Local traffic control of a microregion

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Abstract. The advanced traffic control systems can provide new levels of the efficiency with an increasing sophistication in the detection and the real-time optimization. Those systems use the on-line traffic flow data to set the dynamic parameters of the signal timing plans in response to the random traffic intensity fluctuation. The traffic control system is supposed to be decentralized and hierarchical. One of the control levels is the local control of a microregion. The function of this sectional controller is to deduce the optimal stage green times for each junction in the microregion and their intervals of the possible change.

We formulate the problem of the microregion traffic control as a task of linear programming. But it assumes the complete knowledge of the microregion elements parameters and that is usually impossible at all. So we approximate the non-detected states by Kalman filter.

Keywords: traffic control, linear programming, Kalman filter

1 Introduction

A feature of the majority of urban networks is the high density of the streets with large amount of junctions. The networks were formed during the tens or hundreds years in the past but the traffic demand has continually increased. So in respect to the traffic flow fluency, the existing structures of the streets can't usually accommodate such big volume of the traffic participants and it is either very expensive or even impossible to reconstruct the deficient street network. Due to these facts, efficient traffic control mechanisms are urgently required to reform this situation, particularly if congestion is to be contained (Hong 2002, Hong 2001, Přibyl 2001).

Optimal traffic control of urban street networks is an illustration of the problems of multiple participant decision making. We can comprehend the urban network as the set of microregions, formed by the lesser number of streets and their junctions. It is generally known that the optimal control of each microregion does not necessarily lead to the optimal control of the whole urban network. The resultant traffic flow behaviour of a certain microregion can radically change the traffic situation in the adjacent microregions and consecutively also the global traffic conditions. That is why the traffic flow control task must be formulated and solved consistently.

Traffic signals have become the most widely used form of the traffic flow control in this context (Přibyl 2001). They are commonly used at the road junctions to control pedestrians and vehicular movements to reduce the traffic congestions and to improve road safety. Now, they can also perform dynamically and the signalized junctions within the computer-controlled UTC systems (urban traffic control systems) are increasingly at the heart of the traffic control in cities all over the world (Hong 2001). During the last twenty years, a lot of various computer assisted traffic control schemes were developed that reflected the changes in the optimization criteria evolving consecutively in line with gained experience (Kratochvílová 2003).

The early traffic control systems essentially performed the static optimization of green ”waves” on the specific city routes. But the optimization of the more complex city traffic requires taking into account other characters of the traffic flow as a queue length on the junction arms, the number of vehicle stops during the journey, a total delay, environmental impacts as emissions and so on (Heydecker 1997, Whittaker 1997).

In the recent time, the advanced traffic control systems use the on-line traffic flow data to set the dynamic parameters of the signal timing plans in response to the random traffic intensity fluctuation (Abu-Lebdeh 2002, Hong 1999, Wong 2002). So these control systems can quickly react to the changed traffic conditions at the optimized area in which a functional and effective framework of vehicle detectors (e.g. the loop detectors frequently) exists. Thus those advanced control systems can provide new levels of the efficiency with an increasing sophistication in the detection and the real-time optimization.

However, the problems of the optimal traffic control is still not solved. It is true that there exist a lot of the optimization techniques, successfully finished and tested on the real traffic area. Some of those control systems became the object of the commercial sphere and it is possible to buy them as a software package, e.g. SCOOT, MOTION, etc. (Kratochvílová 2003, Přibyl 2001). They are usually quite expensive and supplied as a ”black box”. For the integration of such system to the real area control, there is then necessary the assistance of the experts to set the parameters of it. It is not guaranteed that such system will be suitable for another traffic control situation, although it has been successfully applied elsewhere (Kratochvílová 2003).

In the recent time, the precise global concept of the traffic control system is known well (Heydecker 1996, Kratochvílová 2003) but the specific optimal methodology is still not clear. There are developed a lot of different approaches which would be possible to use for this purpose (Kárný 1998, Nagy 2003, Valečková 1998). Some of them are very promising (SMART NETS 2002) and they show that the prospective solution can fall back on the known and current methods (Beck 1982, Kárný 1985).

2 Aim of the Work

We consider the optimal traffic control as the task of linear programming because of the assumption of the linear character of the basic traffic flow relations (for example traffic flow changes in addition to the length of the green time) in case of the signal traffic control. The decisive restrictions on the parameters are considered also to be linear and known.

It is obvious that the linear relationship holds well in the ideal conditions where all traffic flow inputs and outputs are detected. In reality, there exist such inputs and outputs that can never be accurately detected: temporary or longtime parking, non-controlled junctions or the streets without traffic detectors. It is shown that such inputs and outputs can reach the high value and it is not possible to ignore them. As it is not possible to measure them permanently, these values must be estimated. Moreover, we intend to describe the state of the junction by the lengths of the queues. This quantity is also not measurable in practice (at least, it is not easy to measure it). We assume to use the Kalman filter for this purpose which can respect such non-detected inputs and outputs or unmeasurable states.

The approach mentioned seems to be quite simple and quick enough. We expect that it will follow the traffic control step by step: microregion by microregion, junction by junction. Moreover, it will respect traffic flow defects with a possibility of prompt information about oncoming traffic flow changes.

3 Traffic Systems

We intend to control the urban traffic region consisting of several microregions. Each microregion is formed by several streets that cross at the junctions which may or may not be signal-controlled. Generally, its shape and extent are not limited (except the computational time limit). The streets and junctions, which pertain to the certain microregion, are usually chosen on the basis of the physical microregion structure and control needs.

For practical reasons, the microregion is usually created by some main traffic line and its adjoining junctions. The limiting amount of the included junctions can pertinently eventuate from the computational possibilities of the proposed algorithm.

3.1 Basic Notions

The urban junctions consist of a set of *approaches* and a *common crossing area* into which these approaches lead. An approach is the part of a street where all vehicles go in the same direction. The approaches consist of one *lane* at least. Some lanes can be reserved only for vehicles turning left, turning right or keeping the straight direction in case of the enough space. The lane can also be determined for allowable combination of turning or straight going vehicles.

In case of two identical lanes, two straight lanes for example, it is assumed that incoming vehicles from both lane queues evenly. In case of more than two different lanes for the approach, the way of vehicle inclusion to the lanes depends on their drive direction in which will continue after coming through the junction. The traffic on equivalent lanes has the right of way simultaneously and the vehicle can expect to pass the signal at roughly the same time whichever lane it chooses.

This structural configuration of lanes is determined in respect to the compound of the traffic flow (i.e. to the proportions of individual or public transportation, etc.) and the prospective traffic intensities obtained from the traffic survey.

The traffic at the junction is divided into *streams* that are portions of the input traffic considered. The stream is formed by all vehicles that cross the junction from the same approach and go in the same direction. Two streams are called *compatible* when they can safely cross the junction simultaneously, otherwise they are called *conflicting*. The aim of the signal control is to separate the streams as much as possible and thus to minimize the conflict situations.

Some of the junctions in the microregion are supposed to be controlled by the *flare* (signal) *equipment*. For such junctions the *traffic signal scheme* is composed on the basis of the traffic solution of the junction.

The *cycle* corresponds to a single repetition of the basic series of signal combinations at the junction, it means that all lanes must get their right of way and must have time, at least the minimal, for passing the junction.

The knowledge of the traffic situation of the junction leads to the defining of the *stage*. It is the part of the cycle time, during which some set of the streams receives their right of way. The stage describes the sequence of the signals during the cycle time. It has three parts: the green, the inter-green and the red time. The duration of the *green* signal may be variable in dependence of the immediate traffic demand. The length of the *inter-green* signal is fixed. The inter-green is interposed before the start of the green signal in order to avoid an interference between the conflict streams of the consecutive stages. The *red* signal is the addition of those parameters appointed to the cycle time.

Thus, for each junction the number of stages and their sequence is specified. The *optimal sequence of the stages* minimize the *total loss time* in the passage through the junction, it means the income and outcome times and the inter-green times. The *optimal cycle time* and the minimal times of green and red signals are deduced for each junction and its stages.

The *offsets* are time differences between the cycle times for successive junctions that may give rise to the ”green” waves along the arterial (i.e. no interruption of the drive) in condition that the drivers keep the suggested speeds. Those parameters must be proposed so that the *capacity* of lanes (i.e. the total amount of the vehicles that can drive through the junction during the green time) are higher than their traffic intensities.

Measurement of the current traffic variables are performed by *detectors*. They are usually placed on each arm of the junction with the flare equipment control. There are two possibilities for placing the detector: sometimes they can be placed on the stop-line or 20 - 30 meters far from it (so called far-away detectors). But there are also special detectors that are called strategic and that are placed on the stage between the two junctions. The *strategic detectors* give the more accurate information about the global traffic situation because the detectors near the junction are influenced by queueing vehicles and their slowing down and moving off. The detectors can provide the following traffic variables:

- *Intensity*: the amount of passing vehicles in unit vehicles per hour [uv/h],
- *Occupation*: the proportion of the sample period when the detector is being activated by vehicles [%],
- *Speed*: the point speed of the passing vehicles [km/h],
- *Density*: the amount of the vehicles per kilometer [uv/h].

3.2 Signal Traffic Control

Practically, there are three possible ways to influence the traffic flow by using the traffic signals on condition that the optimal number of stages and their constitution has been specified (typically solved off-line by a traffic engineer). The controlled parameters are the times of the greens, the cycles and the offsets:

- *Green time (split)*: the green duration of each stage should be optimized according to the actual demand of the involved streams. The most preferably, it should be given the optimal value of the green time and the allowable interval of its change. The longer green time allows the more cars, on the corresponding approaches, to drive through the junction. On the other hand, it causes the longer waiting times for the vehicles queueing on the remainder of the approaches. We consider to optimize the split, i.e. the relative duration of the green time, as the portion of the cycle time. Then the sum of all stage splits and inter-greens is equal one.
- *Cycle time*: The total capacity of the junction can be enlarged by the longer cycle time because this change enlarges the capacities of all approaches at once. The proportion of the inter-green times becomes smaller and conversely, the proportion of the total green time is bigger. The change of the cycle time is considered for the control of several microregions in case of the congestion of the whole traffic region. We consider the fixed cycle time for the local control of one microregion.

- *Offset*: The specification of the offsets allows to create green waves. Ideally, it takes into account the possible existence of the queues. We consider the offset control as a part of the higher level of traffic control where exceptional and irregular events as accidents, closures, the preference of special vehicles and public transport are supposed to be solved.

4 General Design of the Traffic Control System

It is possible to deduce how such traffic control system could be structured. First, it is obvious that the decentralized system is more efficient. The distributed, traffic adaptive and dynamic computer control offers some advantages over centralized and pre-timed approaches:

1. It is obvious that any central controller cannot easily consider the sudden changes in the local traffic flow conditions. The spatial and temporal local conditions must be respected in order to make the relevant decision.
2. Even the high quality communication and computational equipment cannot guarantee the transfer that is faultless and fast enough for the centrally controlled environment.
3. The decentralized system allows the parallel data processing, which permits to make the relevant decisions more quickly. There is also saved the time that would be necessary for data communicating to the individual traffic signals.
4. The changes of local area of the street structure, permanent or temporary, can be realized more easily and inexpensively in case of the distributed controllers.
5. In case of the local computational blackout, the whole system will be not paralyzed at all. It will probably work only with reduced quality and somewhat slowly.

Finally, it should be said that any proposed system must be designed in a way that is open to the further development in the future. The system should be sufficiently general for its application in the different areas, with small modifications dependent on the local traffic conditions.

The system must be able to optimize the traffic signal plan parameters as the cycle time, the offsets and the splits for all junctions in the network. From the network position, the delays and the total stopped time should be also optimized. The intelligent control system could not only react to immediate data inputs but it must be able to forecast impended changes of the traffic flows.

Obviously, it is important to choose the data detection and collection, the way of parameter estimation and the optimization criterion, etc. very carefully. The system should respect the experience acquired (the traffic volume dependence on the time and the local conditions, for example). The user requirements and the public transport requirements above all should be taken into account in case of the urban traffic control. The system must be open to the telematics environment.

4.1 Hierarchy of the Traffic Control System

The system should definitely have two control levels at least - the junction control level and the network one; in other words, the decomposition approach should be applied. Our proposed system has three levels of control:

1. Intersection controller
2. Microregion (local) controller
3. Region controller

The first one works on the level of a single junction. It is supposed that the cycle time, the offsets and the green times of each stage are set from the higher levels and they are fix at the moment. The interval of the maximal change of all the green times of the stages are also recommended. The single junction controller can only change the respective stage green times that means to spin out or to cut them according to the recommended time interval and current traffic conditions that are observed from the loop detectors in the junction. The standard junction controllers handle such operations.

The group of several single junctions forms the microregion that is necessary to control in view of the traffic flow maximization. The function of the microregion controller is to deduce the optimal stage green times for each junction and their intervals of the change. The criterion is the minimal total (weighted) queue length. The queue length directly relates to the waiting time so the minimization of the queue lengths leads also to the minimization of the total loss time. We also consider the penalization of the split changes. The controller has the current measured traffic data at its disposal and the microregion cycle time that is set from the highest level.

It is obvious that the attainment of the optimal solutions in every microregion doesn't necessarily mean the global optimal solution for whole region. The improvement of the traffic conditions of the one microregion can often cause the deterioration of other microregion situation. That is why the higher, the region controller is needed. This controller is supposed to set the cycle times for each microregion in the way that the traffic flow through the urban net is maximized. The special cases as the public transportation preference, the emergency vehicles preference or vehicles' bumps and accidents are supposed to be solved on this level of the control.

5 Local Control of a Microregion

It is necessary to design a suitable model of the traffic flows in the area. Such model must be the macroscopic one. The model of this concept avoids the computational complexity associated with the microscopic models. For example, it is quite sufficient to know the percentages of the cars turning or keeping the same direction at the junction and single junction capacity.

In case of complete knowledge of the microregion element parameters, i.e. parameters of each single junction, that is shown that the relations between the parameters and restrictions on them are linear. The optimization criterion is also possible to construct as linear. From this reason, the linear programming is supposed to use for the solving of this problem. Generally, the traffic control problem then can be described by the following equations:

- State vector: could be formed by the inputs and outputs of the traffic flows, stage splits, queue lengths, etc.

  $$s' = [s_1, s_2, \dots, s_n] \tag{1}$$

  where

s_i	is the input or output of traffic flow in uv/h (i.e. unit vehicles per hour) or it represents the stage green time in s.

- Optimization criterion: is defined as the product of the state and weight vectors.

  $$J = w's = \sum_{i=1}^{n} w_i s_i \tag{2}$$

  where

  $w' = [w_1, w_2, \dots, w_n]$ is a vector of the relative weights.

- Restriction conditions: in the matrix notation for the state vector.

  $$Qs \leq p \tag{3}$$

  where

s	is the state vector,
Q	is the $n \times n$ matrix of restriction parameters,
p	is the $1 \times n$ vector of the right sides.

Unfortunately, not all junctions of the microregion are equipped by detectors. Mostly, the detectors are placed only on those junctions that are controlled by the flare equipment. Thus there is a number of non-detected inputs and outputs of the traffic flow that can be significant and so they can't be ignored in the modelling. Such inputs and outputs can be interpreted as the parking of vehicles, arrivals and departures through the junction arms with no detection, etc. Then the precondition, that the output of one controlled junction is equally the input of the following controlled junction, is not fulfilled.

The traffic detectors are usually placed on each arm of junction with the flare equipment control. But there are also special detectors that are called strategic and that are placed on the stage between the two junctions. Owing to this fact, it is possible to count the mentioned defects of the traffic flow retrospectively. We suppose the approximating of the states and the defect values and subsequent specification of the linear programming parameters by the Kalman filter. Then the benefits of the supposed method approach (specially the low time strenuousness of the computation) can still be released on condition of the parallel parameters' approximating.

6 State Equations

6.1 Junction Diagram

In this paper, we will consider a simple three-arm junction (see fig. 1) with simple (one lane) approaches, just two queues, one external non-detected input and other special traffic conditions (one-way flows). This special junction will be also used for the experiments. The final state model can be easily extended for general traffic flow conditions (multidirectional flows). All quantities are supposed to be related to a fix sampling period.

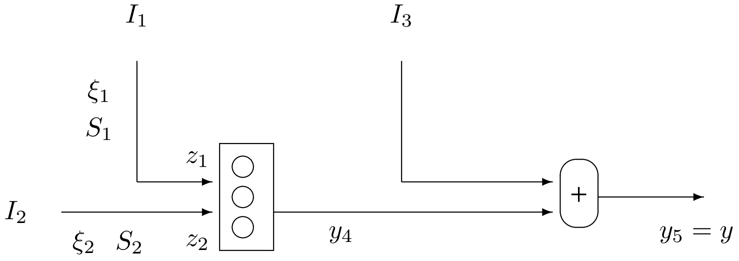

Fig.1: Junction design

where

1, 2, 3, 4, 5	marks of the arms, only No. 3 non-detected,
$I_{1;t}, I_{2;t}, I_{3;t}$	input intensities in time t $[uv/T_s]$,
$\xi_{1;t}, \xi_{2;t}$	queue lengths in time t $[uv/T_s]$,
S_1, S_2	saturation flows ($[uv/T_s]$),
T_s	sample time period,
$z_{1;t}, z_{2;t}$	splits in time t $[\%]$,
y_4, y	output intensities in time t $[uv/T_s]$.

6.2 Model Equations

There exist more possibilities for choosing quantity to form the state vector. It can be for example formed by values of the output flows, the length of green times or splits, the queue length, etc. In order to obtain the observable and stable linear model and to use all information, we consider following form of the junction state vector:

$$x_{t+1} = \left[\xi_{1;t+1};\ \xi_{1;t};\ \xi_{2;t+1};\ \xi_{2;t};\ \tilde{I}_{1;t};\ \tilde{I}_{2;t};\ \tilde{O}_{1;t};\ \tilde{O}_{2;t};\ \tilde{I}_{3;t}\right]' \tag{4}$$

where

$\xi_{i;t}, \xi_{i;t}$	queue lengths, $i = 1, 2$,
$\tilde{I}_{i;t}, \tilde{I}_{i;t}$	intensity deviations from its typical daily course, $i = 1, 2$,
$\tilde{O}_{i;t}, \tilde{O}_{i;t}$	density deviations from its typical daily course, $i = 1, 2$,
$\tilde{I}_{3;t}$	non-detected intensity deviations from its typical daily course.

The form of the state vector is clear now. For deducing the appropriate model, it is necessary to specify the relations between the state vector elements. We suppose the following equations to expres the time course of the queues:

$$\begin{aligned} \xi_{1;t+1} &= \delta_{1;t}\xi_{1;t} + \delta_{1;t}I_{1;t} - \delta_{1;t}z_{1;t}S_1 \\ \xi_{2;t+1} &= \delta_{2;t}\xi_{2;t} + \delta_{2;t}I_{2;t} - \delta_{2;t}z_{2;t}S_2 \end{aligned} \tag{5}$$

where

$\delta_{i;t}$	indicates the possibility of queue creation, alternatively the type of the passage.

That is to say if the queue length and also the input intensity is ”small” enough ($\delta_{i;t} = 0$), then all vehicles (queueing or incoming) can drive through the junction. Logically, there is no queue in the end of the green. In the other case, if the input intensity is too ”big” ($\delta_{i;t} = 1$), only the approach capacity can pass the junction and a queue is made.

We assume the traffic conditions (intensities and splits) don’t change radically during the two following periods (or cycles). It is also known that the vehicles start to queue during the red and inter-green signal of cycles, except the exceptional or irregular cases. Then the conditions of ”big” or ”small” intensities and the appropriate passage can be written consecutively:

$$\begin{aligned} I_{i;t} \leq K_{i;t} = S_i z_{i;t} \quad &\Rightarrow \quad P_{ij;t} = \alpha_{ij}(I_{i;t} z_{i;t} + \xi_{i;t}), \\ I_{i;t} > K_{i;t} = S_i z_{i;t} \quad &\Rightarrow \quad P_{ij;t} = \alpha_{ij} K_{i;t}, \end{aligned} \tag{6}$$

where

$K_{i;t}$	approach capacity $[uv/h]$,
$P_{ij;t}$	passage, i.e. the amount of the vehicles passing the junction from the approach i to j $[uv/h]$,
α_{ij}	directional relations, i.e. the proportions of vehicles driving from approach i to j to total approach intensity.

Now, we specify the time course of the intensity and density deviations. As we said, we consider the typical daily courses of intensities and densities. These courses can be derived by averaging apriori measured data. The deviations are defined as $\tilde{I}_{k;t+1} = I_{k;t+1} - \bar{I}_{k;t+1}$, respectively $\tilde{O}_{k;t+1} = O_{k;t+1} - \bar{O}_{k;t+1}$ where $I_{k;t+1}$,$O_{k;t+1}$ are quantities measured by detectors, $\bar{I}_{k;t+1}$ and $\bar{O}_{k;t+1}$ are their typical daily courses. We assume that the deviations of the intensity and density depend not only on their previous values but also on the length of corresponding approach queue.

In the case of non-detected intensities, we can’t determine the typical daily course from the measured data. We can derive this course as the proportion of the typical one of measured intensities or as the weighted sum of all of them. The non-detected inputs have no direct relation with signal controlled junction and so we don’t assume any dependence on measured or calculated quantities of the junction. The searched equations are following:

$$\begin{aligned} \tilde{I}_{1;t+1} &= \beta^I_{1;t} \tilde{I}_{1;t} + \kappa^I_{1;t} \xi_{1;t} + \omega^I_{1;t} \tilde{O}_{1;t} \\ \tilde{I}_{2;t+1} &= \beta^I_{2;t} \tilde{I}_{2;t} + \kappa^I_{2;t} \xi_{2;t} + \omega^I_{2;t} \tilde{O}_{2;t} \\ \tilde{O}_{1;t+1} &= \beta^O_{1;t} \tilde{O}_{1;t} + \kappa^O_{1;t} \xi_{1;t} + \omega^O_{1;t} \tilde{I}_{1;t} \\ \tilde{O}_{2;t+1} &= \beta^O_{2;t} \tilde{O}_{2;t} + \kappa^O_{2;t} \xi_{2;t} + \omega^O_{2;t} \tilde{I}_{2;t} \\ \tilde{I}_{3;t+1} &= \beta^I_{3;t} \tilde{I}_{3;t} + \bar{I}_{3;t} \end{aligned} \tag{7}$$

Note: All parameters of the previous equations are assumed unknown and they have to be estimated. Moreover, the coefficients κ enter the model as products with the state ξ, which is also estimated. That is why their estimation is non-linear.

The resultant state equation is

$$x_{t+1} = A_t x_t + B_t z_t + F_t + e_t, \tag{8}$$

where

A	represents the matrix 9×9 of parameters,
B	matrix 9×2 reflects the passage dependence on the splits,
z_t	is the vector of control variables, $z_t = [z_{1;t}; \frac{C-t_m}{C} - z_{1;t}], t_m$ is the total time of the inter-green signal
F	vector 9×1 adds the typical courses of intensities,
e	is the state noise.

The output state equation is defined as

$$y_t = C\, x_{t+1} + G_t + \epsilon_t, \tag{9}$$

where

y_t	vector of all measured quantities, $y_t = [I_{1;t+1}; I_{2;t+1}; O_{1;t+1}; O_{2;t+1}; y_{5,t}]'$,
y_t	is the sum of the passages from the preceding arms to the arm No. 5,
C	matrix 5×9 reflects directional relations of the junction,
G_t	vector 5×1 adds the typical courses of intensities and densities,
ϵ_t	is the output noise.

7 Kalman Filter

The state model 8, 9 was used for the common version of the Kalman filter to estimate values of the state vector from the measured data. In our case, the state model is partially based on the relations that are supposed to be known, i.e. given by the physical nature of the transportation system (they are (5)) and partially on the relations that are unknown and have to be estimated (they are (7)). So before the Kalman filter can run, the estimation has to be performed. For testing, we used standard procedure from the Identification package of MATLAB. This estimation is performed in off-line mode, from prior data sample, lately it can repeated with further data and thus the parameter estimates are set more precise. After estimation, the unknown parameters of the state space model are replaced by their estimates and the Kalman filtration can run. During it, the state is identified, i.e. both the queue length and the unmeasured input intensities are estimated. In this way, we have all we need for the linear optimization.

8 Formulation of the Linear Task

What we need here, is to adapt the previously constructed state space model (8), (9) into the form (1), (2), (3) suitable for straightforward application of linear programming. First we have to compose the vector (1), which enters both, the criterion (2) and the system of restrictions (3). The widely used criterion in the traffic control problems is the total delay of vehicles, passing through the microregion. As the majority of the time spent in the microregion is due to standing in queues, we will specify the criterion as a sum of lengths of all queues in the microregion. The restrictions in our case are given by the state space model (8), where the state vector x occurs. Finally, we want to minimize the criterion by adjusting the input variables z. From this follows, that the vector s from (1) must contain (i) the queue lengths, (ii) the state vector x (which is in accordance with (i)) and (iii) the input variables z. So, the following vector s_t at time t must be constructed

$$s_t = [x'_{t+1}, z'_t]'. \tag{10}$$

Then the criterion is

$$J = \xi_{1;t+1} + \xi_{2;t+1} = [1, 0, 1, 0, \ldots, 0] s_t \tag{11}$$

and the major part of restriction is given by (8)

$$x_{t+1} - B z_t = P s_t = A \hat{x}_t + F, \tag{12}$$

where

I	a unit matrix of appropriate dimension and $P = [I, -B]$,
$\hat{x}_t$	point estimates of the last state,
noise	is substituted by its mean value, which is zero.

As the right-hand side of the above equations (12) are constants, the equations represent the restrictions in the form of the equalities. Other restrictions of the same type are laid on the input variables. The relative green times with respect to the cycle (the splits) must be some constant smaller then 1, due to the intergreens. The condition can be constructed as follows

$$[0, \ldots, 0, 1, 1] s_t = 1$$

and can be added to the previous restrictions.

Finally, all queue lengths and splits must be nonnegative, so the last restriction is in the form of inequality

$$\mathrm{diag}([1, 1, 1, 1, -\infty, \ldots, -\infty, 1, 1]) s_t > 0,$$

where

diag(.)	a diagonal matrix, with the specified diagonal,
0	a vector of zeros of appropriate dimension.

With this denotation, the task is prepared for standard use of linear programming.

9 Experiments

For experiments, the junction structure defined above (see 6.1) was used. The typical daily courses of modelled intensities and densities were derived from the real data measured in Prague. The derived typical courses of the measured variables are shown on the figures 1.

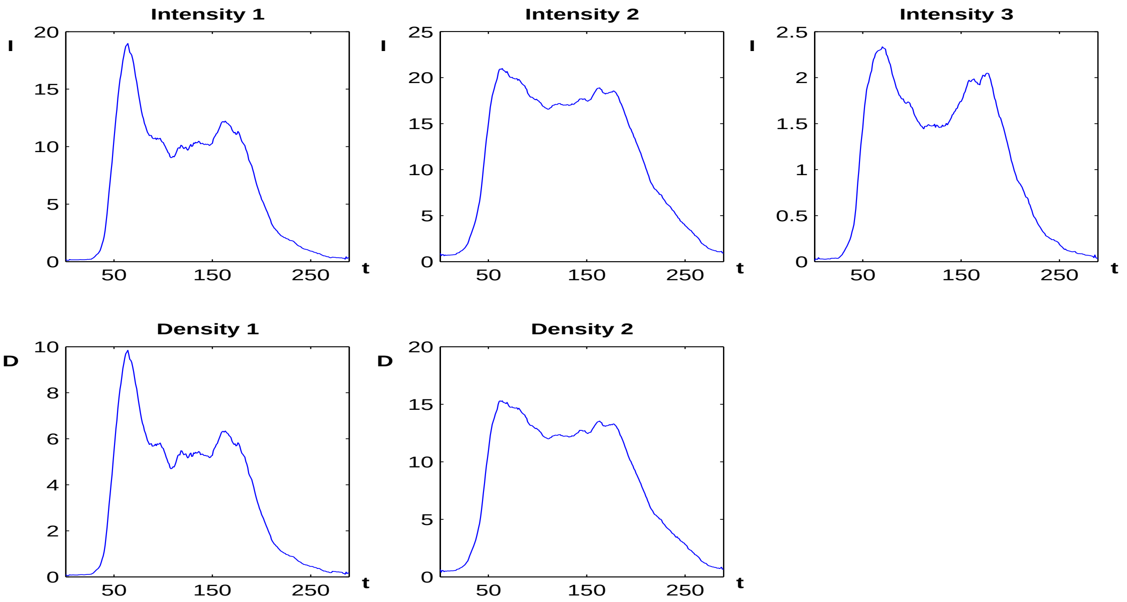

Figure 1: Typical daily course of intensities and densities

This typical daily courses and the model structure (8, 9) with fixed parameters were used for the simulation and also the same structure for the estimation by the Kalman filter. Moreover, a disturbance was added to the first state, i.e. queue length 1. We simulate and estimate the courses and states during one day which represents 288 measurements (in 5 minutes sample period). The simulated queue lengths and their estimates are plotted in the following figure 2.

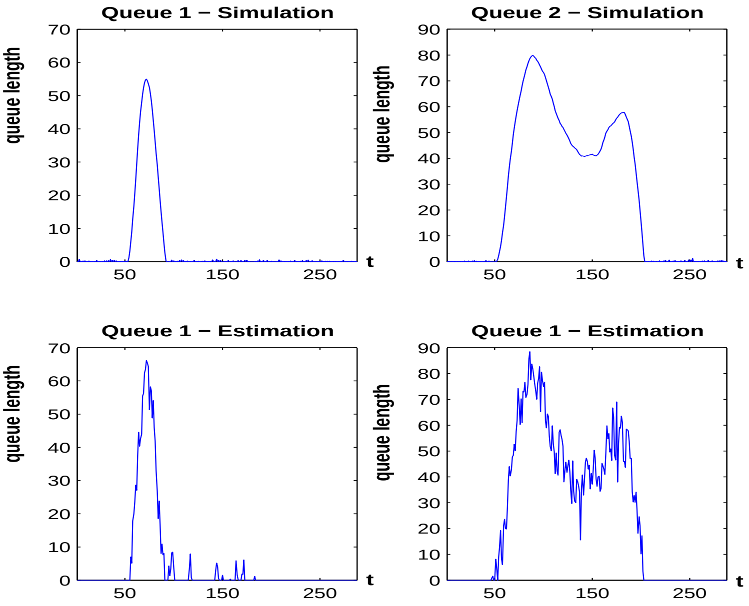

Figure 2: Courses of simulated and estimated queue lengths

As it can be seen, the estimated and simulated curves match well, despite the estimation disturbance of the first queue. The most conclusive experiment, which proofs the efficiency of the proposed optimization method, is the comparison of the automatically and manually controlled junction. We made a control during one day. First, we control the junction optimally by junction parameters but the setting of control variables is constant all the time. Second, we control automatically - the setting of control parameters is changing owing to actual data values. The optimization criterion is the minimal sum of both queue length.

The queue length courses are shown for both cases in the following figures 3 nad 4. Solid lines represent the queue length, the splits are plotted by crosses.

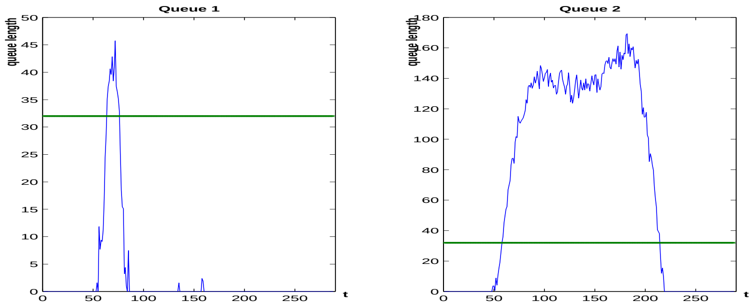

Figure 3: Manually controlled junction

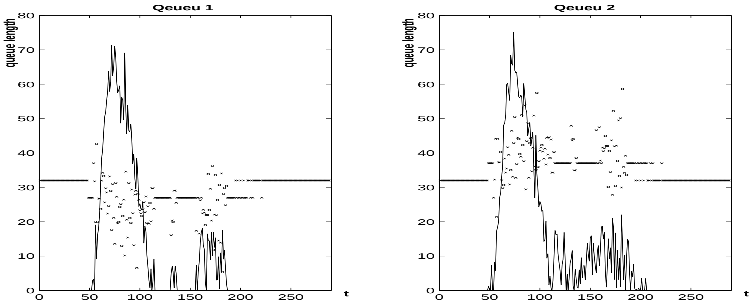

Figure 4: Automatically controlled junction

10 Conclusions

The object of our research is the control of the urban network and the control of the microregion is the first step towards it. In the recent time, we have found the description of microregion by the state model. We have to estimate some of the parameters to get the observable and stable model but this off-line estimation runs without any problem and, moreover, we obtained the feasible form of the model. This form allows to add any new relation between the arbitrary model variables with respect to new measurements. The experiments gave the good results (see figures) and so the proposed method seams to be very promising.

References

Abu-Lebdeh, G. (2002), “Integrated adaptive-signal dynamic-speed control of signalized arterials,” *Journal of transportation engineering, ASCE, Reston*.

Beck, J., Lagová, M., and Zelinka, J. (1982), “Lineární modely v ekonomii,” *SNTL/ALFA, Praha*.

Diakaki, CH., Dinopoulou, V., Aboudolas, K., and Papageorgiou, M. (2002), “Signal MAnagement in Real Time for urban traffic NETworks,” *Deliverable 9: Final System Development Report, IST-2000-28090, Technical University of Crete*.

Heydecker, B.G., and Dudgeon, I.W. (1997), “Calculation of signal settings to minimise delay at a junction,” *Elsevier Science Publishing*.

Heydecker, B.G. (1996), “A decomposition approach for signal optimisation in road networks,” *Transportation Research, vol. 30, no. 2, Elsevier Science Ltd, Great Britain*, pp. 99-114.

Hong, K.Lo (1999), “A novel traffic signal control formulation” *Transportation Research Part A, vol. 33, Elsevier Science Ltd, Great Britain*, pp. 433-448.

Hong, K.Lo (2001), “A cell-based traffic control formulation: Strategies and benefits of dynamic timing plans,” *INFORMS, Transportation Science, vol. 35, no. 2*, pp. 148-164.

Hong, K.Lo, Chang, E., and Chan, Z.Cho (2001), “Dynamic network traffic control,” *Transportation Research Part A, vol. 35, Elsevier Science Ltd, Great Britain*, pp. 721-744.

Hong, K.Lo, and Chow, H.F. (2002), “Adaptive traffic control: Control strategy, prediction resolution and accuracy,” *Journal of advanced transportation: ITS Special Issue, 36(3)*, pp. 323-347.

Kárný, M., Halousková, A., Böhm, J., Kulhavý, R. and Nedoma, P. (1985), “Design of linear quadratic adaptive control: Theory and algorithms for practice,” *Kybernetika, vol. 21, Supplement to No. 3, 4, 5, 6*.

Kárný, M., and Nedoma, P. (1998), “Automatic Processing of Prior Information with Application to Identification of Regression Model,” *ACASP*.

Kratochvílová, J., and Nagy, I. (2003), “Bibliographic Search for Optimization Methods of Signal Traffic Control,” *Research Report, CAS, Prague*.

Nagy, I., Kárný, M., Nedoma, P., and Voráčová, Š.(2003), “Bayesian estimation of traffic lane state,” *International Journal of Adaptive Control and Signal Processing, vol. 17, no. 1*, pp. 51-65.

Peterka, V. (1981), “Bayesian approachto system identification,” *Trends and Progress in System Identification,Pergamon Press,Oxford*, pp. 239-304.

Přibyl, P., and Svítek, M. (2001), “Inteligentní dopravn í systémy,” *BEN - technická literatura, Praha*.

Valečková, M., Kárný, M., and Sutanto, E.L. (1998), “Bayesian M-T clustering for reduced parameterization of Markov chains used for non-linear adaptive elements,” *Preprints of the IFAC Workshop on Adaptive Systems in Control and Signal Processing, IFAC, Glasgow*, pp. 381-386.

Whittaker, J., Garside, S., and Lindveld, K. (1997), “Tracking and predicting a network traffic process,” *Elsevier, International Journal of Forecasting 13*, pp. 51-61.

Wong, C.K., and Wong, S.C. (2002), “Lane-based optimization of traffic equilibrium settings for area traffic control,” *Journal of advanced transportation, INST Transportation, Calgary*.