Adaptive coordinated traffic control for stochastic demand

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A B S T R A C T

Traffic arrivals at intersections are inherently uncertain. This paper develops an adaptive co-ordinated traffic control approach in the presence of traffic demand uncertainty via the notion of Phase Clearance Reliability (PCR). We propose a method to adjust signal offset adaptively in order to deal with stochastic demands. Based on the cumulative queuing regime, this study first extends the delay models, which are usually formulated for isolated intersections, to the case of coordinated intersections by explicitly incorporating the effects of residual queue and signal offset. Two types of delay formulae are considered regarding two different arrival patterns on the intersection approaches, i.e. coordinated approach and non-coordinated approach delay. We then formulate a two-stage stochastic program to optimize (minimize) the expected total delay for the coordinated control system. The base timing plan is derived at the first stage, while the recourse decisions of adaptive signal offsets are made at the second stage to compensate for the overflow effects. Furthermore, a PCR-based gradient solution algorithm is developed to solve the two-stage stochastic program. The case study on a test network confirms the effectiveness of the proposed PCR-based control method in terms of minimizing average total delay. The optimal control performance stems partly from the short cycle lengths, which are attributed to the fact that part of the random arrivals are addressed by adjusting the signal offsets adaptively. This effective use of signal offset provides a new perspective for designing coordinated signal control plans.

1. Introduction

Traffic signal control has long been recognized as one effective means of traffic management in urban area. Signal coordination, which is designed to form a vehicle platoon that can proceed through a series of intersections with possibly no stops and hence little delay, offers great benefits for traffic operations along arterials. Gazis (1964) first pointed out that handling the coupling of inter-sections would be more effective than tackling them independently as isolated control. Coordinated signal control has been devel-oped in many well-known adaptive control systems. Examples include SCOOT (Split, Cycle and Offset Optimization Technique) and SCATS (Sydney Coordinated Adaptive Traffic System) (Robertson and Bretherton, 1991; Sims and Dobinson, 1980).

Optimal signal control plans are usually determined according to some objectives, such as minimization of network total delay or maximization of network capacity. One commonly used way of formulating the objective functions for control optimization is to model the traffic control system as a D/D/1 queuing regime and calculate the total delay accordingly (Allsop, 1972). The control optimization problem can then be viewed as to search for signal timing variables that would lead to a minimal total delay. In addition to cycle length and green split, offset is another crucial timing variable in defining a coordinated control plan. Traditionally, a common and fixed cycle length is designed for the series of intersections in coordinated control systems. Green split and offset are then calculated to allow traffic progression. Some early methods formulated delay-offset relationship from the queue polygon

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diagram at the downstream intersection and optimized offset by conducting an exhaustive search for all possible offset values (Jain, 1996). Abbas et al. (2001) proposed a transitioning algorithm through fine tuning offsets to allow as many vehicles as possible passing through intersections during green window. In Yin et al. (2007), the parameters of common cycle length, green split and offset were decomposed and optimized separately. Furthermore, an offline offset-refiner was developed to address the problem of uncertain start/end of green. Existing studies have made great efforts on finding better offset settings that can have a significant impact on coordinated control system, since poor offset settings would incur additional undesirable delays, especially under over-saturated conditions.

The traditional way of formulating the delay optimization functions usually assumes deterministic arrivals, i.e. traffic arrivals are assumed evenly spread over the analysis period expressed as a constant arrival rate. In general, however, traffic arrivals are inherently uncertain due to variations in traffic conditions (e.g. time of day, day of week). The optimal control plans that are designed for deterministic average conditions could therefore be a poor fit with stochastic traffic conditions in reality. Considering only average flow rate in signal control design may result in sub-optimal performance, compared with that obtained by incorporating traffic variability into the analysis (Heydecker, 1987). The effect of stochastic arrivals is typically taken into account by adding stochastic terms in the delay formulae. The seminal work of Webster (1958) proposed a delay formula known as the Webster delay formula, in which a green time buffer (defined as the excess green time to the optimal plan that is calculated with pure deterministic delay formula) is introduced to hedge against variability. A summary of the development is provided by Heydecker (1995). A main drawback is its inability to capture the transient queuing process and model the overflow delay under oversaturated conditions. Moreover, the open question that how long the green buffer ought to be adds to the challenge of its practical applications. In view of these issues, Lo (2006) developed an approach to capture the transient phenomena by analysing the state of the system from cycle to cycle based on a probabilistic treatment of overflow. A concept of phase clearance reliability (PCR) was proposed to describe the control performance, namely, the probability that the available green time of a given phase is able to clear the approach traffic.

In this study, we adopt the concept of PCR for coordinated signal control optimization, in which we acknowledge the fact that traffic demand (traffic arrivals) is uncertain and model it as a random variable following some specific probability distribution. There are mainly two approaches to address demand uncertainty. One is to make use of robust optimization, which optimizes the objective function against the worst-case scenario. Instead of the robust approach, which may impose conservatism stemming from the requirement that the control settings should be feasible for all demand realizations, we employ the approach of stochastic programming in this paper, which works with known demand distributions. One typical formulation is via a two-stage stochastic program (Ruszczynski and Shapiro, 2003).

Conceptually, the decision process of this stochastic approach takes place in two stages. The first stage decisions represent the here-and-now decisions. Decision makers first take some actions in the first stage. Upon realization of the uncertain demand, recourse or wait-and-see decisions are then made in the second stage to adapt to the random demand. The expected cost of the optimal recourse decisions are then accounted into the objective function by taking the integral over the probability distribution of the random demand. In general, the optimal policy from this two-stage stochastic program is a single first stage policy and a collection of recourse decisions which are actions in response to each random outcome.

The two-stage framework has been applied to the isolated signal control, which takes account of the uncertainty in traffic flows and recursively solves for the signal timing plan that minimizes the expected total delay for two consecutive cycles (Tong et al., 2015). The two-stage stochastic program can be solved by Bender's Decomposition (Benders, 1962) or its variations, such as the L-shaped method which is shown to be an effective solution technique for a variety of problems. However, this method might cut away the global optimal solution in the sub-problem for continuous stochastic program. Moreover, as the formulation typically involves a nonlinear mixed-integer program, solving it repeatedly could be computationally intractable especially for large-size problems (Slyke and Wets, 1969). We proposed an alternative method through the concept of service reliability for transit network design, which is introduced to cover the stochastic demand up to a certain specified level (Lo et al., 2013; An and Lo, 2014, 2015, 2016). In this reliability-based method, the decision variables of the two stages are computed separately for the benefit of solution efficiency, while their coupling effect is addressed by choosing an optimal reliability level. In the context of signal control design, Ma et al. (2016) developed a multi-stage stochastic program for coordinated control under uncertain demand. The multi-stage program is decomposed into two sub-problems through the concept of phase clearance reliability: the base timing plan is determined in the first sub-problem for a certain PCR level, whereas a green extension scheme is developed in the second sub-problem for the coordinated approaches. In Ma et al. (2016), the overflow of the coordinated approaches is addressed by adjusting (extending) the green time, while the offset settings are simply switched between a required clearance time and the green time under oversaturated conditions. What is more, a green extension scheme usually increases cycle length, which often induces large delay and actually reduces the control performance (Campbell and Skabardonis, 2014). In view of the fact that signal offset plays an essential role in improving coordinated control performance, in this paper, we propose an alternative approach to the signal coordination design under demand uncertainty, whereby the random overflow is tackled by the offset settings.

To this end, this study proposes a reliability-based two-stage stochastic program for adaptive coordinated signal control. In the first stage, the base timing variables, including a common cycle length, green times, as well as initial offsets of each intersection are here-and-now decision variables, while actual offsets are determined in the second stage to tackle the random traffic arrivals. Since offsets are affected by the queue sizes along the coordinated direction which usually vary from cycle to cycle, queue evolutions in multiple consecutive cycles are considered in determining the optimal offsets. In this regard, our study contributes to improving the existing delay models by explicitly incorporating the residual queue and offset effects in the delay formulae. This study specifically formulates and solves the two-stage control scheme based on the concept of PCR. The base timing plan is designed to serve the stochastic traffic demand up to a certain specified PCR level. If the realized demand on a particular period exceeds the specified