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Quasi-optimal feedback control for an isolated intersection under oversaturation

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How to manage signalized intersections under oversaturated conditions is a long-standing problem in traffic science and engineering. However, although research works in this area date back to 1960s, an on-line control strategy with theoretically bounded performance is missing, even for the control of an isolated intersection under oversaturation. This paper makes one step further in this area by proposing a QUEUE-based quasi-optimal feedback control (abbreviated as QUEUE) strategy for an isolated oversaturated intersection. The QUEUE strategy is intuitive, simple, and proved to match the off-line optimum in the case of constant demand. More importantly, the bounds of sub-optimality of the QUEUE strategy can be specified quantitatively in general piece-wise constant demand cases. To better deal with the maximum queue constraints, the oversaturation period is divided into the queuing period and the dissipation period with two different objectives. In the queuing period, the primary objective is to keep the queue length within the maximum value; but for the dissipation period, the primary objective is to eliminate all queues at the earliest time. Interestingly, we found that both control objectives can be realized with the same QUEUE strategy. Numerical examples show that the QUEUE strategy approximates the off-line optimum very well. The average sub-optimality in comparison with the off-line optimum in the challenging conditions with Poisson distributed random demand is below 5%.

1. Introduction

More and more traffic intersections in cities are operated under oversaturated conditions, especially during the peak hours. Vehicular queues may grow very long due to heavy demands that exceed the maximum discharging capacity of intersections. It will be even more undesirable if vehicle queues spill back to upstream intersections, and then the spillover spreads to more intersections and potentially leads to the gridlock (Daganzo, 2007). Therefore signal control strategies under such conditions must be carefully designed.

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, even for an isolated oversaturated intersection. For an isolated oversaturated intersection, the main task is to allocate green times among conflicting phases

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to minimize the duration of oversaturation period as well as the total delay time of all vehicles. Although research literature on optimization of the green splits of an isolated oversaturated intersection dates back to 1960s, most of them belong to the category of off-line optimization. The pioneer in this field is Gazis (1964). He solved the continuous-time optimal control problem of an oversaturated intersection with two conflicting streams by semi-graphical method, and then proved the optimality of the solution using Pontryagin's maximum principle. The optimal solution is a bang–bang type two-stage strategy. His method minimizes the duration of the oversaturation period firstly, and minimizes the total delay secondly. Based on Gazis' work, Guardabassi et al. (1984) found the necessary conditions for solution existence. Michalopoulos and Stephanopoulos (1977a) took the maximum queue constraint into account and offered a numerical method to compute the corresponding optimal solution. 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 the real world. These works are able to find the ideal optimal solution analytically, providing benchmarks for control of an isolated oversaturated intersection. However, these methods rely upon perfect knowledge of OD demand for the whole period, which is very demanding. The same problem exists in the methods dealing with multiple oversaturated intersections (e.g., Michalopoulos and Stephanopoulos, 1977b; Lieberman et al., 2000; Liu and Chang, 2011; Lertworawanich et al., 2011; Park et al., 2000).

One common way of extending these off-line optimal control strategies to on-line strategies is by employing the rolling horizon (model predictive) structure (e.g., Aboudolas et al., 2010). The optimal control problem defined in a short horizon is solved on-line iteratively using the current traffic state as well as predicted demand over the finite horizon. Only the first step of the resultant control actions is implemented, then the traffic state is sampled again and the calculations are repeated starting from the new state and prediction. The rolling-horizon structure and real-time measurement greatly favor the real-world application of off-line strategies. However, prediction of future traffic demand is still required.

An alternative way of on-line traffic control for an oversaturated intersection is the state feedback method. This kind of method directly calculates the value of control variables based on current measured state, not requiring prediction of future demand. To manage an oversaturated intersection, ideally, queue lengths on all directions are needed as state variables. It is not easy to estimate queue lengths in case of oversaturation as the phenomenon of queue over detectors is often encountered (Wu et al., 2010), but the recently developed queue estimation method based on high-resolution data provides a potential solution to the problem (Liu et al., 2009).

Research works about on-line feedback control strategy for an oversaturated intersection are limited. Gordon (1969) developed an algorithm for on-line control of queue lengths at oversaturated intersections to keep the queue length ratios on both roads equal so as to delay spillover as long as possible. Gordon's algorithm is meaningful in case when queues are forming, but not necessary when queues are dissolving in the later period of oversaturation. Ioslovich et al. (2011) concluded in their paper that the optimal control law derived from solving the off-line problem is in a feedback form of current queue lengths. But the conclusion is based on constant arrival rate of traffic and unconstrained queue length. Lin et al. (2011) proposed a queue-based feedback control scheme that maintains the proportion of queue length on one road to another in a desired range. Although several choices of the set point were described as examples and the results are promising, it is still unclear how "good" this control strategy is. The traffic-responsive urban control (TUC) strategy (Diakaki et al., 2002) and the maximum pressure (MP) control strategy (Varaiya, 2013) are also novel feedback control examples that adjust the signal over cycle based on real time measurement of queue lengths. Although not explicit designed to manage oversaturated intersections, the TUC strategy and the MP strategy help to mitigate oversaturation by minimizing (residual) queue length. However, vehicular delay might not be minimized underlying the TUC or MP strategy.

It is essential that reliable performance evaluation of a control strategy is achievable before implementation. Specifically, having the benchmark of off-line optimum in hand, we should investigate quantitatively the sub-optimality of a feedback control strategy for an oversaturated intersection. This allows one to judge the quality of the control strategy. The review of literature shows that such quantitative evaluation is still missing in the existing feedback control strategies for an oversaturation intersection. Questions such as "can the feedback control strategy match the off-line optimum in certain conditions?" and "how far is the performance of feedback control strategy from the off-line optimum in the worst condition?" are not answered yet. Our work is to shed light on this issue, in which a QUEUE-based on-line quasi-optimal feedback control (QUEUE) strategy for an oversaturated intersection is developed and theoretically assessed.

The primary contribution of this paper is that we find an innovative way of approximating the off-line optimal control strategy for an oversaturated intersection with an on-line feedback control method. The feedback strategy is based on the availability of detected queue size data, while perfect knowledge or reliable prediction of future demand is not needed. It is proved to match the off-line optimum in case of constant arrival flow rate. More importantly, the upper bounds of the sub-optimality from the off-line optimum are quantified in general cases.

Different from the feedback control models proposed in the past, the QUEUE strategy deal with the maximum queue constraints in a more explicit way. We divide the whole oversaturation period into two parts, namely the queuing period when queues increase continuously and the dissipation period when queues decrease gradually. It is evident that keeping the queue length within the maximum constraints is the primary objective in the queuing period; but in the dissipation period, the primary objective is eliminating all queues at the earliest time, while the maximum queue constraints can be simplified consider or even omitted. Interestingly, we found that the control laws for the two different periods can be developed using the same logic in the QUEUE strategy.

The rest of the paper is organized as follows. Section 2 defines the subject control problem and briefly reviews existing analytical results of off-line optimal control strategy. Section 3 introduces details about the QUEUE strategy, including the