Archives of
Transport System
Telematics

Volume 5

Issue 4

November 2012

Comparison by Simulation of Different Approaches to the Urban Traffic Control

J. PŘIKRYL[a,b], T. TICHÝ[a,c], Z. BĚLINOVÁ[a], J. KAPITÁN[a]
[a] CZECH TECHNICAL UNIVERSITY IN PRAGUE, Faculty of Transportation Sciences
[b] INSTITUTE OF INFORMATION THEORY AND AUTOMATION, ACADEMY OF SCIENCES OF THE CZECH REPUBLIC
[c] ELTODO DOPRAVNÍ SYSTÉMY, S.R.O
EMAIL: prikryl@utia.cas.cz

ABSTRACT

As the urban traffic volumes reach their daily peak values, the surface traffic in modern cities suffers from frequent breakdowns and traffic jams. One of possibilities that could mitigate the problem is the deployment of smarter automatic systems of urban traffic control. Our paper demonstrates a development version of such a system. The system is based on adaptive feedback control approach. It makes use of filtering techniques to account for measurement imperfections and implements the rolling horizon method for optimal signal control. We compare the performance of the proposed system with two typical control approaches – pre-timed (or fixed) control, and traffic actuated (or dynamic) control. Different scenarios will be compared, including rapid changes in traffic volumes and reactions to incidents. The comparison is carried out using our demonstrator tool, based on TSS Aimsun micro-simulator. In order to keep the calibrated simulation as close to reality as possible, in the comparison runs we use real dense input volume measurements and simulate also the behavior of intersection controllers.

KEYWORDS: traffic, ITS, telematics, urban traffic control

1. Introduction

In recent years, many cities suffer from numerous urban traffic-related problems, including traffic safety, and ecology. As a response to this situation, modern traffic management systems are being deployed [1,2,3,4], which are able to adapt to changing traffic demands and are able to provide coordinated signal settings for large urban areas [5].

While local traffic actuated signal plans can work well at isolated intersections, any control algorithm that supervises a larger urban street network has to optimise signal settings at the whole region at once in order to achieve an optimum traffic flow through the controlled area. This cannot be achieved without some kind of a model describing the current traffic situation in the region. Such a model is periodically updated by measurements from different kinds of traffic detectors [5].

The traffic model provides the user with a set of variables describing the state of the system. The model must connect these variables with control variables that influence the state – signal plans, cycle length, and signal plan offsets. In the approach, described in [6], the vector of queue lengths on the approaches to intersections was chosen as the modelled variable describing the system state. The queues are the main cause of the travel delay and the sum of the queue lengths relates to the travel delay in the system, which is a widely accepted criterion of the level of service.

2. Problem formulation

Our goal is to develop an urban traffic control system that will be able to react on measured traffic data and optimise a criterion based on the ideas in [6]. In the first phase, described in this paper, we will attempt to minimise travel times by minimizing the weighted sum of queue lengths at all approaches of all controlled intersections. To achieve our goal, we will derive a feedback system for urban traffic control based on a simple input-output model of a traffic region. The model will use the on-line measurement of traffic volumes and the state of the controlled system will be statistically estimated from currently measured data. On the basis of the estimated model and its state vector, the signal splits will be set so that the weighted sum of the predicted queue lengths at the intersection achieves its minimum. The optimization will be based on linear programming and it will use a rolling horizon for better stability of the control.

3. Model of traffic region

To be able to optimally control a system, we have to model it first and the model needs to be a good approximation of the reality. A typical urban traffic system shows a great amount of noise in the measured data, and therefore its state is to certain degree uncertain. In order to take count of the uncertainties, the model variables are considered to be random variables with estimated mean and variance, and the uncertainty is usually modelled by additional noise with given distribution.

Our model has a form of a discrete-time state-space model and it is based on the model of Homolová and Nagy [6]. We will briefly overview its main components, the state equation and the output equation.

3.1. Model of the queue.

The state of the system is described by two sets of variables – queue lengths ξ at all signalised approaches and the corresponding detector occupancies 0. The part of the model that describes the evolution of the queue follows a simple conservation law [7] that has been modified to keep $\xi>0$:

$$\xi_{t+1} = \begin{cases} \xi_t + I_t - Sz_t & \text{if} \xi_t + I_t > Sz_t, \\ I_t(1 - z_t) & \text{otherwise.} \end{cases} \quad (1)$$

It expresses the fact that at the end of the -th cycle the residual queue length ξ_{t+1} at some approach is equal to the previous queue ξ_t increased by the arriving flow (or demand) I_t and decreased by the flow equal to lane capacity – the lane capacity is given by the saturation flow S and the relative green length for the approach, z_t, given as a ratio of the cycle time when the green signal is on. If the lane capacity exceeds the total demand, the residual queue is approximated by the number of vehicles arriving on red, assuming uniform arrivals.

3.2. Model of the detector occupancy

The detector occupancy 0 is defined as a ratio of detector activated time and the length of the detection period. It has been shown by Diakaki that in certain range the occupancy at the detector has almost linear dependency on the queue length. This leads to the relation

$$O_{t+1} = \kappa \xi_t + \lambda \quad (2)$$

where κ and λ are coefficients of the linear dependency. Their values depend mostly on the detector distance from the stop-bar.

3.3. Model of the output

The model describing the output of the system computes the number of vehicles leaving the intersection given the number of vehicles queueing on its approaches, the turning rates α_{ij} between the i-th and j-th approach, and the number of vehicles arriving during the cycle. The output model has to also take into account different possibilities of queue formation described by (1). The resulting model, although in parts linear, becomes quite elaborate and due to space constraints we refer the kind reader to the original paper [6] for detailed explanation:

$$\eta_t = \sum_{j \in \mathcal{A}} \delta_{j,t} \alpha_j \xi_{j,t} + \left(\delta_{j,t} S_j + \left(1 - \delta_{j,t}\right) I_{j,t}\right) z_{j,t} + I_{j,t} \quad (3)$$

where η_t is the output intensity over some approach, A is the set of all approaches of the intersection, α_j is the turning rate from the j-th approach to the output and $\delta_{j,t}$ is the boolean residual queue flag honouring the two variants of equation (1), $\delta_{j,t}=1$ if $\xi_{j,t}+I_{j,t}>S_j z_{j,t}$, $\delta_{j,t}=0$, otherwise.

3.4. The final model

Using the above building blocks a linear state space model can be built,

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{B}\mathbf{z}_t + \mathbf{F} + \mathbf{w}_t, \quad (4)$$

$$\mathbf{y}_t = \mathbf{C}\mathbf{x}_t + \mathbf{G} + \mathbf{v}_t \quad (5)$$

where the state vector $\mathbf{x}_t$ is composed from queue lengths ξ_t and modelled input occupancies $\mathbf{0}_t$, the vector represents the green $\mathbf{z}_t$ splits, the output vector $\mathbf{y}_t$ is composed from the modelled output intensities and modelled input occupancies $\mathbf{0}_t$, the matrices of the system contain appropriate parts of equations (1)-(3) and the noise vectors $\mathbf{w}_t$ and $\mathbf{v}_t$ cover all uncertainties and disturbances in the model.

3.5. Filtration

The state-space model described by (4) and (5) depends on a number of parameters. Should we consider those parameters known and fixed and all inputs to the system being measured, the model is known completely and its state (queue lengths) can be estimated based on measurements using the simplest version of linear state estimation – the Kalman filter [9].

However, for a robust practical application these conditions do not hold: The values of parameters S and α are usually just approximate, the turning rates α change in the course of the day, and not all inputs can be measured, mainly due to budget restrictions. Only the parameters κ and λ can be considered constant and their values can be pre-computed.

In such a case, the process of simultaneous estimation of the system state and its parameters leads to non-linear estimation and filtration. Numerous methods exist that allow simultaneous estimation of state and parameters, their main problem being numerical stability. In our system we opted for the DD1 filter [10]. This method proves to work well provided that the noise covariances from the model (4), (5) are determined with sufficient accuracy.

3.6. Control

In order to control the system, we need to specify a control criterion that will be minimised. In our case we aim to minimise travel time by minimising the number of vehicles queueing in the controlled traffic network. We define the control criterion as a weighted sum of the delay caused by vehicles queueing on red,

$$J = \sum_{i=1}^{\nu} w_i \frac{\xi_i}{S_i}, \qquad (6)$$

where ν is the number of controlled intersection approaches, w_i denote weight (importance) of the i-th approach and ξ/S represents queue length to maximum throughput ratio, allowing for longer queues at approaches that are able to again rapidly discharge them.

3.7. Model for control

The criterion (6) is expressed through the queue lengths ξ. However, this variable is not directly measurable and we need a control model, connecting the queue lengths to other measurable variables. Such a model can be easily obtained using the state space model (4). We get

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{B}\mathbf{z}_t + \mathbf{F} + \mathbf{w}_t$$
$$\mathbf{x}_{t+1} - \mathbf{B}\mathbf{z}_t = \mathbf{A}\mathbf{x}_t + \mathbf{F} + \mathbf{w}_t$$

and composing new vector x_{t+1} as a concatenation of ξ_{t+1} and z_t we finally arrive at the model for control in the form

$$\begin{aligned} \mathbf{M}\boldsymbol{\chi}_{t+1} &= \mathbf{m}, \\ \mathbf{M} &= \begin{bmatrix} \boldsymbol{I} & \mathbf{0} \\ \mathbf{0} & -\boldsymbol{B} \end{bmatrix} \\ \mathbf{m} &= \mathbf{A}\mathbf{x}_t + \mathbf{F} + \mathbf{w}_t \end{aligned} \qquad (7)$$

3.8. Optimization

With the control model formulated in the form of (7) we may minimise queue lengths by linear programming approach [11] by transforming (6) into linear programming criterion

$$\min_{\mathbf{z}_t} \boldsymbol{c}^{\mathrm{T}} \boldsymbol{\chi}_{t+1}, \qquad (11)$$

using $\mathbf{c} = [\frac{w_1}{S_1}, \frac{w_2}{S_2}, \dots, \frac{w_\nu}{S_\nu}, 0, 0, \dots, 0]$ so that the values of relative greens do not influence the optimality criterion. Additional conditions for optimisation are ξ>0, $z_{min} \leq z \leq z_{max}$ and all relative greens at one intersection have to sum to one.

The optimization presented above will provide optimal green splits for a single cycle using variables measured during the previous cycle. Such a control criterion is very easy to compute, however, it could be unstable as the synthesised control action maximises the current profit and does not take into account historical data and predictions of future traffic situation. That is the reason why a suboptimal control with a rolling horizon is used instead the above mentioned simple case. The only difference is that the control model (7) is constructed using predictions of input intensities up to the rolling horizon length (typically 5 cycles) and the criterion (6) is minimised taking into account all modelled queue lengths over the horizon. The intensity is predicted using an autoregressive model of order 2.

4. Simulated experiments

As a first step towards the real world testing of the system, the model and above proposed controller have been tested using the TSS Aimsun micro-simulator equipped with additional interface to Matlab and simulated intersection controllers. The tested network is located in the western suburbs of Prague, around Zličín public transport terminal and shopping centres [12]. It consists of two coordinated intersections and it is depicted in Figure 1.

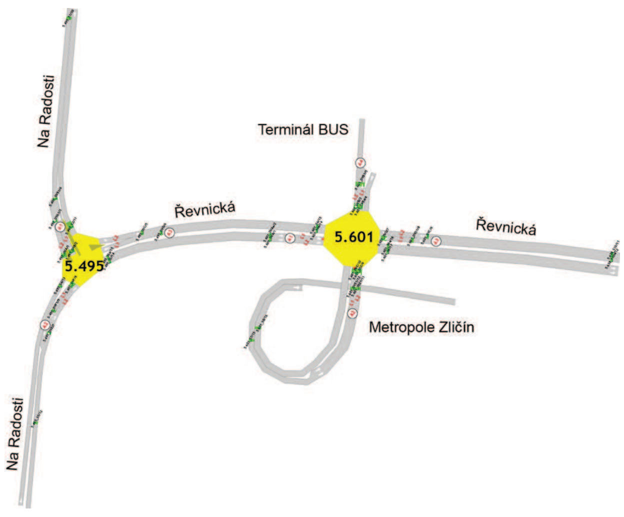

Fig. 1. Test network, consisting of intersections 5.495 and 5.601 at Prague-Zličín. Entrance from TerminalBUS experiences heavy public transport traffic, while entrance to MetropoleZličín may generate and attract large amounts of passenger cars. Řevnickástreet connects the ramps of highway D5 with residence areas to the north and south.

In our aim to keep the simulation as close to reality as possible, we have used true input data with sampling period 90sec, recorded on 2007/12/12, as shown in Figure 2. We have also simulated the existing signal programs of both intersection controllers.

To demonstrate the capabilities of the proposed system, three different traffic scenarios have been tested: Scenario 1 covers one full day of heavy traffic using data recorded on 2007/12/12, Scenario 2 adds an traffic incident of a bus and a passenger car blocking one of the lanes on Řevnická street east from

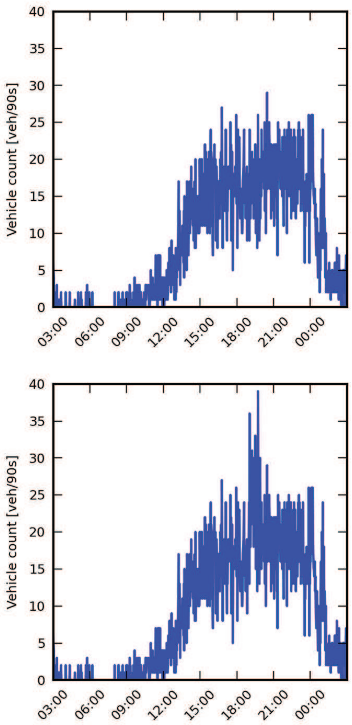

Fig. 2. Vehicle inputs for Metropole Zličín for Scenario 1 and 2 (upper) and Scenario 3 (lower).

intersection 5.601, and Scenario 3 investigates the reaction of the system to heavy traffic attracted and generated by the exit to Metropole Zličín.

Three different configurations of intersection controllers have been tested within each scenario: Configuration A is a backup pre-timed signal plan that is used in case of serious detector failures, Configuration B is a traffic-actuated control with fixed signal plan, and Configuration C is a traffic-actuated control with a signal plan provided by our control system.

The results are summarised in Table 1 and in Figure 3.

Table 1. Global statistics of different scenarios and configurations

Scenario/ Configuration	1A	1B	1C	2A	2B	2C	3A	3B	3C
Delay time [s]	33.9	32.2	32.1	39.3	37.8	36.2	38.1	36.7	35.9
Number of stops [-]	1.02	0.98	0.97	1.33	1.29	1.25	1.21	1.19	1.17

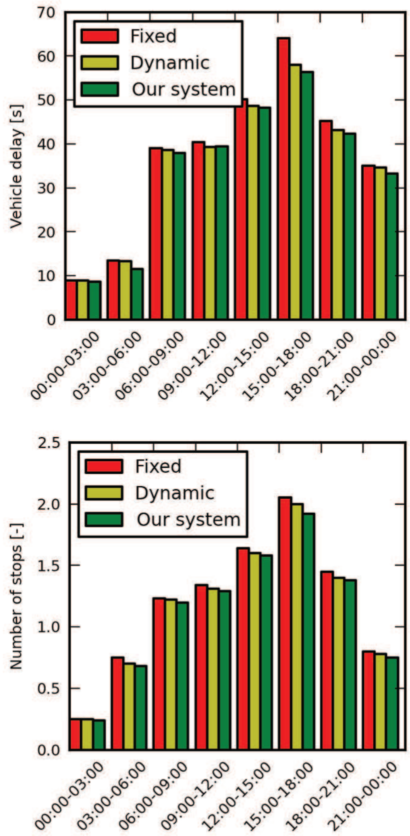

Fig. 3. Average vehicle delays (upper) and number of stops (lower) over all scenarios for configurations A, B, and C.

5. Conclusion

We have proposed and tested in simulation an alternative urban traffic control system based on state-space model of the traffic network.

We were pleased to observe that the system was able to correctly detect the lower capacity of output in Scenario 3 and changed the signal plan accordingly by shortening the affected greens and giving more time to alternative signal group. This could, in real situation, suggest drivers to change their directional preferences and prefer an alternative route to their destination.

On the other hand, the proposed system does not bring much improvement for the common traffic situation as shown by results for Scenario 1. These result clearly show that for a typical day the pre-defined signal plan works quite well with traffic-actuation taking care of all small disturbances in traffic. The proposed control is still marginally better, but the overhead of redefining the signal plan for the controller network may be in some situations even prohibitive. This is an interesting topic for future research.

Given the favourable results of the simulated testing, we will also try to obtain the permission to test the system in real traffic.

Acknowledgements

This work has been supported by the Technology Agency of the Czech Republic under project no. TA01030603 and in part by The Ministry of Education, Youth and Sports through the research centre Data-Algorithms-Decision Making (project 1M0572).

Bibliography

[1] KRUSE G.: MOTION Netzsteuerung – Optimierung der Lichtsignalsteuerung im Einsatz. In Steierwald, M., Martens, S., eds.: Steuerung kommunaler Verkehrsnetze. Number 236, Akademie für Technikfolgenabschätzung in Baden-Württemberg (2003) 37–52 In German.

[2] BRETHERTON D., BODGER M., BABER N.: SCOOT – the future [urban traffic control]. In: Proceedigns of the 12th IEE International Conference on Road Transport Information and Control (RTIC 2004). (2004) 301–306

[3] HOUNSELL N., SHRESTHA B., PIAO J., MCDONALD M.: Review of urban traffic management and the impacts of new vehicle technologies. Intelligent Transport Systems, IET 3(4) (2009) 419–428

[4] TICHÝ T., KRAJČÍR D.: The conception approach to the traffic control in Czech cities – examples from Prague. In: Proceedings of TST 2010, Katowice - Ustron, Poland, (2010) 407–410

[5] GARTNER N.H., POORAN F.J., ANDREWS C.M.: Optimized policies for adaptive control systems: Implementation and field testing. Transportation Research Record 1811 (2002) 148–156

[6] HOMOLOVÁ J., NAGY I.: Traffic model of a microregion. In Horáček, P., Šimandl, M., Zítek, P., eds.: Preprints of the 16thWorld Congress of the International Federation of Automatic Control, Prague, IFAC (July 2005) 1–6

[7] ROUPHAIL N., TARKO A., LI J.: Traffic Flow at Signalized Intersections. In: Revised Monograph on Traffic Flow Theory. Turner-Fairbank Highway Research Center (1997) 9–1–9–32

[8] DIAKAKI C.: Integrated Control of Traffic Flow in Corridor Networks. PhD thesis, Technical University of Crete, Department of Production Engineering and Management (1999)

[9] KALMAN R.E.: New results in linear filtering and prediction theory. Journal of Basic Engineering (1960) 34–45 Transactions ASME.

[10] NØRGAARD M., POULSEN N.K., RAVN O.: New developments in state estimation for nonlinear systems. Automatica 36(11) (2000) 1627–1638

[11] NERING E., TUCKER A.: Linear programs and related problems. Volume 1. Academic Press (1993)

[12] KAPITÁN J.: Využití simulačního prostředí pro ověřování různých způsobů řízení dopravy na vybrané oblasti. Master's thesis, Czech Technical University in Prague, Faculty of Transportation Sciences (2011) In Czech.