MODELS FOR ADAPTIVE URBAN TRAFFIC CONTROL

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CONTEXT

Changing public awareness with respect to the impacts of car traffic in combination with the increasing traffic demand has caused a new orientation of transport and traffic policies in metropolitan areas. In order to minimise negative impacts of car traffic as pollutant emissions and in order to preserve mobility in a sustainable way most cities start implementing strategies to reduce car traffic while improving public transport at the same time. Due to this focus traffic control aims to favour public transport e.g. at signalised intersections. However, many of those particular measures do not really cope with the overall policy since these measures neither respect impacts they cause in the network context nor are they able to balance the needs of different user groups according to an agreed common objective.

To overcome this unsatisfactory situation a number of traffic adaptive network control methods were developed in the United States and in particular in Europe and are getting more and more implemented in complex urban road networks (see Bibliography).

This paper gives an overview to the methodology of the traffic adaptive signal control method BALANCE and focuses on some particular innovative traffic and control models that are involved. In order to allow for an assessments of possible benefits of adaptive control methods some results of field studies are presented at the end.

METHODOLOGICAL APPROACH

The development of new network control methods needs to be oriented on current requirements to flexibility and compatibility. These are in particular

- **Modularity** – each system component operates even without central hard- and software and the architecture of the system allows for compatible use with different other components (e.g. with components of the existing legacy system)

- **Robustness** - the consequences of failure by different parts of the system can be analysed and protection can be provided to ensure continued operation;
• **Evolutionarity** – control systems can be extended independently from the original configuration;

• **Interoperability** – a higher performance can be achieved by mutual information as the parts of the system communicate through standard interfaces so that they can be enhanced and upgraded without affecting the operation of other parts;

• **Integration** – the common strategic approach is guaranteed by the distributed hierarchical system architecture;

The system architecture of BALANCE takes these issues into consideration by its distributed but hierarchically structured design (see Figure 1).

![Figure 1: Basic BALANCE Structure](image)

At the local level MicroBALANCE reacts in a second by second mode to stochastic variations and sudden calls for public transport (pt) priority or other events. It therefore applies a simple microscopic traffic model and uses rolling horizon technique to forecast vehicle arrivals. Both private car traffic and public transport vehicles are represented by this model in an integrated way, hence impacts of pt priority to the overall traffic situation are directly represented. OD estimation at the intersection level uses traffic flow pattern and time dependency to determine
the respective movements. Optimisation takes place within a given frame that constrains the local control due to the requirements for an optimal network-wide traffic situation.

At the tactical level MacroBALANCE optimises network related control variables. In a reference plan for each single local controller network cycle time, offsets and split for different stage sequences are determined. MacroBALANCE uses a heuristic approach and decomposes the optimisation problem into several subproblems that can be easily solved by linear optimisation. For the determination of the relevant criteria of the objective function OD flows are estimated using the information on movements at the intersection and applying a macroscopic queuing model. Evaluations showed that Markovian chain technique using empirically gathered arrival and service distributions performs best.

Due to this architecture BALANCE can be applied at a single junction and can be extended to a complete urban network. The system can be modified without disruption or redundancy of existing components - this provides an evolutionary approach.

The needs of network operators to configure the control and to modify it due to the dynamic aspect of traffic are satisfied by an easy to understand graphical user interface. Changes in the control strategy can be tested and the effects can be visualised offline by connecting BALANCE to the microscopic simulation AIMSUN2.

**OBJECTIVE FUNCTION AND NORMALISED PERFORMANCE INDEX**

Adaptive control methods offer the user a comprehensive way of influencing traffic control according to the respective policies. Therefore the objective function according to which the control is optimised needs to be accessible for the users. BALANCE provides an open interface to the objective function that allows to optimise due to strategic issues. Consequently the optimisation objective is called strategic system optimum and the formulae given below show the general approach for its realisation.

**System Optimum**

\[
\min \quad PI = \sum_{signal\ groups} c_i \cdot q_i = \sum_{signal\ groups} C_i
\]

where \( PI \) Performance Index \( c_i \) general average costs \( q_i \) traffic volume

**Strategic System Optimum**

\[
\min \quad PI = \sum_{signal\ group\ i} \sum_{link\ set\ j} \alpha_{ij} \cdot C_{ij}
\]

where \( \alpha_{ij} \) matrix of coincidence of link sets \( C_{ij} \) over signal groups \( i \)

\[
\alpha_{ij} = \begin{cases} > 0 \quad \forall i \in j \\ = 0 \quad \forall i \notin j \end{cases}
\]

The application of the ‘strategic system optimum’ is shown in Figure 2. In this example different link sets (I-V) are given that may be controlled according to arbitrary weights.
Since all of the considered criteria that are used in the objective function are calculated by an unique traffic model it is possible to normalise the PI at the beginning of each optimisation in order to

- be independent of absolute values of the different criteria
- guarantee stable influence of weights

Figure 3 explains the approach for the calculation of a normalised PI.

\[
\text{if (opt\_step == 0)}
\]
\[
\text{/* calculate and store reference values per criterion */}
\]
\[
\text{for all criteria k}
\]
\[
\text{\{} \text{reference\_value}_k = \sum_{i} \sum_{j} \alpha_{ij} \cdot c_{ij}^k \text{ \}}
\]
\[
\text{\}}
\]
\[
\text{/* calculate PI for the n^{th} optimisation step */}
\]
\[
P_l^n = \sum_k \sum_{i,j} \frac{\alpha_{ij} \cdot c_{ij}^k}{\text{reference\_value}_k} \quad (\Rightarrow P_l^0 = k)
\]

**Figure 3:** Algorithm for the determination of normalised PI's
**MICROSCOPIC TRAFFIC MODEL**

As mentioned above MicroBALANCE uses a simple microscopic traffic model with discrete time steps of one second. In the model each approach of the respective intersection is considered separately by a link representing traffic between the location of data collection and the stop line. On this link vehicles are travelling at constant average speed, stop at the end of the horizontal queue and are discharged according to a constant saturation flow rate. If a movement has to obey priority of another stream (e.g. a left turning movement needs to wait for an opposite stream) it waits till the priority movement is discharged. For the considered horizon of one cycle time vehicle arrivals are measured for the travel time between data collection and queue end. For the rest of the cycle rolling horizon technique is used (see Figure 4).

![Microscopic traffic model of BALANCE](image)

**Figure 4**: Microscopic traffic model of BALANCE

Public transport vehicles are represented together with car traffic. According to the methodology that is shown in Figure 5 the position in queue of the pt-vehicles is calculated every second. In parallel the PI is determined from the unique objective function. Thus the mutual impact of priority schemes on public transport as well as on car traffic can be explicitly assessed and be considered in the optimisation in an integrated way. For this reason the user can directly compare the relative weights of pt and car traffic in the objective function and a direct influence on the performance of pt is possible.
MACROSCOPIC TRAFFIC MODEL

It could be shown that on MacroBALANCE level queue length calculation by Markov chain performed best. Considering the interval \( dt \) between \( t_n \) and \( t_{n+1} \), one can determine probabilities for the number of vehicles \( i \) (\( i = 1, 2, ... \)) in the queue at the time \( t_n \) by the vector

\[
p^n = (p_0^n, p_1^n, p_2^n, ...)
\]

and the probabilities for the number of vehicles \( i \) at the time \( t_{n+1} \) by the vector

\[
p^{n+1} = (p_0^{n+1}, p_1^{n+1}, p_2^{n+1}, ...)
\]

The probabilities for changing from state \( i \) at time \( t_n \) to state \( j \) at time \( t_{n+1} \) are given by the transition matrix \( T(dt) \):

\[
T(dt) =
\begin{bmatrix}
p_{00} & \cdots & p_{0N} \\
\vdots & \ddots & \vdots \\
\vdots & \ddots & \vdots \\
p_{N0} & \cdots & p_{NN}
\end{bmatrix}
\]

Starting by a situation that is determined by vector \( p_0 \) and under application of the transition probabilities \( T(dt) \) the state probabilities at time \( t_{n+1} \) can be consequentially calculated with

\[
p^{n+1} = p^n \cdot T(dt).
\]
Since transition probabilities change over time because of instationary demand $T$ varies and $T= T(dt,t)$. $T(dt,t)$ can be determined by

$$T(dt,t) = A(t) \cdot S(t) \quad \text{with: } A(t): \text{matrix of arrival probabilities}$$

$$S(t): \text{matrix service probabilities}$$

The matrices of arrival and service probabilities have the following form:

$$A(t) = \begin{bmatrix}
    a_0 & a_1 & a_2 & \ldots & a_N \\
    0 & a_0 & a_1 & \ldots & a_{N-1} \\
    0 & 0 & a_0 & \ldots & a_{N-2} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    0 & \ldots & \ldots & \ldots & a_0 \\
  \end{bmatrix}$$

$$S(t) = \begin{bmatrix}
    1 & 0 & 0 & \ldots & 0 \\
    1-s_0 & s_0 & 0 & \ldots & 0 \\
    1-s_0-s_1 & s_1 & s_0 & \ldots & 0 \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    \vdots & \vdots & \vdots & \ldots & \vdots \\
  \end{bmatrix}$$

The probabilities $[a_i]$ and $[s_i]$ can now be formed by the results of analytical probability distributions or they can be built from measured values that are online gathered by the control method. Tests showed a good coefficient of determination $r^2$ of 0.82.

Different to the optimisation of cycle time and split a simple platoon model is used for offset optimisation. The basic idea of the model corresponds to the concept of SCOOT: The impacts of the offset at the considered intersection are calculated for a so-called Mini Area which also comprises the adjacent junctions. Different to SCOOT queue lengths and delays are not determined on the basis of measurements (i.e. the cyclic flow profiles) but by the help of model based approach. Apart from the reduction of data communication this approach provides the advantage that no local component (MicroBALANCE) is required. This complies with the requirement of modularity and in particular for larger networks with heterogeneous components (legacy as well as new adaptive) offset optimisation can be performed. The simple approach allows for online operation also for large networks. Caused by the mutual impact as a consequence of sequential optimisation of the intersections an algorithm has been developed that uses the knowledge on the OD-streams and thus provides a systematic adaptation of offsets according to the relevance of the respective intersections.

**CONTROL MODEL**

The control model of BALANCE uses a cyclic approach since this is the best solution with respect to the above mentioned requirement of modularity. I.e. a cyclic control model allows for being easily co-ordinated to intersections controlled by legacy systems like fixed time or vehicle actuated control. Apart from this the cyclic model offers the engineer to constrain the control arbitrarily according to his needs. In this sense BALANCE provides different means to customise control by following constraints:

- minimal and maximal or fixed cycle time
- minimal and maximal or fixed split per stage assigned by MacroBALANCE
• minimal and maximal or fixed buffer time per stage assigned by MicroBALANCE
• fixed offset for one stage, even by changing cycle time and changing stage sequences
• stage on demand (in particular for pt priority).

In this way BALANCE control can be constrained to fixed time control but also interesting combinations may be realised like fixed time control with public transport priority as it is favoured in Leeds [HALLWORTH ET AL., 2000].

However, if full demand responsiveness and therefore full flexibility of control is desired BALANCE will behave acyclically because of the full variability of the following variables:
- cycle time, offset, and split (minimum optimisation cycle is one cycle time)
- buffer times and stage sequences (optimised each second)

Using a cyclic control method for controlling a network, a common cycle time or a multiple of it is appropriate for the local traffic forecast and for the co-ordination of neighbouring junctions. Therefore the control model in BALANCE is using a common cycle time that is calculated due to the traffic conditions at the critical junction. The decisive junction is determined by impact criteria that result from the calculation of the optimised green periods for the single signal groups. Apart from the total delay $W_{node}$ at the junction as a criterion, the average individual delay $w_{node}$ over the optimisation period is used as well. These delays can be weighted by the factors $\delta, \gamma$.

The decisive or critical junction is the junction whose performance index

$$PI_{CycleTime} = \delta \cdot W_{node} + \gamma \cdot w_{node}$$  \hspace{1cm} (9)

is maximal.

This criterion includes the conditions in the whole network

$$W_{node} = \sum_i \sum_j \alpha_{ij} \cdot W_{ij}^{PT} + \beta_{ij} \cdot W_{ij}^{CT}$$  \hspace{1cm} (10)

with $i, j$ index of signal groups resp. sets of sections
$\alpha_{ij}, \beta_{ij}$ weight factors used in the objective function of the optimisation
$PT, CT$ public transport, car traffic

as the number of vehicles in the network is implicitly included as well as the degree of impact of the considered single road users based on the average individual delay

$$w_{node} = \left(\sum_i \sum_j \alpha_{ij} \cdot w_{ij}^{PT} + \beta_{ij} \cdot w_{ij}^{CT}\right) \cdot \frac{1}{t}.$$  \hspace{1cm} (11)

By including the average delay optimisation takes care of those road users at smaller junctions (with less numbers of lanes per entry section) if there is a higher delay.
For the decisive junction cycle time will be optimised taking into account the constraints of the defined green period proportions and using a macroscopic impact model. The objective function in that case is focused on the maximisation of the capacity which is equal to the minimisation of the delay:

\[
\min_{t_{\text{cy}}(t_{\text{cyc}})} = \sum \sum \alpha_{ij} \cdot W_{ij}^{\text{CT}}(t_{\text{cyc}})
\]

with \( t_{\text{cyc}} \) cycle time; \( t_{\text{cyc}}^{\text{min}} \leq t_{\text{cyc}} \leq t_{\text{cyc}}^{\text{max}} \)

By the approach of maximising capacity for car traffic it is assumed that public transport vehicles that don’t have a segregated lane will profit from the optimisation in the same way as car traffic.

Having calculated cycle time MacroBALANCE optimises the split. By the minimisation of a linear combination of the total and average delay \( W_{\text{CT}} \) and \( w_{\text{CT}} \) respectively:

\[
\min_{t_{\text{g}}(t_{\text{g}})} = \sum \sum \alpha_{ij} \cdot W_{ij}^{\text{CT}}(t_{\text{g}}) + \beta_{ij} \cdot w_{ij}^{\text{CT}}(t_{\text{g}}),
\]

with \( t_{\text{g}} \) green time of phase \( i \), \( t_{\text{g}}^{\text{min}} \leq t_{\text{g}} \leq t_{\text{g}}^{\text{max}} \)

The results of the optimisation form frame signal plans for all intersections of the considered network (see Figure 6). These frame signal plans give the possibility to react to short term fluctuations in traffic demand by MicroBALANCE especially on those junctions that are less saturated. The buffer times that can be used depend directly on the predefined frame values (minimum and maximum green time \( \text{Min}_x \) and \( \text{Max}_x \)) and constraints on the minimal timings \( \text{MI}_x \).

**Figure 6**  
Defining a frame signal plan and distributing green time to stages;

- \( t_{\text{c}} \): Cycle time
- \( \text{Min}_x \): Minimum green time of stage \( x \). For this duration green has to be displayed independently from traffic demand.
- \( \text{MA}_x \): Variable (traffic demand dependent) part of green time that is assigned by MacroBALANCE; range \( [0, t_{\text{c}} - \sum K_x] \).
- \( K_x \): Kernel green time of stage \( x \). Resulting green time of stage \( x \) after optimisation by MacroBALANCE; \( \sum K_x = t_{\text{c}} \).
- \( \text{MI}_x \): Variable part of \( \text{MA}_x \) (buffer time) that is assigned by MicroBALANCE due to short term variations in traffic demand; range \( [0, \text{MA}_x] \).
MicroBALANCE provides to switch smoothly between several stage sequences (see Figure 7). In this way not all stages need to be displayed each cycle time and thus an acyclic control is feasible within a cyclic frame. In order to serve particular demands (e.g. calls for selective vehicle priority) an immediate change to the appropriate stage sequence is applied. Dynamic adaptation of stage duration allows for coping with selectable co-ordination fixpoints.

![Diagram showing stage sequences and adaptation points](image)

**Figure 7** Dynamic change of stages in BALANCE

### RESULTS OF FIELD TRIALS AND SIMULATION STUDIES

A first version of BALANCE has been developed in the frame of the European R+D project Munich COMFORT and has been tested and assessed in a field trial as well as in a simulation study. The prototype developed in Munich COMFORT has then been further extended and improved in the frame of the EC funded demonstration project TABASCO. In particular a new version of BALANCE tailored according to the high requirements of UK control traditions has been developed and was implemented and trialed in London and Glasgow.

All trials and studies performed in the frame of the mentioned projects show comparable results:

- Statistically significant on the 95%-level and with a confidence interval of 3.5% the simulation study for the Munich trial site\(^1\) within Munich-COMFORT showed that using only the tactical level delay of car traffic could be reduced by 19% providing the same quality of pt priority.
- A nine day field trial for the Munich test site resulted in a comparable figure: The assessment showed that 14% of the car traffic delay can be saved enhancing the existing va-technique by MacroBALANCE.

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\(^1\) Trial site was the intersection Pelkoven Straße / Dachauer Straße
• The socio-economic evaluation which was performed in the frame of TABASCO according the German guideline EWS\(^2\) resulted in a cost/benefit ratio of 1/19.

• In the frame of the London trial BALANCE was compared to the adaptive control method MOVA [VINCENT ET AL., 1988]. In this trial both BALANCE levels Micro- and MacroBALANCE were tested. In spite of difficulties with respect to the online data detection good results could be achieved:
  – The average delay of car traffic could be reduced by 4%
  – The longest delay of a vehicle was shorter by 11%
  – The standard deviation of delay was reduced by 45%

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\(^2\) EWS: Empfehlungen für Wirtschaftlichkeitsuntersuchungen von Straßen
• In Glasgow particularly the integrated pt priority function has been tested. In this trial improvements of the pt travel times of 7% could be shown.

![Figure 10: Relative changes in travel time of pt vehicles and the respective span width for the trial in Glasgow (Glasgow City Council, TABASCO Report 9.3, 1998)](image)

**SUMMARY AND PERSPECTIVES**

Apart from safety relevant aspects traffic signal control in metropolitan road networks needs to consider in particular requirements with respect to economic operation and urban planning policies. Traditional control methods that only regard the local environment and that decide on the basis of simple plausibility criteria do not fulfil this requirement. However, the developments in traffic modelling enable to quantify online the impacts of control and to reflect them in an objective function to be optimised.

According to this aim and with respect to precedent work in this area the architecture for a new adaptive signal control method has been developed. The open architecture provides the frame for the joint operation of different components, i.e. of advanced adaptive and legacy modules. Thus the requirements concerning flexibility and compatibility are fulfilled (i.e. as mentioned at the beginning: modularity, robustness, evolutionarity, inter-operability and integrated operation).

The system architecture distributes the control problem on three levels: The strategic level offers the opportunity to actively influence control according to traffic policies (strategic system optimum). On the tactical level the traffic situation in the considered network is modelled online and thus allows for the optimisation of network-wide relevant control variables that form frame plans for the local control. Within the frame plans the local control reacts to stochastic variations due to the results of online microscopic modelling. The overall system is realised by the commercial software BALANCE.
Evaluations in the context of different demonstration projects (LLAMD, TABASCO and others) have shown that the application of BALANCE significantly reduces costs in terms of delay and queue lengths. In average savings of about 15% compared to vehicle actuated control could be achieved.

Larger scale implementations in Munich (Figure 11) and other cities are currently in progress. Favoured by its system architecture BALANCE will become main building block of a strategic control system in Munich that allows for active influence on different control methods and networks by a supervisor.

Figure 11: Overview to the road network in the area of the new Munich trade fair with more than 20 BALANCE controlled intersections

**LITERATURE / BIBLIOGRAPHY**


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