COMBINING THE TUC URBAN TRAFFIC CONTROL STRATEGY WITH BANDWIDTH MAXIMISATION

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Abstract: The offset control module of the TUC strategy for urban traffic control strategy is replaced by a bandwidth maximisation module. Bandwidth maximisation is performed online based on split and cycle changes. Simulations of a five junction arterial were carried out with results indicating that performance is comparable to optimally adjusted fixed-time plans. *Copyright©2006 IFAC*

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1. INTRODUCTION

Traffic signaling of junctions in urban networks is indispensable as a tool for management of conflicts, safety, and fluidity of the traffic. Very often, it is desirable to perform signal coordination between adjacent junctions. Two classes of coordination methods can be distinguished. In the first one, the focus is on coordination of traffic signals without explicitly considering traffic phenomena such as dispersion. The works of Morgan and Little (1964) and Little (1966) in arterial bandwith maximisation methods rank as the best known in this class. Generalisation of these to include multiphase optimisation, coordination of triangular networks, among other improvements gave rise to MAXBAND (Little *et al.*, 1981). MULTIBAND (Gartner *et al.*, 1990) is similar to MAXBAND, but capable of adapting to specific flow patterns by assigning weights to each road section, thus generating a variable bandwidth.

The second class of coordination methods uses traffic models and optimisation algorithms to coordinate traffic signals through the optimisation of criteria such as number of stops and vehicle delay. TRANSYT (Crabtree *et al.*, 1996) is perhaps the best known method in this class. The nature of the second class of methods, where the optimisation takes into account flow phenomena not considered in the first class, in general does not produce maximum bandwidths for arterials.

The above methods are designed for fixed time operation. In order to enable online response to flow variations, in the 80s and 90s several online urban traffic control systems were developed. Systems based on split, cycle, and offset concepts, known as cyclic systems, include SCOOT (Robertson and Bretherton, 1991), SCATS (Lowrie, 1982), and TUC (Diakaki *et al.*, 2003).

Another approach, based on dynamic traffic models and optimisation strategies with rolling horizon, or acyclic systems, led to systems as PRODYN (Farges *et al.*, 1990), OPAC (Gartner, 1983),

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and RHODES (Head *et al.*, 1998). Acyclic systems are computationally complex, and therefore have a local, decentralised operation.

All online systems include mechanisms for obtaining signal coordination, either explicitly or implicitly. However, although widely used in fixed time systems, bandwith maximisation has not been implemented in online traffic control systems.

In the literature, Jovanis and Gregor (1986) developed a method for coordination of actuated arterial traffic signal systems, but their approach differs from the one presented in this paper since their actuation is limited to split variations based on local measurements. The RHODES system applies a coordination strategy called REALBAND (Dell'Olmo and Mirchandi, 1995). Although seeking for bands based on platoon lengths, REALBAND is not a bandwidth maximisation method. The resulting band is achieved by an optimisation procedure that optimises a performance criterion after propagating predicted platoons by means of a traffic model for a given time horizon.

The online traffic control strategy used in this paper is the Traffic-responsive Urban Control - TUC (Diakaki *et al.*, 2003), which implements split, cycle and offset control. In field experiments, TUC performance is comparable to other control strategies as, for example, SCOOT (Bielefeldt *et al.*, 2001). TUC has not been especially designed for two-way arterial signal coordination. Hence, the use of a bandwidth maximisation method for offset calculation in TUC is proposed.

2. BACKGROUND METHODS

Due to its modularity, TUC strategy lends itself to integration with any offset calculation technique. In this paper, the offset is calculated using the algorithm provided in Morgan and Little (1964) (hereafter refered to as ML method). Other methods have been considered, but not used because they offer no advantages in this context. MAXBAND, for example, can design speeds and cycle times, whereas TUC assumes pre-defined speeds and its cycle control module is going to be used. Multiphase optimisation and queue clearance time are left to future research. Next, both the maximisation method and TUC are described, drawing from (Morgan and Little, 1964) and (Diakaki *et al.*, 2003), respectively.

2.1 Bandwidth Maximisation Method

Morgan and Little (1964) consider a procedure for determining offsets for equal maximal bandwidths in each direction, given common cycle time, green splits, and speeds and distances between adjacent signals. The method allows to stipulate different design speeds between adjacent signals, in both directions, and to adjust each directional bandwidth on the basis of platoon length.

2.1.1. Basic Concepts. Consider a two way arterial with n traffic signals. Directions on the arterial are denoted as outbound and inbound. The signals are denoted S_1, S_2, ..., S_n, with the index increasing in the outbound direction as shown in Fig. 1. Let:

C be the cycle time of the signals (s);
r_i be the red time at signal S_i (cycles);
b ($\bar{b}$) be the outbound (inbound) bandwidth (cycles);
t_{ij} ($\bar{t}_{ij}$) be the travel time from S_i to S_j in the outbound (inbound) direction (cycles);
θ_{ij} be the relative offset of S_i and S_j, measured as time from center of a red of S_i to next center of red of S_j (cycles); by convention $0 \leq \theta_{ij} \leq 1$;
x_i be the position of S_i on the street (m);
v_i ($\bar{v}_i$) be the outbound (inbound) speed between S_i and S_{i+1} (m/s); and
$\delta_{ij} \in \{0, \frac{1}{2}\}$.

Time quantities can be expressed in cycles by dividing by C. A set θ_{ij}, $j = 1, \ldots, n$ for any i is called a synchronisation of the signals. Travel times between adjacent signals are presumed known and fixed.

A signal is said to be critical if one side of S_j's red touches the green band in one direction and the other side touches de green band in the other direction. Critical signals are divided into two groups. Group 1 has the signals whose reds touch the front of the outbound band and the rear of the inbound band. Group 2 signals touch the opposite directions. A signal can be in both groups. In Fig. 1, signals S_1 (Group 2) and S_i (Group 1) are critical. The front and the rear of the band are identified by f and r, while changes in slope means changes in the design speed.

Maximal bandwidth is achieved when offsets are on half-integer synchronisation. Offsets are on half-integer synchronisation if

$$\theta_{ij} = man\left[\frac{1}{2}(t_{ij} + \bar{t}_{ij}) + \delta_{ij}\right] \qquad (1)$$

where $man(x) = x - \lfloor x \rfloor$. The operational meaning is easier to understand when the speeds are the same in each direction, $t_{ij} = -\bar{t}_{ij}$, then $\theta_{ij} = \delta_{ij} \in \{0, \frac{1}{2}\}$, and two signals in the same group will have their reds exactly in phase or out of phase.

2.1.2. Synchronisation for Maximal Equal Bandwidths. Through the development of theorems,

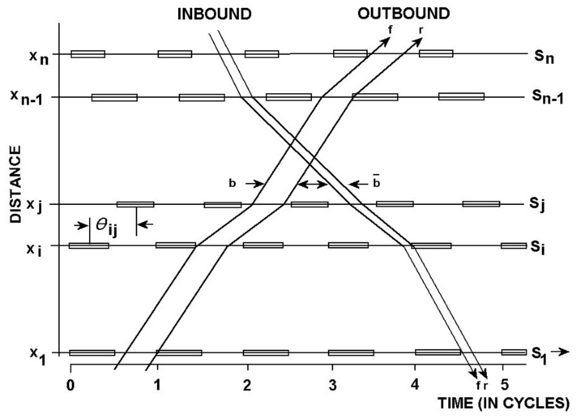

Fig. 1. Space-time diagram for an arterial (Morgan and Little, 1964).

Morgan and Little show that it suffices to examine cases with half-integer synchronisation and only in the outbound direction. The maximal equal bandwidth is $\max(0, B)$,

$$B = \max_{i} \min_{j} \max_{\delta \in \{0, \frac{1}{2}\}} [u_{ij}(\delta) - r_j]$$

where B is the value of the bandwidths and

$$u_{ij} = 1 - man\left[-\theta_{ij} - \frac{r_j}{2} + \frac{r_i}{2} + t_{ij}\right]$$

is the time that the trajectory that touches the red side of S_j passes S_i, assuming that the right side of S_i's red as the origin of measurements. A maximising $i = c$ has corresponding maximising δ's, $\delta_{c1}, \ldots, \delta_{cn}$ that substituting in Eq. 1 yields the maximal equal bandwidths synchronisation set $\theta_{c1}, \ldots, \theta_{c2}$.

2.1.3. Synchronisation for Maximal Unequal Bandwidths. After calculating equal bandwidths, the total band can be split, if feasible, between directions on the basis of platoon lengths. When the length of platoons exceeds the band in a direction and not in the other, or when it is desired to place bandwidth to residual queues, deriving from secondary ways, the band can be shifted so that both platoons pass unimpeded.

2.2 Traffic-responsive Urban Control - TUC

TUC (Diakaki *et al.*, 2003) is a traffic signal control strategy based on methods of the automatic control theory. TUC consists of four modules which perform split control, cycle control, offset control, and public transport priority. The latter is not applied in this study and will not be covered.

2.2.1. Split Control. TUC formulates split control as a Linear Quadratic Regulator (LQR) optimal control problem based on a store-and-forward type of mathematical model. The control seeks to minimise the risk of oversaturation and the spill-back of link queues at all network junctions. Green times vary about some nominal values without affecting either the offsets or the cycle times. The resulting multivariable control law is:

$$\mathbf{g}(k) = \mathbf{g^N} - \mathbf{L} \cdot \mathbf{x}(k) \qquad (2)$$

where k is the discrete-time index for each cycle, $\mathbf{g}$ is the vector of the green times for all stages of all junctions, $\mathbf{g^N}$ is the vector of their nominal values, $\mathbf{L}$ is the control matrix, and $\mathbf{x}$ is the vector of numbers of vehicles x_z within the network links z that approach the considered controlled junctions. The control matrix $\mathbf{L}$, calculated offline using the LQ methodology, reflects the specific network characteristics. It is applied online with Eq. 2. Constraining the obtained $\mathbf{g}$ to admissible green times is done by applying a computationally low-cost algorithm.

2.2.2. Cycle Control. TUC employs a common cycle time for the whole network in order to enable coordination via suitable offsets. As usual, cycle control acts to limit the maximum observed saturation level in the network. TUC applies a proportional-type feedback algorithm that uses the current maximum saturation level of a pre-specified percentage of the network links as a criterion for the cycle setting. The cycle control algorithm comprises three steps:

(1) a pre-specified percentage p of network links with currently maximum load $\sigma_z(k) = x_z/x_z^{max}$ is identified and the corresponding loads are averaged to provide the average maximum load $\sigma(k)$;
(2) the network cycle is calculated from the feedback control law (proportional controller)

$$C(k) = C^N + K^C(\sigma(k) - \sigma^N) \qquad (3)$$

where C^N is the nominal network cycle time; σ^N is a nominal average load; and K^C is a control parameter. After the application of Eq. 3, the calculated cycle time is constrained within the range of permissible cycle times $[C_{min}, C_{max}]$, if necessary;
(3) if the resulting network cycle $C(k)$ is sufficiently high while all links approaching specific junctions have sufficiently low saturation levels, i.e. their current load $\sigma_z(k)$ is less than a pre-specified threshold σ_t, then these undersaturated junctions are double-cycled.

2.2.3. Offset Control. The offset control in TUC is based on the following assumptions:

- offset is initially specified along one-directional arterials that do not intersect. Arterials are defined here as an arbitrary sequence of links

that do not need to correspond to physical network arterials;
- in case of two-directional arterials, an offset is specified for each direction and the offset that will be finally implemented is a weighted sum of the offsets of the two directions. Alternatively, the most loaded direction may be selected in real time to determine the arterial offsets (auto-offset);
- in case of arterials that do intersect, TUC considers a pre-specified priority order of the arterials according to their relative importance regarding offset specification, and offset control is implemented to each arterial sequentially starting from the arterial that has the highest priority.

TUC performs offset control in a decentralised way, i.e., for sucessive pairs of junctions along the pre-defined offset arterials. For each pair of junctions, the offset specification changes the starting time of a specific "main" stage of the upstream junction whereby this main stage is uniquely determined from the arterial composition. TUC considers the possible existence of vehicle queues while specifying the offset between two successive junctions through the application of a decentralised feedback control law:

$$t_{j_1,j_2}(k) = \frac{l_z}{v_z} - l_z K_z^o \frac{x_z(k)}{x_z^{max}} \quad (4)$$

where j_1 is the upstream junction, j_2 is the downstream junction, l_z is the link length, v_z is the link free flow mean speed, and K_z^o is a control parameter equal to $(v^c - v_z)/(v^c v_z)$, with v^c the speed of a kinematic wave generated due to green light switching at the downstream junction j_2. A second offset in the opposite direction (j_2 to j_1) is also specified using Eq. 4. The offset $t_{1,2}$ between the two junctions is then calculated as follows:

$$t_{1,2}(k) = W_{j_1,j_2} t_{j_1,j_2}(k) + W_{j_2,j_1} t_{j_2,j_1}(k) \quad (5)$$

where $W_{j_1,j_2} + W_{j_2,j_1} = 1$, are the weights, according to which the offset of each direction will contribute to the final offset between two junctions. To implement the new offset specified in Eq. 5, a transient cycle time is temporarily implemented in junction j_2.

3. PROPOSED APPROACH

Applying ML method with TUC strategy for online control brings up three main problems:

i) offset changes of half cycle;
ii) band sensitivity to split changes; and
iii) band sensitivity to cycle changes.

Problem (i) appears because bandwidth optimality implies centering of red signals. Junctions that

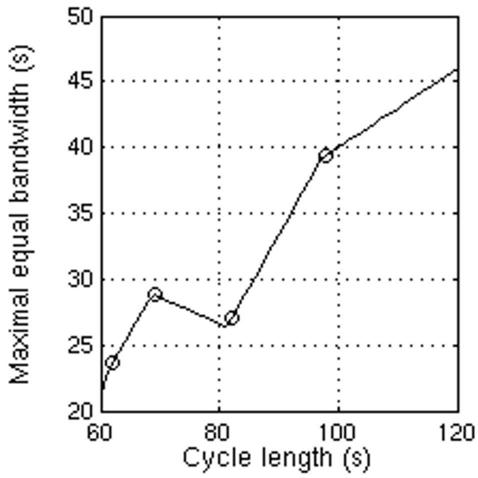

Fig. 2. Bandwidth as a function of cycle time.

have their offset changed should be shifted for half a cycle to adjust to the new synchronisation set. A transition plan would be needed, but that has been neglected at this time. Thus, in the experiments that will follow, offset changes may infringe minimum green requirements for phases that have their splits smaller than twice the minimum green.

Problem (ii) is avoided here due to a suitable choice of traffic flows so that splits are almost constant in the simulation experiments. In this way, only the effect of cycle changes is studied.

To understand problem (iii), Fig. 2 shows what happens when splits are fixed and bandwidths are calculated according to cycle time variation in the 60 s to 120 s range. Circles indicate when the synchronisation set changes in response to cycle variation. As can be seen (e.g., around the 82 s cycle), a small change in cycle time implies a sudden change in the synchronisation set. The implication of problem (iii) is that offsets must be recalculated every time TUC calculates a new cycle time. TUC cycle control is evaluated every n seconds, and offset control is then applied every kn seconds, with $k = 1, 2, \ldots$ being a design parameter. In this work, k must equal 1 to preserve maximal bandwidth.

4. EXPERIMENTS

Simulations to evaluate the proposed approach were carried out using the Sitra (SODIT, 2002) traffic micro-simulator.

4.1 Simulated Network

The simulation site comprises five signaled junctions in a two kilometer long arterial. Distance between junctions range from 300 to 400 m. There are three lanes in the E-W direction and six lanes in the W-E direction. Secondary links have two

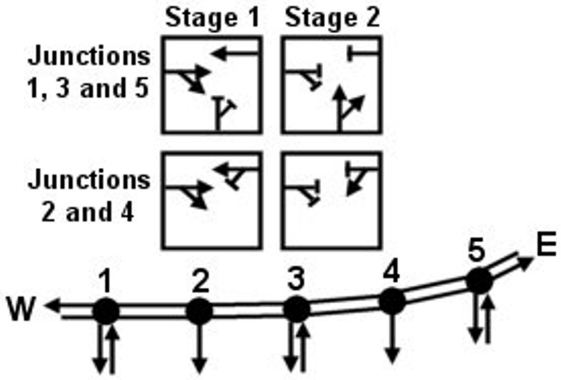

Fig. 3. Simulated arterial network.

lanes each. The saturation flow in each lane is 1800 veh/h. Turning rates were established in such a way that flows arriving at each junction are almost the same. Fig. 3 depicts the simulated arterial network and also the junction stages.

4.2 Simulation Setup

Three simulations of 75 minutes duration were carried out, each one with a different control strategy. Table 1 summarises simulation flow input.

Table 1. Traffic flow pattern (veh/h).

Time (min.)	0-40	40-45	45-50	50-55	55-75
Arterial W-E	5696	6036	6276	6716	7056
Arterial E-W	2848	3018	3188	3358	3528
Secondary	502	532	562	592	622

Two fixed time plans obtained using Webster's (1969) and ML's methods were applied in the first simulation. The plans were switched after 50 minutes. The TUC strategy with split, cycle and offset control was applied in the second simulation. Finally, the third simulation applied the TUC-ML strategy obtained by replacing TUC's offset control module with the ML method.

4.3 Simulation results

Network results (Tables 2, 3, and 4) show that TUC strategy performs better than fixed time. TUC-ML on the other hand has a worse perfomance than fixed time. TUC-ML has less stop times than fixed time at the 20-40 and 40-55 time slices. But it has no improvements when compared to TUC strategy.

It must be pointed out that very little tuning of the TUC and TUC-ML parameters was done. Then, it is expected that better results can be achieved with fine tuning of these strategies. Both operate with low cycle times (88 s and 90 s, respectively) compared to Webster's optimal cycle (115 s) during the 55-75 min time slice. This can be observed at 55-75 time slice, where the difference in performance between TUC strategy and fixed time reduces, contrary to the expected worse performance of bandwith progression systems with greater traffic volumes (Little *et al.*, 1981). The same can be observed in the arterial results that follow. Still, TUC has a good performance while compared to an optimally adjusted fixed time strategy.

Table 2. Fixed time network results.

Time (min.)	20-40	40-55	55-75
Average speed (km/h)	36.90	34.25	26.59
Number of stops	5684	10402	24096
Stop time (h)	8.18	11.28	31.17

Table 3. TUC network results.

Time (min.)	20-40	40-55	55-75
Average speed (km/h)	39.15	35.28	27.12
Number of stops	4151	6177	24344
Stop time (h)	8.67	8.15	29.23

Table 4. TUC-ML network results.

Time (min.)	20-40	40-55	55-75
Average speed (km/h)	36.71	31.70	24.91
Number of stops	5211	8602	27068
Stop time (h)	8.99	12.37	39.26

When analysing arterial results per vehicle (Tables 5, 6, and 7) TUC once again improves the fixed-time performance. In the E-W direction TUC stop time is greater than fixed time at 20-40 time slice, with a larger number of stops at 55-75 time slice. TUC-ML was expected to have better arterial results than TUC and fixed time due to the application of a progression method. This happens only in the E-W direction. In the W-E direction TUC outperforms TUC-ML and fixed time. Fixed-time performs slightly better than TUC-ML in this direction, with the same number of stops at the 20-40 time slice.

Table 5. Fixed time arterial results.

Direction	Time (min.)	20-40	40-55	55-75
W-E	Av. speed (km/h)	39.72	24.56	31.37
	Number of stops	1.82	4.12	5.41
	Stop time (s)	6.24	13.03	21.04
E-W	Av. speed (km/h)	39.41	30.07	27.59
	Number of stops	2.36	6.31	10.84
	Stop time (s)	10.26	24.22	28.97

Table 6. TUC arterial results.

Direction	Time (min.)	20-40	40-55	55-75
W-E	Av. speed (km/h)	43.42	37.94	32.44
	Number of stops	0.83	2.64	5.85
	Stop time (s)	3.54	6.92	14.05
E-W	Av. speed (km/h)	40.07	35.75	28.58
	Number of stops	2.07	3.57	10.28
	Stop time(s)	13.16	20.14	28.93

The unbalanced results in the two directions reflect the differences in traffic behaviour in each direction. Although not shown in the paper, the aggregation of performance indices shows that

Table 7. TUC-ML arterial results.

Direction	Time (min.)	20-40	40-55	55-75
W-E	Av. speed (km/h)	38.53	33.81	29.63
	Number of stops	1.82	4.67	7.35
	Stop time (s)	7.77	12.31	21.98
E-W	Av. speed (km/h)	41.67	35.73	29.89
	Number of stops	1.59	3.40	8.52
	Stop time (s)	9.21	19.50	24.50

TUC has a better arterial performance. TUC-ML results are very close to fixed time with a smaller number of stops at 20-40 and 40-55 time slices, and smaller time stopped at 40-55 and 55-75 time slices. During the transition time slice (40-55) TUC-ML performs better than fixed time.

A total of three cycle changes occurred during TUC-ML simulation resulting in two synchronisation setting changes, with as much as seven violations of minimum green requirements, and a cycle excursion from 68 s to 90 s.

5. CONCLUSIONS AND FUTURE WORK

The combination of Morgan and Little (1964) method for synchronising traffic signals for maximal bandwidth and the control strategy TUC (Diakaki *et al.*, 2003) was presented. Results have shown that further research is necessary to asses ML method in real time instead of the TUC offset control module, since progression with the TUC-ML approach is not as expected. Moreover, further experiments shall be conducted to check whether fine tuning of the TUC controller parameters and adjustments in the online ML method can improve performance of these methods. So far, simulation results indicate that the best performance is achieved by TUC with its original offset calculation method.

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