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International comparative field evaluation of a traffic-responsive signal control strategy in three cities ☆

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Abstract

The recently developed network-wide real-time signal control strategy TUC has been implemented in three traffic networks with quite different traffic and control infrastructure characteristics: Chania, Greece (23 junctions); Southampton, UK (53 junctions); and Munich, Germany (25 junctions), where it has been compared to the respective resident real-time signal control strategies TASS, SCOOT and BALANCE. After a short outline of TUC, the paper describes the three application networks; the application, demonstration and evaluation conditions; as well as the comparative evaluation results. The main conclusions drawn from this high-effort inter-European undertaking is that TUC is an easy-to-implement, interoperable, low-cost real-time signal control strategy whose performance, after very limited fine-tuning, proved to be better or, at least, similar to the ones achieved by long-standing strategies that were in most cases very well fine-tuned over the years in the specific networks.

☆ The commercial and intellectual property rights of the signal control strategy TUC are with the Dynamic Systems and Simulation Laboratory, Technical University of Crete, Chania, Greece.

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1. Introduction

In view of the imminent traffic congestion and lack of possibilities for infrastructure expansion in urban road networks, the importance of efficient signal control strategies, particularly under saturated traffic conditions, can hardly be overemphasized. It is generally believed that real-time (traffic-responsive) systems responding automatically to the prevailing traffic conditions, are potentially more efficient than clock-based fixed-time control settings, possibly extended via a simple traffic-actuated (micro-regulation) logic.

On the other hand, the development of real-time signal control strategies using elaborated network models is deemed infeasible due to the combinatorial nature of the related optimisation problem (Papageorgiou et al., 2003); as a consequence, all developed or implemented signal control strategies must include some simplifications or heuristics, which renders a theoretical efficiency comparison of different strategies extremely difficult thus calling for simulation-based or, even better, field evaluation and comparison of different control strategies. However, field implementation of different strategies in the same traffic network may be a very costly undertaking in view of different requirements regarding the system architecture, communications, detector numbers and locations etc., hence extensive field comparisons of signal control strategies have been very rarely reported in the past.

The recently developed real-time network-wide signal control strategy TUC (Diakaki et al., 2002, 2003) has been conceived so as to be easily applicable due to low and little-specific control infrastructure requirements, without sacrificing efficiency, particularly under saturated traffic conditions. TUC (Traffic-responsive Urban Control) employs advanced automatic control methodologies and had shown significant improvements in simulation tests and small-scale implementations compared with optimised fixed-time settings (Diakaki et al., 2000, 2002, 2003; Dinopoulou et al., 2005). This motivated a major inter-European effort, co-funded by the European Commission, aiming at implementing and evaluating TUC in three urban networks with quite different traffic and control infrastructure characteristics: Chania, Greece (23 junctions); Southampton, UK (53 junctions); and Munich, Germany (25 junctions), where it has been compared to the respective resident real-time signal control strategies TASS, SCOOT and BALANCE (Bielefeldt et al., 2001).

After a brief outline of TUC, this paper presents the three application networks; the application, demonstration and evaluation conditions; as well as the comparative evaluation results. Main conclusions are summarized in a final section.

2. The TUC signal control strategy

TUC (Traffic-responsive Urban Control) consists of four distinct interconnected control modules (Fig. 1) that allow for real-time control of green times (split), cycle time, offsets, as well as for the provision of public transport priority. These four control modules are complemented by a fifth data processing module.

All control modules are based on feedback concepts of various types, which leads to TUC's computational simplicity as compared to model-based optimisation approaches, without actually sacrificing efficiency, as the results of this paper indicate. The split control and data processing modules were the first to be developed (see Diakaki, 1999; Diakaki et al., 2002, for details) while the other three control modules were developed at a later stage (see Diakaki et al., 2003, for details).

2.1. Split control

This is a network-wide control module, i.e. all available measurements are used to calculate the green time of each stage via the multivariable regulator

$$\mathbf{g}(k) = \mathbf{g}_{\mathrm{N}} - \mathbf{L}\mathbf{x}(k-1) \tag{1}$$

where $k = 0, 1, 2, \ldots$ is the discrete time index with sample time period typically equal to the cycle time c (but note that the Munich implementation had a sample period of 5 min due to local technical reasons); the vector

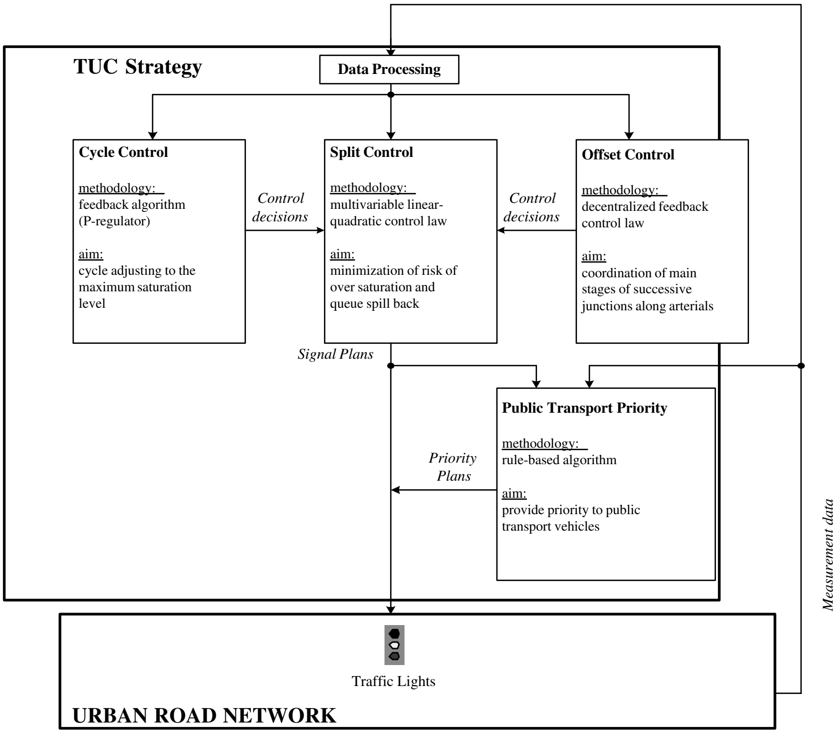

Fig. 1. Functional architecture of TUC.

$\mathbf{g}(k)$ includes the green times of all stages in all junctions to be applied during the next cycle; $\mathbf{g}_N$ is a pre-specified fixed plan whose impact on the resulting control was found to be limited; the vector $\mathbf{x}(k-1)$ comprises the number of cars in all network links during the last cycle, estimated by the data processing module; $\mathbf{L}$ is the control matrix (with dimensions number-of-stages/number-of-links) which results from an off-line applied software code based on the Linear-Quadratic (LQ) regulator design procedure; the traffic data required to calculate $\mathbf{L}$ are: saturation flows of links; average turning rates at junctions; maximum numbers of cars $x_{z,\max}$ in links z; the control results were found to be little sensitive w.r.t variations of these data. The aim of (1) is to minimize and balance the relative space occupancies $\sigma_z = x_z/x_{z,\max}$ in the network links z so as to minimize the risk of queue spillovers which may lead to a waste of green time and even to gridlocks; to this end the regulator (1) may apply an inherent gating, i.e. reduce the green time of links that feed a saturating road, even if these links are two or more junctions away. The green times for the stages of each junction resulting from (1) will generally not add up to a cycle and may also violate minimum-green constraints; a suitably designed knapsack optimisation modifies the green times so as to satisfy these constraints but keep the relative proportions of the green times as close to the ones of (1) as possible.

2.2. Cycle control

One single cycle c is calculated for all network junctions (in order to enable offset-coordination) according to the feedback P-type regulator

$$c(k) = c_N + K^c[\sigma(k-1) - \sigma_N] \tag{2}$$

with sample time period typically equal to 5–10 min; c_N is a nominal cycle time, typically equal to the minimum admissible cycle time $c_{\min}$; σ is the average space-occupancy of a pre-specified percentage (e.g. 10%) of network links z with currently highest space occupancies $\sigma_z = x_z/x_{z,\max}$; σ_N is a nominal space-occupancy, typically equal to 0.1; K^c is a regulator parameter which affects the intensity of the control reaction. The regulator (2) adjusts the cycle time to the currently observed maximum saturation level reflected in $\sigma(k-1)$ so as to increase the network capacity when and to the extent needed. The $c(k)$-value resulting from (2) is constrained within the range $[c_{\min}, c_{\max}]$ of pre-specified admissible cycles. Double-cycling may be allowed in selected junctions under the condition that all σ_z-values of the corresponding adjacent links are below a specific threshold.

2.3. Offset control

Offset calculation is based on a decentralized (by couple of junctions) feedback control law that modifies the offsets of the main stages of successive junctions along pre-specified arterials (or, more generally, along pre-specified link sequences), so as to create "green waves", taking into account the possible existence of vehicle queues in the respective links. More specifically, the offset of each couple of junctions is calculated such that the first vehicles released from the upstream junction at the green phase arrive at the tail of the link queue exactly at the time the last queuing vehicles start to move due to the downstream green phase. This procedure considers only one direction of two-way arterials that can be pre-selected; alternatively, the module may specify automatically in real time the offset direction to be the currently most saturated one. Implementation of the new offsets involves the creation of a transient cycle; therefore the sample time periods of the cycle and offsets control modules must be identical.

2.4. Public Transport Priority (PTP)

A rule-based PTP module is typically, but not necessarily, implemented in the local junction controllers to enable second-by-second communication with specific PT vehicle detectors which must, as a minimum, detect the passage or presence of a PT vehicle within a link. The PTP module may be enabled at selected junctions to provide priority to PT vehicles via suitable modification (e.g. green extension, stage recall etc.) of the signal settings delivered by the other control modules. Various options, constraints, conditions and levels of priority may be pre-selected, e.g. provision of priority only if a pre-selected saturation level in the adjacent links is not exceeded; respect or not of cycle time; check of PT headway adherence etc.

2.5. Data processing

The real-time measurements required by the split, cycle and offset control modules are average numbers x_z of vehicles within the network links z over a cycle. Unless the network is equipped with a video detection system, such measurements are not available. In this case, occupancy measurements o_z collected via one traditional detector loop cross-section in each link z may be utilized to estimate x_z via a suitable function

$$x_z/x_{z,\max} = f(o_z, \lambda_z) \tag{3}$$

where $\lambda_z = l_z/L_z \in [0, 1]$; L_z being the link length and l_z the detector distance from the stop line. Eq. (3) allows TUC to be applicable for any detector location within links while other strategies may have higher (more detectors per link) or stricter requirements, e.g. detectors placed at the upstream link boundaries or at the stop line etc. It should be noted, however, that best TUC performance is usually achieved when $\lambda_z \approx 0.5$, i.e. when the detectors are placed around the middle of the links. The x_z-values resulting from (3) may be exponentially smoothed so as to avoid unnecessarily strong changes of the signal settings over time. The data processing module is also automatically replacing missing data (due to lack of detectors in some links or due to detector failures) with suitable averages of available adjacent-link measurements.

It should be noted that any combination of TUC's four control modules may be selected for application while the non-employed control modules may be replaced either by fixed settings (e.g. fixed offsets) or by other external modules (as in the Munich implementation for cycle and offsets). The available real-time measurements from the network detectors are conveyed (once at each cycle) to the data processing and eventually to the control modules; the cycle and offset modules perform their tasks (according to their sample time period) and forward their decisions to the split module where the final network-wide signal settings are specified. Note that the network-wide character of TUC calls for a central computer where at least the above four modules must be implemented, while the PTP module may be implemented in the local junction controllers, in which case the communication requirements between local controllers and central computer are limited to one data package exchange per cycle. Note that TUC may be combined with an available micro-regulation (traffic-actuated) logic at the local controllers level, which was actually enabled in the Munich implementation.

All TUC modules are packed in a generic on-line software code that is plugged in the network's central computer via specific interfaces, while the specific network characteristics (topology, staging, saturation flows, average turning rates) are fed to the generic code via input files. A generic code is also available for the off-line design of TUC, i.e. for the calculation of the control matrix **L**, based on the network data included in input files; in case of network re-arrangements (staging, one-way streets etc.) or extension, the control matrix **L** must be updated by running the off-line design code with accordingly modified input files. As a matter of fact, the same generic off-line and on-line codes were applied and implemented in all past and present implementations of TUC; merely the interfaces of the on-line software had to be tailored to the individual characteristics of each control centre.

The generic TUC codes provide the possibility to subdivide the overall application network into smaller regions, in which case (1) is applied region- (rather than network-) wide and each region has its own cycle calculated from (2). This option was used in the Chania and Southampton network applications, each of which was divided in two regions.

Upon the wish of the operators of the three networks, an extension to the original TUC concept was introduced which indeed proved very valuable as a means to fine-tune TUC's performance or to purposedly influence its otherwise automatic functioning when necessary. More specifically some so-called "importance factors" f_z were introduced for each link z, such that the x_z-values resulting from (3) are multiplied with the corresponding f_z before being used by the control modules. The default values are $f_z = 1$, but the operator may select a real value $f_z \in [1, 3]$ so as to increase the importance of specific links, i.e. make them look more saturated than the measurements actually reflect. This measure proved particularly useful for origin links (located at the network boundaries), where a detector placed, say, 100 m from the stop line may not reflect properly a long queue extending beyond the network boundaries.

TUC could be appropriately modified to consider wider policy-based objectives (e.g. for specific gating actions or traffic reduction measures) but no such option was considered in the reported implementations where best operational performance was the main objective pursued.

3. The application networks and conditions

3.1. Chania, Greece

Fig. 2 displays the Chania city-centre network where TUC was applied (junctions with common signalling have the same number, e.g. 1A, 1B, 1C). The network includes the city's main shopping district and faces

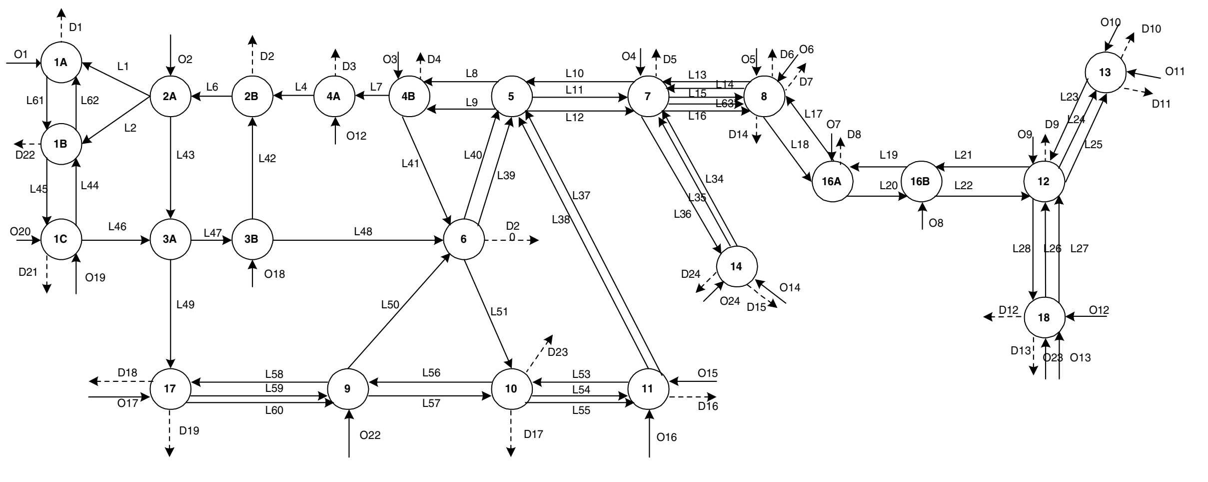

Fig. 2. The Chania application network.

serious congestion during the morning (8–9 a.m.), afternoon (2–3 p.m.) and evening (9–10 p.m.) peak hours with link queues that may spill back into upstream links. A particular issue that can be hardly faced by real-time signal strategies is the frequent double or illegal parking of vehicles in specific links for short periods of time (deliveries, quick shopping etc.) which may strongly distort the detector measurement relevance and reduce the concerned link and junction capacities. Typical detector locations within the Chania network links are either around the middle of the link or some 40 m upstream of the stop line.

The resident control strategy TASS (Siemens, 2000) selects every 15 min one out of six pre-defined signal plans (each with different cycle, splits, offsets), depending on the current traffic conditions in the network, and transfers the selected plan to the junction controllers for application. The junction controllers may modify (within certain limits) the received signal settings by application of a simple traffic actuation logic based on local traffic measurements (micro-regulation). The strategy includes a high number of parameters and settings that were fine-tuned to virtual perfection over the last five years.

For the application of TUC, the network was divided in two regions, the first region comprising the city centre and the second region comprising the junctions 12 and 13 that are located at an important entrance/exit gate of the city. All TUC modules except PTP were applied. Fine-tuning was focussed mainly on the issue of illegal and double parking but also on some origin links with high loads; the K^c parameter of the cycle control law (2) was also fine-tuned for each region separately. One of the six available TASS fixed signal plans was used as $\mathbf{g}_N$ in (1). In order to calculate the control matrix $\mathbf{L}$, saturation flows were guessed based on the number of lanes and movement direction (straight, right or left) of links while the utilised turning rates were based on rough estimations of the network operators. The cycle time was allowed to vary within the limits [60 s, 120 s]. Double-cycling was enabled on some boundary junctions (e.g. 14, 17) with moderate loads.

The TUC on-line code was implemented in a PC that was interfaced to the resident control infrastructure, and a special user interface was designed on the same PC specifically for the TUC operation.

3.2. Southampton, UK

Two distinct but interconnected regions within Southampton were selected for TUC application, the city centre and the Bitterne arterial leading to the city centre (Fig. 3). The city-centre region contains both the main shopping area and the commercial and business centre of Southampton; the main railway station and three port entrances are also contained within this region. All these factors combine to cause high road traffic demand on a constrained and cramped road network leading to congestion in the morning (8–9 a.m.) and evening (5–6 p.m.) peak periods. Exceptional events include the Premier League football matches on Saturdays as well as the arrival and departure of large cruise ships. Generally, congestion within the city centre is at its worst on Saturdays when it typically extends from mid-morning to late afternoon. The Bitterne corridor region leads to the city centre via Northam Bridge which is often severely congested at peak periods. On the arterial route traffic is gated, effectively at one major entry point (link 54), during the a.m. peak period to allow public transport priority and to ensure that the capacity at the bridge is not exceeded. As a rule, detectors in the Southampton network are placed at the upstream link boundaries according to the SCOOT requirements.

The well-known resident control strategy SCOOT (Hunt et al., 1982) was developed in the late 1970's and has benefited from many developments since then. The SCOOT application in Southampton has been extensively fine-tuned over the last 20 years and is counted as one of the best-maintained implementations anywhere.

TUC was applied to the two regions separately, employing all available modules; note that a hybrid version, whereby SCOOT delivered cycles and offsets while TUC calculated splits, was also successfully tested, but the corresponding results are not reported in this paper. TUC fine-tuning was limited to a few days and focussed mainly on origin links with high loads but also on some critical internal network links and the K^c parameter of (2) that was given different values for the two regions. No updated fixed signal plan was available to be used as $\mathbf{g}_N$ in (1), hence a probably outdated older plan was used to this end. Saturation flows used by SCOOT were used for TUC's control matrix calculation while turning rates were estimated from a number of traffic counts.

As for Chania, the cycle time bounds were 60 s and 120 s, respectively, while double-cycling was mainly enabled at pedestrian crossing signals to reduce pedestrian waiting times.

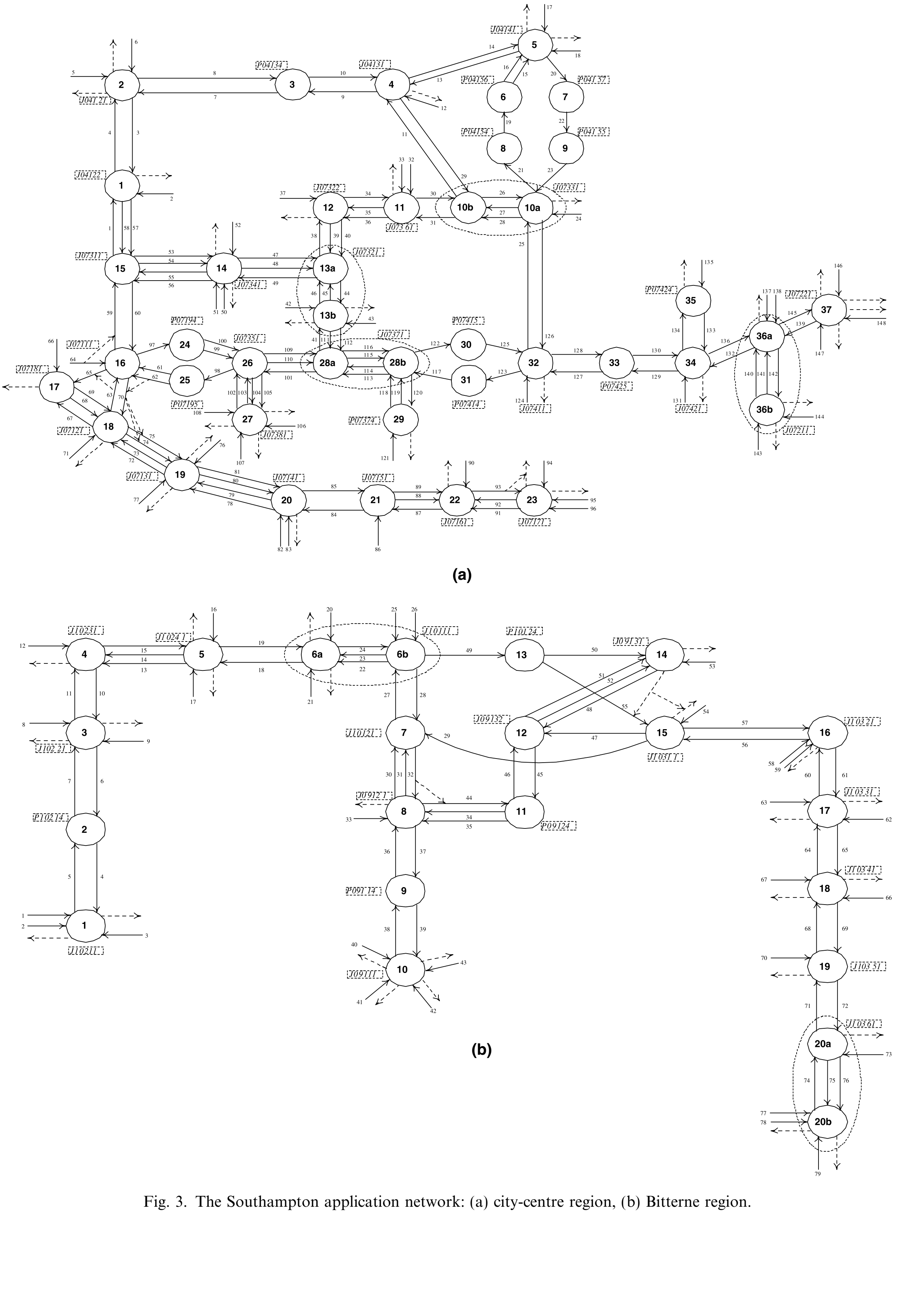

Fig. 3. The Southampton application network: (a) city-centre region, (b) Bitterne region.

The TUC on-line code was implemented in a PC that was interfaced to the resident control infrastructure. No special user interface was available for TUC operation in the Southampton implementation.

3.3. Munich, Germany

The Munich signal control infrastructure has been gradually upgraded in the last years from a fixed-time, locally traffic-actuated towards a network-wide real-time (traffic-responsive) architecture, and TUC implementation (as well as implementation of BALANCE, the resident strategy) was undertaken during the upgrading works. Due to unexpected technical problems in the upgrading process, the operation of TUC and BALANCE in Munich suffered from many technical problems and system faults that were independent of the strategies themselves.

Fig. 4 displays the Munich application network which is located in the district Haidhausen; grey junctions in Fig. 4 were not controlled by TUC or BALANCE for technical reasons. The second largest railway station of Munich is contained in this area. The network faces significant congestion during the morning and evening peak hours, mainly due to commuter traffic. Surface public transport is dense in this area with four LRT lines and six bus lines. An elaborated logic for PTP is installed in the local controllers which is beyond the control of the tested strategies; in fact, whenever a PT vehicle is approaching a junction, the local PTP logic takes over the control of the signals for the corresponding cycle. Typical detector location within the Munich network links is some 40 m upstream of the stop line.

The resident control strategy BALANCE (Friedrich and Ernhofer, 2000) is a model-based optimisation tool calculating splits, cycle and offsets that was also implemented for the first time in the test network. The centrally calculated signal settings may be modified by an actuated control logic implemented in the local junction controllers. The same micro-regulation option was activated also for TUC-calculated signal settings in the Munich implementation.

TUC in Munich was applied only for splits, while cycle and offset were provided by BALANCE. This hybrid control system will be referred to as TUC in the next section for brevity. Signal settings were updated every 5 min for technical reasons. Fine-tuning of both BALANCE and TUC was limited to a couple of days

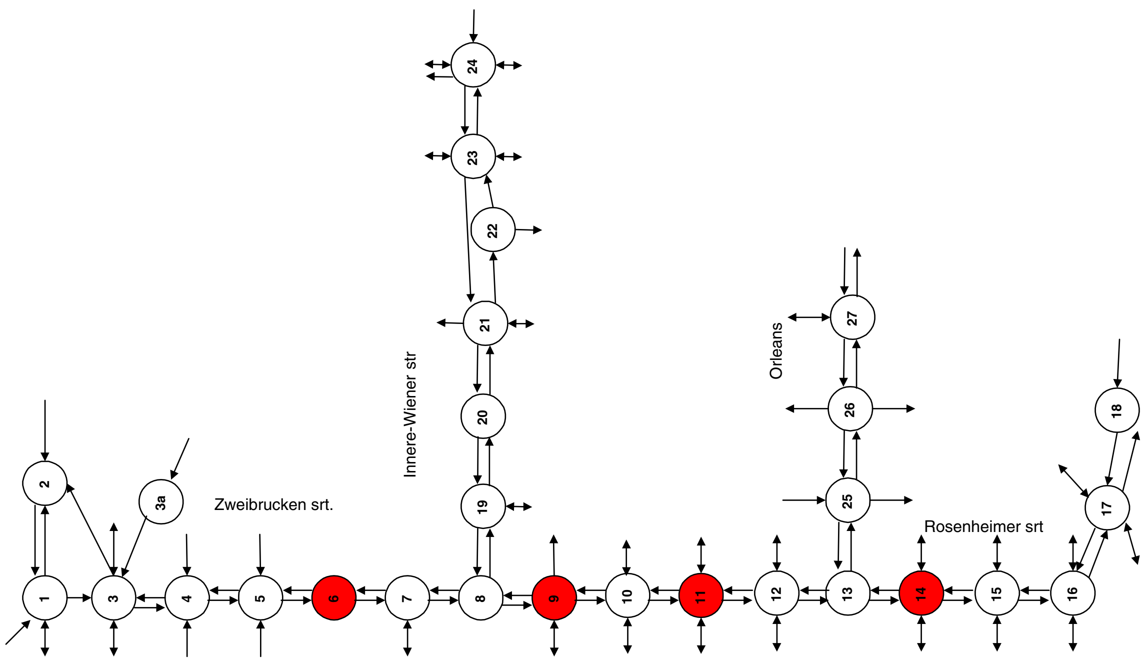

Fig. 4. The Munich application network.

for each strategy. An updated signal plan was used as $\mathbf{g}_N$ in (1), while turning rates and saturation flows needed for the calculation of the control matrix **L** were guessed based on network experience. The TUC on-line code was integrated in the central computer of the resident control centre.

3.4. Practical difficulties

Although TUC implementation in the existing infrastructure of the three networks was quite straightforward, a number of practical difficulties, quite typical for this kind of field implementations, were encountered and had to be circumvented, where possible, before the final evaluation. Here are some examples of practical and other difficulties:

- TUC relies on occupancy measurements rather than flow measurements used by other strategies. Several kinds of faults in the occupancy measurements delivered by otherwise properly working detectors had to be identified and corrected.
- Observed occasional spiky behaviour of detector data was addressed via truncation and smoothing measures.
- The existing staging was in some cases (Chania network) not the most appropriate for a real-time strategy, but it was decided for technical reasons to leave it as is during TUC application.
- The introduction of more regions with different cycle times (e.g. SCOOT regions in Southampton city-centre comprise only 3–4 junctions each) would most likely improve the performance of TUC but would have required longer and closer observation. In the case of Chania, the introduction of more than two regions would help to address the problem of short-term illegal and double parking but could not be implemented due to technical constraints.
- Detectors straddling two lanes for some Southampton links were handled by use of a specifically developed formula for occupancies (Papageorgiou and Dinopoulou, 2003).
- Last not least, fine-tuning of TUC was rather limited in time as the local operators did not have the time to familiarize with the new system and its "play-buttons".

4. Comparative evaluation

4.1. Evaluation method

The two control strategies per application site to be compared were applied in the field in weekly alteration for the period of one month (2 weeks per strategy). Two basic sources of information for the comparative evaluation of the strategies performances were available, each with its strengths and weaknesses.

Loop detectors installed in the vast majority of network links of each site, deliver measurements of flow (veh/h) and occupancy (%). This information was stored during the strategies demonstration and was used for comparative performance evaluation. The main advantage of this source of information is the high availability (except for temporary detector faults) over the whole demonstration period, but there are also two noteworthy weaknesses.

(a) For technical reasons beyond the scope of this paper, the accuracy of flow measurements delivered by loop detectors is limited, particularly when vehicles are moving slowly over the loop. This may be caused by the "masking error", whereby the detector cannot distinguish between two or more slowly passing vehicles due to limited sampling time resolution (250 ms in Southampton) or due to other technical reasons. As a consequence, flow measurements under high occupancy appeared frequently undercounted with an according impact on the comparative evaluation results.

(b) Loop detectors are installed at a specific link position. As a consequence, the delivered occupancy measurements are not necessarily fully representative for the traffic conditions along the whole link length. In other words, a local time-occupancy measurement is used as space-occupancy in urban road links that are typically characterized by high inhomogeneity due to continuous queue formation and dissolution. On the other hand, the usage of the same kind of measurements for both control strategies under comparison weakens this disadvantage as far as the relative strategies performances are concerned.

Floating Car Data (FCD) collected manually by specifically instructed drivers and co-drivers, deliver journey times for specific routes and times-of-day. The main weaknesses of FCD are:

(a) It was not possible to drive on all links in the extended Southampton network.
(b) There is a relatively limited amount of FCD data (due to the involved high-effort) which, in case of strongly variable traffic conditions, may not accurately reflect the relative performances of the control strategies under comparison.

Further issues that may have affected the accuracy of the comparative performance results are:

(a) Although the weekly alteration of strategies was aimed at guaranteeing similar demand condition for both strategies, demand variations do occur in real networks for a multitude of reasons.
(b) Weather conditions were monitored during the demonstration, and extreme cases (snow storms in Munich) were excluded from the evaluation. However, the sensitivity of any control strategy to, e.g., rainy weather was found to be higher than the performance difference among strategies.
(c) Very few major incidents were observed (and corresponding data were excluded from the evaluation) but the possibility of unobserved minor incidents cannot be excluded.

Note that this kind of evaluation-disruptive issues is virtually inevitable in a "dirty" real environment as opposed to comparative simulation-based studies. Nevertheless, control strategies should be best tested in real environments to reveal all their strengths and weaknesses; it is felt that in the reported investigations the above difficulties did not obscure the major evaluation findings.

Some performance indices to be used in the following are defined next. To start with, if the time-occupancy $o_z(k)$ (in %) delivered by the detector for link z and period k is used as a space-occupancy, then the corresponding average car count is

$$\chi_z(k) = L_z \alpha_z o_z(k) \tag{4}$$

where L_z is the link length and $\alpha_z = \mu_z/(100\Lambda)$ with μ_z the number of lanes of link z and Λ the average vehicle length. The total time spent (TTS) (in veh h) in the network over K periods of length T is then given by

$$\text{TTS} = T\sum_{k=1}^{K}\sum_{z}\chi_z(k) \tag{5}$$

while the total distance travelled (TTD) (in veh km) is

$$\text{TTD} = T\sum_{k=1}^{K}\sum_{z} q_z(k)\cdot L_z \tag{6}$$

where $q_z(k)$ are the flow measurements. An average mean speed (MS) may then be calculated as

$$\text{MS} = \text{TTD}/\text{TTS}. \tag{7}$$

Key evaluation findings from each demonstration network are summarized below, while details can be found in respective reports for Chania (Kosmatopoulos et al., 2004); Southampton (Richards et al., 2004); and Munich (Mueck et al., 2004); as well as in the comparative evaluation report (Condie et al., 2004).

4.2. Evaluation for chania network

The final demonstration period for Chania comprised the four weeks of November 2003. The overall TTD (see (6)) figures were found to be similar for both systems under comparison, which indicates similar demand conditions. Fig. 5 displays the average %-difference (TUC vs. TASS) of the network mean speed MS estimated according to (7) over the times-of-day (8:00 a.m.–10:00 p.m.); Fig. 5(a) indicates that TUC outperforms TASS in region 1 for most of the day by up to 13%, the only hours where TASS appears to perform better being 5:00–9:00 p.m. but with only 6% maximum improvement by TASS. For the small region 2 (two junctions) there was no notable difference between both strategies for reasons that are detailed in (Kosmatopoulos et al., 2004). Fig. 6 displays two second-order polynomial curves (for TUC and TASS, respectively) that reflect the average MS vs. TTD behaviour of region 1; both curves were fitted to corresponding hourly (MS, TTD)-data and indicate a superiority of TUC over TASS.

Fig. 7 displays the average FCD journey time differences for region 1 (journey times for region 2 were similar for both strategies), for a number of times-of-week, whereby a total of 10 FCD journey times per strategy were available and the corresponding driven route covered virtually all region-1 links. All shown times-of-week are peak periods except for Wednesday evening when shops are closed. It may be seen from Fig. 7 that TUC outperforms TASS during the peak hours by 5–25%.

4.3. Evaluation for Southampton network

The final demonstration period for Southampton comprised the 4 weeks of November 2003. The local control infrastructure in Southampton delivers for each detector, in addition to flow and occupancy, also speed and ALOTPV, i.e. average loop occupancy time per vehicle. However, it should be noted that

- ALOTPV (which is essentially an inverse of the mean speed of vehicles passing the detector) may be positively biased in case of high occupancies due to the aforementioned masking effect of detectors.
- The detector speed is quite different than MS in (7), as it reflects the average vehicle speed around the link detectors, while MS is an estimation of the average vehicle speed in a network (part) including delays due to queuing and signalling.

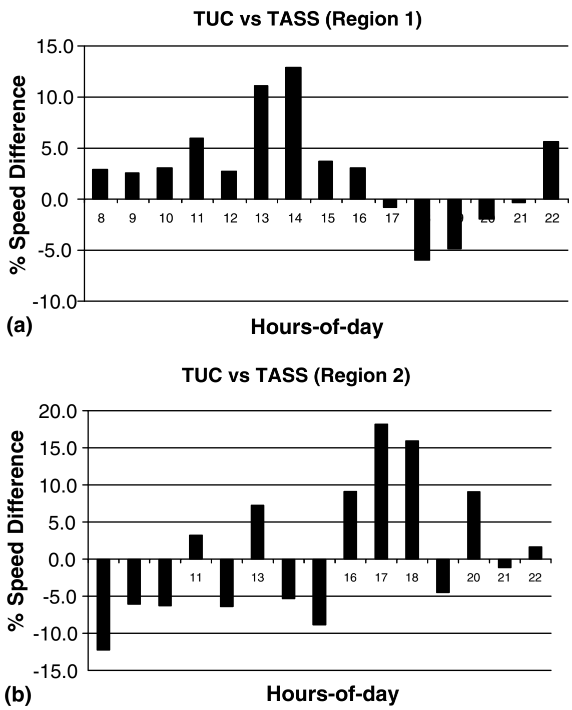

Fig. 5. %-difference (TUC vs. TASS) of MS in Chania (positive differences correspond to higher speeds for TUC): (a) region 1, (b) region 2.

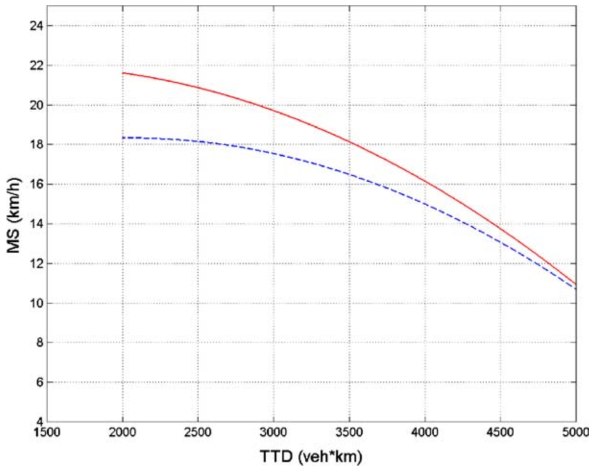

Fig. 6. TUC (continuous line) versus TASS (dashed line) MS-TTD behaviour in Chania region 1 (fitted curves).

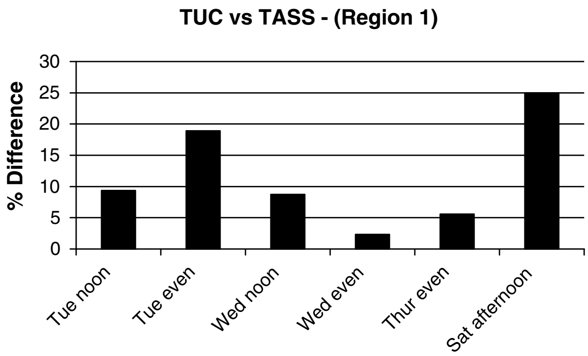

Fig. 7. %-difference in journey times based on FCD in Chania (region 1) (positive differences correspond to lower journey times for TUC).

Tables 1, 2 display the average speeds (factored by flow and link length) and ALOTPV over specific times-of-day for SCOOT and TUC for both network regions (city centre and Bitterne). The tables indicate that both systems perform at a similar level, with SCOOT's performance slightly better in the city-centre region and TUC's performance better in the Bitterne region. Note that the average speed increase of 18.4% achieved by TUC at Bitterne in the 8:00–9:00 a.m. period is partly due to the apparently harsh gating applied by SCOOT in link 54 during this time period as mentioned earlier.

Only two daily detector data-sets per strategy were available for Saturdays, and generally showed little difference between the performance of TUC and SCOOT. However, TUC was running on the Saturday morning of the televised Rugby World Cup Final, and traffic volumes in the city increased dramatically once the match

Table 1
Average speed and ALOTPV for Southampton city centre region

Time interval (h)	Speed (km/h)		ALOTPV	
	SCOOT	TUC	SCOOT	TUC
08:00–09:00	27.7	26.2	464	613
12:00–13:00	31.6	31.5	412	429
17:00–18:00	28.0	27.6	619	710
07:00–19:00	31.3	31.0	449	494
Sat:11:00–12:00	27.4	33.0	913	462

Table 2
Average speed and ALOTPV for Southampton Bitterne region

Time interval (h)	Speed (km/h)		ALOTPV	
	SCOOT	TUC	SCOOT	TUC
08:00–09:00	22.8	27.0	612	624
12:00–13:00	33.6	33.9	362	404
17:00–18:00	29.0	29.7	540	511
07:00–19:00	32.4	33.5	425	432
Sat:11:00–12:00	33.5	36.0	408	336

concluded. TUC coped remarkably well with this sudden surge of traffic: when TUC had to accommodate the very high volume of 530 veh/h (average flow per detector), the speed still stayed at 27 km/h, while under SCOOT the speed already dropped to this same level at the 26%-lower flow of 420 veh/h on the following Saturday.

FCD were collected in Southampton on two major routes, one in the city centre and one in Bitterne for three times-of-(working-)day (start times at 8:00 a.m. (morning peak); 12:30 p.m. (off-peak), for Bitterne only; 5:00 p.m. (evening peak); respectively), whereby 10 FCD samples were available per strategy and time-of-day. Regarding the major Bitterne route (which comprised 17 intermediate checkpoints, see Fig. 8), the 8:00 a.m. journey times were found 30% higher under SCOOT compared to TUC. Note that checkpoint 13 in Fig. 8 with journey time more than tripled under SCOOT compared to TUC, corresponds to link 54 that is gated under SCOOT. When factoring the journey times according to the average flow on each route section, the benefit under TUC reduces from 30% to 11%. Note, however, that flow factoring does not necessarily provide a more relevant picture of the network performance in this case because the SCOOT gating changes the flow patterns within the network considerably. FCD for the same route at 12:30 p.m. and 5:00 p.m. showed journey time improvements of 5% under TUC compared to SCOOT; when factored by the corresponding flows, the TUC benefit did not change for the noon period but increased to 10% for the p.m. peak period.

Regarding the city-centre route, FCD average journey times for 8:00 a.m. were found about 10% higher with TUC compared to SCOOT, mainly due to journey time increases at two (out of 14) checkpoints, while journey times at other checkpoints were similar for both strategies. The 5:00 p.m. average journey times in the city-centre route were about 19% higher for TUC compared to SCOOT mainly due to journey time increases at the same two checkpoints as in the 8:00 a.m. results. Both percentages did not change after factoring by the flow. Note that the considerable FCD journey time increase for TUC in the p.m. peak is not really reflected in the corresponding detector data of Table 1 and may therefore partially result from the specific subset of city-centre links that were included in the FCD route.

4.4. Evaluation for Munich network

The demonstration period for Munich comprised the four weeks of January 2004. The Munich demonstration was affected by a number of nuisances independent of the tested control strategies, most importantly by

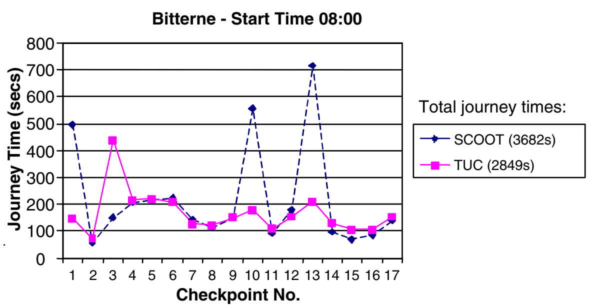

Fig. 8. Average FCD journey times on the major Bitterne route for weekday 8 a.m.

Table 3
Average occupancies and flows for the Munich demonstration

Time interval (h)	Occupancy (%)		Flow (veh/h)	
	BALANCE	TUC	BALANCE	TUC
07:45–08:45	20.6	21.2	768	794
07:00–10:00	20.5	20.7	765	788
10:30–13:30	18.7	17.8	706	703
16:00–19:00	23.9	24.6	884	907
08:00–19:00	20.8	21.0	788	801

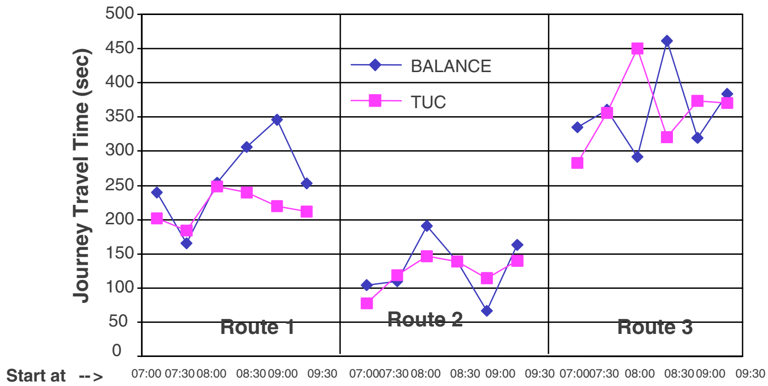

Fig. 9. Average FCD journey times for three routes and various start times in Munich.

frequent faults of the communication lines and local controllers; in addition, the override of the strategy decisions by the local public transport priority logic and the extreme weather conditions (snow storms) on a few days, mentioned earlier, reduced the amount and reliability of available data; hence the Munich results should be viewed with some degree of caution.

Table 3 shows the averages of flow and occupancy measurements for various times-of-day for both tested strategies, TUC and BALANCE. The summarized results reflect little performance differences between both strategies. TUC's average occupancy seems 1% higher (around 3% in the a.m. and p.m. peak hours) but with higher flows, i.e. 2% in average and around 3% in the a.m. and p.m. peak hours.

FCD were collected in Munich on three routes covering the whole network with exception of the side links. Each route was driven at 6 distinct start times (7:00, 7:30, 8:00, 8:30, 9:00, 9:30, all a.m.), five times per strategy; this results in 30 FCD journey times per strategy and route. However, due to technical problems mentioned earlier, 74% of these data had to be excluded from the evaluation. Fig. 9 displays the average journey times for each route, start time and strategy. It may be seen that major differences occurred only on route 1 (which is the most loaded one during the a.m. peak as it leads to the city centre) for the trips starting at 8:30, 9:00 and 9:30 a.m. The average journey times were found lower for TUC than for BALANCE by an average of 15.4% on the most loaded route 1, by 6.3% for route 2 and by 2% for route 3.

5. Conclusions

The recently developed network-wide real-time signal control strategy TUC was successfully implemented and tested in three urban road networks in three European countries. The demonstrations proved that TUC is a robust and credible signal control strategy, both as a stand-alone system, as in Chania and Southampton, and as a hybrid system. Despite its limited fine-tuning, TUC stood up very well against the well-established and well-fine-tuned resident systems of the test networks, which have very different characteristics with regard to network layout, detector locations within the links and traffic behaviour.

Overall, user acceptance of TUC was very high. The operators reported that TUC is an excellent strategy that, with careful fine-tuning, can show a very efficient performance and they all felt that TUC had performed remarkably well compared with much more established and well fine-tuned systems. The implementation of TUC was very straightforward in all sites, with the main effort involved being in the development of the interface between TUC and the existing control infrastructure.

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