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Managing oversaturated signalized arterials: A maximum flow based approach

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ABSTRACT

Under oversaturated traffic conditions, signal timings need to be adjusted accordingly in order to alleviate the detrimental impacts caused by oversaturation. In this research, our focus is to mitigate two types of detrimental effects, signal phase failure with residual queue and downstream queue spillover. Building upon our previous work on the oversaturation severity indices, a maximum-flow based approach to manage oversaturated intersections is developed. The proposed model maximizes the discharging capacity along oversaturated routes, while satisfying the constraints on available green times. We show that a simple Forward–Backward Procedure (FBP) can be used to obtain the optimal solution to the maximum flow model. The forward process aims to increase green time to mitigate oversaturation, therefore improve the throughput for the oversaturated approach; and the backward process aims to gate the traffic at some intersections to prevent residual queues and downstream queue spill-back when the available green time is insufficient. The algorithm is tested using a microscopic traffic simulation model for an arterial network in the City of Pasadena, CA. The results indicate the model can effectively and efficiently reduce oversaturation and improve system performance.

1. Introduction

It is well-known that managing oversaturated arterials requires significantly different approaches for signal timing than those used for under-saturated conditions (Koonce et al., 2008). Over the past fifty years, a fairly large body of literature has been devoted to this research area. For isolated intersections, optimal control policies were designed to balance the queuing delay on conflicting approaches by switching the green durations between minimum and maximum (e.g. Gazis and Potts, 1963 and Gazis, 1964; Michalopoulos and Stephanopoulos, 1977a, 1977b; Chang and Lin, 2000; etc.). To deal with oversaturated arterials, Pignataro et al. (1978) and Rathi (1988) proposed negative offset control strategy, which advances the downstream green in order to flush the residual queue. Lieberman et al. (2000) and Chang et al. (2010) developed traffic gating/metering control strategy, which aims to prevent downstream blockage by restraining upstream input. Liu and Chang (2011) presented a signal optimization model, which specifically considers the queue evolution by lane groups and can capture the queue spillback. At network level, Abu-Lebdeh and Benekohal (1997), Park et al. (1999), and Lo et al. (2001) developed large-scale optimization models maximizing throughput with constraints on downstream storage capability and green time utilization.

However, in reality, none of these approaches have been widely accepted or implemented by practitioners because of the following reasons. Firstly, the basic assumption for most of the above models is that time-dependent traffic demand

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information is available. This is apparently problematic since most of the existing detection system fails to provide accurate arrival information, especially when traffic is congested. More importantly, the demand information, even it is available, cannot describe completely the level of oversaturation or the cause of oversaturation. Secondly, building large-scale optimization models is technically feasible but not very practical simply due to the complexity. It is almost impossible, especially for real-time traffic control, to solve large optimization programs with hundreds, or even thousands of decision variables and constraints; so most of these approaches cannot obtain an analytically optimal solution and have to rely on heuristic approaches. Finally, many practitioners do not feel comfortable to implement the "black-box" method provided by most of the optimization models.

We should note that adaptive signal control systems were also developed to perform real-time optimization of traffic signal splits, offsets and cycle lengths based on estimated or predicted traffic conditions, such as SCOOT (Hunt et al., 1982), SCATS (Sims, 1979), OPAC (Gartner, 1983), RHODES (Head et al., 1992) and ACS-Lite (Luyanda et al., 2003). It has been shown that these adaptive control systems can reduce delay in light to medium traffic conditions (Martin, 2007). When oversaturation happens, it is possible that these control systems may even worsen the situation due to the false estimation or prediction of traffic conditions (for example, arrival flow rate). Another impediment to adaptive traffic control systems is the cost associated with the deployment of additional detection systems that can supply the necessary traffic data for on-line decision-making.

To overcome the above difficulties, in this paper, we propose a simple but effective control model to deal with oversaturation on signalized arterials. The control model is not based on time-dependent demand information, as most of the previous studies do. It is built upon the characterization of oversaturation discussed by Wu et al. (2010), in which, oversaturation is quantified by the detrimental effects either in temporal dimension (indicated by a residual queue) or in spatial dimension (indicated by a spillover). The *Oversaturation Severity Index* (*OSI*) indicates not only the level of congestion, but also the cause of oversaturation. With the information of *OSI*, we formulate a maximum flow based signal control model to manage oversaturation. Comparing with previous studies, this model has the following contributions:

(1) The proposed model can effectively and efficiently manage oversaturated routes without the requirement on time-dependent traffic demand as model inputs. It can be easily implemented at typical signalized intersections where the standard detection system is available.
(2) Instead of dealing with hundreds of decision variables and constraints, the control model can be solved by a simple Forward–Backward Procedure (FBP), which makes the practical use of the model much more promising.

In the following, Section 2 briefly reviews the definition of Oversaturation Severity Index, which implies the possible mitigation strategies for oversaturation. Section 3 defines the problem we try to solve in this paper, followed by the maximum flow based formulation in Section 4. Section 5 introduces the FBP, which generates the optimal solution for the control model. The proposed model is evaluated through microscopic traffic simulation and the evaluation results are presented in Section 6. Concluding remarks are offered in the last section of this paper.

2. OSI-based mitigation strategies for single intersection

The proposed model is built upon our recent developments on the diagnosis of oversaturation (Wu et al., 2010) using high-resolution traffic signal data (Liu and Ma, 2009; Liu et al., 2009). In Wu et al. (2010), an Oversaturation Severity Index (OSI) was proposed to quantify the severity level of oversaturation by measuring its detrimental effects. The detrimental effect is characterized by either a residual queue at the end of a cycle or a spillover from downstream traffic, both of which create "unusable" green time. In the case of residual queue, the "unusable" green time is the equivalent green time to discharge the residual queue in the following cycle, but for spillover, the "unusable" green time is the time period during which a downstream link is blocked, therefore the discharge rate from the upstream intersection is zero. OSI is defined as the ratio between unusable green time and total available green time in a cycle, which is a non-negative percentage value between 0 and 100, with 0 indicating no detrimental effect for signal operation, and 100 being the worst that all available green time becomes unusable. OSI is further differentiated into *TOSI* (Temporal Oversaturation Severity Index, caused by the residual queue that creates the detrimental effect in temporal dimension) and *SOSI* (Spatial Oversaturation Severity Index, caused by the spillover that creates the detrimental effect in spatial dimension). Specifically, *TOSI* and *SOSI* can be calculated by Eq. (1). More detailed derivation and explanation of the two indices can be found in Wu et al. (2010).

$$\begin{cases} TOSI = \frac{\text{Green time to discharge residual queue}}{\text{Total available green time}} \\ SOSI = \frac{\text{Unusable green time due to spillover}}{\text{Total available green time}} \end{cases} \tag{1}$$

With *TOSI* and *SOSI*, not only can the severity level of oversaturation be quantified, but also the causes of arterial traffic congestion can be identified. Positive *TOSI* indicates that the available green time is insufficient for queue discharge and a residual queue is formed at the end of a cycle; and positive *SOSI* indicates that the queue length at the downstream link has reached the upstream intersection and blocked the discharging traffic. Based on measured *TOSI* and *SOSI* values, three basic mitigation strategies are designed for different oversaturation scenarios between two intersections.