A Hybrid Strategy for Real-Time Traffic Signal Control of Urban Road Networks

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***Abstract*—The recently developed traffic signal control strategy known as traffic-responsive urban control (TUC) requires availability of a fixed signal plan that is sufficiently efficient under undersaturated traffic conditions. To drop this requirement, the well-known Webster procedure for fixed-signal control derivation at isolated junctions is appropriately employed for real-time operation based on measured flows. It is demonstrated via simulation experiments and field application that the following hold: 1) The developed real-time demand-based approach is a viable real-time signal control strategy for undersaturated traffic conditions. 2) It can indeed be used within TUC to drop the requirement for a prespecified fixed signal plan. 3) It may, under certain conditions, contribute to more efficient results, compared with the original TUC method.**

***Index Terms*—Real-time signal control, Traffic-responsive Urban Control (TUC) signal control strategy, traffic signal control, Webster formula.**

I. Introduction

DESPITE continuous research and development efforts toward efficient signal control systems over the last 50 years, urban network congestion continues to grow in most cities around the world. Although additional measures, such as road pricing, improved public transport operations, access restrictions of various kinds, driver information, and guidance, may also help to alleviate the congestion problem in urban networks, improved signal control strategies remains a significant objective.

Real-time signal control systems automatically responding to the prevailing traffic conditions are deemed to be potentially more efficient than clock-based fixed-time (FT) control settings. A variety of real-time signal control strategies have been developed during the past few decades, some of which have been actually implemented while others are still in a research stage (see, e.g., [1] and [2] for a review). Early signal control strategies were most efficient for undersaturated traffic conditions, whereby all queues at the signalized junctions are served during the next green phase. A particular challenge for real-time signal control strategies is the need to efficiently address both undersaturated (off-peak) and oversaturated (peak-period) traffic conditions.

A design avenue for real-time network-wide signal control under oversaturated traffic conditions is based on the store-and-forward modeling paradigm, which was first proposed in [3]. A particular signal control strategy under this class is the feedback control strategy Traffic-responsive Urban Control (TUC) [4], [5], which has been successfully implemented in several large networks in Europe and South America (see [6] and [7] for some recent field results). TUC incorporates a predetermined plan of fixed greens for each stage at each signalized junction. Extensive investigations [8], [9] have shown that TUC's sensitivity to the particular utilized fixed plan is minor under high-demand conditions; in contrast, when demands and queueing are low, TUC's split decisions are close to the utilized fixed plan. Since fixed plans may not be available, may be aging, or may be different for different times of the day, there is a need to appropriately replace this requirement, i.e., develop a (preferably simple) procedure that can determine efficient splits in real time when traffic conditions are undersaturated.

To this end, this paper proposes a real-time version of the traditional rules by Webster [10] and Webster and Cobbe [11] that have been extensively used by traffic engineers in the last 50 years for the design of FT splits under known (historical) constant demands. The derived real-time method is efficient, as long as traffic conditions are undersaturated but fails when queues start to form in network links due to increasing demand. Therefore, a hybrid approach is proposed, whereby signalized junctions are controlled by the real-time Webster-type demand-driven strategy as long as traffic conditions are undersaturated while a switching to TUC is effectuated when traffic conditions are close to saturation. Microscopic simulation investigations for the network of the city of Chania, Greece, demonstrate the capabilities of the hybrid approach. Field results from the same network confirm the efficiency of the approach during both the off-peak and the congested peak-period traffic conditions.

II. Signal Control Strategies Employed

A. Definitions and Constraints

The urban road network is represented as a directed graph with links $z \in Z$ and junctions $j \in J$. For each signalized junction j, we define the sets of incoming I_j and outgoing O_j links. It is assumed that the offsets and the cycle time C_j of junction j are fixed or calculated in real time by another algorithm. In addition, to enable network offset coordination, we assume that $C_j = C$ for all junctions $j \in J$. Furthermore, the signal control

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plan of junction j is based on a fixed number of stages that belong to the set F_j, whereas v_z denotes the set of stages where link z has right of way (r.o.w.). Finally, the saturation flow S_z of link $z \in Z$ and the turning movement rates $t_{w,z}$, where $w \in I_j$ and $z \in O_j$, are assumed to be known and constant.

By definition, the constraint

$$\sum_{i \in F_j} g_{j,i} + L_j = C \tag{1}$$

holds at junction j, where $g_{j,i}$ is the green time of stage i at junction j, and L_j is the total lost time at junction j. In addition, the constraints

$$g_{j,i} \geq g_{j,i,\min}, \qquad i \in F_j \tag{2}$$

where $g_{j,i,\min}$ is the minimum permissible green time for stage i at junction $j \in J$, are introduced to guarantee allocation of sufficient green time to pedestrian phases. Based on the preceding definitions, we may also calculate the green time of a link $G_z = \sum_{i \in v_z} g_{j,i}$.

B. Signal Control Strategy TUC

Store-and-forward modeling of traffic networks was first suggested by Gazis and Potts [3] and has since been used in various works, notably for urban traffic signal control. This modeling philosophy circumvents the inclusion of discrete variables in the signal control problem formulation, thus allowing the application of polynomial-complexity solution methods of optimization and control. In particular, the split control part of the TUC signal control strategy is derived from a problem formulation in the format of a linear–quadratic (LQ) control problem (see [4], [5], and [8] for details), which leads to the multivariable regulator

$$\mathbf{g}(k) = \mathbf{g}^N - \mathbf{L}\mathbf{x}(k) \tag{3}$$

where

- $k = 0, 1, 2, \ldots$ discrete time index reflecting corresponding signal cycles;
- $\mathbf{g}$ vector of the green times $g_{j,i}$ of all stages $i \in F_j$ and all junctions $j \in J$ in the network; $\mathbf{g}(k)$ are the green times to be applied during the starting cycle k;
- $\mathbf{g}^N$ vector of nominal green times $g_{j,i}^N$ for all network stages; these nominal green times correspond to a prespecified fixed signal plan for the network;
- $\mathbf{x}$ vector of the vehicle-numbers in all network links x_z, $z \in Z$; $\mathbf{x}(k)$ are the vehicle-numbers at the start of cycle k, i.e., at the end of the previous cycle $k-1$; thus, $\mathbf{x}(k)$ represents a feedback from the network under control, based on which the new green times are calculated via (3) in real time;
- $\mathbf{L}$ constant gain matrix (of appropriate dimensions) that is calculated offline based on a straightforward procedure according to the LQ regulator methodology. The matrix depends on the network geometry, the turning rates, and the saturation flows but was found to be little sensitive to moderate variations of these values [8], [9].

The TUC feedback control law (3) is executed in real time at each cycle k, based on the current network state $\mathbf{x}(k)$, to calculate the green times $\mathbf{g}(k)$ to be applied during the next traffic cycle. The required real-time information on the vehicle numbers $x_z(k)$ in each network link z can only be directly obtained via corresponding video sensors. Since this type of sensors may not be available, an approximate procedure was developed (see [8] for details) that produces estimates $\hat{x}_z(k)$ based on time-occupancy measurements delivered by loop detectors (or other comparable devices); the loop detectors may be placed anywhere within the link, but the estimation procedure is most accurate for detector locations around the middle of the link.

The feedback control law (3) was developed to minimize and balance the space occupancies $x_z/x_{z,\max}$ of the network links, where $x_{z,\max}$ is the maximum number of vehicles that can be stored in link z. In fact, balancing the space occupancies, i.e., $x_z/x_{z,\max} \approx x_\zeta/x_{\zeta,\max}$, $\forall\ z, \zeta \in Z$, reduces the risk of link overspilling and, hence, of potential gridlock in the network.

Note that equation (3) calculates the green times (splits) only, whereas the cycle time and offsets are updated in real time by other parallel algorithms, as described in [5].

To enable the application of the LQ methodology and, hence, the derivation of the simple feedback control law (3), the constraints (1) and (2) were not included in the problem formulation; hence, the green times $\mathbf{g}(k)$ resulting from (3) may violate these constraints. Thus, the green times $\mathbf{g}(k)$ resulting from (3) must be appropriately modified to satisfy the constraints (1) and (2). This is done by solving in real time a real-valued quadratic knapsack problem for each junction j, which is given here.

For the given $g_{j,i}$ [resulting from (3)], find the modified green times $\tilde{g}_{j,i}$, $\forall i \in F_j$ that minimize

$$\Phi(\tilde{g}_{j,i}) = \frac{1}{2} \sum_{i \in F_j} (\tilde{g}_{j,i} - g_{j,i})^2 / g_{j,i} \tag{4}$$

subject to (1) and (2).

It may be readily shown that the minimization of (4) subject to (1) alone would lead to a solution that satisfies $\tilde{g}_{j,i}/g_{j,i} = \tilde{g}_{j,l}/g_{j,l}\ \forall (i,l)$, i.e., the modified $\tilde{g}_{j,i}$ would preserve the same splits as $g_{j,l}$, along with satisfying (1). The preceding real-valued quadratic knapsack problem approximates this solution to the extent allowed by the additional constraints (2). The exact numerical solution of a real-valued quadratic knapsack problem is known [8], [12] to call for at most as many iterations as the number of involved variables, which, in our case, hardly exceeds three or four stages at each junction.

The feedback control law (3) includes a prespecified fixed signal plan $\mathbf{g}^N$. Extensive investigations [8], [9] indicate that the resulting signal control is little sensitive to the particular signal plan $\mathbf{g}^N$ employed in (3) if the network state is quite loaded, i.e., if $x_z(k)$ are relatively high. On the other hand, it may be concluded by mere inspection of (3) that, when $x_z(k)$ are small (e.g., during off-peak periods), then the resulting green times $\mathbf{g}(k)$ are increasingly depending on $\mathbf{g}^N$, and in fact, we have $\mathbf{g}(k) = \mathbf{g}^N$ if $\mathbf{x}(k) = \mathbf{0}$. As a consequence, the feedback control law (3) may lead to less-efficient control during off-peak periods if $\mathbf{g}^N$ is not sufficiently adjusted. More specifically, if $\mathbf{g}^N$ is not well suited to the prevailing undersaturated traffic conditions, queues $x_z(k)$ may grow at some links that are eventually dissolved (at increased "cost") by the second term of (3), then grow again, and so forth.

The succeeding sections propose a possibility to calculate appropriate values for $\mathbf{g}^N$ in real time without any further prerequisites. This way, TUC becomes readily applicable, even in cases where an appropriate fixed plan is not available; updates of the fixed plan, e.g., due to aging, are also not necessary.

C. Demand-Based Approach

Consider an undersaturated signalized junction with two antagonistic stages 1 and 2 and one incoming link per stage. The number of arriving vehicles on each link i is equal to d_iC, where d_i, $i = 1, 2$, are the respective link demands (in vehicles per hour), whereas the maximum number of vehicles that can be served by each stage/link is equal to g_iS_i, where S_i, $i = 1, 2$, are the respective link saturation flows. The green times g_i, $i = 1, 2$, may then be calculated such that the saturation levels $(g_iS_i)/(d_iC)$ of both links are equalized, i.e.,

$$\frac{d_1}{g_1S_1} = \frac{d_2}{g_2S_2}. \tag{5}$$

Equation (1) for this simple case takes the form $g_1 + g_2 = C - L$, which, combined with (5), yields

$$\begin{aligned} g_1 &= \frac{d_1/S_1}{d_1/S_1 + d_2/S_2}(C - L) \\ g_2 &= \frac{d_2/S_2}{d_1/S_1 + d_2/S_2}(C - L). \end{aligned} \tag{6}$$

This procedure may be generalized to the general case of a junction with more than two stages and more than one link receiving r.o.w. within each stage as follows:

1) If a link receives r.o.w. at more than one stages, then a single "dominant" stage must be selected for this link; thus, each link is assigned to one single stage.
2) All links z assigned to a specific stage i receive the same green time $g_{j,i}$; thus, the link with the maximum value for d_z/S_z will have the maximum saturation level among the stage's links and may compete with its counterparts of other stages for equal saturation levels. This way, we specify a single link (the most saturated one) per stage i and denote it $z(j, i)$.

On the basis of the preceding conditions, it is quite straightforward to generalize (6) for a general junction j as follows:

$$g_{j,i} = \frac{d_{z(j,i)}/S_{z(j,i)}}{\sum_{n=1}^{|F_j|} d_{z(j,n)}/S_{z(j,n)}}(C - L_j) \tag{7}$$

$\forall\, i = 1, 2, \ldots, |F_j|$.

Note that the green times $g_{j,i}$ resulting from (7) satisfy (1) but may not satisfy (2). Therefore, they may have to be modified by the knapsack algorithm, as discussed earlier.

If a link receives r.o.w. at more than one stages, the preceding procedure may assign to it extra green time, i.e., a lower saturation level, at the expense of other links. This issue may be addressed by further refining the aforementioned procedure, as proposed in [13].

The preceding procedure was first proposed by Webster [10] and has been extensively used by traffic engineers for the design of fixed signal plans based on historical or expected demands for each junction link. Although originally proposed as a delay-minimizing procedure, it was eventually shown to rather lead to a maximization of the junction's capacity [14]. A more rigorous procedure to this end, based on the solution of a linear programming problem, was proposed in [15]. It should be noted that the equalization of link saturation levels is a popular control goal pursued by several signal control strategies (most prominently by Split Cycle Offset Optimization Technique [16]), albeit based on different models and procedures than that described here.

In this paper, we propose the usage of (7) in real time, i.e., based on measurements of the arriving link demands $d_z(k-1)$ during the last cycle (exponentially smoothed to avoid strong variations), the procedure may be used to calculate the green times $g_{j,i}(k)$ to be applied at the next cycle. This real-time procedure, which is referred in the following as the demand-based (DB) signal control strategy, reaches its limitation when the junction under control approaches saturation. This is because, when the junction's capacity reserves are close to be exhausted, queues may build up on the links and, consequently, the flows measured by the link detectors do not reflect the arriving demand but the flows served, which leads to a breakdown of the calculations in (7).

The next section therefore proposes a hybrid signal control strategy that overcomes the shortcomings of both the TUC and the DB methods. More specifically, a junction is real-time controlled under the DB method until an appropriate saturation criterion is reached; beyond this criterion, the junction control switches to the LQ regulator (3), with $g_{j,i}^N$ being equal to the latest respective values applied by the DB method. This way, there is no need for a prespecified $\mathbf{g}^N$ in (3), and in fact, the $\mathbf{g}^N$ values used in (3) are likely to be better adapted to the traffic conditions at the start of each peak period.

D. Hybrid Signal Control Strategy

As previously outlined, the hybrid signal control strategy makes use of either the LQ regulator (3) or the DB control law (7) to calculate in real time the green times of each junction. This decision is individually made for each junction according to a saturation criterion that may depend on the flow measurements d_z or the vehicle-number estimates $\hat{x}_z$ for all links $z \in I_j$ approaching the junction j. Preliminary simulation and field tests indicated that it is most reliable to use both possibilities to ensure proper switching between both control laws. More specifically, for each junction j, three conditions hold.

1) If the DB law (7) was applied in the last cycle, the (estimated) space occupancies $x_z/x_{z,\max}$ of all incoming links $z \in I_j$ are checked. If there is even one z for which $x_z/x_{z,\max} \geq b_2$, where b_2 is a threshold, then the junction switches to LQ for the next cycle; else, it continues operating with the DB law.

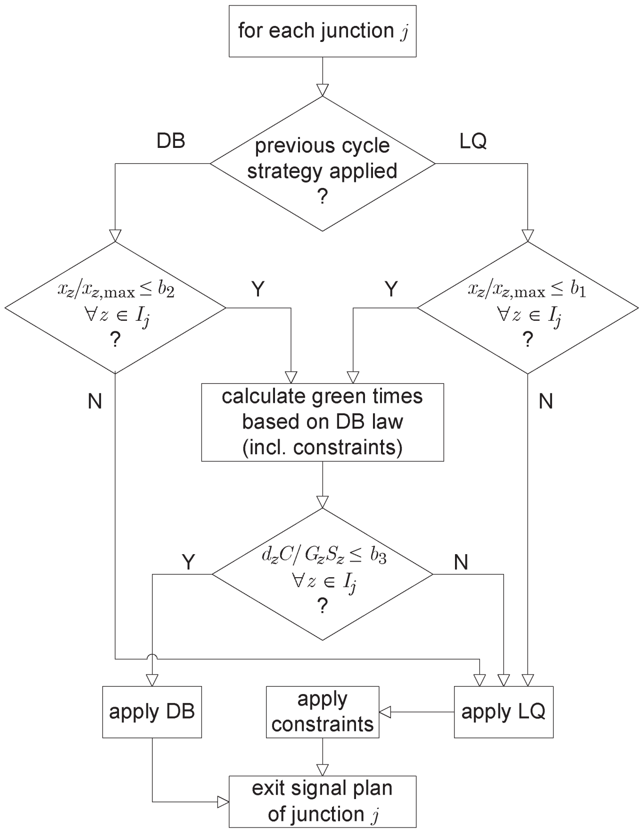

Fig. 1. Switching logic of the hybrid signal control strategy.

2) If the LQ law (3) was applied in the last cycle, a switching to the DB law (7) is due if all space occupancies are sufficiently low, i.e., if $x_z/x_{z,\max} \le b_1$, $\forall\ z \in I_j$; else, the junction continues to operate with the LQ law. Note that b_1 should be chosen lower than b_2 to create a switching hysteresis to suppress switching oscillations; $b_1 = 0.3$ and $b_2 = 0.5$ were empirically found to lead to good results.
3) If the (preliminary) decision is to go with the DB law in the next cycle, the corresponding calculations are actually made, but, before implementation, it is asked whether the achieved saturation levels d_zC/G_zS_z of all incoming links are less than a threshold b_3; if not, the LQ law is applied to the junction; $b_3 = 0.7, \ldots, 0.8$ were empirically found to be suitable values.

Fig. 1 displays the complete switching logic of the hybrid signal control strategy for each junction.

III. Simulation Results

To investigate and demonstrate the efficiency of the proposed hybrid approach under several different conditions, a microscopic simulation study for the urban network of the city center of Chania was carried out. The control strategies compared are fixed signal control (roughly optimized for each considered demand scenario), the LQ approach, and the hybrid control strategy under different load scenarios.

The commercial microscopic simulator Advanced Interactive Micro-Simulation for Urban and non-urban Networks (AIMSUN) (Version 6.0.1) [17] was employed as a simulation tool. AIMSUN enables a closed-loop operation that resembles the real application of the control strategies. More specifically, AIMSUN delivers the (emulated) flow and occupancy measurements at the locations where detectors are placed (as in real conditions). These measurements are used by (real-time) control strategies, which are coded in the provided application programming interface, to produce the traffic signal settings. These signal settings are then forwarded to the microsimulator for application.

A. Network and Scenario Description

The urban network of the city center of Chania (Fig. 2) consists of $|J| = 16$ signalized junctions and $|Z| = 60$ links. Typical loop-detector locations within the Chania urban network links are either around the middle of the link or some 40 m upstream of the stop line. Severe congestion problems occur in the actual Chania network during the peak periods, which may sometimes lead to partial gridlock situations. We omit the details on turning rates $t_{w,z}$, lost times L_j, staging v_z, and saturation flows S_z. The typical cycle time $C = 90$ s and offsets applied in the network are considered and kept fixed for all simulation investigations. Finally, we consider a simulation step $T = 0.25$ s for the microscopic simulation model.

To investigate and compare the behavior of the three signal control methodologies, three demand scenarios were used, each with a time horizon of 4 h (160 cycles), with the following three characteristics:

1) low demand in network origins, following a smooth trapezoidal trajectory;
2) low demand with relatively strong low-frequency variations;
3) high demand; in this scenario, the network faces serious congestion for some 80 cycles (2 h) with some link queues spilling back into upstream links.

With regard to the signal control strategies, the FT signal control was roughly optimized for each of the three demand scenarios previously outlined. The linear multivariable (LQ) feedback regulator uses the same $\mathbf{g}^N$ for all three scenarios, with the utilized $\mathbf{g}^N$ being equal to the specific FT plan used in scenario 1. Finally, the proposed hybrid approach includes, in addition to the LQ control law, a DB component, as described in the previous section. Both real-time control strategies update their decisions at each cycle C. To this end, the strategies are fed with the emulated occupancy and flow measurements from the available link detectors.

B. Assessment Criteria

For each of the three distinct scenarios and for each control approach, three evaluation criteria are gathered for comparison from the microscopic simulator AIMSUN. The average delay time per km traveled (in seconds per kilometer)

$$\mathrm{DT} = \frac{\mathrm{DT}_s}{\mathrm{N}_s}, \quad \text{with} \quad \mathrm{DT}_s = 1000 \sum_{i=1}^{\mathrm{N}_s} \frac{\mathrm{TDT}_i}{\mathrm{D}_i}$$

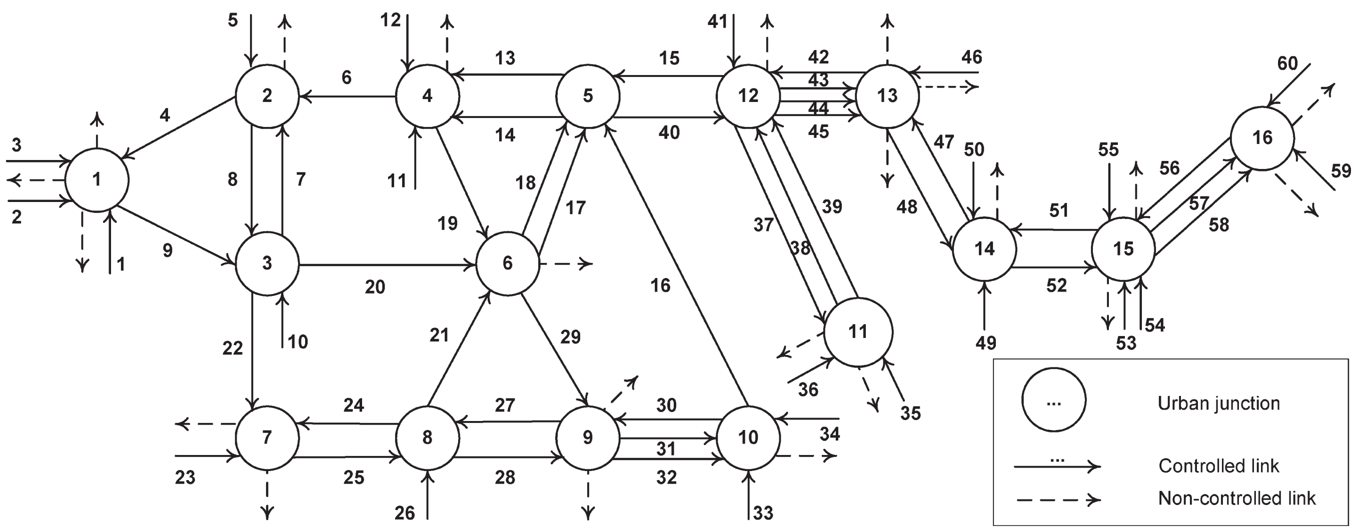

Fig. 2. Chania urban road network.

TABLE I
(a) ASSESSMENT CRITERIA FOR FT, LQ, AND HYBRID STRATEGIES. (b) COMPARISON OF ASSESSMENT CRITERIA

(a)

Scenario	1			2			3		
Strategy	DT	NS	MS	DT	NS	MS	DT	NS	MS
FT	86.6	2.67	23.4	120.1	3.20	19.2	313.6	6.05	9.4
LQ	85.5	2.66	23.5	94.8	2.91	22.2	237.1	5.02	11.8
hybrid	83.5	2.65	23.8	85.7	2.75	23.5	218.7	4.75	12.6

(b)

Scenario	1			2			3		
Strategy	DT	NS	MS	DT	NS	MS	DT	NS	MS
LQ vs. FT (%)	-1.2	-0.4	0.8	-21.1	-9.1	15.6	-24.4	-17.0	25.1
hybrid vs. FT (%)	-3.5	-0.8	2.1	-28.6	-14.1	22.4	-30.3	-21.5	33.2
hybrid vs. LQ (%)	-2.3	-0.4	1.2	-9.6	-5.5	5.9	-7.8	-5.4	6.4

the average number of stops per kilometer traveled

$$\mathrm{NS} = \frac{\mathrm{NS}_s}{\mathrm{N}_s}, \quad \text{with} \quad \mathrm{NS}_s = 1000 \sum_{i=1}^{\mathrm{N}_s} \frac{\mathrm{TNS}_i}{\mathrm{D}_i}$$

and the overall mean speed (in kilometers per hour)

$$\mathrm{MS} = \frac{\mathrm{MS}_s}{\mathrm{N}_s}, \quad \text{with} \quad \mathrm{MS}_s = 3.6 \sum_{i=1}^{\mathrm{N}_s} \frac{\mathrm{D}_i}{\mathrm{TEX}_i - \mathrm{TEN}_i}$$

where

- N_s number of vehicles that exit from the network during the scenario time horizon;
- TEN_i entrance time of the ith vehicle in the network (in seconds);
- TEX_i exit time of the ith vehicle from the network (in seconds);
- D_i total distance traveled by the ith vehicle in the network (in meters).
- TNS_i total number of stops accumulated in the network by the ith vehicle;
- TDT_i total delay time accumulated in the network by the ith vehicle (in seconds).

C. Global Simulation Results

For every control case, i.e., a) an FT strategy with fixed plans adapted to the demand scenarios, b) an LQ strategy, and c) the proposed hybrid strategy, and each demand scenario, ten replications (with different seeds) were carried out with AIMSUN to account for stochastic effects of the simulator. The mean values of the assessment criteria obtained by the ten replications of each case studied are displayed in Table I(a), whereas Table I(b) presents some comparative changes among different couples of strategies.

For scenario 1, it may be seen that the assessment criteria obtain very similar values across all control strategies. Since vehicle numbers in the network links are very low, the LQ strategy is dominated by the same nominal plan $\mathbf{g}^N$ used for fixed control, and hence, the improvements achieved by LQ, compared with FT, are only on the order of 1%. The hybrid strategy in this scenario exclusively uses the DB control law due to very low saturation levels. Despite the fact that the FT plan is well adapted to the present scenario, the proposed DB control manages to slightly improve the performance indices. In conclusion, this scenario demonstrates that there is little space for improvements of a well-adapted fixed signal plan if demands are constant and low. However, the results also demonstrate the capability of the DB approach to automatically adapt to the prevailing undersaturated traffic conditions.

Scenario 2 features low saturation levels as well, but the demand values exhibit low-frequency variations over time; naturally, the FT plan cannot be well adapted to several network traffic patterns evolving over time for this scenario, and hence, its performances are seen to significantly deteriorate, compared to scenario 1. On the other hand, the nonadapted nominal plan $\mathbf{g}^N$ of the LQ method, along with the time variations of the demand, leads to the occasional creation of queues that are addressed in real time via the second term of (3); the significant improvement of all performance indices indicates that the LQ strategy can indeed partly compensate for less appropriate values of $\mathbf{g}^N$ in (3), even under undersaturated traffic conditions. Finally, the hybrid strategy exclusively applies, also for this scenario, the DB control law due to low saturation levels. Due to its real-time flexibility, the hybrid strategy (in this case actually, the DB control law) significantly improves all performance criteria, compared to FT, because it rapidly adapts to the changing traffic demands; moreover, the hybrid strategy delivers improvements over the LQ control as well due to its DB component (since the LQ component is never activated in this scenario). In summary, we have the following.

1) FT is less appropriate for low demands exhibiting relatively strong time variations.
2) LQ control using a nonadapted $\mathbf{g}^N$ partly compensates for the less-appropriate fixed part of (3).
3) DB control adapts to the time variations of the demand and leads to sensible improvements, even when compared with LQ control, which justifies the development of the hybrid control strategy.

Scenario 3 is quite heavily loaded, particularly during the second and third hours of the four-hour simulation horizon. The rigid FT plan cannot cope with the situation, and the created link queue spillovers and partial gridlocks lead to a strong performance deterioration, compared to both previous scenarios. The application of LQ control in this situation brings along substantial improvements (17%–25%) due to a much better and flexible handling of the forming link queues. The hybrid control employs LQ for more than half of the simulation horizon, particularly during the most heavy middle period. However, the LQ control is known [8], [9] to be a little sensitive to the values of $\mathbf{g}^N$ during oversaturated conditions, and hence, the improvements achieved by the hybrid strategy compared with LQ in this case are rather modest (5%–8%). Nevertheless, this scenario demonstrates that the LQ regulator may be successfully employed without a prespecified $\mathbf{g}^N$.

D. Selected Simulation Results

In this section, we report on some selected illustrative results focusing on the city's main shopping district (junctions 3 and 5 in Fig. 2). Each of the results presented in this section stems from a particular simulation replication that has been selected to have its assessment criteria close to the respective case's average (of all replications).

Fig. 3(a) displays the applied control (green times for two stages) by each strategy at junction 3 for scenario 1. FT and LQ apply virtually identical controls because of the small values of vector $\mathbf{x}(k)$ in (3) (recall that $\mathbf{g}^N$ in this scenario equals the FT plan), whereas the hybrid strategy—applying only the DB law for all junction-cycles—automatically calculates green times that are seen to be close to the roughly optimized FT green times. This demonstrates that the Webster procedure is feasible and viable in real time for undersaturated traffic conditions, assuming, of course, that detector measurements are reliable.

Fig. 3(b) and (c) displays the green times delivered for scenario 2 at junction 5 (three stages) by the LQ and hybrid strategies, respectively, whereas Fig. 3(d) and (e) displays the respective (estimated) space occupancies $x_z/x_{z,\max}$ for all links z approaching junction 5. The green times of both strategies have similar shapes; however, the hybrid strategy (its DB component) reacts to the changing demands, whereas the LQ strategy reacts to the forming queues. Hence, for LQ control, the link queues are slightly longer, and the control time variations are partially stronger, compared to the hybrid strategy. It should also be emphasized that its less-adapted $\mathbf{g}^N$ forces the LQ regulator to undertake substantial deviations of its green times via its second term, whereas the proposed DB strategy keeps all space occupancies below the threshold $b_2 = 0.5$, and hence, no activation of the LQ component is needed.

Fig. 4(a) and (b) displays the green times delivered for scenario 3 at junction 5 by the LQ and hybrid strategies, respectively, whereas Fig. 4(c) and (d) displays the respective (estimated) space occupancies for all approaching links. Fig. 4(b) includes a discrete indicator of the applied strategy component at each cycle, where 0 indicates LQ and 4 indicates DB application. The LQ strategy greens [see Fig. 4(a)] are seen to bear increasingly strong deviations after cycle 20 due to accordingly modified traffic conditions; after cycle 70, there is even a crossing of the green times of the two main stages of the junction. For the hybrid strategy, the DB component is active up to cycle 47 and after cycle 122 [see Fig. 4(b)]. After cycle 20, the DB strategy is seen in Fig. 4(b) to similarly (although more smoothly) react as the LQ strategy in Fig. 4(a), but at cycle 47, a surge of arriving demand from upstream junctions leads to an increase in a couple of link queues beyond the threshold $b_2 = 0.5$ [see Fig. 4(d)], thus triggering the activation of the LQ component of the hybrid strategy that remains active due to heavy loads until cycle 122. The link queues are seen [see Fig. 4(c) and (d)] to be reasonably bounded for both strategies, except for the period between cycles 90 and 120, where several links are seen to saturate due to high loads from upstream junctions.

For an additional evaluation of the heavy scenario 3 that leads to the saturation of several links over periods of time, we define a network link as saturated if its occupancy $x_z/x_{z,\max}$ is higher than $b_1 = 0.5$. Let $m(k)$ denote the number of saturated links at the simulation cycle k for a specific control strategy, and let

$$M(k) = \sum_{\kappa=0}^{k} m(\kappa) \tag{8}$$

denote the accumulated number of saturated links up to cycle k. Clearly, $M(K_{\rm s})$ then denotes the total accumulated number of saturated links at the end ($K_{\rm s} = 160$) of the simulation horizon. Fig. 4(e) displays the $M(k)$ quantities for each investigated signal control strategy for the heavy scenario 3. As expected, the ranking of the strategies with respect to this criterion

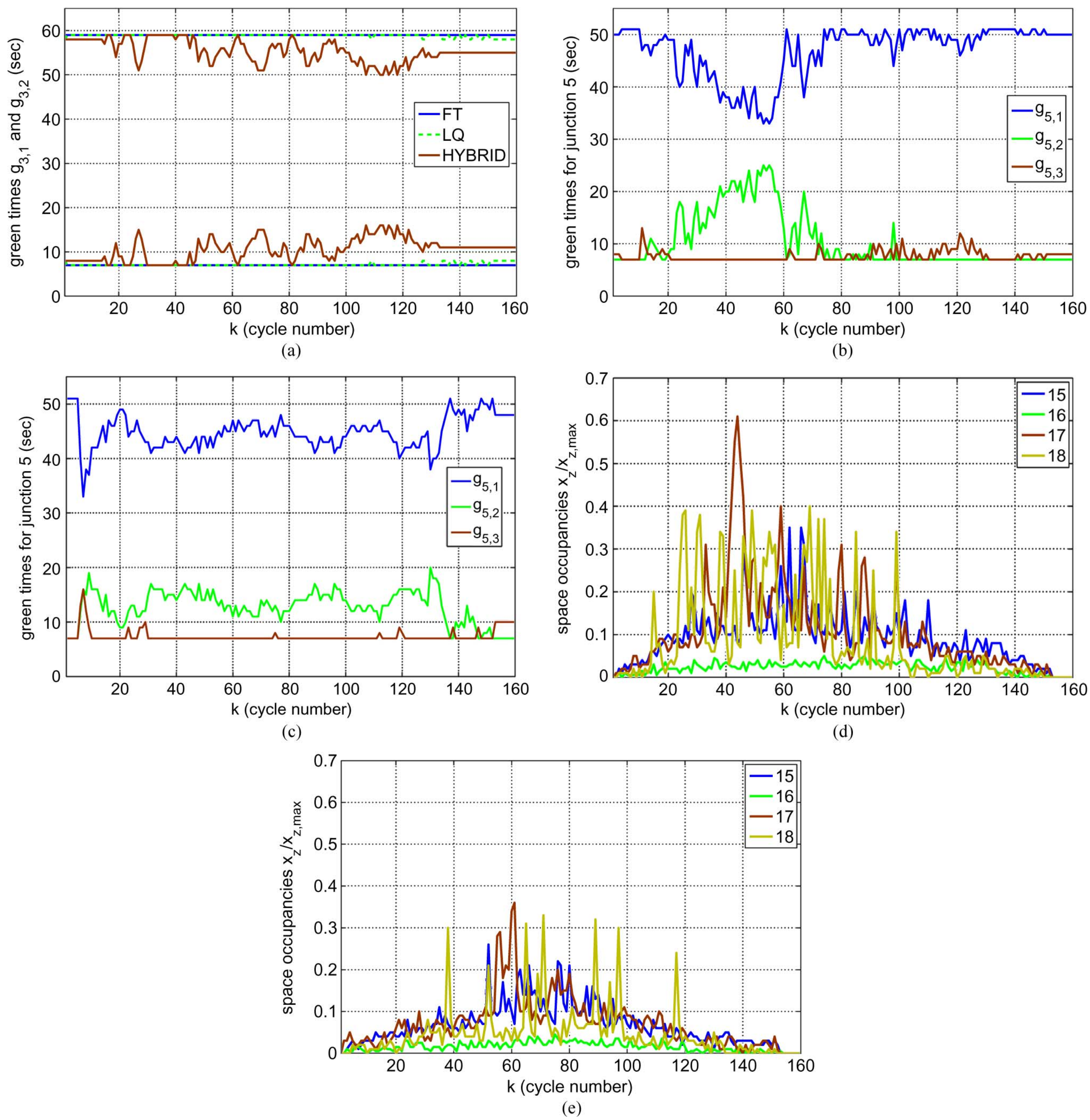

Fig. 3. (a) Green times at junction 3 for scenario 1. Green times at junction 5 for scenario 2 (b) for LQ strategy and (c) for hybrid strategy. Estimated space-occupancies $x_z/x_{z,\max}$ for all links z approaching junction 5 for scenario 2 (d) for LQ strategy and (e) for hybrid strategy.

is in agreement with their respective global index values of Table I(a). The figure also underlines the clear superiority of the LQ and hybrid control strategies to handle urban network congestion, along with a slight advantage of the latter. Indeed, the results of scenarios 2 and 3 indicate that the application of the hybrid control scheme may lead to a slightly delayed appearance of the saturation in the network.

IV. Field Implementation

Following its successful simulation testing [13], the developed hybrid signal control strategy was implemented in the control center of the city of Chania, and the achieved field results were contrasted with those obtained by use of the commercial semi-real-time signal control strategy Traffic-Actuated Signal plan Selection (TASS) by Siemens [18], which is also implemented in the control center.

A. Application Network and Conditions

The application network is the urban network of the city of Chania, shown in Fig. 2. The original TUC system (LQ approach) had been already implemented in this network at a

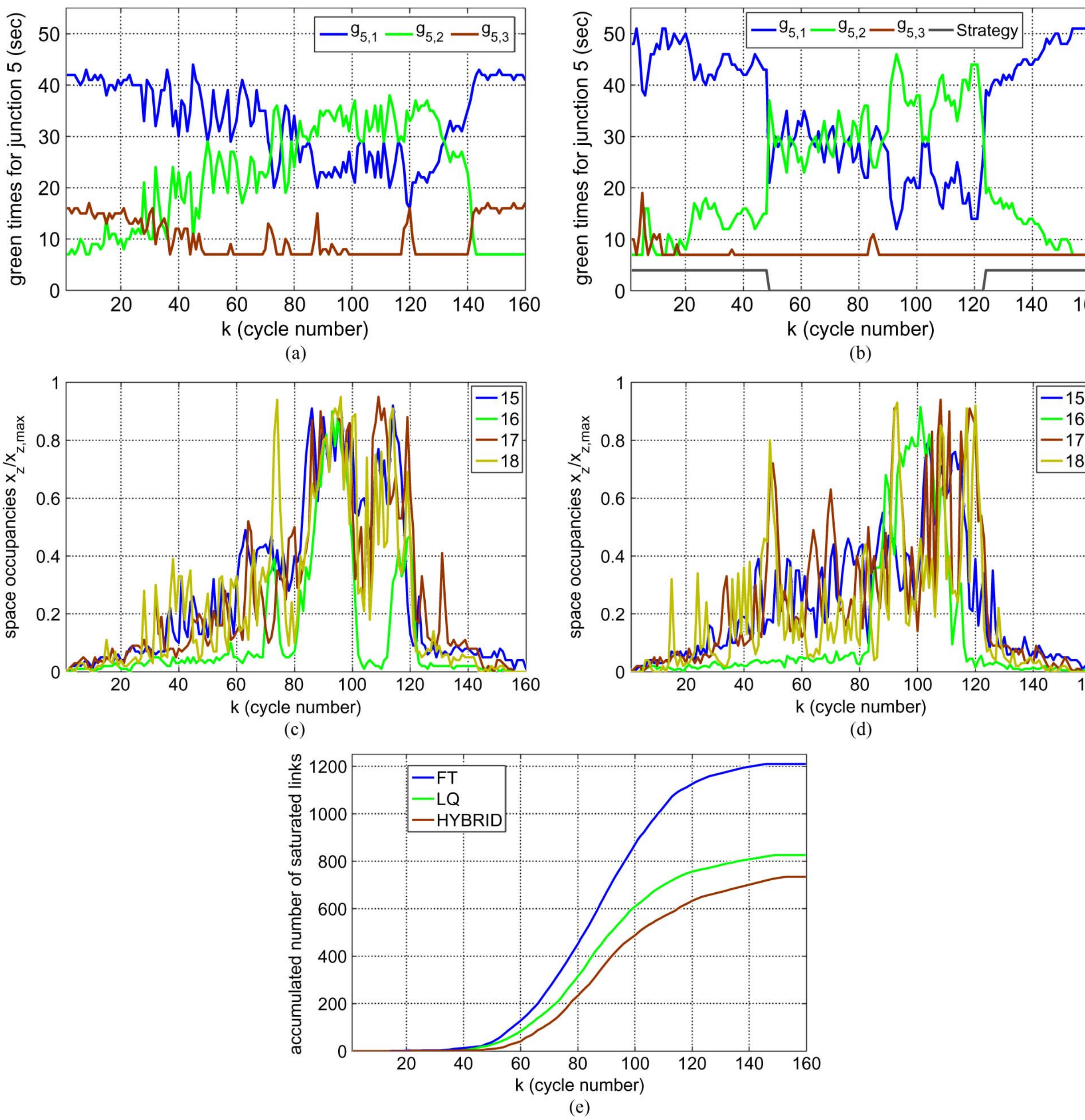

Fig. 4. Green times at junction 5 for scenario 3 (a) for LQ strategy and (b) for hybrid strategy (see text for explanation of the strategy indicator). Estimated space-occupancies $x_z/x_{z,\max}$ for all links z approaching junction 5 for scenario 3 (c) for LQ strategy and (d) for hybrid strategy. (e) Accumulated number of saturated links for each signal control strategy for scenario 3.

previous stage (see [6]). For the current implementation, the software of TUC was extended to the hybrid signal control strategy presented earlier (referred here as the TUC/HYBRID signal control strategy). It should be noted that, in contrast to the simulation investigations of the previous section where the cycle time and offsets were kept constant for all strategies, this field implementation also includes the real-time cycle time and offset control modules of TUC [5], [6].

The Siemens strategy TASS [18] selects, every 15 min, one out of six fixed predefined network signal plans (each with different cycle times, splits, and offsets), depending on the current traffic conditions in the network, as reflected by the measurements of a number of "strategic" detectors placed at appropriate network locations. The selected plan is transferred to the local junction controllers for application, but each junction controller may modify (within certain limits) the received signal settings by application of a simple traffic-actuated logic based on local measurements (microregulation). The overall strategy includes a high number of parameters and settings that were manually fine-tuned to virtual perfection by the system operators over many years.

Some performance indices to be used in the following are defined next. The indices are based on the obtained link loop measurements of time occupancy $o_z(k)$ (in percentage) and flow $q_z(k)$ (in vehicles per hour), where z is the link where the measurement is collected, and $k = 0, 1, 2, \ldots$ is a discrete time index reflecting corresponding cycles. To start with, if the measured time occupancy is assumed to approximately reflect the link's space occupancy, then the corresponding average number of vehicles in the link (during the last cycle) is

TABLE II
DAILY AND AVERAGE PERFORMANCE INDICES TUC/HYBRID VERSUS TASS

Weekday	TUC/HYBRID			TASS			% diff. MS TUC/HYBRID vs. TASS
	TDT (veh·km)	TTS (veh·h)	MS (km/h)	TDT (veh·km)	TTS (veh·h)	MS (km/h)	
Tuesday	47445	4577	10.4	46554	5017	9.3	11.8
Wednesday	46820	4344	10.8	48235	4642	10.3	4.9
Thursday	46449	4030	11.5	46514	4404	10.6	9.1
Friday	51710	4600	11.2	51524	5606	9.2	21.7
Saturday	50651	3801	13.3	50599	4428	11.4	16.7
Sunday	40098	2567	15.6	42045	2861	14.7	6.1
Average	47196	3987	11.8	47579	4493	10.6	11.3

given by

$$\chi_z(k) = L_z a_z o_z(k)$$

where L_z is the link length, and $a_z = \mu_z/(100\Lambda)$, with μ_z being the number of lanes of link z and Λ being the average vehicle length. Assume that we are interested in the performance index values for a set $\mathcal{S}$ of links (e.g., for one single link or for all links approaching a junction or for the whole network) and for a time horizon K (e.g., 1 hr or one day). The total time spent (TTS, in veh · h) by all vehicles in $\mathcal{S}$ over K periods is then given by

$$\text{TTS} = \sum_{k=1}^{K} \sum_{z \in \mathcal{S}} C(k)\chi_z(k)$$

where $C(k)$ is the cycle time applied during cycle k. The total distance traveled (TDT, in veh · km) by all vehicles in $\mathcal{S}$ over K periods is given by

$$\text{TDT} = \sum_{k=1}^{K} \sum_{z \in \mathcal{S}} C(k) q_z(k) L_z$$

whereas the mean speed (MS, in kilometers per hour) is

$$\text{MS} = \text{TDT}/\text{TTS}.$$

B. Field Results

The TUC/HYBRID signal control strategy was operated and closely observed in the network over a period of several months. By daily observation of the traffic conditions by the experienced system operators and the research group, it was felt that this hybrid version of the TUC strategy is a viable signal control strategy that performs similarly well as the original TUC strategy (fed with a good precalculated fixed plan $\mathbf{g}^N$ in (3), albeit without the need to have a precalculated fixed plan $\mathbf{g}^N$ available that is sufficiently efficient for undersaturated traffic conditions. Two conditions should be noted.

1) Observations by experienced operators are valuable, because available measurements may sometimes not reveal specific operational problems.
2) A good $\mathbf{g}^N$ is available for the particular Chania network; hence, the added value of the hybrid strategy (compared with TUC) is limited for this network. Nevertheless, the hybrid strategy is helpful, because a fixed $\mathbf{g}^N$ may need to be changed from time to time due to aging or daily or seasonal demand variations.

A more rigorous evaluation was conducted during May–June 2006, where the TUC/HYBRID signal control strategy and the TASS strategy were applied in weekly alternation to enable a fair comparison in view of the fact that seasonal variations of the traffic demand are quite significant in Chania due to tourism and other reasons. However, due to technical problems independent of the control strategies (malfunctioning of several loop detectors) during this period, the comparative evaluation reported here is limited to only eight junctions (No. 1–6, 12, and 13 in Fig. 2) of the network. Finally, the number of evaluation days had to be reduced by excluding days with abnormal conditions such as strong rain, roadworks, holidays, or demonstrations.

Table II displays the TUC/HYBRID versus TASS average performance indices per week day. It should be noted that traffic conditions in Chania are quite different, even among weekdays, due to differences in shop opening times. Mondays are not displayed in Table II due to insufficient data. It may be seen that TUC/HYBRID outperforms TASS on all days of the week, albeit by different percentages. On average, TUC/HYBRID increases the mean speed by 11.3%, compared with the perfectly fine-tuned semi-real-time strategy TASS.

Fig. 5(a) compares the network-wide MS hourly values (from 9 A.M. to 11 P.M.) of TUC/HYBRID versus TASS for two consecutive Tuesdays (30 May and 6 June), where both strategies were alternated. The traffic demand and its time distributions are very similar (not shown). The extended morning (9 A.M.–2 P.M.) and evening (6 A.M.–9 P.M.) peak periods due to open shops are clearly visible (low MS values), as well as the afternoon off-peak period (2 P.M.–6 P.M.). TUC/HYBRID is seen to outperform TASS during the peak periods, as already observed without the hybrid extension [6], but it also performs well during the off-peak periods where the DB component of the hybrid strategy version dominates. Similar results were produced for each network junction, allowing a more detailed analysis of the comparative performances of both strategies. For example, Fig. 5(b) displays the same information as Fig. 5(a) but only for junction 12, i.e., based on the measurements of the links approaching junction 12 ($\mathcal{S} = I_{12}$).

Fig. 5(c) displays the green times applied in the field at junction 5 by the TUC/HYBRID strategy on a particular day. Recall that cycle times are also modified in real time; hence, contrary to the simulation results of last section, the displayed green times do not sum up to a constant value. Cycle times are shorter during the afternoon and late-evening off peaks and longer during the peak periods. Fig. 5(c) includes a discrete indicator of the applied strategy component at each cycle: 0

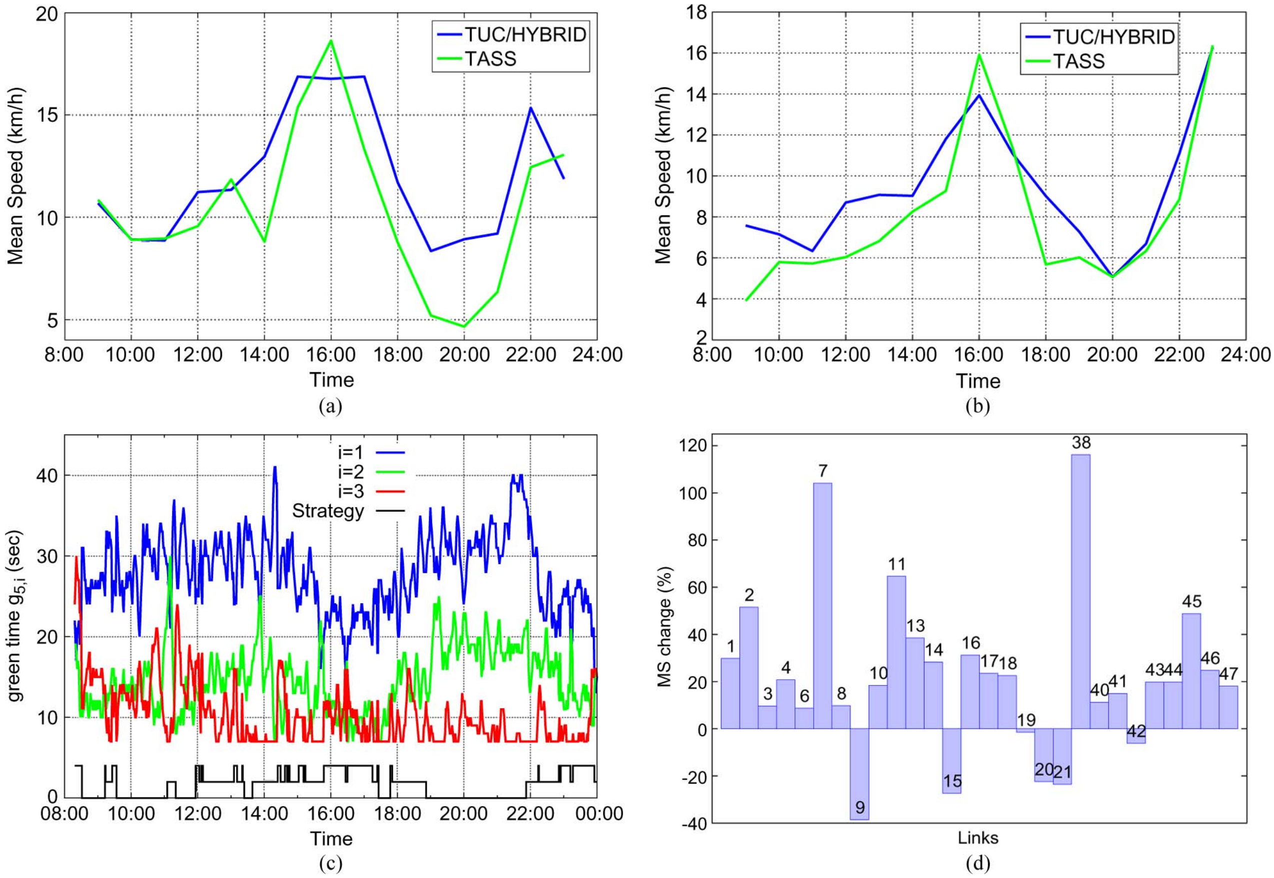

Fig. 5. Comparative MS values over a day (a) for the whole network and (b) for junction 12 for two consecutive Tuesdays. (c) Green times and indicator of the applied component of the hybrid strategy over a day for junction 5 (see text for explanation of the strategy indicator). (d) Percentage of MS change by link.

denotes LQ application, 4 denotes DB application, and 2 denotes that the original decision was for DB but was suppressed due to the saturation level being higher than b_3 according to Fig. 1. It is seen that the DB strategy is mainly applied during the off-peak periods and only at same rare occasions elsewhere.

Field results were also analyzed by link. Fig. 5(d) displays the average MS change of TUC/HYBRID versus TASS for each link. It is seen that TUC/HYBRID quite consistently improves the mean speed for most links. However, these results do not take into account the significance (throughput) of each link. In fact, some of the links where TUC/HYBRID performs worse carry quite substantial traffic loads.

In conclusion, the field evaluation has demonstrated that the real-time DB approach by itself is viable in real traffic for undersaturated conditions and may, in fact, be used as a complement to the LQ regulator of TUC to drop the requirement for a good nominal plan $\mathbf{g}^N$.

V. Conclusion

The recently developed signal control strategy TUC includes the requirement for a fixed signal plan that is sufficiently efficient in undersaturated traffic conditions. To drop this requirement and its implications (aging and different traffic patterns at different times of day), the well-known Webster procedure was appropriately employed for real-time operation (under the name DB approach). It was demonstrated via simulation experiments and field results that the developed real-time DB approach is indeed a viable strategy under sufficiently undersaturated traffic conditions and that it can be used in combination with TUC's LQ control law to drop the requirement for a prespecified fixed signal plan. Under certain conditions (e.g., low but time-varying demands), the proposed extended strategy TUC/HYBRID has been shown to improve over the original TUC version.

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