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Quasi-optimal feedback control for a system of oversaturated intersections

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ABSTRACT

Oversaturated intersection control is a long-standing problem in traffic science and engineering. The problem becomes even harder when we consider a system of oversaturated intersections. Most of the research works in this area are off-line studies that require fully knowledge of origin–destination demand, which would be difficult to obtain in reality. Although several on-line feedback control methods are proposed, they only aim at preventing queue spillover, not able to minimize vehicular delay time. Moreover, these on-line control strategies are not theoretically evaluated how optimal (or sub-optimal) they are. We propose in this paper a quasi-optimal decentralized QUEUE-based feedback (abbreviated as QUEUE) control strategy for a system of oversaturated intersections. The QUEUE strategy is applied cycle-by-cycle based on measurement of current queue sizes, but its overall result is able to approximate the optimal one derived from off-line studies. Details of the feedback control laws for upstream and downstream intersections, in the queueing period and the queue dissipation period, are discussed. Superior to the existing feedback control strategies, the upper bounds of sub-optimality of the QUEUE strategy generating from demand fluctuation and coupling of intersections are specified quantitatively. It is also theoretically proved that the queue measurement error or demand estimation error would not be amplified by the QUEUE strategy. Numerical examples show that the QUEUE strategy performs very well and is robust to errors.

1. Introduction

It is not uncommon that signalized intersections are operated under oversaturated conditions, especially during the peak hours. Vehicular queues may grow very long due to heavy demand that exceeds the maximum discharging capacity of intersections. It will be more undesirable if vehicle queues spill back to upstream intersections, and then the spillover spreads to other intersections and potentially leads to the gridlock (Daganzo, 2007). Unless employing innovative intersection designs (e.g., Xuan et al., 2011; Sun et al., 2015) to increase the overall capacity, the signal control strategies play a key role in efficiently utilizing the existing capacity. Therefore signal control strategies under such conditions must be carefully designed. But unlike the control of undersaturated intersections for which theories and technical tools are well-established, consensus has not been reached regarding the control policies for oversaturated intersections.

In the literature, most of the control strategies developed for oversaturated intersections belong to the category of off-line optimization. For one isolated intersection, Gazis (1964) first pointed out that the theoretical optimal signal control strategy

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is a two-stage bang–bang type. The optimality of the solution was proved using Pontyagin's maximum principle. Based on Gazis's work, Guardabassi et al. (1984) investigated the necessary existence condition for the optimal solution. Michalopoulos and Stephanopoulos (1977a) took the maximum queue constraint into account. Chang and Lin (2000) and Zou et al. (2012) proposed discrete-time optimal control models so as to better match the cycle-by-cycle signal control in real world. These works are theoretically studies that provide valuable benchmarks for control of an isolated oversaturated intersection, but are not readily used in practice. The critical problem is that these methods rely upon perfect knowledge of origin–destination (OD) demand, which is difficult to obtain.

For oversaturated signalized arterials or networks, as the number of intersections under consideration increases, more variables need to be determined and more constraints are imposed. Therefore the analytical optimal control policy becomes not explicitly achievable (Michalopoulos and Stephanopoulos, 1977b; Zhao et al., 2011). Under this condition, heuristic algorithms were usually adopted for numerically solving the off-line optimization problem for a system of oversaturated intersections (Park et al., 1999, 2000; Abu-Lebdeh and Benekohal, 2000; Lieberman et al., 2000; Lo et al., 2001; Lertworawanich et al., 2011; Liu and Chang, 2011; Jang et al., 2015), yet the solutions derived from heuristic methods lack the interpretability.

On-line feedback strategies are good candidates to address the aforementioned problems, because they usually have clear control logic, require little computational work, and are robust to demand fluctuation. However, research works about on-line feedback control strategy for oversaturated intersections are limited. The queue lengths are usually selected as the input variables in a feedback control scheme for traffic signals. Although estimation of queue lengths under oversaturation is not an easy task as the phenomenon of queue over detectors is often encountered (Wu et al., 2010), the recently developed queue estimation method based on high-resolution data provides a potential solution to the problem (Liu et al., 2009). Ideally, queue states of all intersections in the network are needed to manage oversaturated intersections (e.g., Hu et al., 2013). However, in contrast to a network-wide model with large number of decision variables, a decentralized strategy is usually preferred, because it facilitates the implementation to each intersection and requires less computational effort. The max pressure control strategy proposed by Varaiya (2013) is a good example. The strategy runs locally at each intersection to maximize the throughput of a signalized network. Gordon (1969) suggested a balance queue strategy that keeps the ratio of the queue sizes to the maximum link storage space on all approaches equal so as to prevent spillover. It is meaningful when queues are forming, but not necessary when queues are dissolving in the later period of oversaturation. Lin et al. (2011) proposed a robust feedback control strategy that maintains the proportion of queue length on one road to another in a pre-determined range. Several choices of the desired queue proportion were described as examples and the results provided promising solutions, but it is still unclear how "good" this control strategy is. Diakaki et al. (2002) proposed the traffic-responsive urban control (TUC) strategy that adjusts the signal over cycle based on real time measurement of queue lengths. Most recently, Christofa et al. (2013) suggested monitoring the vehicle queue status using connected vehicle's information to prevent queue spillback. Although not explicit designed to manage oversaturated intersections, these strategies help to mitigate oversaturation by minimizing (residual) queue length or preventing spillover. However, these strategies could not minimize vehicular delay time as the off-line optimal strategy cloud.

It is important that reliable performance evaluation of a feedback control strategy is achievable before implementation. This allows one to judge the quality of the control strategy. In our previous paper, we proposed a quasi-optimal QUEUE-based feedback (QUEUE) control strategy for an isolated intersection under oversaturation (Sun et al., in preparation). The QUEUE strategy is for on-line implementation based on system feedback, so perfect knowledge or prediction of future demand is not required. It was proved to match the benchmark of off-line optimum in case of constant demand, and the upper bounds of sub-optimality were specified quantitatively in fluctuated demand cases. In this paper, the QUEUE strategy for an isolated intersection under oversaturation is extended to manage a system of oversaturated intersections. Such extension is not straightforward. Efforts must be made to prevent the queue spillover to upstream intersection as well as the waste of green time caused by insufficient supply to downstream intersection. The QUEUE strategy is promising because it approximates the off-line optimum in an on-line feedback control method. More importantly, superior to the existing feedback control strategies, the upper bounds of sub-optimality generating from demand fluctuation or coupling of adjacent intersections are specified quantitatively with the QUEUE strategy. It is also found that the queue measurement error or demand estimation error would not be amplified by the QUEUE strategy.

The rest of the paper is organized as follows. Section 2 defines the subject control problem, and introduces the division of oversaturation period and the corresponding QUEUE strategy for each period at upstream or downstream intersection. The optimality of the QUEUE strategy is quantitatively assessed in Section 3 by evaluating the upper bounds of sub-optimality that generate from demand fluctuation and coupling of intersections, respectively. Section 4 discusses the impact of errors generating from queue size measurement and demand estimation. Numerical examples are employed to show the performance of the QUEUE strategy in Section 5. Section 6 introduces briefly the way of extending the QUEUE strategy to multi-phase signals. Section 7 concludes this paper and discusses future studies.

2. The QUEUE strategy

This section introduces the problem to be investigated, the division of the oversaturation period, and the details of feedback control laws of the QUEUE strategy.