Examining Perimeter Gating Control of Urban Traffic Networks With Locally Adaptive Traffic Signals

Mehdi Keyvan-Ekbatani, Xueyu (Shirley) Gao, Vikash V. Gayah, and Victor L. Knoop

Abstract Traditionally, urban traffic is controlled by traffic lights. Recent findings of the Macroscopic or Network Fundamental Diagram (MFD or NFD) have led to the development of novel traffic control strategies that can be applied at a network-wide level. One pertinent example is perimeter flow control (also known as gating or metering), which limits the rate at which vehicles are allowed to enter an urban region. This paper studies to which extent a combination of adaptive traffic control and gating improves the traffic flow. To this end, combinations of gating and traffic signal timing tested implemented in a microsimulation. It is found that gating is much more effective than adaptive signal timing for high traffic loads. Adaptive signal timing can improve the network performance by increasing the maximum flow and increasing the critical accumulation, i.e. the number of vehicles inside a protected network for which the performance is maximized. The latter helps to reduce queuing outside the protected network.

1 Introduction

The objective of urban traffic control (UTC) has traditionally been to implement signal timings that minimize the total vehicular delay in the network. UTC systems constitute a scientific field with long-lasting and extensive research and development activities. Widely applied UTC strategies like SCATS (Sydney Coordinated Adaptive Traffic System) [1], despite being applicable to large-scale networks, are not very efficient when the traffic network is saturated or oversaturated. On the other

Keyvan-Ekbatani and Knoop
Delft University of Technology, Stevinweg 1, 2628 CN Delft, e-mail: m.ekbatani@tudelft.nl and v.l.knoop@tudelft.nl

Gao and Gayah
Pennsylvania State University, University Park, USA e-mail: xug103@psu.edu and gayah@engr.psu.edu

hand, traffic-responsive strategies like OPAC [2], which are more advanced, apply optimization algorithms with exponential increase of complexity. Because of this complexity, these do not permit a practical central network-wide application. In fact, Gayah et al. [3] showed that in an extremely congested network, typical adaptive traffic signal control schemes might have little to no effect on the network due to downstream congestion and queue spill-back. Moreover, the aforementioned methods may allow too much traffic to enter into the part of the network to be protected from over-saturation and only act after the congestion starts occurring. This might be an important reason that most of the existing adaptive traffic control strategies do not operate efficiently in highly congested urban road networks.

Assuming a constant length of the trip in a network, one can also show that the outflow of the network (i.e., rate vehicles reach their destination) is maximized if the accumulation is at the critical accumulation. For accumulations less than the critical value, the relationship between outflow and accumulation is increasing. The relationship between these two macroscopic traffic values at the network level is called Macroscopic or Network Fundamental Diagram (MFD or NFD). Geroliminis and Daganzo [4] verified the existence of the NFD using the data of downtown Yokohama in Japan. The notion of NFD is still under thorough investigation in various aspects, but it can be applied as a basis for development of urban signal control strategies. As details of individual links are not required to describe the real-time traffic state at the network level, NFD is useful to introduce elegant control concepts that can maintain the accumulation at the capacity level.

The control idea derived from the aforementioned approach is to hold vehicles back upstream of a "protected network (PN)" such that the accumulation does not exceed the critical value in order to maximize the outflow. This control strategy is called gating or perimeter control. This concept has already been utilized to numerous efficient perimeter flow control policies in homogeneous networks (see [5] for single region, and [6] for multiple concentric regions).

As discussed in [7], the scatter and hysteresis in the NFD might be decreased slightly by applying only gating or perimeter control strategy, since the PN will operate at the capacity level and possible gridlocks are avoided as much as possible. considering the fact that the PN utilizes the fixed-time signal control plan, the network may still experience heterogeneity in distribution of congestion. To the best of our knowledge, for a more homogeneous distribution of the density in PN, none of the existing gating strategies consider an adaptive traffic control. Up to now, these two (control) schemes (i.e. adaptive traffic control and gating control) have only been implemented separately in the studies. This paper tries to fill this gap and integrate the gating concept at the boundary of the PN with the traffic-responsive adaptive signal control strategy inside the PN. Two different adaptive traffic signal strategies are considered with the feedback-based gating strategy developed in [5]: (1) a simple volume-based strategy and (2) a modified version of the SCATS algorithm. To this end, we set up six different control scenarios in the microscopic simulation environment AIMSUN. The control scenarios are as follows: (1) fixed control, (2) modified SCATS [8], (3) volume-based strategy [3], (4) only-gating, (5) gating plus modified SCATS, (6) gating plus volume-based strategy. Two overall performance indexes (i.e., average delay (s/km) and maximum virtual queue (veh)) have been utilized to evaluate the efficiency of the tested scenarios. The study shows that application of adaptive traffic signal control in PN increases the critical accumulation in NFD and consequently leads to shorter virtual queue sizes (i.e. vehicles waiting to enter the network) during the gating time.

The remainder of this paper is set up as follows: section 2 presents the control strategies (i.e. gating and adaptive control). Section 3 discusses the simulation set-up and the test-bed description. Section 4 illustrates a comparative appraisal of the six simulated scenarios. Finally, summary and conclusions are included in the last section.

2 Control strategies

Four different control strategies are implemented in this study. As a base-line we applied the fix-time control. Two different adaptive control strategies are used within the PN: (1) volume-based strategy; (2) modified SCATS and the recently developed feedback-based gating control strategy [5].

2.1 Adaptive traffic responsive strategies

In this paper, two different adaptive traffic responsive strategies (adopted from previous efforts) were considered. The goal of both strategies was to provide more green time to the approach(es) with more traffic. Offsets between adjacent signals were not modified by either strategy. In the first strategy, a fixed cycle length was adopted for each signal that was then divided among competing approaches every cycle. A simple proportional algorithm was used to allocate the available green time at each intersection based on traffic volume measured at upstream detectors on each approach. In this algorithm, the green time to a subject approach i is determined as follows:

$$g_i(t) = (C-L)\,\frac{v_i(t-1)}{\sum_i v_i(t-1)} \tag{1}$$

where $g_i(t)$ is the green time allocated to approach i during cycle t, C is the fixed cycle length, L is the lost time for vehicle movement (usually due to and directly proportional to the number of phase changes) and $v_i(t-1)$ is the volume observed on approach i during cycle $t-1$. All available green time was allocated in this way. Thus, it is possible that some approaches received zero green time if no vehicles were queued at the approach. This strategy was called the “volume-based” strategy. In this paper, a fixed cycle length of 90 seconds was used for all adaptive traffic signals.

The second strategy is a simplified version of the realistic SCATS, which is currently applied in many cities throughout the world. This strategy was adopted from

[8] where it was used to assess the impacts of adaptive signal control on the NFD using simulation. In this strategy, both the green time and total cycle lengths are variable and adjusted based on volume data obtained from upstream loop detectors. As described in [8], an appropriate cycle length is first select based on the volume ratio observed during the previous cycle. This cycle length is designed to maintain a volume ratio between 0.85 to 0.95 during the next cycle and is selected based on the following rules:

$$C(t) = \begin{cases} STOPPER & \text{if } C(t) = \text{MIN}, R(t-1) > 0.4 \\ MIN & \text{if } C(t) = \text{STOPPER}, R(t-1) < 0.2 \\ \min\{C(t-1) + \text{STEP, MAX}\} & \text{if } R(t-1) > 0.95 \\ \max\{C(t-1) - \text{STEP, STOPPER}\} & \text{if } R(t-1) < 0.85 \\ C(t-1) & \text{otherwise} \end{cases} \quad (2)$$

where MIN and MAX are the minimum and maximum cycle lengths, respectively, STOPPER is an intermediate cycle length that allows for sharp increases in cycle length due to sharp increases in traffic demands, and $R(t-1)$ represents the volume ratio at a given intersection during cycle $t-1$. The cycle length is allocated among the competing approaches based on the vehicle demand on each approach. The following equation is used to allocate this green time:

$$g(t) = (C(t) - L - G_{\min}) \frac{d_i(t-1)}{\sum_i d_i(t-1)} + g_{i,\min} \quad (3)$$

where $G_{\min}$ is the minimum green time allocated to each approach, and $g_{i,\min}$ is the vehicle demand on approach i. For this paper, the following values were used for the adaptive signals with SCATS: MIN=42 s, MAX=132s, STOPPER=66s, STEP=6s, $g_{i,\min}$=6s.

2.2 Feedback-based gating control

Keyvan-Ekbatani et al. (2012) [5] developed a control design model and an appropriate feedback controller for the described gating task. Given the derived model structure (4), the following proportional-integral-type (PI) feedback controller is appropriate:

$$q_g(k) = q_g(k-1) - K_p [TTS(k) - TTS(k-1)] + K_I \left[\widehat{TTS} - TTS(k)\right] \quad (4)$$

TTS is the Total Time Spent, $\widehat{TTS}$ is desired set-point (critical accumulation in NFD, see [5] q_g is the gated flow ordered by the controller, K_P and K_I are the proportional and integral gains, respectively. The flow calculated by the regulator (5) must be constrained by pre-specified minimum and maximum values to account for operational constraints. Proper controller parameter may be derived by the methodology presented in [6] or manual fine tuning.

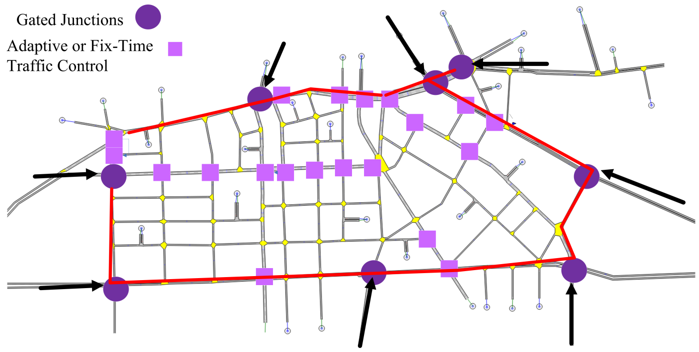

Fig. 1 Part of Chania urban network modelled in AIMSUN; the PN is indicated by bold red line.

3 Simulation setup and scenario description

A greater part of Chania urban network in Greece is modelled in the microscopic simulator AIMSUN. Since the objective was to test our proposed control strategies on a network with realistic features but not completely identical, we manipulated the number of traffic lights in the PN. Fig.1 demonstrates the location of the eight gated links (shown by the black arrow and violet circle) and the traffic lights controlled with fix-time and adaptive (i.e. modified SCATS and volume-based) traffic control signal plan (shown by violet squares) within the protected network. In the middle of every link inside the red border line, a loop detector has been installed, and the related measurements are collected every cycle (90 seconds in the case of the fixed cycle lengths). The utilized 4-hour trapezoidal demand profile simulates traffic conditions similar to the real traffic conditions (mimicking the peak and off peak period).

The following control scenarios (including gating and no-gating) are simulated in this study:

1. (no-gating) the traffic lights in the PN (indicated by square and circle) are controlled applying fix-time control signal plan.
2. (no-gating) "volume-based" traffic responsive control strategy is implemented to control all the traffic lights within PN.
3. (no-gating) adaptive traffic control strategy "modified SCATS" is used for controlling the signalized junctions within PN.
4. Gating at the perimeter and fix-time control inside PN.

5. Gating at the border and "volume-based" for the rest of the traffic lights in the PN.
6. Gating at the boundary and "modified SCATS" within PN.

We use 15 different replications (i.e. simulation runs) for each investigated scenario and then calculated the average value of the 15 runs for each performance index (the average vehicle delay (s/km) and maximum queue length (veh)) in order to compare different control strategies.

4 Simulation Results

Fig.2 (a) displays the NFD (TTD vs. TTS; TTD is Total Travelled Distance) for the Chania PN (assuming that all links are detector-equipped) for the first 2 h of the employed scenarios 1, 2 and 3, i.e. the loading period of the network, and the congestion is created; 15 different replications (shown by empty dots in the plot) were carried out. Utilizing equations (1)-(3), the TTD and TTS of the PN are estimated every 90 (cycle time of all the fixed traffic lights in the network). For a better clarification of the PN traffic state, a moving-average curve for the scattered MFD of each scenario has been shown with different color. An interesting finding at this stage of the study is the fact that using adaptive traffic control lead to higher critical accumulation (750 vehicles for the green and the blue curve). The shifted $\widehat{TTS}$ value in the case of adaptive traffic control signal plan might be extremely beneficial since it allows more vehicles into the PN during gating. This might help to reduce the gated queue size at the boundary of protected network and reduce the negative impact of the growing queues upstream of the gated junctions. To illustrate better the advantageous effect of the gating strategy on the traffic flow throughput (i.e. TTD) in the PN, the MFDs for scenarios 4, 5 and 6 are shown in fig.3 (b). Obviously, the feedback controller has perfectly performed and maintained the TTS or the vehicle accumulation in the PN close to the critical value of the corresponding scenario (in a region of TTS 700 to 750 veh) and consequently kept the network throughput at the maximum level during the peak period. The TTD for the gating scenarios plus adaptive control has higher value compared to the gating plus fix-time.

Table 1 Average values of performance indexes for different control scenarios (over 15 replications)

Performance Index	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
delay (sec/km)	389	294	351	203	193	203
max virtual queue (veh)	728	696	702	965	808	888

Table 1 summarizes the average simulation results for the six different scenarios (over 15 runs each) studied in this research. In the no-gating case, the adaptive traffic control strategies lead to an improved mobility (lower average delay) compared to the fix-time signal plan. Under gating, the average delay improved significantly compared to the no-gating scenarios.

Fig.3 illustrates the controller action during the simulation for scenario 4. Concentrating on fig.3 (a), the controller managed perfectly to maintain the TTS close to the set-value (shown by the green horizontal dashed line). Similar results are obtained for scenarios 5 and 6. The red line in fig.3 (b) shows the actual flow crossing the stop bar at the gated junction and entering the PN. There is a gap between the actual flow and the flow ordered by the controller (red and black lines). This could be due to the flow distribution policy, which in this case is only based on the saturation flows of the gated links. In an on-going work, a queue management policy will be implemented at the gated junctions in order to reduce the chance of wasting green times due to blockages downstream or lack of demand at the gated links.

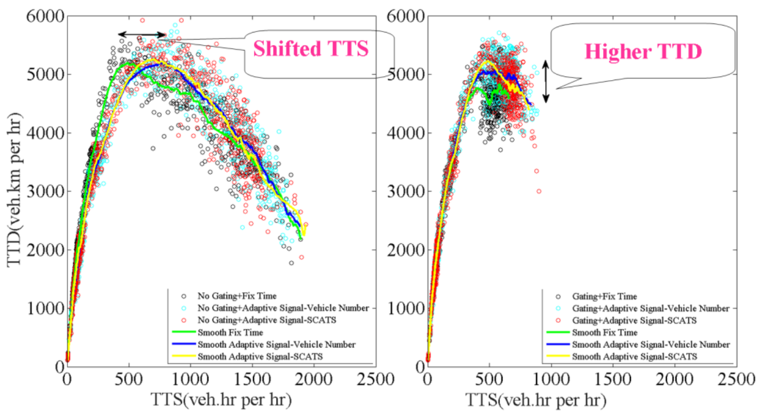

Fig. 2 (a) NFD of the no-gating scenarios (Scenario 1, 2 and 3); (b)and for the gating scenarios (Scenario 4, 5 and 6) for the first 2 hour.

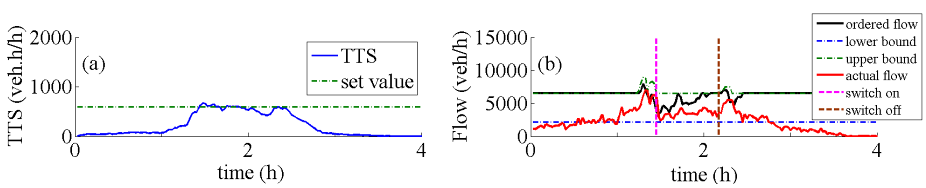

Fig. 3 TTS vs. time for Scenario 4; (b) flow vs. time for Scenario 4

5 Conclusions

In this paper, we examined the joint implementation of two unique urban traffic control strategies: perimeter gating of a protected network and adaptive traffic signal control. The former limits vehicle entries into a protected network to maximize throughput within the protected region. The latter modifies signal timings at individual intersections in response to real-time traffic fluctuations. Here, we have showed that the combination of these two strategies can be even more beneficial. The adaptive signal control strategies help to provide more efficient NFDs in which more vehicles can be accommodated within the protected network with higher overall throughputs. The gating strategy makes use of these higher accumulations and throughputs, which results in fewer vehicles queuing at the boundaries of the protected network during the implementation of gating. Overall, the results find that the combination of gating and adaptive signal control results in lower network delays, shorter boundary queues (on average).

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