COMBINATION OF TRAFFIC-RESPONSIVE AND GATING CONTROL IN URBAN NETWORKS: EFFECTIVE INTERACTIONS

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ABSTRACT

Recent findings regarding macroscopic relationships of urban traffic measures such as 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. In general, these gating strategies seek to prevent a network from becoming congested and maximize network efficiency/productivity by maintaining an optimal accumulation of vehicles within the network. Several studies have found that NFDs are more well-defined (i.e., have less scatter and show better overall network performance) when adaptive traffic signals are installed that dynamically respond to local traffic conditions. A combined gating and adaptive traffic control scheme can leverage the more reproducible macroscopic traffic patterns achieved with adaptive signals to provide more robust and efficient gating control. The purpose of this paper is to explore the benefits of combining perimeter gating with locally adaptive traffic signals through micro-simulation of the Chania, Greece traffic network. Two adaptive traffic signal strategies are considered with the feedback-based gating strategy: (1) a simple volume-based strategy and (2) a modified version of the SCATS algorithm. The results of the combined gating/adaptive signal control scheme are compared to gating under fixed traffic signals and the implementation of adaptive signals only. Overall, the study finds that travel delays and congestion can be considerably reduced with the combined strategy. This is because the adaptive traffic signals allow the network to achieve higher network productivity while the gating control allows the network to maintain this higher efficiency for a longer period of time than if left uncontrolled. The results are promising for the implementation of perimeter gating strategies in practice.

Keywords: Macroscopic or network fundamental diagram, gating or perimeter control, traffic-responsive control, SCATS

1. INTRODUCTION

The world population in urban areas is growing and so are the traffic problems related to urban areas. Urban traffic has been controlled by traffic signals for many years. Whereas this first was primarily a safety issue, traffic signals now serve as a remedy for solving the congestion problem. 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. Although many approaches have been developed up to now, there is still space for proposing new, efficient and practicable control schemes, particularly for saturated traffic conditions.

Widely applied UTC strategies like SCOOT (Split Cycle Offset Optimization Technique) [1] and SCATS (Sydney Coordinated Adaptive Traffic System) [2], despite being applicable to large-scale networks, are not very efficient when the traffic network is saturated or oversaturated. SCOOT, which is an adaptive system that responds automatically to fluctuations in traffic flow, is the most common UTC system used in the UK. SCATS was developed in Australia in the early 1970s and has been used in Australia for the past 40 years [3]. The system optimizes cycle lengths, phase splits, and offsets on a cycle-by-cycle basis. The degree of saturation is used to adjust the cycle length. The more recently developed control strategy TUC [4] is also a practical approach for real-time traffic control and is already being implemented in several cities. On the other hand, traffic-responsive strategies like OPAC [5], PRODYN [6], 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. Most of the existing control strategies face limitations when it comes to saturated traffic conditions that are frequently observed in large-scale urban cities. According to FHWA report [7] in 2008; "No current generally available tool is adequate for optimizing [signal] timing in congested conditions". In fact, Gayah et al. [8] 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.

Daganzo [9] showed that it is possible to monitor and control aggregate vehicular accumulations at the neighborhood level even without knowing the origin-destination table or the precise system dynamics. He argued that for a system, the total accumulation of the elements might be able to predict overall network behavior. In fact, in many systems, including transportation systems, average speeds decrease as the number of elements (vehicles) in the system increase. The total flow (production) is the product of the number of elements and the speed. Thus, a clear relationship exists between network accumulation and production. Production is zero for accumulations of zero (empty network) and the maximum value (gridlocked network). In between, there is a maximum production which is achieved at some critical accumulation. 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. For accumulations greater than this value, the relationship is decreasing. 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 [10] verified the existence of the NFD using the data of downtown Yokohama in Japan. Although the exact NFD curve may depend on the origin-destination demand, it may be quite stable from day to day, particularly if the traffic load is homogeneously distributed in network links. Leclercq et al. [11] addressed that the O-D matrix may have a significant influence on the macroscopic traffic dynamics related to a given road network. Leclercq and Geroliminis [12] has also shown that flow distributions associated to driver route choices may influence the NFD shape for a simple parallel network. Other interesting studies related to network level relations for simulated and real networks have examined how these relationships change based on types of measurements and potential instabilities ([13], [14], [14], [15]). 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 [16] for single region, [17] and [18] for multi-region and [19] for multiple concentric regions). Knoop et al. [20] and Yildirimoglu et al. [21] exploited the NFD for route guidance. Haddad and Shraiber [22] designed a robust perimeter control considering uncertainties in NFD-based dynamics (e.g. the NFD scatter) systematically. Hajiahmadi et al. [23] developed a switching controller which aims at changing fixed-time plans with a gating controller. Ramezani et al. [24] introduced a hierarchical perimeter flow control problem by integrating the NFD heterogeneous modeling.

As discussed in [25], 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. But 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. However, adaptive traffic signals have shown to produce better and more reliable NFDs ([26]; [8]). 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 [16]: (1) a simple volume-based strategy and (2) a modified version of the SCATS algorithm. The purpose of this paper is to explore the benefits of combining perimeter gating with locally adaptive traffic signals through micro-simulation of the Chania, Greece traffic network.

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 [25] which is a simplified version of the SCATS strategy implemented in the field, (3) volume-based strategy [8], (4) only-gating, (5) gating plus modified SCATS, (6) gating plus volume-based strategy. Four different overall performance indexes (i.e. average delay (s/km), mean speed (km/h), maximum virtual queue (veh) and average virtual queue (veh)) have been utilized to evaluate the efficiency of the tested scenarios.

The principal findings of this work are as follows: (a) 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 (b) higher network throughput (i.e. higher total flow in NFD) can be reached by combing gating with a traffic responsive control strategy (c) gating traffic control showed much more efficient than the implemented traffic responsive control strategies under oversaturated traffic conditions (d) the study showed that variance of link densities in the PN is minimized when implementing the proposed control strategies (gating + adaptive traffic control) compared to only-gating and fix-time control.

The remainder of this paper is set up as follows: section 2 presents the methodology, including NFD derivation, description of the two implemented traffic-responsive control strategies and the feedback gating concept. 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. METHODOLOGY

This section gives first an overview of NFD and its derivation. Then, the implemented feedback gating concept is described. Finally, the two adaptive traffic signal control strategies are introduced.

2.1. NFD derivation

Recently, it was found that the notion of a fundamental diagram (e.g. in the form of a flow-density curve) can be applied (under certain conditions) to two-dimensional urban road networks. The two-dimensional fundamental diagram relates the summation of weighted flow and average density. A unimodal curve is generally expected: as the accumulation or density is increasing, the traffic flow increases up to a point that the capacity is reached. Exceeding the range with critical density, the network starts degrading and enters the over-saturated region. The aim of most network-wide traffic control strategies is to maintain the overall traffic state in the range of maximum total flow and to avoid spillover and gridlock creation by applying various traffic management tools (e.g. traffic signal optimization, gating, route guidance and etc.).

According to the definitions introduced in ([16], [27]), the NFD can be alternatively plotted as Total Travelled Distance (*TTD* in veh·km per h) for the y-axis and Total Time Spent (*TTS* in veh·h per h) for the x-axis. The *TTD* and *TTS* are obtained from the (emulated) loop measurements via the following equations:

$$TTS(k) = \sum_{z \in \mathbb{M}} \frac{T \cdot \hat{N}_z(k)}{T} = \sum_{z \in \mathbb{M}} \hat{N}_z(k) = \hat{N}(k) \tag{1}$$

$$TTD(k) = \sum_{z \in \mathbb{M}} \frac{T \cdot q_z(k) \cdot L_z}{T} = \sum_{z \in \mathbb{M}} q_z(k) \cdot L_z \tag{2}$$

where z is the link where a measurement is collected; $\mathbb{M}$ is the set of measurement links; $k = 0,1,2,...$ is a discrete time index reflecting corresponding cycles; T is the cycle time; q_z is the measured flow in link z during cycle k; L_z is the length of link z; $\hat{N}(k)$ is the estimated number of vehicles within the links in the set of $\mathbb{M}$. *TTS* is the estimated total time spent, which turns out to equal the estimated number of vehicles in the subset of the links and $\hat{N}_z(k)$ is the estimated number of vehicles in link z during cycle k, which is derived from occupancy measurements via the following equation

$$\hat{N}_z(k) = L_z \cdot \frac{\mu_z}{100\lambda} \cdot o_z(k-1) \tag{3}$$

where $o_z(k)$ is the measured time-occupancy (in %) in link z during cycle k; μ_z is the number of lanes of link z; and λ is the average vehicle length. The link estimated number of vehicle is fairly precise, if the detector is located around the middle of the link [27].

2.2. Feedback-based gating control

The development of feedback control methodologies has had a tremendous impact in many different fields of the engineering. Feedback control is actually better able to keep the process variable close to the desired value in spite of disturbances and variations of the process dynamics.

The typical feedback control system consists of actuator, process and sensor. The actuator is the device that can influence the controlled variable of the process [29]. In this work, traffic lights and *TTS* in the PN are the actuator and control variable, respectively. The control variable *TTS* is indirectly influenced by the traffic lights. In other words, traffic lights influence the inflow to PN and consequently the *TTS* (estimated number of vehicles in PN) is also affected by the traffic lights. The sensor (i.e. detectors in traffic control) measures the control variable, where in the case of urban traffic control, since *TTS* is not measureable (estimated from (1)) the occupancy is measured by the detectors. In control engineering, a single input single output (SISO) system is a simple control system with one input and one output. In a

SISO control system (e.g. proportional integral (PI) feedback control), the control goal is to maintain the process value close to a pre-specified value (i.e. reference or set value).

According to [25], the process (i.e. the traffic state), in the general case (considering time-delayed system) can be modelled by the following discretized control design model of the continuous-time state equation of the PN (using the conservation equation and the NFD)

$$\Delta TTS(k+1) = \mu \cdot \Delta TTS(k) + \zeta \cdot \Delta q_{\mathrm{g}}(k-m) \tag{4}$$

where Δ-quantities reflect corresponding deviations from nominal values (e.g. $\Delta TTS(k) = TTS(k) - T\hat{T}S$, $T\hat{T}S$ is desired set-point (critical accumulation in NFD)), μ and ζ are the model parameters, k=1,…, K is the control step, $\Delta q_{\mathrm{g}}(k) = q_{\mathrm{g}}(k) - \bar{q}_{\mathrm{g}}$, q_g is the gated flow and m corresponds to the time-delay.

The targeted set-point $T\hat{T}S$ should be selected within the range of critical accumulation (in which production is at maximum level), in order to avoid throughput degradation. Keyvan-Ekbatani et al. [16] 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

$$q_{\mathrm{g}}(k) = q_{\mathrm{g}}(k-1) - K_{\mathrm{P}}\left[TTS(k) - TTS(k-1)\right] + K_{\mathrm{I}}\left[T\hat{T}S - TTS(k)\right] \tag{5}$$

where 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 [19] or manual fine tuning.

2.3. Adaptive traffic responsive strategies

Adaptive traffic signal systems modify signal timings to accommodate real-time changes in traffic characteristics. 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:

$$g_i(t) = (C-L) . \frac{v_i(t-1)}{\sum_i v_i(t-1)} \tag{6}$$

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 $\mathrm{v}_i(t)-1$ 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. It was first applied to examine the impacts of adaptive signal control on the NFD in an analytical investigation [8] and was used here to represent the simplest adaptive control algorithm that might be considered in practice. 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 Sydney Coordinated Adaptive Traffic System (SCATS), which is currently applied in many cities throughout the world. This strategy was adopted from [26] 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 [26], 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:

$$C(t)=\begin{cases} STOPPER & if\ C(t)=MIN, R(t-1)>0.4 \\ MIN & if\ C(t)=STOPPER \quad \text{and} \quad R(t-1)<0.2 \\ \min[C(t-1)+STEP, MAX] & if\ R(t-1)>0.95 \\ \max[C(t-1)-STEP, STOPPER] & if\ R(t-1)<0.85 \\ C(t-1) & \text{otherwise} \end{cases} \tag{7}$$

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 $R(t\text{-}1)$ 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:

$$g_i(t)=\left(C(t)-L-G_{min}\right).\frac{d_i(t-1)}{\sum_i d_i(t-1)}+g_{i,min} \tag{8}$$

where G_{min} is the sum of the minimum green times for each approach, $g_{i,min}$ is the minimum green time allocated to each approach, and $d_i(t-1)$ 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 = 132 s
- $STOPPER = 66$ s
- $STEP = 6$ s
- $g_{i,min} = 6$ s

3. SIMULATION SETUP AND SCENARIO DESCRIPTION

A greater part of Chania urban network in Greece is modelled in the microscopic simulator AIMSUN (see FIGURE1). 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. The original network consists of 27 signalized junctions, but in this study we added extra traffic lights within the PN to make the implementation of the adaptive traffic control strategies more feasible without changing the geometric and topographic characteristics of the network. FIGURE 2 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). The central business district (CBD) of the Chania urban road network, where the congestion usually starts during the peak period, is considered as the protected network (shown by red bold line in FIGURE 1 and FIGURE2). The protected network includes 28 (19 in the original network) signalized junctions and consists of 165 links. 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). To choose the gating locations, we tried to select the links with the highest inflow into the PN and sufficient space for vehicle queuing. The introduced O-D flows are realistic but not exact (particularly with

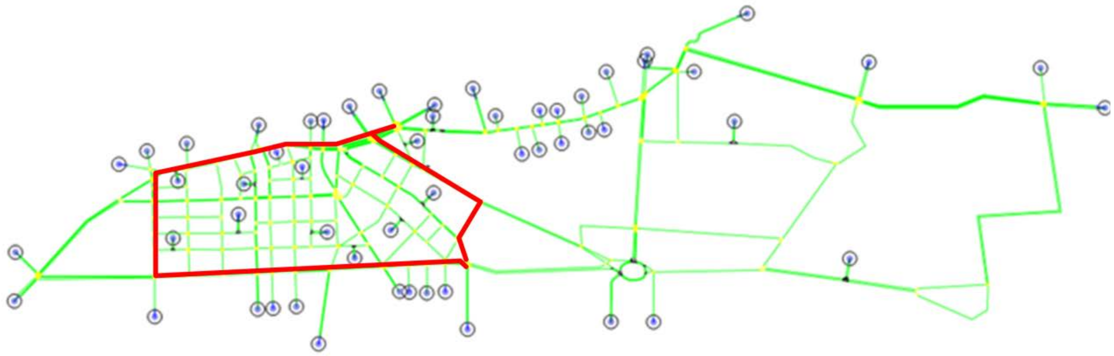

FIGURE 1 Chania urban network modelled in AIMSUN.

regard to the used O-D rates). A route choice system (c-logit) distributes the vehicles over the different paths from each origin to each destination, while running the simulation. A time step of 30 s is chosen as the route choice period in this study. This means that the route choice distribution is updated every 30s while AIMSUN is running. This was done because adaptive driver routing was found to provide more stable and reliable NFDs ([30], [31], [32]). The utilized 4-hour trapezoidal demand profile simulates traffic conditions similar to the real traffic conditions (mimicking the peal and off peak period).

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

- *Scenario 1*: (no-gating) the traffic lights in the PN (indicated by square and circle) are controlled applying fix-time control signal plan.
- *Scenario 2*: (no-gating) “volume-based” traffic responsive control strategy is implemented to control all the traffic lights within PN.
- *Scenario 3*: (no-gating) adaptive traffic control strategy “modified SCATS” is used for controlling the signalized junctions within PN.
- *Scenario 4*: Gating at the perimeter and fix-time control inside PN.
- *Scenario 5:* Gating at the border and “volume-based” for the rest of the traffic lights in the PN.
- *Scenario 6:* Gating at the boundary and “modified SCATS” within PN.

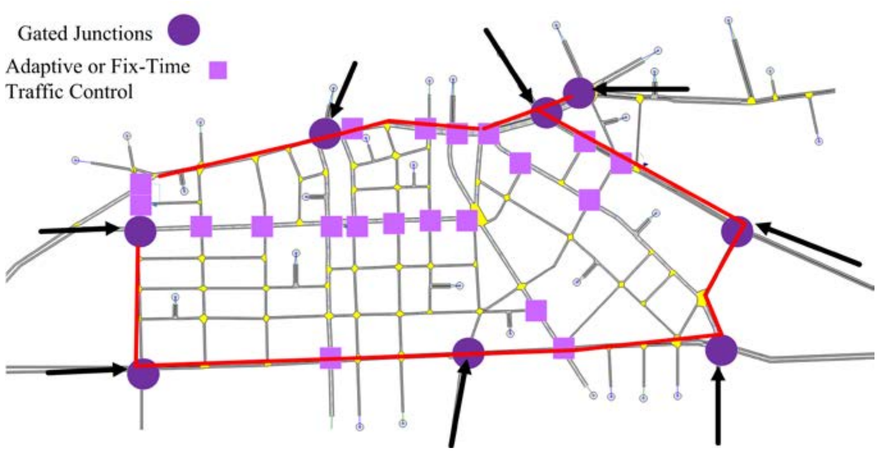

FIGURE 2 Traffic lights location within the PN (indicated by the red border).

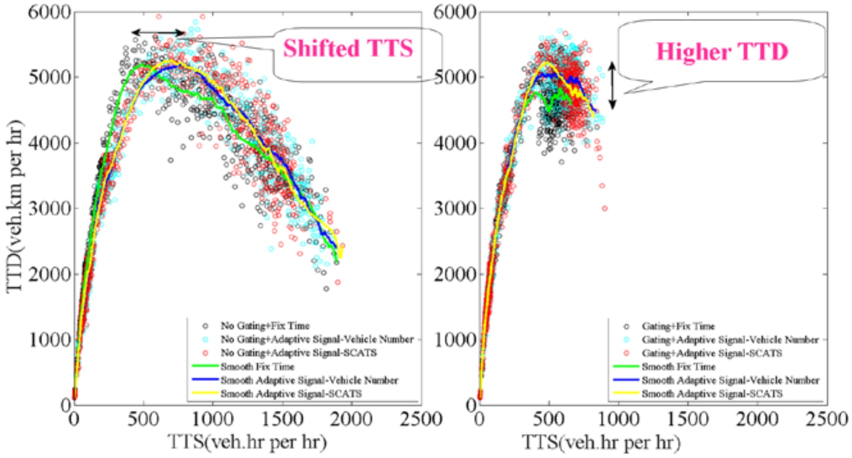

FIGURE 3 (a) NFD of the no-gating scenarios (Scenario 1, 2 and 3) for the first 2 hours; (b) NFD of the gating scenarios (Scenario 4, 5 and 6) for the first 2 hour.

4. COMPARATIVE APPRAISAL OF CONTROL SCENARIOS

Due to stochastic nature of microscopic simulator AIMSUN, different simulation runs (replications) with different random seeds may lead to different results. We used 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 in order to compare different control strategies. In principal, five network-wide performance indexes has been applied: the average vehicle delay (s/km), the mean speed (km/h), maximum virtual queue (veh), average virtual queue (veh) and the total number of vehicles that exit the overall network during the whole scenario.

4.1. NFD analysis of simulated scenarios

FGURE 3 (a) displays the NFD 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). The *TTD* starts from very low value and reaches the capacity (highest value) in all three scenarios. The simulation runs for the three different (no-gating) scenarios are distinguished by different colors. For a better clarification of the PN traffic state, a moving-average curve for the scattered NFD of each scenario has been shown with different color. For scenario 1, the maximum *TTD* value in the diagram (shown by black curve) occurs with a *TTS* of 600 veh.h per h (i.e. the $T\hat{T}S$). If accumulation is allowed to increase beyond this limit, then *TTD* (and hence the PN throughput) decreases. For the no-gating case (FIGURE 3 (a)), the highest *TTD* is reached (green curve) when scenario 3 is implemented (adaptive traffic SCATS). 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), which verifies the findings first observed in ([26], [8]). The shifted $T\hat{T}S$ 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 NFDs for scenarios 4, 5 and 6 are shown in FIGURE 3 (b). Obviously, the feedback

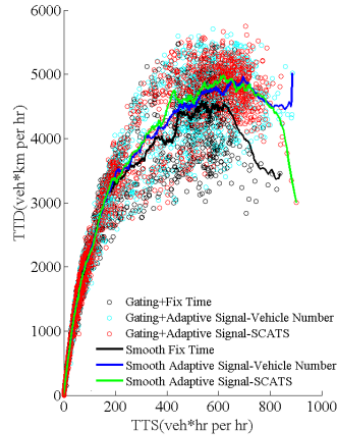

FIGURE 4 NFD of scenarios 4, 5 and 6 for the 4-hour simulation (fitted curve for the loading period).

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 NFDs for the 4-hour simulation of the gating scenarios is illustrated in FIGURE 4. Focusing on the fitted curves (for the loading period) shown in FIGURE 4, it can be realized that the combination of gating control with the adaptive traffic control strategies (i.e. volume-based and SCATS) lead to NFDs with higher maximum values compared to the previous studies (fix-time control in PN) and consequently increased throughput.

4.2. Variation of link densities within PN for different scenarios

The spatial distribution of vehicle density in the network is one of the key components that affect the scatter of an NFD and its shape ([15], [32]). As addressed in [19], production and variance of accumulation in the network are inversely correlated. This means a smart demand distribution may address the variability of link densities to keep the network production at a higher level.

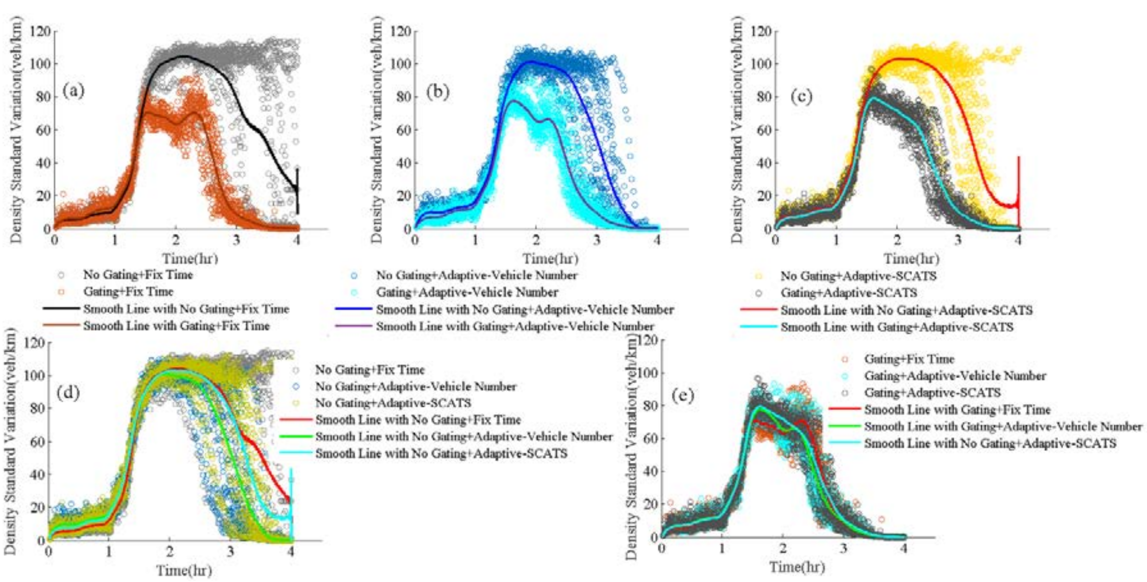

FIGURE 5 Density standard deviation vs. time for 15 runs; (a) Scenario1 and Scenario 4; (b) Scenario 2 and Scenario 5; (c) Scenario 3 and Scenario 6; (d) Scenario 1, 2 and 3; (e) Scenario 4, 5 and 6.

In this section, we compare the standard deviation (S.D.) of link densities versus time evolution in all control scenarios. FIGURE 5 (a)-(c) presents the comparison between the density S.D. in the case of (no-gating) and (gating) control implemented on scenarios 1 to 3 for all the 15 simulation runs. Comparing each pair of scenarios (1 and 4), (2 and 5) and (3 and 6), we realize that after applying gating, the density variations decreases significantly. This might be more visible by comparing the fitted curves to the data in each scenario. Moreover, it is shown that in the no-gating scenarios the standard deviation of individual link densities increased compared to the fix-time control when applying the two adaptive traffic control strategies (see FIGURE 5(d)). Since the gating activation (there is a switch on/switch off policy, see section 4.3 for more details) in the gated scenarios (4, 5 and 6) are during various time intervals, a direct comparison cannot be made. However, during the time period of $t \in [2, 2.2]$ (hr), which is the peak period in almost all the scenarios (and simulation runs) and the gating strategy is activated, implementing adaptive traffic controlled showed less density variation compared to the fix-time control. Thus, the combination of adaptive signals and gating help to reduce the variation of individual link densities more than any other strategy.

4.3. Evaluation of the simulated scenarios results

In this study, gating is implemented at the perimeter of the PN. Thus, there is no time-delay imposed on the traffic system (m = 0 in (4)). According to a time-optimal dead-beat regulator behaviour, $K_P = \mu/\zeta$ and $K_I = (1-\mu)/\zeta$. Based on a model identification procedure, the model parameters μ and ζ are derived (see Keyvan-Ekbatani et al [25] for more details). Once the parameters been specified, the regulator parameters for (set-point) dead-beat behavior were calculated to be $K_P = 20$ and $K_I = 5$.

To enable an illustrative comparison of the gating results of the three different scenarios (4, 5 and 6), the respective detailed results of a replication are displayed in FIGURE 6. Each row in FIGURE 6 belongs to a specific scenario (scenarios 4 to 6). As shown by the vertical dashed lines on the right column of FIGURE 6, gating is activated during a time-window but the regulator runs continuously in the background and orders flow during the whole period (the black line in (d)-(f)). The gating period obviously

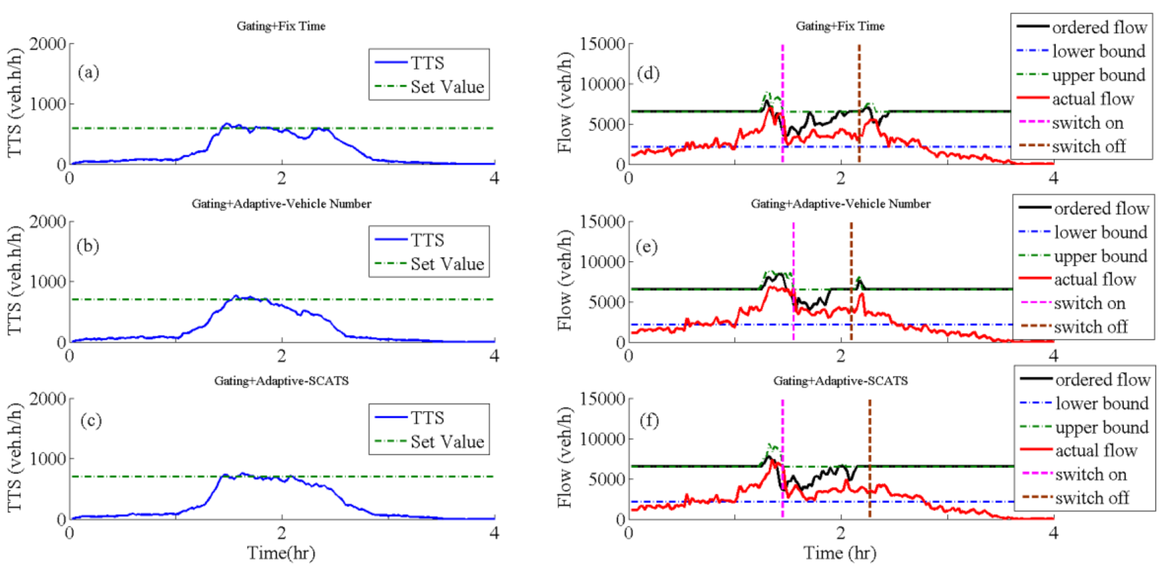

FIGURE 6 (a) and (d) *TTS* vs. Time and ordered controller action for Scenario 4; (b) and (e) *TTS* vs. Time and ordered controller action for Scenario 5; (c) and (f) *TTS* vs. Time and ordered controller action for Scenario 6.

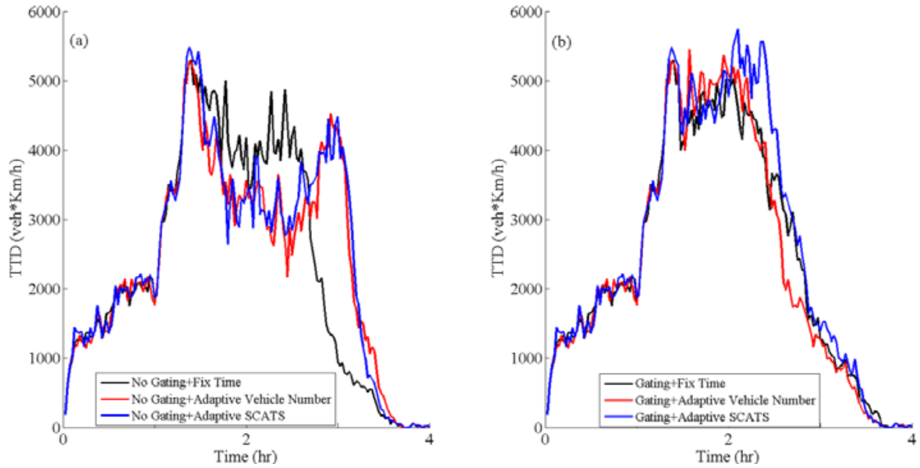

FIGURE 7(a) *TTD* vs. Time for Scenario 1, 2 and 3 (no-gating); (b) *TTD* vs. Time for Scenario 4, 5 and 6 (gating)

varies in different gating scenarios (this was already earlier pointed out in this paper). In this work, gating is switched on only when *TTS* (accumulation) exceeds a threshold, that is selected slightly lower than (in this case 85% of) the set-point, and is switched off when *TTS* falls below a 2nd, slightly lower threshold. Concentrating on the left column of FIGURE 6 (a)-(c), the controller managed perfectly to maintain the *TTS* close to the set-value (or $\hat{TTS}$, shown by the green horizontal dashed line) in all the gating scenarios. The red line in (d)-(f) 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. As stated in Section 2.2, the ordered flow is constrained by a maximum and minimum value which is shown in (d)-(f) by the horizontal dashed lines.

FIGURE 7 (a) and (b) displays the evoloution of *TTD* over time in the (no-gating) and (gating) scenarios. It can been easiliy seen that in all the gating scenarios the throughput of *TTD* is maximized compared to the no-gating scenarios. More specifically, the combination of gating with the adaptive tarffic control strategies based on the link volumes lead to higher *TTD* valuse among the three gating sceanrios. In this specific replication, (no-gating) fix-time scneario experienced higher throughput compared to the adaptive traffic control strategies.

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 (higher mean speed, lower average delay) compared to the fix-time signal plan. Under gating, the average delay and overall mean speed improved significantly compared to the no-gating

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

Performance Index	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario5	Scenario 6
delay (sec/km)	389	294	351	203	193	203
speed(Km/h)	8	10	9	13	14	13
avg. virtual queue (veh)	252	166	204	206	164	194
max virtual queue (veh)	728	696	702	965	808	888
vehicle out	12675	12913	12801	12924	12912	12923

scenarios. Interestingly, (gating + adaptive traffic control) lead to the best average results (highlighted in the table) with lowest average delay and the highest mean speed. It should be noted that, applying gating strategy might increase queuing at the boundary at the protected network (see the values for maximum and average virtual queue). The highest virtual queue size belongs to scenario 4 (gating + fix-time). This has been improved considerably by applying adaptive traffic control within the PN.

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. Previous research efforts have found that each of these applied individually can improve overall traffic conditions within a network. 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. This is indeed an important finding because the impact of queuing on the vicinity and sufficient space for storing the queuing vehicles at the gated links were always a crucial challenge. Overall, the results find that the combination of gating and adaptive signal control results in lower network delays, shorter boundary queues (on average), higher speeds and higher overall vehicle throughputs.

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