REAL-TIME CONTROL OF QUEUE SPILLBACKS ON SIGNALIZED ARTERIALS

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INTRODUCTION

In the last decades, drastically increased traffic demands in cities have resulted in congestion problems. The development of Intelligent Transportation System (ITS) technologies with new monitoring paradigms and computational tools enables to alleviate congestions by estimating traffic states in real-time and thus implementing traffic-responsive signal control schemes instead of fixed one, which is particularly not adapted to oversaturated conditions [1]. Although an appropriate use of these new technologies will ameliorate traffic in local congested areas, an optimal traffic-responsive signal control in scale of an arterial or a network is computationally intractable.

In urban networks with signal-controlled intersections, when demand exceeds capacity queues fail to clear during the allocated green times that creates oversaturated traffic conditions. Spillovers occur when growing queues at the downstream link block the arrivals from the immediate upstream link such that vehicle queues cannot discharge at capacity, although the signal phase is green. Spillbacks may also occur when turning vehicles fill up the available storage length of turn bays and block the through movements. This results in a significant reduction of the intersection capacity and also excessive delay both for the through traffic movement and the cross-street traffic entering the arterial.

This paper advances the state-of-the-art of traffic signal control in congested urban arterials by integrating a clustering approach into a control policy of long queues prior to spillover occurrence to reduce the risk of spillovers through a feedback strategy. First, we introduce an arterial clustering approach that detects in real-time the links with long queues along one direction of the arterial, clustering them together if they are consecutive and then identifying the entrance and exit intersections of each cluster. These intersections indeed constitute critical junctions (considering the analogy of an active bottleneck in a freeway) and therefore, proper adjustment of the signal timing settings in those intersections could improve traffic conditions in the whole arterial. Thus, it enables to implement locally smaller-sized decentralized signal control strategies while ensuring at the same time the global coherence of these strategies along the arterial. In this manner, we seek to improve traffic on arterial at a very low cost by acting merely on critical intersections, as opposed for instance to network-wide optimization process. This approach is adaptive and does not require information about turning movements, which is difficult to be estimated in real-time.

Hence, the purpose of this paper is to develop an elegant signal control strategy based on the arterial clustering approach that enables to act only locally on specific intersections. Including an advanced detection of oversaturated states and a specific focus on queue spillovers prevention, it leads to significant reduction of congestion and thus improves the network traffic conditions [2].

ARTERIAL PARTITIONINNG

The clustering approach consists in detecting in real-time the arterial links with long queues, grouping them together if they are adjacent, and consequently identifying the entrance and exit intersections of each cluster. These intersections constitute critical junctions along the arterial. Thus, by proper modifications of the signal settings at those locations one could expect improvements in the traffic situation of the whole arterial. The developed methodology can be integrated in existing coordinated or actuated strategies as it intervenes in only a few intersections, with the objective of decreasing the risk of spillbacks.

The arterial partitioning first utilizes a criterion to differentiate oversaturated or close-to-spillback links from the uncongested ones based on the queue length at the end of each red phase. It is assumed that queue lengths can be estimated with some error from loop detectors and/or probe vehicle data by using existing state-of-the art techniques [3].

A cluster of congested links consists of consecutive congested links in the arterial delimited with non-congested links. The entrance intersection designates the signalized intersection located at the upstream limit of the group of congested links. This intersection is denoted by l and the link just downstream $l+1$. Correspondingly, the exit intersection is located at the downstream limit of the group of congested links and is denoted by f as well as the link just upstream (see Fig. 1 (a)).

The choice of the threshold to decide whether a link is considered as congested or not is based on a preventive strategy that detects moderate queues that exceed the capacity of the corresponding approach at the downstream intersection. Hence, considering arterial partitioning for cycle $k+1$, we propose: if $q_k^i > q_{cr}^i$, link i is considered as congested, where q_k^i is the queue (veh/lane) in link i at cycle k and $q_{\mathrm{cr}}^i = g_{\mathrm{init}}^i . s$ which is maximum queue of vehicles per lane in link i that can completely be cleared during the next green phase g_{init}^i for the arterial through movement with fixed-time control. (s denotes the saturation flow per lane.)

The pseudo code for arterial partitioning approach is as follows:

1. *If* cycle k of all intersections has been completed
    2. *Loop* $i=1,2\ldots,\ i_{max}$ ($i=1$ stands for the most upstream link in the arterial)

3\. *If* $q_k^i > q_{cr}^i$

If (*i=1*) *or* ($q_k^{i-1} \le q_{cr}^{i-1}$)

Append intersection *i-1* to the entrance intersections *l*

Else

Append intersection *i-1* to the interior intersections

End If

If (*i=i*) or ($q_k^{i+1} \le q_{cr}^{i+1}$)

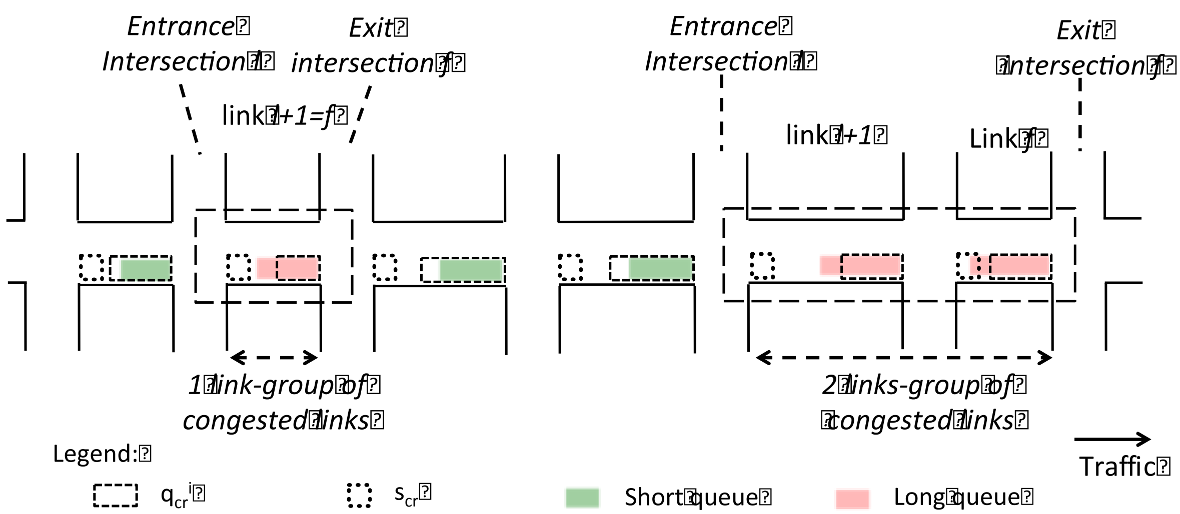
Append intersection *i* to the exit intersections *f*

End If

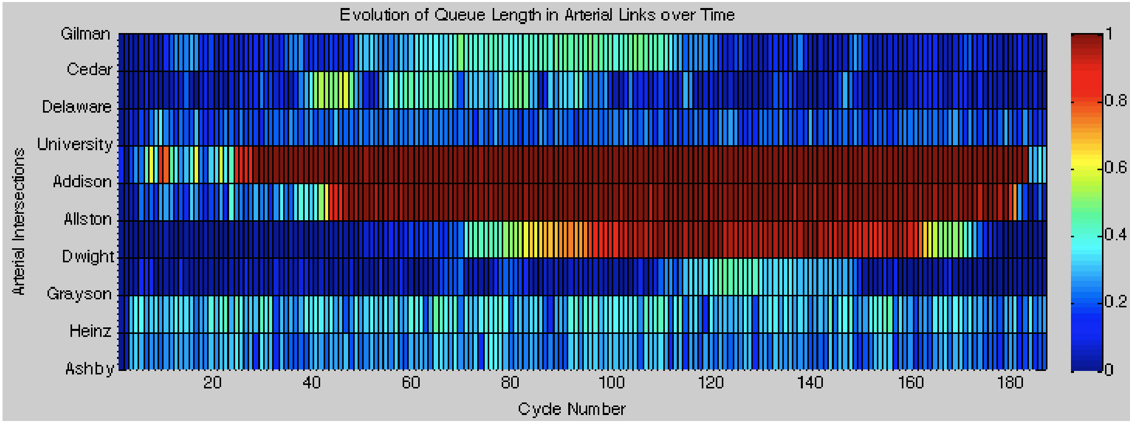
End If

End Loop

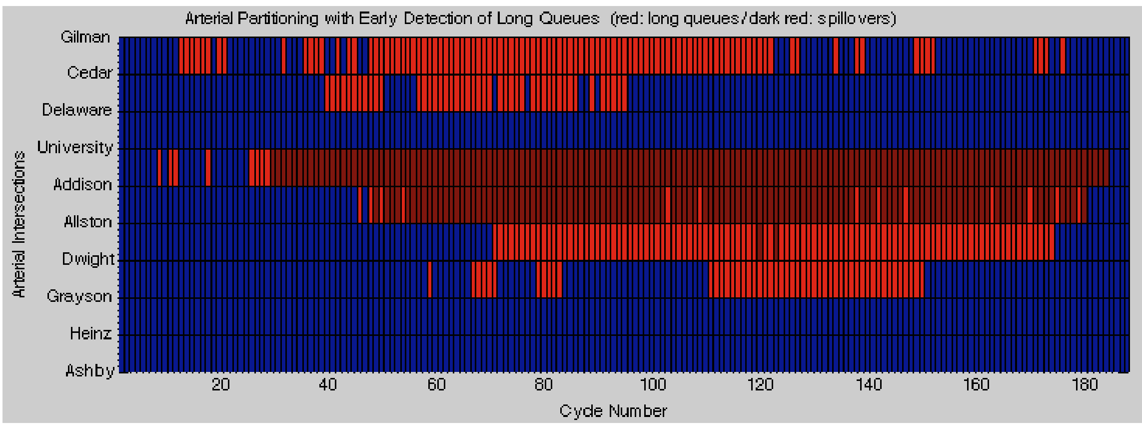
Figure 1 illustrates arterial partitioning, as the demand creates queues that spill back upstream San Pablo/University critical intersection on several links up to San Pablo/Dwight intersection with fixed-time signal control. Congestion is consistently present from cycle 25 until the end of the simulation when very low demand enables all long queues to clear. Hence, San Pablo/University intersection is an exit intersection for the larger part of the simulation period (see Fig. 1 (c)), whereas San Pablo intersections with Addison, Allston, Dwight and Grayson are successively entrance intersections during the simulation. Arterial partitioning and fixed-time signal control in Fig. 1 (c) reveals that besides these queue spillovers phenomena, Cedar and Gilman streets also face oversaturated conditions (i.e. $q_k^i > q_{cr}^i$) for about half of the simulation. Thus, arterial partitioning methodology appears also to be a valuable performance measurement tool independently of signal controlling.



(a) Schematic example of arterial partitioning.



(b) Evolution of link queue lengths over time with fixed-time control (links queue occupancy from 0 to 1).



(c) Arterial partitioning
(blue: no detection of long queue/ red: long queue detection/ dark red: queue spillover detection).

FIGURE 1 Arterial Partitioning of San Pablo Avenue (Berkeley, CA) northbound approach.

SIGNAL CONTROL STRATEGY

Arterial partitioning at each cycle identifies group of congested links that are delimited with exit and entrance intersections. The seminal intuition of the proposed signal control strategy is to act only on exit and entrance intersections along the arterial. If one considers a critical group of congested links as a whole, to regulate its accumulation to the uncongested state, we need to manipulate the inflow and outflow of the critical group of congested links. Thus, the general direction is to increase the green phase duration of the arterial through movement at the exit intersection (increase the outflow) and also, to decrease the corresponding green phase duration at the entrance intersection (decrease the inflow). The corollary of such control strategy is that the interior intersections of a group of congested link are still controlled with initial fixed timings.

Exit intersection signal control

Arterial partitioning is triggered once the queue in a link exceeds the corresponding intersection's capacity. At cycle *k+1* for which exit intersection signal control is activated, green extension is based on the difference between previous queue length q_k^f and q_{cr}^f. In addition, when the risk of a potential queue spillover in link f becomes significant ($s_k^f < s_{cr}$) another compensatory term is added to the green extension. Hence, the control strategy for the first cycle of activation is:

$$g^{f}_{k+1} \;=\; g^{f}_{init} + K\left[q^{f}_{k} - \; q^{f}_{cr}\right] \;+\; K_{s1}\left[s_{cr} - \min\left(s^{f}_{k}\;, s_{cr}\right)\right], \qquad (1)$$

where $g^{f}_{k+1}$is the cycle $k+1$ green time for the through arterial movement at intersection f, and K and K_{s1} represent time increments (in seconds) for each additional vehicle queuing respectively beyond q^{f}_{cr} and passed s_{cr} threshold. For the next cycles as long as $q^{f}_{k} > q^{f}_{cr}$, a feedback control is implemented based on the attributes of the two last cycles, *k* and *k-1*:

$$g^{f}_{k+1} \;=\; g^{f}_{k} + K\left[q^{f}_{k} - \; q^{f}_{k-1}\right] + \; K_{s1}\left[\min\left(s^{f}_{k-1}\,, s_{cr}\right) - \min\left(s^{f}_{k}\;, s_{cr}\right)\right]. \qquad (2)$$

Note that, feedback controller parameters, K and K_{s1}, have to be chosen according to proper control engineering methods or manual fine-tuning to maximize the reduction of the network delay time, however, feedback controllers are shown to be robust to a moderate range of parameter values [4].

Entrance intersection signal control

The objective of the entrance control is to prevent or at least delay queue spillovers occurrence. Therefore, reduction of the arterial through movement green time at the entrance intersection is only profitable when there is a substantial risk of queue spillovers occurrence, that is when $s^{l+1}_{k} < s_{cr}$. Hence, we propose the following feedback control:

$$g^{l}_{k+1} \;=\; g^{l}_{k} - \; K_{s2}\left[\min\left(s^{l+1}_{k-1}\,, s_{cr}\right) - \min\left(s^{l+1}_{k}\,, s_{cr}\right)\right], \qquad (3)$$

where K_{s2} is a parameter to be calibrated to maximize the reduction of the delay time.

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