TRAFFIC-RESPONSIVE URBAN NETWORK CONTROL USING MULTIVARIABLE REGULATORS

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Abstract

The paper presents the philosophy, the aim, the development, the advantages, and the potential shortcomings of the TUC (Traffic-responsive Urban Control) strategy. Based on a store-and-forward modelling approach and using well-known methods of the Automatic Control Theory, the approach followed by TUC designs (off-line) and employs (on-line) a multivariable regulator for traffic-responsive co-ordinated network-wide signal control. Simulation investigations are used to demonstrate the efficiency of the proposed approach. Based on the presented investigations, summarising conclusions are drawn and future work is outlined.

1. INTRODUCTION

Despite the long-lasting research and developments worldwide, urban signal control is still an area susceptible of further significant improvements. The usually limited availability of space in the urban centres prevents the extension of the existing infrastructure, and, along with the continuously increasing mobility requirements, urge for solutions that will release the serious congestion problems through the best possible utilisation of the already existing infrastructure. From the control point of view, this may be translated into the employment of actuated systems that respond automatically to the prevailing traffic conditions. This is the aim of the TUC (Traffic-responsive Urban Control) strategy, which was initially developed [16] as part of an integrated traffic control system for corridor networks within the European Telematics Applications in Transport project TABASCO (Telematics Applications in BAvaria, SCotland, and Others).

The aim of this paper is to present the basic philosophy, the aim, the development, the advantages, and the current shortcomings of the TUC strategy. Three alternative approaches of the multivariable regulator employed by TUC are presented and discussed. Simulation investigations for a Glasgow (Scotland) based network under different scenarios of demands and incidents are used to demonstrate the efficiency of the proposed method. Summarised conclusions are presented, and future work is outlined.

2. BACKGROUND

The first traffic-responsive urban network control strategies were introduced in the 1980s with the first field implementations of the British SCOOT [12], and the Australian SCATS [13]. SCOOT and SCATS aim at a network-wide co-ordinated control with SCATS adopting a bilevel approach whereby the upper level performs network-wide co-ordination while the lower junction level modifies (within certain limits set by the upper level) the network-wide signal settings so as to respond to the prevailing local traffic conditions. Both SCOOT and SCATS perform control through incremental changes of splits, offsets, and cycles, and for this reason, they have been judged [6] to lack a real traffic-responsive behaviour during rapidly changing conditions such as those occurring during the daily business peaks or in case of incidents. This is possibly one of the reasons why after so many years of developments, extensions, implementations, and tests, field results still find them to score both successes and failures compared with traditional fixed-time control [9,11].

More recently, a number of advanced traffic-responsive strategies were developed like the American OPAC [8] and RHODES [18], the French PRODYN [7] and CRONOS [2], and the Italian UTOPIA [14]. These strategies do not consider explicitly splits, offsets, and cycles. They formulate the traffic-responsive urban control problem as an optimisation problem, and, with the exception of CRONOS, they employ exponential-complexity algorithms to solve for a global minimum. For this reason, these strategies, though conceptually applicable to a whole network, are not real-time feasible for more than one junction, hence, they employ heuristic superior control layers with the task of the network-wide co-ordination. Their network-wide efficiency, however, is still questionable due to the limited field implementations and evaluations as yet. CRONOS on the other hand, employs a heuristic global optimisation method with polynomial complexity which allows for simultaneous consideration of several junctions, albeit for the price of specifying a local (rather than the global) minimum.

For all the above reasons, there is still a lack of efficient co-ordinated control strategies applicable to large-scale networks. In 1963, Gazis and Potts [10] suggested the so-called store-and-forward modelling approach that describes the traffic flow process in a way that permits the use of highly efficient optimisation and control methods with polynomial complexity, thus allowing for the co-ordinated control of large-scale networks. Based on the store-and-forward modelling approach and using well-known methods from Automatic Control Theory, the proposed TUC approach designs (off-line) and employs (on-line) a multivariable regulator for the traffic-responsive co-ordinated urban network control in a systematic and generic way.

3. THE TUC STRATEGY

3.1 Introduction

For the development of the TUC strategy, the basic methodology employed is the formulation of the urban traffic control problem as an optimal control problem and the derivation of a multivariable regulator through the application of the Linear-Quadratic (LQ) methodology [19] to the formulated optimal control problem. The multivariable regulator approach, although less sophisticated than other systematic approaches like nonlinear optimal control, linear programming, quadratic programming, etc., if appropriately employed, may approximate their efficiency based on a much simpler code, as the real-time calculations do not involve any modelling equations. The mathematical model of the process under control is used off-line for control design purposes only.

The development of TUC strategy is based on the assumption that in undersaturated traffic conditions available techniques exist (like e.g. TRANSYT optimisation) that may be used to determine nominal values for the green times of the considered urban signalised junctions that are optimal for a given historical demand. These nominal values are optimal in that they lead to steady-state traffic conditions whereby the developed link queues are close to 0. In reality, however, the demands change dynamically. As a result, the determined nominal values of the green times may become far from optimal, and may lead to a serious deterioration of the traffic conditions in the controlled network. The aim of the multivariable regulator presented in Section 3.2 is to modify in real-time these nominal values so as to respond to the changes of the demands such that the capacity of the controlled network is utilised in a balanced way and the developing link queues remain as short as possible. However, in some cases, neither the techniques nor the data required for the determination of the nominal green values are available. The multivariable regulators presented in Section 3.3 have been developed to tackle the signal control problem even in absence of nominal values.

3.2 Regulator Design

For the derivation of the multivariable regulator, the urban traffic control problem is formulated as a LQ optimal control problem consisting of three components: the mathematical model of the urban network traffic process, the constraints and the control objective.

For the development of the mathematical model, the urban network is represented as a digraph with links $z \in Z$ and junctions $j \in J$. For each signal controlled junction j, I_j and O_j denote the sets of incoming and outgoing links, respectively, and the following assumptions are made:

- All the permissible movements of a link $z \in I_j$ receive the right of way (r.o.w.) simultaneously.
- The cycle time C_j and the total lost time L_j of junction j are fixed; for simplicity, it is assumed $C_j = C$ for all junctions $j \in J$.
- The offsets are fixed (i.e. the beginning of the main stage of each cycle is fixed).
- The signal control of junction j is based on a fixed number of stages that belong to the set F_j, while ν_z denotes the set of stages where link z has r.o.w.
- The saturation flows S_z, $z \in I_j$, are known.
- The turning movement rates $t_{z,w}$, $z \in I_j$, $w \in O_j$, are fixed and known.

By definition, the following constraint applies at junction j

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

where $g_{j,i}$ is the effective green time of stage i at junction j. Additionally, the following constraints are introduced to guarantee allocation of green time to all stages

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

with $g_{j,i,min}$ the minimum permissible effective green time for stage i at junction $j \in J$, while in

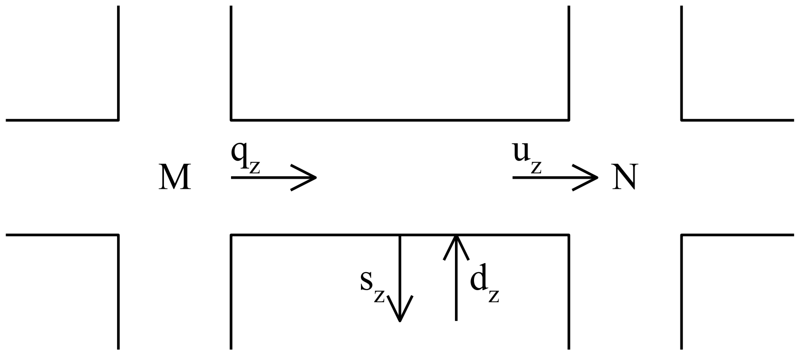

Figure 1: An urban road link.

some cases constraints like the following may apply

$$g_{j,i} \le g_{j,i,max} \quad \forall i \in F_j \tag{3}$$

with $g_{j,i,max}$ a maximum permissible effective green time for stage i at junction $j \in J$.

Consider now a link z connecting two junctions M, N such that $z \in O_M$ and $z \in I_N$ (see Figure 1). The dynamics of link z are expressed by the following equation

$$x_z(k+1) = x_z(k) + T[q_z(k) - s_z(k) + d_z(k) - u_z(k)] \tag{4}$$

where x_z is the number of vehicles within link z; q_z and u_z are the inflow and outflow, respectively, of link z over the period [kT, (k+1)T] with T the control interval and k=1, 2, … a discrete time index; and d_z and s_z are the demand and the exit flow, respectively.

For the exit flow the following formula holds

$$s_z(k)=t_{z,0}\, q_z(k) \tag{5}$$

with exit rates $t_{z,0}$ considered fixed and known. Taking into account eq. (5), the following is obtained from (4)

$$x_z(k+1) = x_z(k) + T[(1-t_{z,0})q_z(k) + d_z(k) - u_z(k)]. \tag{6}$$

The inflow to the link z is given by

$$q_z(k) = \sum_{w \in I_M} t_{w,z} u_w(k) \tag{7}$$

where $t_{w,z}$ with $w \in I_M$ are the turning rates towards link z from the links that enter junction M.

Assuming that space is available in the downstream links and that x_z is sufficiently high, the outflow u_z of a link is equal to the saturation flow S_z if the link has r.o.w., and equal to zero else. However, if the control interval T is chosen not less than the cycle time C, an average value is obtained as follows

$$u_z(k) = \frac{S_z G_z(k)}{C} \tag{8}$$

where G_z is the effective green time of link z, calculated as

$$G_z(k) = \sum_{i\in v_z} g_{N,i}(k) + e_z. \tag{9}$$

In (9), e_z is a constant that may take positive or negative values. In case that link z receives r.o.w. in more than one consecutive stages, thus using their intermediary intergreen periods with green light, and/or the green light for link z starts earlier or ends later than the corresponding stage(s) at which it receives r.o.w., e_z takes positive values that correspond to the extra green time utilised by the link. In the case that the green light for link z starts later or ends earlier than the corresponding stage(s) at which z receives r.o.w., e_z becomes negative. In any other case, e_z is equal to 0.

Substituting (7), (8), and (9) into (6), the following equation results that describes for each link $z\in Z$, the time evolution of its state in terms of the number of vehicles within it

$$x_z(k+1) = x_z(k) + T\left[(1-t_{z,0})\sum_{w\in I_M}\frac{t_{w,z}S_w\left(\sum_{i\in v_w} g_{M,i}(k)+e_w\right)}{C} + d_z(k) - \frac{S_z\left(\sum_{i\in v_z} g_{N,i}(k)+e_z\right)}{C}\right]. \tag{10}$$

Assuming the existence of non-saturating constant nominal demands d_z^N, nominal values $g_{j,i}^N$ for $g_{j,i}$ may be found, as mentioned in Section 3.1 that lead to constant nominal values x_z^N. Under this assumption the steady-state version of (10) reads

$$0 = T\left[(1-t_{z,0})\sum_{w\in I_M}\frac{t_{w,z}S_w\left(\sum_{i\in v_w} g_{M,i}^N+e_w\right)}{C} + d_z^N - \frac{S_z\left(\sum_{i\in v_z} g_{N,i}^N+e_z\right)}{C}\right]. \tag{11}$$

Subtracting the steady-state equation (11) from (10), the following state equation is obtained

$$x_z(k+1) = x_z(k) + T\left[(1-t_{z,0})\sum_{w\in I_M}\frac{t_{w,z}S_w\left(\sum_{i\in v_w} \Delta g_{M,i}(k)\right)}{C} + \Delta d_z(k) - \frac{S_z\left(\sum_{i\in v_z} \Delta g_{N,i}(k)\right)}{C}\right] \tag{12}$$

where $\Delta g_{j,i} = g_{i,i} - g_{j,i}^N$ and $\Delta d_z = d_z - d_z^N$.

Applying (12) to an arbitrary network comprising several signalised junctions $j\in J$, the following state equation (in vector form) describes the evolution of the system in time

$$\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\,\Delta\mathbf{g}(k) + \mathbf{T}\,\Delta\mathbf{d}(k) \tag{13}$$

where $\mathbf{x}$ is the state vector of the numbers of vehicles x_z within links $z \in Z$; $\Delta\mathbf{g}$ is the vector of $\Delta g_{j,i} = g_{j,i} - g_{j,i}^N$, $\forall i \in F_j$, $\forall j \in J$; $\Delta\mathbf{d}$ is the vector of $\Delta d_z = d_z - d_z^N$; and $\mathbf{A} = \mathbf{I}$, $\mathbf{B}$, and $\mathbf{T}$ are the state, input and disturbance matrices, respectively. In contrast to other applications of store-and-forward modelling, x_z in the above formulation denotes the number of vehicles within a link z instead of the queue length within it, which circumvents the need of incorporating time lags in the state equation (13).

In order for the application of the LQ methodology to lead to a feedback control law without feedforward terms, i.e. a control law that reacts to the manifest impact of the disturbances on the controlled process rather than to disturbance forecasts, $\Delta\mathbf{d}(k) = \mathbf{0}$ is assumed, leading from (13) to the following state equation

$$\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\,\Delta\mathbf{g}(k). \tag{14}$$

It should be stressed here that the LQ optimisation methodology should be viewed as a vehicle for deriving an efficient gain matrix rather than as an attempt to optimise a meaningful criterion subject to accurate modelling equations and constraints. Within this frame the underlying assumption of zero disturbances is acceptable and (14) is utilised as the mathematical model within the LQ optimal control problem.

Regarding the control objective, the goal of minimising and balancing the link queues, mentioned in Section 3.1, may be addressed via introduction of the relative numbers of vehicles within the network links $x_z/x_{z,max}$, where $x_{z,max}$ is the storage capacity of link $z \in Z$ (measured in vehicles). A quadratic criterion that considers this control objective has the general form

$$\Im = \frac{1}{2}\sum_{k=0}^{\infty}\left(\|\mathbf{x}(k)\|_{\mathbf{Q}}^2 + \|\Delta\mathbf{g}(k)\|_{\mathbf{R}}^2\right) \tag{15}$$

where $\mathbf{Q}$ and $\mathbf{R}$ are nonnegative definite, diagonal weighting matrices. The infinite time horizon in (15) is taken in order to obtain a time-invariant feedback law according to the LQ optimisation theory [19]. The first term in (15) is responsible for minimisation and balancing of the relative numbers of vehicles within the network links. To this end, the diagonal elements of $\mathbf{Q}$ are set equal to the inverses of the storage capacities of the corresponding links. Furthermore, by the choice of the weighting matrix $\mathbf{R}=\rho\mathbf{I}$, the magnitude of the control reactions can be influenced. To this end, the choice of ρ is performed via a trial-and-error procedure so as to achieve a satisfactory control behaviour for a given application network.

Minimisation of the performance criterion (15) subject to (14) leads to a LQ control law

$$\mathbf{g}(k) = \mathbf{g}^N - \mathbf{L}\,\mathbf{x}(k) \tag{16}$$

where $\mathbf{g}^N$ is the vector of the nominal values of the effective green times $g_{j,i}$, $\forall i \in F_j$, $\forall j \in J$, and $\mathbf{L}$ is the resulting control matrix which depends upon the problem matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{Q}$, and $\mathbf{R}$. The control matrix was found in extensive investigations [3] to have little sensitivity with respect to variations of traffic parameters (such as turning rates, saturation flows, etc.). The calculation of $\mathbf{L}$ may be very time consuming for problems with high dimension. However, this computational effort is required only off-line, while on-line (i.e. in real-time) the calculations are limited to the execution of (16) with a given constant control matrix **L** and state measurements **x**(k). On-line computational requirements are therefore limited, and control reactions are easily understood.

In order to apply (16), availability of measurements for all state variables is required in real-time. However, the numbers of vehicles x_z are usually not directly measurable, unless video detection systems are utilised. For this reason, occupancy measurements o_z, collected in real time by traditional detector loops, may be transformed into (approximate) numbers of vehicles via suitable non-linear functions $x_z(k) = f_z(o_z(k))$ [3]. Moreover, since the LQ methodology does not take into account the existence of control constraints, after application of (16), a suitable algorithm modifies the calculated green light durations so as to satisfy the constraints (1)-(3) [3].

The multivariable regulator (16) has a reactive rather than anticipatory behaviour (i.e. it reacts to real-time measurements of the process under control) whereby it responds indirectly to unknown disturbances, and therefore it does not need any predictions of the future traffic conditions. However, it should be emphasised that its reactive control behaviour is by no means a myopic one, since it relies on real (measured) state information and it is designed on the basis of an infinite optimisation horizon.

3.3 Alternative Multivariable Regulators

The control law (16) requires availability of nominal values $\mathbf{g}^{\mathbf{N}}$. In some cases, however, neither the techniques nor the data required for the determination of the nominal green values are available. In such cases the control law (16) may be employed in the following form, where $\mathbf{g}^{\mathbf{N}}$ is not needed

$$\mathbf{g}(k) = \mathbf{g}(k-1) - \mathbf{L}\,[\mathbf{x}(k) - \mathbf{x}(k-1)]. \tag{17}$$

The control law (17) is obtained by subtracting (16) for control period k−1 from (16) for control period k.

A further control law that eliminates the need of nominal values $\mathbf{g}^{\mathbf{N}}$ may be obtained through the formulation of the urban traffic control problem as a Linear-Quadratic-Integral (LQI) optimal control problem based on the same modelling approach and pursuing the same control objective as before [1, 3]. For the application of the LQI methodology [19], the state equation (14) is augmented by use of the integrators

$$\mathbf{y}(k+1) = \mathbf{y}(k) + \mathbf{H}\,\mathbf{x}(k) \tag{18}$$

with **y** the vector of the integral parts, and **H** a matrix consisting of 0's and 1's such that a number of elements or linear combinations of elements of **x** are integrated in (18). In the current application, each element of **y** corresponds to a particular control variable $g_{j,i}$, and the elements of **H** are determined according to the particular control variable $g_{j,i}$ and the particular state variable x_z to which they correspond, as follows

$$H(z,(j,i)) = \begin{cases} 0 & \text{if } i \notin \nu_z \\ 1 & \text{if } i \in \nu_z \end{cases}. \tag{19}$$

In general, matrix **H** is chosen such that the steady-state error of some selected state variables or their linear combinations becomes 0 in case of constant disturbances, and this is the typical reason for applying the LQI instead of LQ methodology. In our application however, the main reason for applying the LQI methodology is to obtain a control law that does not need nominal control values $\mathbf{g}^N$.

For deriving the LQI control law, the performance criterion (15) is also augmented and takes the form

$$\Im = \frac{1}{2}\sum_{k=0}^{\infty}\left(\|\mathbf{x}(k)\|_{\mathbf{Q}}^2 + \|\mathbf{y}(k)\|_{\mathbf{S}}^2 + \|\Delta\mathbf{g}(k)\|_{\mathbf{R}}^2\right) \tag{20}$$

where $\mathbf{S}=s\mathbf{I}$ is an additional non-negative definite, diagonal weighting matrix obtained through a trial-and-error procedure so as to achieve a satisfactory control behaviour for a given application network.

Minimisation of the performance criterion (20) subject to (14), (18) leads to the following LQI control law [1, 3]

$$\mathbf{g}(k) = \mathbf{g}(k-1) - \mathbf{L_1}\,\mathbf{x}(k) - \mathbf{L_2}\,\mathbf{x}(k-1) \tag{21}$$

where $\mathbf{L_1}$ and $\mathbf{L_2}$ are control matrices that depend upon the problem matrices **A**, **B**, **H**, **Q**, **S**, and **R** but were found [1] to have little sensitivity with respect to variations of traffic parameters (such as turning rates, saturation flows, etc.).

After the application of either (17) or (21), the same algorithm mentioned in Section 3.2, modifies the calculated green light durations so as to satisfy the constraints (1)-(3). In order to avoid wind-up phenomena in the regulators, the values $\mathbf{g}(k-1)$ required in (17) and (21) are set equal to the *bounded* values of the previous control period (i.e. after application of the constraints (1)-(3)).

3.4 A Gating Feature of the Multivariable Regulators

A desired feature for modern traffic-responsive urban control systems is to protect downstream links from overload in the sense of limiting, to the extent possible, the entrance in a link when this link is close to overload. This may be effectuated through the reduction of the green times of the links that lead to the overloaded link. Structurally, the control matrices **L** and $\mathbf{L_1}$ provide the control laws (16), (17) and (21), besides queue balancing, with such a gating feature. Roughly speaking, the higher the number of vehicles within a particular link z, the more the green times of the links that lead to z are decreased through the application of (16) or (17) or (21).

In order for the gating feature of the multivariable regulators to be further accentuated, the utilised x_z values may be weighted such that the higher the value of x_z, the higher its weight. More precisely, the accentuation is achieved if the values of x_z utilised in the control laws are replaced by their weighted counterparts x_z' according to the following relationship

$$x_z'(k) = x_z(k)/\psi\left(x_z(k)\right) \tag{22}$$

with $\psi(x_z)\in\left(0,1\right]$ a monotonically decreasing function of x_z. It is obvious from (22) that $\psi(x_z) \to 0$ yields $x_z' \to \infty$ and $\psi(x_z) \to 1$ yields $x_z' \to x_z$ while any intermediary values of $\psi(x_z)$ lead to $x_z' \geq x_z$. The function $\psi(x_z)$ is selected as follows

$$\psi(x_z) = 1 - \left(bx_z / x_{z,\max}\right) \tag{23}$$

where $b \in [0,1)$ is a parameter that affects the level of achieved accentuation of the gating feature. The selection of the parameter b should be performed through a trial-and-error procedure during which the resulting control behaviour should be checked carefully. This is due to the fact that high values of b lead to accordingly strong weighting of the measurements and eventually to a very nervous control behaviour, high fluctuation in the values of x_Z, and possibly instability of the control system. Figure 2 displays examples of different values of the parameter b.

It should be noted here, that the control law (21) was found in simulations [3] to possess the gating feature in an enhanced way so that it does not need further weighting of the elements of **x** in contrast to both (16) and (17).

4. SIMULATION INVESTIGATIONS

For the simulation investigations of the TUC strategy, the example network of Figure 3 is used. The example network that consists of 13 signalised junctions and 61 links, is based on the Glasgow network for which the initial development of the IN-TUC strategy took place within the TABASCO project [15]. For the LQ formulation described in Section 3.2, 61 state variables corresponding to the numbers of vehicles within the considered network links and 43 control variables corresponding to the effective green times of all stages of all considered junctions are introduced. Moreover, for the LQI formulation described in Section 3.3, 43 additional state variables are introduced that correspond to the integrators of the particular problem.

For the simulation tests, the example network is modelled via METACOR [4], a macroscopic modelling tool for simulating the traffic flow in motorway, urban, or corridor

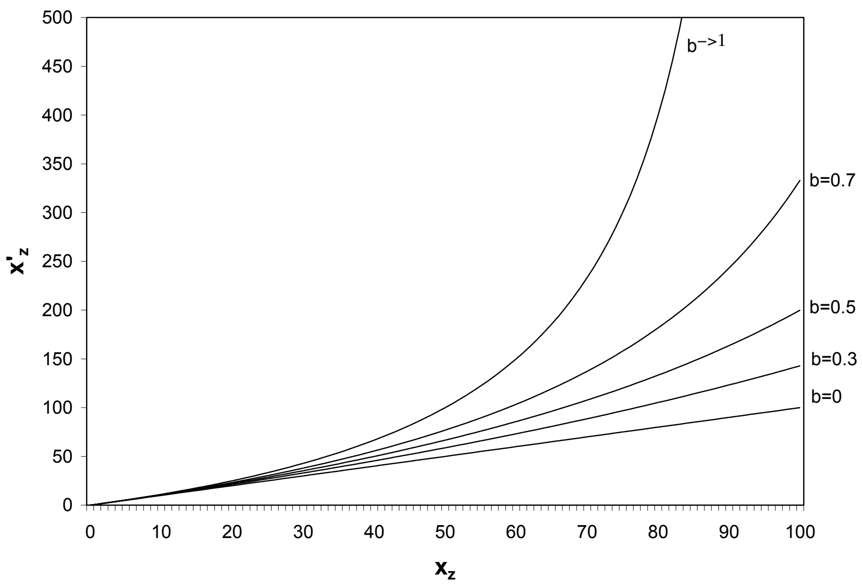

Figure 2: Relationship of x'_z and x_z for different values of the parameter b.

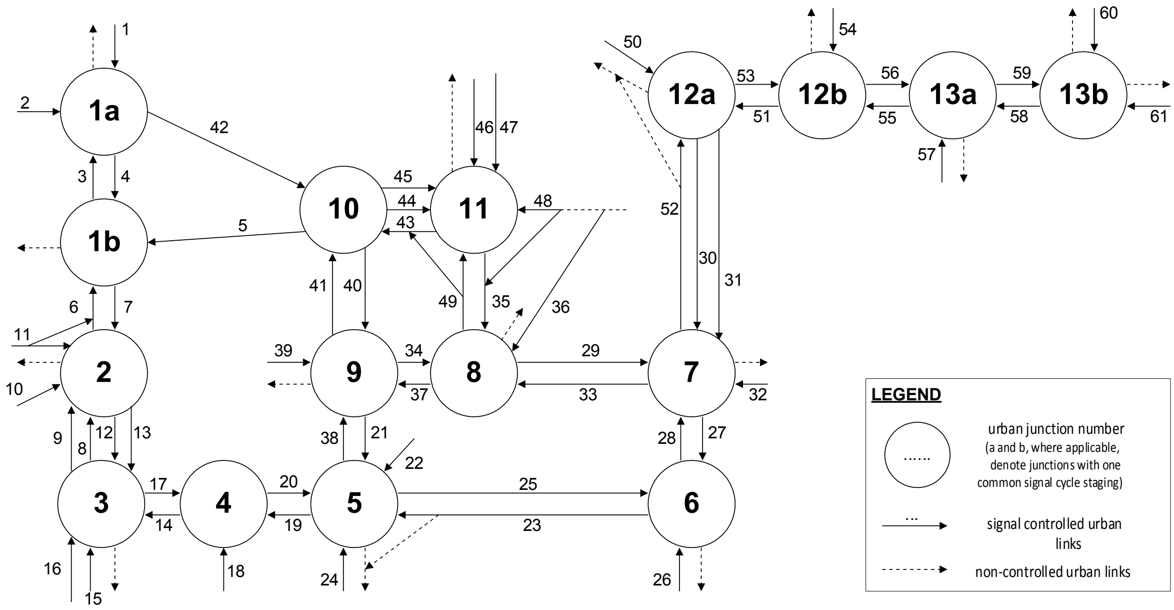

Figure 3: The example network.

networks. The parameters used in the model are those obtained through the METACOR model validation process that took place within TABASCO [15], while the traffic data are developed based on data obtained from the real network. The investigations are based on 4-hour simulations with TUC strategy running every 2 min, a control interval that is equal or twofold to the cycle time of all the considered junctions.

Initially, simulations are performed with fixed-time signal control for five different scenarios of demands and incidents. Then, the control laws (16), (17) and (21) are applied and tested with the METACOR model for five demand and incident scenarios with the following characteristics:

(i) Low demand in all but a few network origins.
(ii) High demand (approximately 40% higher than scenario (i)) in almost all network origins.
(iii) Demands present high time-fluctuations between the extremes of scenarios (i) and (ii).
(iv) Demands like scenario (i) and a major incident occurring before the peak period.
(v) Demands like scenario (i) and a major incident occurring during the peak period.

Table 1 summarises the results of the simulation tests in terms of the performance indices *total waiting time* (at the network origins), *total travel time*, *total time spent*, and *total fuel consumption*, for all vehicles during the 4-hour simulation horizon with TUC employing the multivariable regulator (16). In these investigations, it is assumed that the numbers of vehicles within the urban links are measurable in real-time (e.g. through a video detection system). The figures of Table 1 indicate that the TUC strategy leads to a significant reduction of all performance indices. More specifically, the total waiting time at the network origins is reduced by 100% for all investigated scenarios, while the total travel time, the total time spent, and the total fuel consumption are reduced in the ranges of 19-34%, 20-54%, and 13-23%, respectively, depending upon the investigated scenario.

Figure 4 displays the time evolution of the number of vehicles within some selected links under fixed-time signal control and the TUC strategy employing (16), for the demand scenario (i). The vertical axis in Figure 4 represents the fraction of number of vehicles x_z of a link z to the maximum storage capacity $x_{z,max}$ of the link. By inspection of the network sketch in Figure 3 and the diagrams of Figure 4, one may see that under fixed-time signal control, congestion develops in link 34 at junction 8. This congestion spills back through links 38, 20,

Table 1: Simulation results for fixed-time signal control (FSC) and TUC strategy with control law (16) using accurate x_z-measurements.

	Total Waiting Time		Total Travel Time		Total Time Spent		Total Fuel Consumption	
	veh*h	percentage change	veh*h	percentage change	veh*h	percentage change	veh*lt	percentage change
	FSC	TUC	FSC	TUC	FSC	TUC	FSC	TUC
scenario (i)	128	-100	2129	-34	2257	-38	3875	-23
scenario (ii)	2042	-100	3383	-26	5424	-54	5500	-18
scenario (iii)	4	-100	2365	-19	2369	-20	4237	-13
scenario (iv)	128	-100	2166	-34	2294	-38	3920	-23
scenario (v)	120	-100	2108	-32	2228	-35	3849	-21

The Total Waiting Time refers only to the queues at the network origins

17, and reaches link 13. Under the TUC strategy the same congestion does not even reach junction 9. Similar performance is also achieved in the other investigated demand scenarios.

If the numbers of vehicles within urban links utilised in (16) are estimated through occupancy measurements, the performance indices of Table 2 are obtained. In this case, the achieved amelioration of the traffic conditions is lower but still significant as compared to the fixed-time signal control. More specifically, the waiting time at the network origins, the travel time, the total time spent, and the total fuel consumption are reduced in the range of 72-100%, 10-30%, 14-34%, and 6-20%, respectively, depending upon the investigated scenario.

The simulation investigations of both (17) and (21) using measured or (occupancy-based) estimated values of numbers of vehicles within links indicate a similar performance with the control law (16). Tables 3 and 4 summarise the values of the performance indices for the five examined scenarios of demands and incidents, with measured and estimated values of numbers of vehicles within links, respectively. Given the similar performance of the three regulators, the selection of the approach to be employed may be based on other criteria like e.g. requirement of network authorities to utilise nominal values or lack of nominal values, etc.

5. CONCLUSIONS AND FUTURE WORK

The paper presents the traffic-responsive co-ordinated urban network control strategy TUC. TUC has been developed through the formulation of the urban traffic control problem

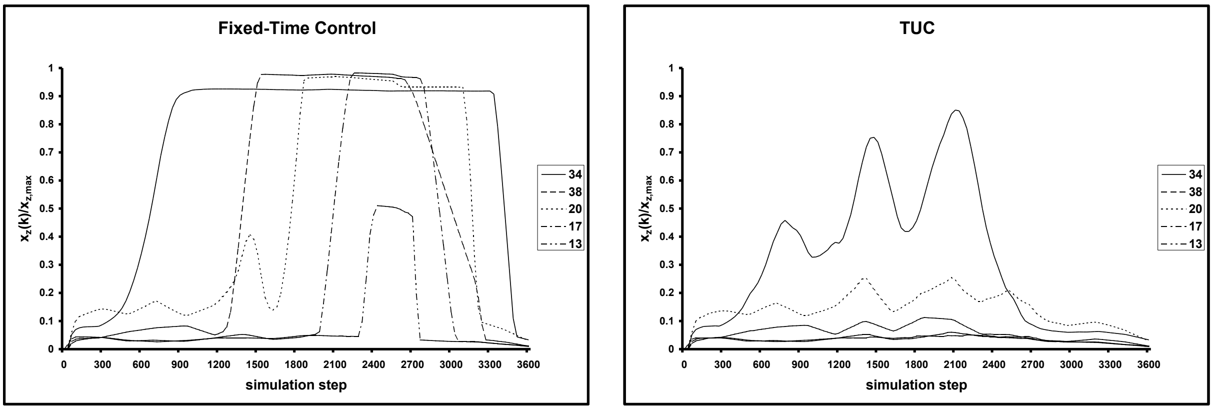

Figure 4: Comparison of fixed-time signal control and TUC for scenario (i).

Table 2: Simulation results for fixed-time signal control (FSC) and TUC strategy with control law (16) using estimations for x_z.

	Total Waiting Time		Total Travel Time		Total Time Spent		Total Fuel Consumption	
	veh*h	percentage change	veh*h	percentage change	veh*h	percentage change	veh*lt	percentage change
	FSC	TUC	FSC	TUC	FSC	TUC	FSC	TUC
scenario (i)	128	-100	2129	-30	2257	-34	3875	-20
scenario (ii)	2042	-72	3383	-10	5424	-34	5500	-6
scenario (iii)	4	-100	2365	-14	2369	-14	4237	-9
scenario (iv)	128	-100	2166	-28	2294	-32	3920	-19
scenario (v)	120	-100	2108	-26	2228	-30	3849	-17

The Total Waiting Time refers only to the queues at the network origins

Table 3: Simulation comparison of alternative control laws for TUC using accurate x_z-measurements.

	Total Waiting Time (veh*h)			Total Travel Time (veh*h)			Total Time Spent (veh*h)			Total Fuel Consumption (veh*lt)		
	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)
scenario (i)	0	0	0	1399	1399	1394	1399	1399	1394	2985	2985	2978
scenario (ii)	0	0	5	2486	2500	2526	2486	2500	2530	4494	4510	4541
scenario (iii)	0	0	0	1905	1895	1913	1905	1895	1913	3677	3664	3686
scenario (iv)	0	0	0	1431	1436	1430	1431	1436	1430	3023	3029	3022
scenario (v)	0	0	0	1444	1449	1434	1444	1449	1434	3039	3046	3027

The Total Waiting Time refers only to the queues at the network origins

TUC-(1) refers to the multivariable regulator (16)

TUC-(2) refers to the multivariable regulator (17)

TUC-(3) refers to the multivariable regulator (21)

Table 4: Simulation comparison of alternative control laws for TUC using estimations for x_z.

	Total Waiting Time (veh*h)			Total Travel Time (veh*h)			Total Time Spent (veh*h)			Total Fuel Consumption (veh*lt)		
	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)	TUC-(1)	TUC-(2)	TUC-(3)
scenario (i)	0	0	0	1488	1488	1450	1488	1488	1450	3093	3093	3046
scenario (ii)	562	569	99	3040	3048	2798	3602	3617	2897	5165	5172	4873
scenario (iii)	0	0	0	2042	2041	2031	2042	2041	2031	3844	3843	3830
scenario (iv)	0	0	0	1551	1561	1500	1551	1561	1500	3169	3182	3108
scenario (v)	0	0	0	1561	1558	1493	1561	1558	1493	3182	3178	3100

The Total Waiting Time refers only to the queues at the network origins

TUC-(1) refers to the multivariable regulator (16)

TUC-(2) refers to the multivariable regulator (17)

TUC-(3) refers to the multivariable regulator (21)

as an optimal control problem based on a store-and-forward modelling approach. The employment of this modelling approach has the following consequences for the derived strategy:

- The control interval cannot be shorter than the cycle times of the considered signalised junctions, hence real-time decisions cannot be taken more frequently than at the maximum employed signal cycle.
- The effect of offset for consecutive junctions cannot be directly considered.

Additionally, the time-variance of traffic parameters like the turning rates and the saturation flows cannot be taken into account when deriving the multivariable regulators (16), (17), and (21). Finally, the centralised functional architecture of TUC does not allow for immediate consideration of modifications and expansions of the controlled network.

Regarding the traffic parameters (turning rates, saturation flows), extensive simulation investigations [1,3] showed that, although the control matrices $\mathbf{L}$, $\mathbf{L_1}$, and $\mathbf{L_2}$ depend on them, they present a low sensitivity to their changes, hence the efficiency of the strategy remains practically unaffected. In case of modifications and expansions of the controlled network, the strategy has to be completely re-designed. Nevertheless, the re-design is a straightforward task as it is performed using available generic software tools and exploits all the information that has come out from the initial design. The lack of flexibility of TUC regarding modifications and expansions of the controlled network is the price to be paid for its centralised functional architecture that allows for the simultaneous consideration of all junctions with the application of a single and simple matrix equation independently of the network size.

Despite these minor shortcomings, the employed modelling and control approach has led to a highly efficient and extremely simple co-ordinated control strategy, applicable to large-scale networks as demonstrated in the presented simulation investigations, that carries also important features like:

- robustness with respect to measurement inaccuracies,
- simplicity and transparency of the real-time code, and
- generality so that it may be transferred with minor modifications to networks with arbitrary topology and characteristics.

TUC has been implemented and is currently operational in a part of Glasgow's (Scotland) urban network with excellent results [5,17], while investigations for an implementation in the city of Chania (Greece) are under way.

Future research activities aim at comparing TUC with other urban traffic control strategies and at developing additional algorithms for the real-time modification of the signal cycles and the offsets.

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