Traffic Monitoring and Control in Metropolitan Areas

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Abstract. The knowledge on the current traffic state is a prerequisite for reliable traffic information and advanced adaptive network control methods. Hence this information is crucial for any successful traffic management. Up to now the online estimation of the traffic state for metropolitan road networks consistent over space and time could only be realised to a certain extent. Starting with an overview on the state of the art this paper addresses the problems concerned with online traffic monitoring and presents ideas to overcome existing deficiencies using data fusion techniques. Furthermore, a way for strategic control of metropolitan areas coherently influencing different adaptive control methods is introduced.

Key Words: online traffic monitoring, data fusion techniques, strategic control

1 Context and Objectives

Real time traffic management in urban road networks requires information on the present and future traffic state. This information needs to be as complete and precise as possible. Today, traffic information comes from a variety of sources such as inductive loops, video observation and floating car data (FCD). All data acquisition techniques suffer from certain problems. Thus, inductive loops and other local detection techniques do not provide information on the actual traffic state in terms of level of service or in terms of queue lengths and delays respectively. Apart from that it was shown that data from these sources are to a high degree unreliable [1]. For floating car data recent scientific work [2] revealed that travel time estimates are characterised by particularly high variances and need to be post-processed.

Since the measurements per se do not give sufficient information or are to a certain extent unreliable, it is necessary to use traffic models in order to compute the traffic state in a consistent way. In this respect some online traffic monitoring systems came into operation recently (e.g. [3], [4] and [5]). But also these implementations face the challenge to estimate traffic demand and OD-relations from data on volumes and occupancies at certain locations. Furthermore the missing feedback between modelled and real criteria of the traffic state (e.g. delays, queues) represents a particular problem.

FCD monitoring systems do not suffer from the missing feedback link, but the implementations are not post-processed (e.g. [6]) and, even more important, cannot be used for the impact assessment of traffic management measures.
There exists a direct interdependence between traffic monitoring and control. The better the traffic situation can be monitored the more precise and more effective traffic control measures will be. Therefore the objective of this paper is twofold: It will first introduce a concept for the consistent integration of data from different sources (FCD, inductive loop and signalling data) for online traffic monitoring and second present a way for strategic control of metropolitan areas coherently influencing different adaptive control methods.

2 Traffic Monitoring

2.1 State of the Art

Traffic state estimation needs information from different sources to provide consistent flows and travel time. These sources can be divided in measurements (data collected by detectors or coming from traffic light timing, etc.) and additional information gained by using the measurements in estimation algorithms or similar methods. Those additional information can be the estimated flows within intersections ([7], [8], [9]), the estimated movements at intersections with traffic lights ([10], [11]), propagated link flow counts [12] or estimated queue lengths and waiting times at intersections with traffic lights [13]. Data deriving from floating cars (floating car data, FCD) have recently been described as valuable supplementary information [14]. At present those data sources exist parallel and are barley used corporately.

2.2 Methodology of the Approach

The concept of a new method for online traffic state estimation presented in this paper is to split the system into a network level and an intersection level. On the intersection level data fusion techniques are applied in real time to combine detected flow data and information on the signal timing. The respective algorithms generate information on turning movements, queue lengths, delay and flow. On network level the enhanced data then serves as basis for the determination of consistent flows and travel times.

Figure 1 gives an overview on the concept and on the data, data flows and models:

- Based on the fusion of traffic counts and traffic light timings, i.e. data which is available to a certain degree for all networks, the volumes for all movements within an intersection are calculated.

- The volumes calculated in that way then are propagated to the circumjacent sectors while accuracy is considered. This procedure offers the opportunity to obtain more exact data at each detected intersection and also to fill data gaps on links where no detector is available.
• Queue lengths are estimated using again data fusion technique by combining traffic counts and traffic light timing. Floating car data (FCD) may be used to compare and calibrate the estimation.

• Given the information on link flows (and in particular on turning movements) and using a guess of the route choice a first OD matrix can be estimated.

• A traffic assignment then uses the processed data on volumes, queue lengths and OD-relations and results in consistent flows and travel times. Based on this data a new iteration of OD-estimation and assignment is performed. Floating car data again can be used to compare and calibrate travel times as well as an additional information (weight) for the OD-estimation.

2.3 Components of the Model

2.3.1 Queue estimation

As shown by MÜCK [15] queue lengths at signalised intersections can be estimated with good performance on the basis of vehicle counts from detectors located close to the stop line in combination with information on the signal timings. The investigations of MÜCK show that the time elapsing between the begin of red and continuous occupancy on the detector (fill up time) gives an indication for the queue length, a short fill-up time being a sign for congestion. Comparing the fill-up times against a threshold $dt_0$ gives an characteristic value $\delta$ for the queue:

$$\delta = \begin{cases} 
1 & dt \leq dt_0 \\
0 & dt > dt_0 
\end{cases}$$
Smoothing the characteristic value \( \delta \) one obtains at time \( n \) a value \( \delta_n \) ranging between 0 and 1:

\[
\delta_n = \alpha \cdot \delta_n + (1 - \alpha) \cdot \delta_{n-1}
\]

Empirical analysis showed that the smoothed values and the queue lengths strongly correlate and have a linear relation:

\[
L_n = m \cdot \delta_n
\]

The slope \( m \) also can directly determined from the measurements. The delay can be approximated with the relation \( w = L/\lambda \) known from queueing theory where \( \lambda \) represents the arrival rate and can roughly be estimated through the vehicle counts.

\[
\begin{array}{c}
\text{Munich, Controller S1-37-1, Detector D82, 15.05.01} \\
\quad
\end{array}
\]

\[
\begin{array}{c}
\text{Figure 2: Regression of measured queue length to smoothed fill-up time} \\
\text{(Source: TRANSVER GmbH)}
\end{array}
\]

FRIEDRICH et. al. [16] have shown, that a high performance gain could be achieved employing this estimation module as a quasi measurement with Kalman filtering technique in queueing theory models (e.g. Markovian chains, Kimber-Hollis). Using this feed back procedure the problem of systematic instability of queue length and delay estimation could be improved especially in cases of high and varying degree of saturation.

2.3.2 Intersection Movements

Combining signal phase timing information and detected flow data by probability functions for each particular movement over time MATSCHKE ET AL. [10] developed a method to determine the intersection movements. Using the temporary dependence of detection time and signal phasing of the different streams, estimates of the fractions can be made, because not all of the possible streams which pass the same detector could be green lighted at the same time. This approach was implemented and tested (see [10], [11]) and resulted in a high performance of the estimation of turning flows at an intersection (determination coefficient of estimated compared to real turning flows > 0.9).
2.3.3 Introducing supplementary information to OD estimation

In recent years a number of models have been developed to estimate an origin-destination matrix from link traffic count data (e.g. [17], [18] and [19] among the most cited papers). Typically, entropy maximising, information minimizing, and least squares estimators have been proposed and applied. The concept of the models is to update or improve an old OD matrix provided so that the estimated link volumes are consistent with the measured ones. VAN ZUYLEN, for example, has used the principle of minimum information to define the most likely OD matrix as

$$T_{ij} = t_{ij} \cdot X_0 \cdot \prod_a X_a \left( \frac{a_{ij}^0}{a_{ij}} \right) \quad (g_{ij} = \sum_a p_{ij}^0),$$

where $t_{ij}$ is a priori guess of the OD matrix, $X_0 = \frac{T}{\sum_i \sum_j t_{ij}}$ a factor to include information on the total number of trips and $X_a^{n+1} = X_a^n \cdot \frac{q_a^{\text{real}}}{q_a^{\text{est}}}$ are factors for the iterative solution of the equation using observed and estimated traffic volumes $q_a^{\text{real}}$ and $q_a^{\text{est}}$ respectively for the adjustment.

Apart from historic information included in $t_{ij}$, the assignment process which converts the knowledge of the trip matrix into link flows has a high influence on the quality of OD estimation. The accuracy of the assignment information $p_{ij}^0$, the fraction of trips from origin $i$ to destination $j$ that passes over link $a$, is important in the matrix estimation process.

To analyse the effects that can be obtained by the inclusion of additional information on intersection movements within the OD estimation the network depicted in Figure 4 was prepared. The reference OD matrix which is given in Figure 4 and a specific OD route fraction and OD flow were assumed. Objective of the estimation is to reconstruct the given matrix using only the information on link volumes. No historic information should influence the estimation and $t_{ij}$ were set to 1 (except the diagonal ele-
ments which equal 0). The information on turning flows was used as quasi traffic counts and thus the set of input data could be extended.

![Test Network](image)

**Figure 4: Test Network**

Besides the set of counted links also the precision of the assignment information $p^i_j$ has an impact on the OD estimation. This impact was analysed by using an exact assignment, a nearly exact assignment, an assignment with some different OD flow proportioning and an all-or-nothing assignment. The exact assignment was considered to be the reference.

The scenarios are evaluated using the average estimation error (Route Mean Square Error - RMSE). Therefore, the estimated OD matrix is compared to the reference OD matrix and the average RMSE of the OD pairs is determined (the diagonal elements are not considered). A comparison of the results of the different scenarios is shown in **Table 1**.

<table>
<thead>
<tr>
<th>Quality of assignment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle counts for</strong></td>
<td>veh</td>
<td>veh</td>
<td>veh</td>
<td>veh</td>
<td></td>
</tr>
<tr>
<td><strong>Scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all links, all movements</td>
<td>0.19</td>
<td>4.82</td>
<td>11.58</td>
<td>40.07</td>
<td></td>
</tr>
<tr>
<td>only links</td>
<td>19.77</td>
<td>20.02</td>
<td>29.51</td>
<td>52.53</td>
<td></td>
</tr>
<tr>
<td>only movements</td>
<td>0.30</td>
<td>8.92</td>
<td>15.88</td>
<td>34.10</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: RMSE for the different scenarios**
The results show that the inclusion of the additional turning flows improves the OD estimation significantly. Especially scenario 2 compared to scenario 3 proves that the OD-estimation benefits particularly when turning flows are known.

2.3.4 FCD as Additional Information

Figure 1 illustrates the different options to include additional data from floating cars in a consistent model for online traffic monitoring. The market penetration of FCD and the sample sizes affect the model only qualitatively, i.e. in the sense that a higher coverage over time and space will probably result in more precise results. Hence, a low coverage with FCD does not jeopardise the complete system but will contribute even with some few data to the improvement of the traffic monitoring.

To represent the supposed user equilibrium in the network in the best way, the real travel times in the different links and in particular at the intersections need to be known. For route search purposes therefore travel time functions depending from the saturation rate are used and their parameters need to be calibrated. Over FCD gathered travel times offer now the opportunity for online optimisation of these parameters and lead to self-learning systems.

In this sense FCD also can be used to improve OD estimation. Samples of measured OD-relations can be included as weights $t_{ij}$ within the model of VAN ZUYLEN. Respective investigations to the improvements which can be obtained in this way still need to be performed.

3 Traffic Control

3.1 State of the Art

To provide and to preserve sustainable mobility in metropolitan areas strategic policies need to be realised by a bundle of measures. Traffic control has of course one of the most important impacts on the quality of mobility. However, for most cases control methods and the respective system architectures are not designed due to this requirement. Even in the rare situation that adaptive network control methods are applied these methods normally are operating without being integrated on a higher, more strategic level.

Most of the known approaches to strategic traffic management have a static character, i.e. they use predefined scenarios and corresponding predefined control measures. However, these static solutions do not meet the need to respond to frequently changing situations.

3.2 Methodological Approach

The respective control methods will be embedded in a distributed and modular system architecture and a strategic component will guarantee an integrated approach of traffic control according to overall traffic policies. Following requirements guided the design of the system architecture:

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

• Inter-operability - the parts of the system communicate through standard interfaces so that they can be enhanced and upgraded without affecting the operation of other parts;

• Integrated Data Management - the data used by the system can be managed and stored in the most efficient way.

In order to migrate from the existing legacy control system to the envisaged advanced system the following system architecture is proposed. The overall road traffic control and monitoring system is decomposed into three logical levels, i.e. a local, a tactical and a strategic level.

![Figure 5: Schematic system architecture]

1. On the local level the adaptive control methods respond to short term variations in traffic demand and to stochastic events (e.g. priority request of a public transport vehicle) according to a predefined objective function. This reaction may take place within a given frame that is provided by the tactical level. At the same time the microscopic data which are collected on this level on a second by second mode are being aggregated and transmitted to the tactical level.

2. The adaptive control methods on the tactical level use the aggregated traffic flow information, estimate origin-destination relations for the network they are responsible for and accomplish short to medium term demand forecasts. On this basis and under use of appropriate impact models optimal frame plans due to a given objective function are determined.

3. On the strategic level, the control and the calculated traffic state is monitored. Also, software tools on this level assist the traffic experts and operators to customise the parameters of the respective objective functions for the different control systems according to the transport policy for the metropolitan area. In this
way consistency of objectives for different control systems (interurban, urban, public transport, etc.) can be achieved. The strategic level may from the physical point of view also be distributed and may comprise different control centres, which may reflect existing organisational structures. However, an integration of these traffic control systems is extremely important for implementing the common transport policy in a most efficient way and for optimising the capacity of all these transport systems as a whole.

According to the decomposition this design provides subsidiarity of each single component on the one hand. On the other hand due to the clear hierarchical structure it guarantees consistent accomplishment of every control decision which is given by a higher level. By excluding central control methods the system is very robust and each single component may operate even if a component on a higher level fails. However, the system is at the same time fully integrated since a common policy is respected by all actors in a concordant way. The relevant information on strategic goals is being exchanged by the parameters of the objective functions of the adaptive control methods.

A commonly agreed objective function comprises in a linear combination all the characteristic criteria which are of relevance for sets of links of the road network. The sum of all weighted and normalised criteria within the considered network are forming the performance index (PI) due to which the control is optimised. As mentioned above the objective function is not being optimised on the strategic level but decentrally by the respective subsystems within the distributed system. A variety of possible PI's can be chosen for optimisation according to the multiple different traffic policies. Relevant for the selection of criteria are of course the possibilities which are given by the traffic models used in the control methods.

With respect to traffic policies we distinguish user and system optimal solutions. Whereas user-optimal control

\[ \min! \ PI = \sum_{\text{control device}} c_i \]

with \( c_i \) general average costs

may lead to traffic situations which do not reflect the objectives of city planning (i.e. bundling traffic on major roads), system-optimal control

\[ \min! \ PI = \sum_{\text{control device}} c_i \cdot q_i = \sum_{\text{control device}} C_i \]

with \( q_i \) traffic volume \( C_i \) general total costs

may not be accepted by the road users.

Therefore an objective function is needed which will respect both requirements, i.e. the one of the community and the one of the individuals. A solution which will fulfils both requirements was found in the strategic system optimum.

\[ \min! \ PI = \sum_{\text{control device}} \sum_{\text{link set}} \alpha_{ij} \cdot C_{ij} \]

with \( \alpha_{ij} \) coincident matrix of link sets over control devices
The strategic system optimum allows for not optimal solutions in the overall system in order to protect sensible parts of the network (e.g. residential areas). In this respect the objective function needs to be extended by the dimension of the road classification in order to take into account location- and link-specific weights of the criteria. The classification of the road network is being reflected by the introduction of link sets. A set comprises the links of a certain road category. In this way the major arteries or a ring road may each represent a specific set.

In the given formula above the different criteria of the objective function are represented by the general term $C$ that stands for costs. This general formulation can be distinguished into the different criteria of relevance. These criteria typically are

- delays of car traffic, public transport and pedestrians
- queue lengths
- number of stops of car traffic and public transport respectively
- noise and pollutant emissions of motorised traffic
- fuel consumption

With respect to the single impact criteria the general formulation of the strategic system optimum follows as

$$PI = \sum_i \sum_j \alpha_{ij} \cdot W_{ij}^{OV} + \beta_{ij} \cdot W_{ij}^{mIV} + \gamma_{ij} \cdot H_{ij}^{DV} + \delta_{ij} \cdot H_{ij}^{mIV} + \ldots$$

### 3.3 First Applications

Having designed a system architecture according to the mentioned requirements (i.e. modularity, robustness, evolutionarity, inter-operability, integrated data management) the authorities of the City of Munich and the State of Bavaria have started to implement within the demonstration project MOBINET (1998 – 2003) advanced control methods which will be integral part of the new system and thus comply with the system architecture (Figure 6). The different control and information systems have now been evaluated in demonstration areas and there is the intention to extend and transfer them to usual day to day operation [3].
4 Conclusions and Perspective

In near future the relevance of dynamic navigation systems will increase. Since several years industry shows a high interest for this market and respective technologies and products are already available. However, the necessary information on the travel times as the basis for traffic dependent guidance of road users in particular in metropolitan areas is not yet available in a satisfactory quality.

At the same time the awareness of the authorities with respect to the opportunities and chances of adaptive network control and to strategic traffic management is rising. Correspondingly different cities have established new traffic management centres or intend to do so. But to enable the anticipated functionality of the traffic management policies, the information on the traffic situation consistent over space and time is required. In first implementations online network monitoring is used sporadically. But despite the progress achieved so far, the actual information is not available in an appropriate quality.

Recently new developments were published which are based on data fusion techniques and allow for the online calculation of turning movements and queue lengths at signalised intersections. This paper shows that these models for local monitoring can contribute to improve quality and reliability of online monitoring at network level. The paper presents the respective methodological approach, explains the theoretical background of the building blocks and demonstrates by the help of empirical analysis the general potential of the methodology. Apart from that, a concept for the exploitation of FCD as part of and consistent with a model based approach is proposed. Further investigations need to prove scientifically up to which extent the supposed potential can be realised.
With respect to traffic management a system architecture is introduced which provides the opportunity to integrate different adaptive control methods into one single policy. Again, the most relevant characteristic of the approach is the consistency which is provided to combine different control measures into one common strategic traffic management policy. Due to the present activities of the responsible authorities a continuous extension of the management systems is expected and therefore clear structures and architectures are required. In this respect the paper may disseminate respective ideas which particularly support the consistency of the systems.

References


