1999). Mirchandani and Head (2001) proposed a real-time traffic-adaptive signal control system. Its control architecture can be decomposed into hierarchical sub-problems that allow for fast solutions. Yu and Recker (2006) first formulated the adaptive signal control problem as a decision making problem with the Markov process model. Cai et al. (2009) employed approximate dynamic programming to revise the timing plans at a fast rate for isolated intersections operated under adaptive controllers.

Pre-timed, actuated and adaptive control methods can be used for either isolated intersections or coordinated arterials. Isolated control intends to find the optimal signal settings for an individual intersection (Koonce et al., 2008). Sun et al. (2016) proposed a queue-based real-time control strategy for an oversaturated intersection. In the queuing period, the queue length is restricted by an upper bound whereas in the dissipation period, all queues are eliminated at the earliest time. Lee et al. (2015) developed a real-time estimation approach for lane-based queue length. Yan et al. (2014) investigated the capacity optimization problem through phase swap sorting strategy. Researchers also combined signal timings with other considerations, such as emissions (Li et al., 2011), automated vehicles (Li et al., 2014), and pedestrians (Ma et al., 2015). Coordinated control intends to provide a green wave along streets in order to reduce travel time, stops and delay. Signal coordination can be used to provide smooth vehicle progression along corridors (Cheng et al., 2006; Spall and Chin, 1997; Gartner et al., 1975).

Coordinating pre-timed signals only requires a common and fixed cycle time for a series of intersections. Offset is carefully calculated such that a platoon can travel along the mainline street without stops (Koonce et al., 2008). Coordinated actuated systems fix the cycle time, gap out interval, minimum green, maximum green and yield point, but allow green splits and offsets to change with vehicle arrivals. Previous studies have demonstrated good performance of the coordinated actuated systems in terms of delay and travel time, especially at intersections with high demand variances (Zheng and Recker, 2013; Lee and Messer, 2003; Skabardonis et al., 1998). Among the existing studies, one group focuses on optimizing offsets to improve the performance of coordinated actuated signals. The system parameters, like common cycle and offset, and the individual parameters, like green splits, are detached and optimized separately (Yin et al., 2007). Another group of studies aims to optimize the timing plans of all intersections simultaneously, with the help of microsimulation software, such as VISSIM or SYNCHRO (Stevanovic et al., 2009). Recently, Zhang and Lou (2013) drew upon the convenience of the cell transmission model and established a mixed integer nonlinear programming model for coordinated actuated signals. Cesme and Furth (2014) proposed a new self-organizing scheme based on isolated actuated control with additional rules to create coordination. He et al. (2014) implemented signal coordination in actuated controls by adding virtual coordination requests to the model formulation.

Coordinated adaptive systems also prove their great advantages in reducing delay and travel time under various road networks, traffic and driving conditions since they can respond to real-time traffic patterns (http://www.scats.com.au). In addition, the adaptability of an actuated controller is restricted by a set of predefined, fixed control parameters, whereas an adaptive controller is not. The most popular adaptive system that allows signal coordination includes SCATS (Sydney Coordinated Adaptive Traffic System) and SCOOT (Split Cycle Offset Optimization Technique) (Robertson and Bretherton, 1991; Sims and Dobinson, 1980). Based on detector data and the current signal timing plan, future traffic volume is predicted. Such information is then sent to a centralized system to update the green splits and offsets, so that the best timing plan can be found for the operation of the entire network.

The main challenge to coordinate actuated/adaptive signals arises from the interaction of variable control parameters such as green splits and fixed parameters such as cycle length. Unlike conventional adaptive control, the cycle length in such a system is fixed, and the green splits of the coordinated phases can only be extended to maintain a minimum through-band, while the green split of a non-coordinated phase can be decreased, if needed. Therefore, it is necessary to investigate the impacts of green split changes due to stochastic vehicle arrivals when deriving the optimal cycle length. However, only a few studies have addressed this issue in the context of coordinated actuated control (Zhang and Lou, 2013), but not for adaptive systems. The second challenge is the offset adjustment in signal coordination. Existing studies typically set the coordinated phase as the last phase. When low demand is detected on the non-coordinated phase, its green time is cut off and the spare green time is given to the coordinated phase. Hence, the coordinated phase can begin earlier than its nominal starting time but always ends at its nominal ending time. Cesme and Furth (2014) pointed out that this scheme could cause spillback at downstream intersections or starvation at this particular intersection, due to the biased early return to green. This issue calls for a proper offset setting to balance between spillback and starvation. Abbas et al. (2001) designed a real-time offset transitioning algorithm to mitigate the effect of early-return-to-green problems. This algorithm, however, becomes unstable under oscillatory traffic patterns caused by spillbacks. Moreover, the impacts of overflow on the performance of coordinated adaptive control have not been well-studied in literature. On one hand, if overflow occurs in the coordinated approach and is not eliminated on time, it will not only affect the current cycle but also the following several cycles, which may eventually block the upstream intersection and ruin signal coordination. On the other hand, insufficient green splits for the non-coordinated phase may lead to overflow of side traffic, which also substantially increases the total intersection delay. Indeed, the overflow problem should be addressed well, to sustain the effectiveness of signal coordination.

In light of these challenges, this paper studies an adaptive signal optimization problem under coordinated control, with a particular focus on reducing overflow in the coordinated phase considering stochastic vehicle arrivals and signal truncation between adjacent intersections. The synchronized intersections operate under a base timing plan, which ensures good