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Signal coordination models for long arterials and grid networks

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ABSTRACT

This paper proposes two models to tackle traffic signal coordination problems for long arterials and grid networks. Both models, denoted as MaxBandLA and MaxBandGN, are built based on Little's bandwidth maximization model, and the resulting formulations are both small-sized mixed-integer linear programs. Model MaxBandLA can optimize arterial partition plan and signal coordination plans of all the subsystems simultaneously. Model MaxBandGN directly optimizes the offsets for all the signals in a grid network, and as such, no 'cycle constraints' need to be constructed. Numerical tests are presented to show that both models have the potential to produce coordination plans that are comparable to signal plans optimized by Synchro.

1. Introduction

Signal coordination is a traffic control strategy that determines the timings of grouped signals together so as to improve overall traffic flow propagation. It has long been recognized as one of the most efficient and economical methods to avoid or mitigate traffic congestion.

Extensive research can be found in the literature that investigated various signal coordination problems. A recent review of relevant studies can be found in Zhang et al. (2015). Generally, the models proposed are of two types: bandwidth-based models and performance-based models. Little's bandwidth maximization model maximizes two-way green bandwidths of a given arterial so that vehicles may have larger chances to traverse the arterial without any stops (Little, 1966). The model is in the form of a mixed-integer linear program (MILP), and can be solved to global optimum very efficiently with readily available commercial solvers. This seminal model lays the foundation for many studies carried out over several decades. For example, Chang et al. (1988) introduced an extension of the model to consider left-turn phase sequence in general networks, Gartner et al. (1991) proposed another variant that maximized the bandwidth of each individual road section, Zhang and Yin (2008) and Li (2014) considered the uncertainties in arterial signal coordination, and Gomes (2015) introduced vehicle arrival functions to maximize the benefit from signal coordination. Performance-based models try to optimize signal settings to directly improve measures of effectiveness relating to delay, stop or queue, see, e.g., Park et al. (1999), Zhang et al. (2010), Hu et al. (2013), He et al. (2014) and Ye et al. (2015). Yang (2001) applied both bandwidth-based and delay-based models to an arterial with nine signalized intersections in Lawrence, Kansas and found that the bandwidth-based approach generally outperformed the delay-based approach. The models proposed in this paper are built based on Little's MILP formulation, thus the introduction primarily focuses on bandwidth-based models.

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According to the formulations of bandwidth-based models, it's not hard to observe that when the number of signals in a system increases, the green bandwidths generated will decrease, due to that more constraints need to be imposed on the bandwidths. Under their problem settings, Ma et al. (2011) actually found that two-way green bandwidths were not achievable when the number of signals increased to sixteen, indicating that it may not be a wise strategy to coordinate very long arterials as a whole system. A natural idea that came up was to divide a long arterial into several small subsystems and then perform signal coordination for each individual subsystem. Conventional approaches to determine the partition plan of a long arterial are mainly based on evaluation indexes, such as Coupling Index, Strength of Attraction and Coordinatability Factor, which consider factors like traffic volume, signal distance, travel speed and cycle length (Hook and Albers, 1999). These approaches may still produce long subsystems when the evaluated signal indexes along the arterial are similar. Tian and Urbanik (2007) proposed a heuristic that divided an arterial into several subsystems with three to five intersections based on distance, volume, queue length and saturation degree between adjacent intersections. Zhang and Zhang (2014) applied improved K-means clustering to search for feasible partition plans, and then utilized PASER-II to produce coordination plans for all the subsystems. These above studies provide different methodologies to coordinate signals on long arterials, but none proposes an explicit mathematical formulation for the problem.

While studies on long arterials are rare, much attention has been paid to the signal optimization problem for area-wide networks. Algorithms developed for adaptive control systems optimize network signal timings step-by-step with coordination plans explicitly or inexplicitly embedded. Their control objectives are usually performance-based, see, e.g., Timotheou et al. (2015), Yang and Jayakrishnan (2015), Di Febbraro et al. (2016) and Guilliard et al. (2016). Some other methodologies are more suitable for off-line optimization, e.g., Ozan et al. (2015) combined a reinforcement learning algorithm with TRANSYT-7F to optimize area-wide signal timings to minimize a weighted sum of delay and stop. Cantarella et al. (2015) proposed two strategies that employed meta-heuristics to solve the network signal setting problem, aimed at minimizing total system delay. Recent studies are mostly performance-based, while few look at green bandwidths. Actually, Little (1966) also proposed a methodology to coordinate signals at the network level, with an aim to maximize the weighted sum of the bandwidths of all the arterials in the network. The network program mainly consists of the individual arterial coordination programs and the 'cycle constraints'. When coordinated arterials form a closed loop, the offsets of those signals at the intersections of the arterials will sum up to be integer numbers of the half cycle length, which is called 'cycle constraint'. One 'cycle constraint' needs to be introduced whenever one closed loops is formed by coordinated arterials. If the analyzed network is too large, it can be expected that the procedure to build all possible cycle constraints can be time consuming. Most of the bandwidth-based network coordination studies follow the above methodology, see, e.g., Chaudhary et al. (1991) and Gartner and Stamatiadis (2002, 2004).

This paper attempts to synchronize signalized long arterials and gird networks along the line of bandwidth maximization. The model to be built for long arterials is able to simultaneously generate an optimal network partition plan, as well as the coordination plans for all the subsystems generated. And the model for grid networks takes the offsets of all the signals as decision variables, thus that no efforts are required to build 'cycle constraints'. The both models obtained are explicit mathematical models in the form of MILPs, which are small-sized and can be solved to global optimum in seconds by commercial solvers. The remainder of the paper is organized as follows: Section 2 briefly introduces Little's bandwidth maximization formulation. Section 3 builds the coordination model for long arterials, and three numerical tests are presented. Section 4 gives the coordination model for grid networks with another set of numerical tests. Concluding remarks are provided in the last section.

2. Introduction to Little's MILP formulation

Little's bandwidth maximization model is covered here first since the models proposed later are built upon this model. Given an arterial with fixed number of signals, whose split information are known in advance, the bandwidth maximization model optimizes the common cycle length and offsets for these signals to maximize the sum of inbound and outbound green bandwidths.

Let S_h and S_i be two successive intersections in the outbound direction. Fig. 1 shows the green bandwidths between the two signals. Some notations used in the formulation are given first as follows:

$b/\bar{b}$	outbound /inbound bandwidth (cycle)
r_i	red time of the synchronized phase of signal i (cycle)
$t(h,i)/\bar{t}(i,h)$	travel time from signal $h(i)$ to signal $i(h)$; $t_i = t(i,i+1)$
$w_i/\bar{w}_i$	time from the right/left side of $S_i's$ red to the green band (cycle)
$\phi(h,i)/\bar{\phi}(i,h)$	time from the center of red at S_h to the center of a particular red at S_i. The two reds are chosen so that each is immediately to the left /right of the same outbound /inbound green band (cycle)
$\tau(h,i)$	$= \phi(h,i) + \bar{\phi}(i,h); \quad \tau_i = \tau(i,i+1)$
T_1, T_2	lower and upper bounds on cycle length (s)
z	signal frequency, or the inverse of cycle length
$d(h,i)$	distance from S_h to S_i (s); $d_i = d(i,i+1)$
$e_i, f_i/\bar{e}_i, \bar{f}_i$	lower and upper bounds on outbound /inbound speed (m/s)