TRAFFIC FLOW CONTROL

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Abstract: The paper introduces a new concept of the hierarchical regulator of the traffic flows. This regulator has two control levels: (i) the local control of micro-regions, and (ii) the coordination of whole traffic region consisting of several micro-regions. Its aim is to derive such a signal setting of the traffic lights that is optimal for the actual traffic conditions. State space model of micro-region is based on using maximum utilization of available information from all measured traffic variables and it estimates lengths of queues formed on arms of junctions with traffic lights. The queues are calculated according to the hydrodynamic analogy and their values are corrected by Kalman filtering in case of defects or measurement inadequacy. The model for the coordination is derived analogically. The control variables are relative green signals of all junctions included. Both models and all variable restrictions are linear and this fact allows us (on condition of linear criterion) to use the linear programming as the optimization tool. For this reason, the criterion is the minimization of the sum of the weighted queue lengths. The model and control strategy efficiency is demonstrated by several experiments.

Keywords: traffic flow control, queue length model, Kalman filter.

1. INTRODUCTION

Better traffic control is the only way how to solve problems caused by an increasing number of vehicles in our cities. It is still more and more complicated and expensive to magnify the existing traffic infrastructure, mainly in historic city centers. The way how to decrease congestions during the peak hours is to apply a proper control via traffic signal lights. Reduction of the passage time through a traffic area and the lost time brings strong positive environmental impacts and improving the quality of a daily human life [Kratochvílová and Nagy (2003)].

Many control systems for urban traffic have been designed [Papageorgiou et al. (December 2003)] but the universal and definitive solution was not still found because of the stochastic and area depended nature of the traffic. Traffic flow models usually model dependence of velocity or density on intensity. Due to their general relations, such models are non-linear [Papageorgiou et al. (December 2003)]. It is also possible to model other traffic quantities like a number of vehicles within a link in dependence of inflows and outflows of the link [Diakaki et al. (2002)]. The basic principle of traffic flow control is traditionally minimization of the lost times, the passage times and the number of stopping during a journey, which are proportional to the queue length [Ch. Diakaki (2002)]. Such criteria are usually quadratic and linear-quadratic control method is often used.

In this paper, we design a concept of the traffic regulator suitable for traffic flow control. The suggested models of the regulator describe the mentioned problem in a linear way. The proposed local model counts and estimates the queue length using maximum available traffic information. This task is trivial in case of complete knowledge of all measured traffic quantities for all junction arms. Then, the model simply counts the queue length from known input and output intensities. However, the net of all needed detectors is not usually complete and some significant traffic flows (parking cars, etc.) are not measurable in practice. In this case, the model estimates the queue length relative to modelled and estimated traffic characteristics.

The coordination level of the controller ensures minimize blocking of a crossing area for component microregions in the traffic region. The aim is to balance traffic loads of microregions. Model for this control level counts amounts of vehicles within microregions. The state estimation is precise enough on the local level, therefore no other estimation is needed at the coordination level.

2. TRAFFIC DATA

The basic data that are necessary for an on-line traffic flow control are measured by traffic detectors. These devices can measure several traffic characteristics like occupancy, intensity, velocity or density. In practise, only two of them are always measured:

Occupancy: determines relative time of the detector activation during sample period, i.e. the proportion of time when the detector has been occupied and the total time of measuring period. The occupancy unit is [%].

Intensity: denotes the number of vehicles which have passed a detector during sample period. Usually, value of this quantity is transformed into an hourly intensity of unit vehicles, i.e $[uv/h]$.

Intensity captures the queue dynamics in the sense of the queue protraction but it does not fully determine the actual situation - the value of intensity can be low because of low traffic or high density which are two converse traffic situations. Intensity is very important information for considered models from a counting point of view.

Occupancy has similar meaning as density and, moreover, it is usually measured. Higher density decreases the vehicles velocity and intensities and queues are formed on the arms. That is why the value of occupancy of the detectors under the queue increases. Conversely, if the vehicles can go through faster in case of low traffic and they loose minimal time by queueing, the occupancy decreases.

3. REGULATOR DESIGN

It is assumed that the regulator has three control levels in total: (i) junction level, (ii) local level, and (iii) coordination level. Control of a single junction is realized through a traffic distributor implemented in signal traffic lights equipment of the junction. This control level can adjust the length of green signals of all phases included in a junction signal scheme. The changes are made during the cycle using the actual measurements after an evaluation of a logic condition. The green signal can be only extended or shortened by the given increment. This control level is already implemented in practice. Therefore, in this paper, only design of local and coordination control levels is considered.

The controller levels communicate with each other in terms of intervals of green splits. The optimized green splits are not used directly in their absolute values but they are used for an assessment of the interval bounds. The coordination level prescribes the splits bounds for the local level and then these bounds can be changed again by the local level. The final splits bounds are given to the junction control level. The medians of intervals are supposed to be set for the actual signal scheme, the traffic distributor can change them only in the given bounds.

4. LOCAL LEVEL

The local level controls traffic flows in a microregion that is a part of whole traffic region consisting from several junctions with traffic lights. A microregion is delimited by strategic detectors. The local level state space model counts queue lengths that are formed on junction arms during the day in consequence of light signal control of the traffic. The model consists of two basic equations for each arm in a microregion where vehicle queueing is possible. The first one is a hydrodynamic analogy for a queue length and traffic inflows and outflows:

$$\xi_{t+1} = \xi_t + I_t - P_t, \tag{1}$$

where

ξ_{t+1}	queue length at time $t+1$ $[veh/T_p]$;
I_t	input intensity $[veh/T_p]$;
P_t	output intensity (passage) $[veh/T_p]$;
T_p	sample time $[h]$.

As can be seen, no queue length can be counted without prior information. However, it is easy to assume that there are zero queues at night. Passages from arms depend on the actual traffic situation. he structural arrangement of the junction (or the corresponding quantity of the saturation flow) and the actual control (or the relative duration of the green signal) determine the capacity of a given arm, i.e. the maximum number of vehicles that can pass safely the junction during the green light. According to initial traffic conditions, a passage through the junction can be less or equal to its. In an simplified way, if the number of vehicles is higher than the capacity, only the capacity can pass the junction. If not, the whole demand can be satisfied during one cycle. The passage from an arm can be determined by the following equation:

$$P_{i;t} = (1 - \delta_{i;t})(I_{i;t} z_{i;t} + \xi_{i;t}) + \delta_{i;t} K_{i;t}, \qquad (2)$$

where

- $P_{i;t}$ passage from arm i at time t;
- $I_{i;t}$ input intensity of arm i;
- $\delta_{i;t}$ indicator of passage from arm i;
- $z_{i;t}$ split (relative green time) for arm i at time t.

The second equation is a presumptive linear relation between occupancy and queue length:

$$O_{t+1} = \kappa_1 \xi_{t+1} + \kappa_2, \qquad (3)$$

where

- O_{t+1} occupancy on an input junction arm at time $t+1$ [%];
- κ_1, κ_2 coefficients of linear relation;
- ξ_{t+1} queue length on the same arm at time $t+1$.

This relation is used for the correction of the first one (1) and it was derived theoretically. In practice, it was shown that this relation is not purely linear but increasing and slightly quadratic Diakaki (1999). The increasing course was also proved by simulation using a traffic microsimulator. The model efficiency has been also tested with disruption of this relation. In spite of very strong disruption, the estimates are still satisfactory.

5. STATE ESTIMATION

The net of junction detectors nets can be imperfect with respect to our measurement needs and some traffic flows that can reach significant intensities (parking, etc.) are not even measured or measurable at all. Some traffic net parameters need not to be accurate and that is why the state estimation is also realized on the local level. The state estimates (queue lengths and input occupancies) are corrected through Kalman filter by prediction errors that are counted in dependence of actual measurements of output intensities and input occupancies. It is assumed that not only all input detectors but also some output detectors are at disposal. Thus the output vector consists of occupancies of all input arms (with input detector) and intensities of all measured outputs.

Two equations form the output model: equation for output intensity and equation of identity for occupancies. The output intensity for the junction arm is given by weighted sum of passages from remainder junction arms to this output arm:

$$y_{h;t} = \sum_{i \neq h} \alpha_{ih} P_{i;t}, \qquad (4)$$

where

- α_{ih} weights (direction ratios).

6. COORDINATION LEVEL

The coordination level of the controller ensures minimization of blocking of a crossing area for component microregions in the traffic region. The aim is to balance traffic loads of microregions that can lead to a displacement of an unwanted traffic behind the border of a microregion.

The prior value of the state vector that is composed from amounts of queueing vehicles inside a microregion is counted from the queue length estimates. Each microregion is represented by sum of queues in the microregion with the exception of those on the microregion borders that are not between two optimized microregions. It means that there are added all queues with directly controlled or control depended input intensity:

$$X_{m;t} = \sum_{k} \xi_{m,k;t} \qquad (5)$$

where

- $X_{m;t}$ amount of vehicles inside the microregion m;
- $\xi_{m,k;t}$ length of queue k inside the microregion m.

Model for this control level models states by the same hydrodynamic analogy as (1):

$$X_{m;t+1} = X_{m;t} + I_t^{total} - P_t^{total}, \qquad (6)$$

where

- $X_{m;t+1}$ amount of vehicles inside the microregion m;
- I_t^{total} total input intensity at the microregion m;
- P_t^{total} total passage from the microregion m.

The total input intensity for a microregion is given by sum of all intensities of those input junction arms that are also inputs arm of the whole microregion. The total passage is also derived analogically. It is given by sum of passages from output arms that are also outputs of the microregion.

The coordination level uses the state estimates of queue lengths, derived on the local level. The estimation is precise enough, thus no other estimation and, consequently, no correction equation at the coordination model is needed.

7. CONTROL

The traffic flows can be controlled only by changing of signal scheme parameters. In general, cycle times, coordination offset times or signal proportions at phases (i.e. splits) can be changed. In this paper, we focus only on control of splits. We suppose that all coordination offset times between junctions are set optimally and all cycle times are constant. From point of whole traffic region view, it means, that green waves can be made and the prior design of all signal scheme is relevant, thus composition, number and sequence of phases is optimal.

The control strategy is aimed to determine optimal proportions of green and red signal for each phase of a signal scheme. Thus, the amounts of passing cars (and junction capacities) can be influenced. The main constraint for each signal scheme and all phases included is:

$$1 = \sum_f t_f / T_C + \sum_f z_f. \tag{7}$$

where

- t_f phase offset (security time distance from start of next phase green);
- T_C cycle time (period of traffic signals repetition);
- z_f split for the phase f.

Besides the cycle constraint and the model equations, other constraints are given by non-negativity of all variables and minimal allowable green time (5 seconds in the Czech Republic).

All modelled relations and all traffic variables constraints considered for optimization are linear and this fact allows us to use linear programming as the optimization method for determination of the required control parameters.

The optimization criterion is minimization of the weighted sum of all queue lengths in a microregion for the local level:

$$J_m = \sum_{i=1}^{n} w_i \xi_{m,i;t} \tag{8}$$

where

- J_m value of criterion for the microregion m;
- n number of queues in the microregion m;
- w_i weight (e.g. preference of some directions);
- $\xi_{m,i;t}$ length of queue i in the microregion m.

This requirement ensures the balanced queue lengths for each junction. The weights can be set with respect to the traffic preference of some directions in the traffic net.

It is not easy to specify a control criterion for the coordination level. One possibility is to minimize the difference between the weighted amounts of vehicles inside the microregions. In case of two microregions only, the criterion can looks like:

$$\begin{aligned} J_1 &= w_1 X_{1,t+1} - w_2 X_{2,t+1} \rightarrow \quad min \quad or \\ J_2 &= w_2 X_{2,t+1} - w_1 X_{1,t+1} \rightarrow \quad min \end{aligned} \tag{9}$$

where

- $X_{h,t+1}$ amounts of vehicles inside the microregion h;
- w_h weight.

The control criterion for the coordination level is chosen in dependence of the sign of the residuum. The weights are set with the respect to the sizes of the partial microregions.

8. EXPERIMENTS

The proposed local model and estimation algorithms were tested with respect to their basic properties and efficiency, including case studies of disturbances that can arise in practice, such as the memory defect, incorrect model parameters or a disruption of linear relation between occupancy and queue length. The results were very good and proved the meaningfulness of the proposed models and the estimation algorithm for different microregions (1, 2 up to 10 junctions).

These initial experiments allowed to test the whole conception of the traffic regulator. The tested region consisted of two microregions formed by 4 (first microregion, $M1$) and 6 (second one, $M2$) signal controlled junctions. The border between the microregions consisted of one input and one output arm for each microregion only. In the region, there were five measured inputs, three of them in the first microregion. There were also 3 measured output detectors for each microregion. The signal schemes for all junction were two-phased and we know prior traffic solution (the consequence of phases and all junction parameters).

In the experiments, real input intensities were used in order to keep the experiment close to reality. The occupancies, output intensities and queue lengths had to be digitally simulated because the corresponding measurements were not at our disposal. The first experiment (Exp1) represents the situation without any control. The splits were constant during the whole day. Next experiment (Exp2) aimed at local control of microregions only and the third one (Exp3) at local together with coordination control.

The last experiment (Exp4) aims again at the local control but of the transformed microregion. The whole traffic region was reconsidered as one single microregion of 10 signal control junction and local control strategy was applied. Such control should be optimal. If we divide this region into two microregion and apply the local control including the mutual coordination, the solution would be always only suboptimal. This experiment was important for finding how close is such solution to the optimal one.

The solutions were assessed by average queue length (AQL) that is thetime average of sum of all queue length in a microregion. The results of the described experiments were the following:

AQL	Exp1	Exp2	Exp3	Exp4
M1	236	100	65	-
M2	131	103	101	-
M1+M2	367	203	166	149

It is shown that each control level improves traffic situation over the fixed control and the suboptimal solutions are closed to the optimum.

9. CONCLUSIONS

The aim of this paper was to introduce new concept of a hierarchical traffic regulator, specially its local and coordination level. The local level controls traffic flows in a traffic microregion. A state space model for description of traffic microregions determines queue lengths formed on junction arms during the day in consequence of the traffic signal control. Some traffic net parameters need not to be accurate and therefore the state estimation is also realized on the local level.

The aim of the coordination level is to prevent negative influences between microregions. This aim is realized by balancing their traffic loads. The model determines queueing vehicles within microregions. The coordination level uses the state estimates of the queue lengths, derived on the local level, thus no other estimation is needed at the coordination level.

All modelled relations and all traffic variable constraints considered for the optimization are linear and this fact allows us to use linear programming as the optimization method for determination of the required control parameters.

The basic properties and efficiency of the proposed models, estimation and control algorithms were tested, including case studies of disturbances that can arise in practice. The results are very good and it is shown that each control level improves traffic situation over the fixed control.

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