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Using the intelligent unit for traffic management of saturated urban road networks

V. FALTUS[a], T. TICHÝ[b], Z. BĚLINOVÁ[a]
[a] CZECH TECHNICAL UNIVERSITY, Faculty of Transportation Sciences, Praha 1, Czech Republic,
[b] ELTODO DOPRAVNÍ SYSTÉMY, S.R.O, Praha 4, Czech Republic
EMAIL: faltus@fd.cvut.cz

ABSTRACT

Telematics systems development has already become a necessity due to the limited capacity of the road infrastructure. Transport can thus be better managed; also relevant information can be provided directly into the vehicles. Based on the development of communication technologies, namely „car-to-infrastructure" (C2I), the requirements are continuously rising – not only on the on-board units (OBU) but also on the infrastructure equipment and solution of particular modules for traffic management systems as well. The paper focuses on the design and simulation of control system in an intelligent unit on infrastructure that will be able to respond to the actual traffic situation and to communicate with the vehicles. The goal of this paper is to present the possibility of using such units in urban road infrastructure and to present an approach to traffic nodes management for saturated or over-saturated traffic states.

KEYWORDS: traffic, ITS, telematics, urban traffic control

1. Introduction

Development of urban traffic, as can be seen in periodic traffic yearbooks in the Czech Republic, is still rising. For example, there was an increase in traffic of 36% in Prague since 2000. Traffic in the whole Czech Republic increased of 35% on motorways and I., II. and III. class roads.

The number of cars in the Czech Republic in ratio to population increased of 16% since 2000. The number of cars in Prague is 1 car/1,8 resident. This ratio puts Prague among the cities with the highest level of motorization in Europe. This trend can be noticed in other cities in the Czech Republic as well, also in the context with the economic development of the countries of Central and Eastern Europe.

The present trend in traffic telematics is acquiring new information using communication interface "vehicle – infrastructure" (V2I or C2I) and then the application of this information to inform drivers and traffic management, including relevant control methods on the level of controller optimization at the intersection or in the transport network in general. The vehicle have to be equipped by a communication unit for the "vehicle – infrastructure" communication, which is in the vehicle usually a part of the OBU (On-board Unit), in the infrastructure located on the RSE (Road-Side Equipment).

Another option for modern telematic systems is a communication among vehicles themselves, resp. their OBUs. This communication is called V2V (or C2C), and as well as V2I communication is a part of the cooperative systems.

DSRC system (Dedicated Short-Range Communication) is the most frequently used for V2I communication. It is a wireless communication, using frequency band 5,8 – 5,9 GHz. This frequency band is earmarked specially for the use in road transport. Other communication options are RFID systems, CALM, WiFi, etc. There are systems waiting for put into practise, which provide traffic information and communication between node/traffic controller and vehicle.

CALM architecture could help the development of "vehicle – infrastructure" communication. CALM (Communication Access for

Land Mobile) is a package of standards developed by International Standardization Organization (ISO), enabling communication of any ITS application using any wireless technology. CALM defines the interface for wireless communication for medium and long distance at mutual high speeds. The network layer contains other IP protocols as well (CALM FAST).

The advantage of direct communication between vehicle and infrastructure is the use of this communication for information distribution and also as the input for new control algorithms (including managing of oversaturated road network). To be able to achieve this, construction of specialized infrastructure is necessary. This issue is discussed in the ALFA program, funded by TAČR (TA02031360) – Universal Intelligent Control Unit (UNIR).

2. Traffic management in oversaturated networks

In this chapter, the description of the chosen suitable method is presented in more details. The method is called split optimization and it is being developed in cooperation with the UNIR project for possible testing and implementation into universal control unit. The basic features of the split optimization and demonstration of its specific use in isolated signalized intersection are below. The aim is to use the methodology on other traffic situations, even though the method is primary for intersections, and thus transform and verify the method in simulation.

The aim of the split optimization is to find the optimal signal program for the following control cycle based on current traffic situation [1]. The goal is to react and adapt to the actual available information about the traffic flow, not to change the control in the long-term (such as hours). This means that the signal plan is updated after each cycle, similar to the control method based on queue lengths.

The adaptive control is proposed as an extension over the classical dynamic control. However the response to the most variable features of the traffic flow remains at the level of dynamic control i.e. especially extension of the phases or the phases selection is not affected by the adaptive control. Adaptive control "just" adapts maximum duration of each phase in a dynamic control, resp. its inclusion into the extension traffic area or coordinated group of traffic lights.

3. Choice of optimization parameters

In the proposed control method, the utilization of intersection entrances and the delays of vehicles are the chosen optimization parameters [1].

Generally, the split optimization normally optimizes the queue lengths, or according to reserve of the entrances utilization (reserve of traffic lights capacity). Both cases are similar, because of high entrance utilization over a value 1 (insufficient capacity of traffic lights) generates (or extends) queue length (number of vehicles) in the amount corresponding to the surplus of the capacity.

Optimization according to reserve of intersection entrances utilization is one of the chosen optimization method. The advantage of this method is that it aims to compensate the utilization of all intersection entrances, i.e. primarily to minimize the passage of vehicles in more cycles of traffic lights. By traffic detection on the intersection entrances we observe the ratio of input flow and capacity of traffic lights (output flow of vehicles) given by the green time, cycle time and saturated flow. But with the condition of the same utilization of all entrances (optimal state) it means that if the entrance utilization is over a value of 1 there are longer queues for the overloaded entrance then for the other entrances. Travel time in long and short queues is then similar, causing larger total delay of all vehicles in the intersection and worse PI (performance index), comparing to supporting the overloaded directions. Capacity condition also leads to the selection of the maximum cycle time, which does not have to be always advantageous for travel time. For this reason, the capacity condition is not the only optimization criterion in the proposed method.

Another parameter, the degree of saturation, was found unsuitable as the optimization criterion because it depends on the relationship between intersection inputs and road parameters and does not have direct relation to the creation of queues and delays.

Optimization according to the length of queues (i.e. according to the difference between the input flow and capacity of traffic lights) needs not to be beneficial for the performance index of all vehicles. While it leads to similar lengths of queues at all entrances, in principle it does not distinguish how long vehicles stay in these queues. Although it appears that queues of the same length support the directions with higher flows (where vehicles are delayed shorter time), the delay in this type of optimization is not the direct optimization criterion. This was the reason, why the delay was chosen as the second optimization criterion in the proposed control method.

It is clear, that optimization according to delay of vehicles can lead to the situation, when the minimum delay of all vehicles means queue generation of in some intersection entrance even when for another optimization the queue does not form at all. That's why the optimization algorithm is set that if there is a risk of exceeded entrance utilization value, the preferred criterion is the entrances utilization instead of total delay of vehicles.

4. Utilization of intersection entrance for optimization

The reserve of utilization of intersection entrances, resp. the capacity reserve on light signalling equipment, is the first optimization criterion. In order to determine the reserve of utilization, it is first necessary to determine the actual capacity of the light signalling equipment. With the capacity of light signalling equipment for the intersection entrances, to the demands N of these entrances – outputs from the model – are compared. This comparison is characterized by the utilization of the intersection entrance ρ [1].

The aim is therefore that all vehicles present at the entrance of the intersection passed the intersection in one cycle. The minimum green time which allows passage for all current vehicles entering the intersection is given by the following relation:

$$t_{gs} = 3600\frac{N}{q_s} \qquad (1)$$

N Number of vehicles at the intersection entrance, which is going to drive through the intersection in a given cycle (veh)
q_s Saturated flow at the entrance to the intersection (veh/hr)
t_{gs} Minimum (required) green time for the passage of all the vehicles at the intersection entrance (sec)

For the current proposed maximum green time, the following relation applies:

$$t_g = 3600\frac{N_c}{q_s} \qquad (2)$$

N_c Maximum number of vehicles at the entrance, which can pass the intersection in a given cycle at the proposed signal program (veh)
q_s Saturated flow at the entrance to the intersection (veh/hr)
t_g Proposed green time for appropriate intersection entrance (sec)

Number of vehicles N is the output from the mathematical model based on the data measurement on intersection detectors and the data transferred using V2I communication. With the knowledge of relations (1) and (2), the utilization of the intersection entrance is expressed also by the time the green times as follows:

$$\rho = \frac{t_{gs}}{t_g} \qquad (3)$$

ρ Intersection entrance utilization coefficient
t_g Proposed green time for appropriate intersection entrance (s)
t_{gs} Minimum (required) green time for the passage of all the vehicles at the intersection entrance (sec)

Optimization is then performed that it attempts to minimize the maximum capacity reserve of the intersection entrance for the proposed signal program. The relations (1) and (2) apply, provided that the vehicles are passing the light signalling equipment "productively" in the saturated flow. The reality is slightly different, but due to the subsequent ratio utilization in the equation (3), this deviation can be neglected.

5. Delays of vehicles on the light signals for optimization

During the split optimization, one of the optimization criteria are delays of vehicles on light signalling equipment. The delays of vehicles can be divided into two components: the delay t_{d1} on signals itself during the cycle time, and the delay t_{d2} in a queue. The queue is considered here as a case where the vehicles are passing the intersection during more than one cycle. Then the optimization criterion [1] can be written as follows:

$$J = \sum_i t_{dc} = \sum_i \left(t_{dc1} + t_{dc2}\right) = \sum_i \left(\sum_1^N t_{d1}(n) + \sum_1^N t_{d2}(n) \right) \to \min \qquad (4)$$

i Intersection entrance index
J Optimization criterion
n Order of the vehicle at the intersection entrance
N Number (claim) of vehicles at the intersection entrance (veh)
t_{d1} Average delay time of one vehicle on the signals (sec)
t_{d2} Average delay time of one vehicle in the queue (s)
t_{dc} Total delay time of all vehicles at one intersection entrance (sec · veh)
t_{dc1} Total delay time of all vehicles on the signals at one intersection entrance (sec · veh)
t_{dc2} Total delay time of all vehicles in the queue at one intersection entrance (sec · veh)

The resulting delay time is not possible to directly transform as an optimization criterion for the selection of a suitable cycle time and green time, because it is not dependent on the proposed signals, but on the current signals, resp. currently measured traffic. Total delay estimation for any (proposed) signal set is possible to do through the knowledge of current claim N of vehicles at the intersection entrances. During the split optimization, it is therefore necessary to estimate the delay on the signals different from the actual values, depending on the proposed arrangement of the signal program and the current claim N.

Vehicle delays t_{d1} on the signals during the cycle time depend on the random arrivals of the vehicles at the intersection. We are now not considering a coordinated section where this randomness does not apply and the delay time decreases significantly. In the case when the vehicle arrives at the green or yellow[1] signal, the delay time is zero. In the case when the vehicle arrives at the red or red-yellow[2] signal, the delay time varies – corresponds to the time to the beginning of the green signal.

This situation is well illustrated in Fig. 1, where the purple curve shows the vehicle delay depending on the arrival time at the signalized intersection. The horizontal axis shows the elapsed time, and the vertical axis displays the delay time of the individual vehicle. The proposed cycle time is indicated as t_c and the proposed green time as t_g. The largest delay is always just at the beginning of the red signal, the value of the delay equals to the red signal time plus red-yellow signal time (incl. in the red part in the Fig. 1).

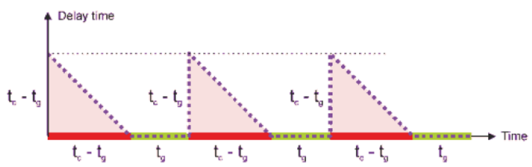

Fig. 1. Delay time on the signals depending on the arrival time at the signalized intersection [1]

[1] Transition signal between the green and the red signal used in the Czech Republic and more countries.

[2] Transition signal after the red before the green signal used in the Czech Republic and more countries.

The total delay time t_{dc1} on the signals in case of random vehicle arrivals for proposed cycle time t_c and green time t_g then corresponds to the product of the number (claim) of vehicles at the intersection entrance and the average vehicle delay time of one vehicle. The formula can be obtained based on Fig. 1. The average delay time of one vehicle $\overline{t_{d1}}$ is the total delay time per cycle divided by the cycle time.

$$t_{dc1} = \sum_{1}^{N} t_{d1}(n) = N \cdot \overline{t_{d1}} = N \frac{(t_c - t_g)^2}{2 \cdot t_c} \tag{5}$$

N Number of vehicles at the intersection entrance, which is going to drive through the intersection in a given cycle (veh)
t_c Proposed cycle time (sec)
t_{dc1} Expected total delay time on signals (sec)
$\overline{t_{d1}}$ Expected average delay time on signals (sec)
t_g Proposed green time for the appropriate intersection entrance (sec)

The delay on signals shown above applies to all vehicles entering the intersection and practically depends only on the randomness of arrivals of the vehicles at the intersection.

The second part of the vehicle delay then reflects the time spent in the queue for those vehicles which fall into the queue. The time spent in the queue corresponds to the number of the cycles during which the vehicle not passes the intersection. Number of vehicles N_c, which passes the intersection during one proposed cycle time, resp. one proposed green time, is derived from the current claim N of vehicles at the intersection entrance and utilization of the intersection entrance ρ. Relation (6) follows from (2) after substituting (1) and (3).

$$N_c = \frac{q_s}{3600} t_g = \frac{N \cdot t_g}{t_{gs}} = \frac{N}{\rho} \tag{6}$$

N Number of vehicles at the intersection entrance, which is going to drive through the intersection in a given cycle (veh)
N_c Number of vehicles at the entrance, which can pass the intersection in a given cycle for the proposed green time (veh)
q_s Saturated flow at the entrance to the intersection (veh/hr)
t_g Proposed green time for appropriate intersection entrance (sec)
t_{gs} Minimum (required) green time for the passage of all the vehicles at the intersection entrance (sec)
ρ Intersection entrance utilization coefficient

With the knowledge of the number of vehicles N_c able to pass the intersection during the cycle time, we can now derive the total delay in the queue t_{dc2} of all the vehicles at the intersection entrance. Some vehicles from N, i.e. from 1 to the number N_c, is not delayed in the queue. Another part, from $N_c + 1$ to $2N_c$, is delayed for one cycle, etc.

This situation is shown at Fig. 2. The purple dashed line shows the model of delays in the queue for the particular part of the vehicles at the intersection entrance. The shaded portion represents the overall delay t_{dc2} of all vehicles at the intersection entrance.

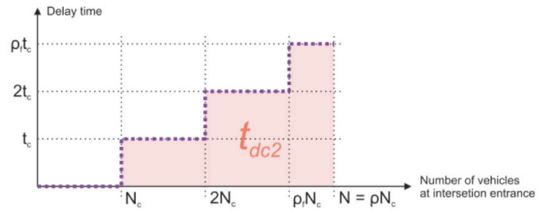

Fig. 2. Delay time in the queue depending on the number of vehicles at the signalized intersection entrance [1]

The total delay in the queue of all vehicles at the signalized intersection entrance is then determined in (7) on the basis of Fig. 2 and knowledge of the relation (6). The value in square brackets corresponds to the area in the scope in the units of ρ. The first part corresponds to the shaded area of the entire rectangles in Fig. 2, the second part to the rest of the shaded area.

$$t_{dc2} = \frac{N}{\rho} t_c \left[\frac{(\rho_f - 1)^2 + (\rho_f - 1)}{2} + (\rho - \rho_f)\rho_f \right] \tag{7}$$

N Number of vehicles at the intersection entrance, which is going to drive through the intersection in a given cycle (veh)
t_c Proposed cycle time (sec)
t_{dc2} Expected total delay time in the queue (s)
t_g Proposed green time for appropriate intersection entrance (sec)
ρ Intersection entrance utilization coefficient
ρ_f Integer part of the intersection entrance utilization coefficient

The total delay of all vehicles at the entrance is then obtained by summing the two parts according to (4), i.e.

$$t_{dc} = t_{dc1} + t_{dc2} = N \frac{(t_c - t_g)^2}{2 \cdot t_c} + \frac{N}{\rho} t_c \left[\frac{(\rho_f - 1)^2 + (\rho_f - 1)}{2} + (\rho - \rho_f)\rho_f \right] \tag{8}$$

t_{dc} Expected total residence time at the intersection entrance (sec)
t_{dc1} Expected total residence time on signals at the intersection entrance (sec)
t_{dc2} Expected total residence time in the queue at the intersection entrance (sec)

6. Microsimulation

The above methodology was simulated in suitable simulation environment. In the UNIR project, the goal is to simulate the control unit itself, not only for the intersection control using the split optimization, but also as a separate functional element or component for "vehicle-infrastructure" communication, containing the control part and also navigation, informing the drivers etc. In the first stage, a model of isolated intersection was used as it is suitable in terms of testing of the proposed algorithm.

The proposed split optimization was simulated on the "ideal" intersection and the algorithm was implemented onto the simulation tool AIMSUN. This tool seems appropriate because it allows creation of software extensions without necessity to purchase special software modules. The tool consists of SW AIMSUN for simulation and allows to create the extensions programmed in language C or Python.

It is not possible to create a universal simulation for any traffic control, that is why an example of "common" four legged intersection was created to verify the proposed algorithm [1]. Communications are bidirectional, lane width is 3,5m, maximum speed is 50km/h.

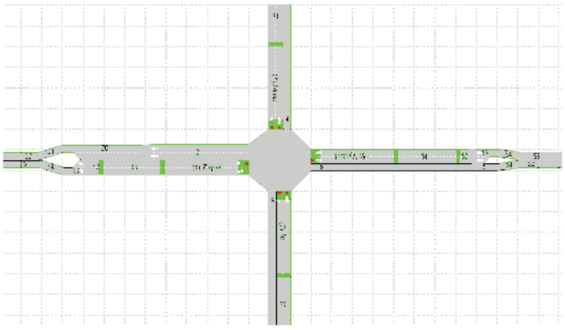

Fig. 3. Situation scheme of the intersection [1]

The results of the test show an improvement in the tens % on the simulated ideal intersection. The proposed system of adaptive control is robust enough. It does not response to each vehicle, but it works with accurate data. Response to individual vehicles is performed by dynamic control according to common practices. Model data are smoothed so that the response is not slow too much. The model of delay estimation is during smoothing set so that precedes information from direct measuring. Direct measuring is loaded with delay, as we find out the travel time at the moment, when the vehicle passes the controlled intersection. The same applies in the case of queue dissipation. Model is set up so it can filter out the excesses caused by stopping of vehicles for transport reasons or blocking the queue by another one when the queues merge in front of the extension detector.

7. Conclusion

The article describes a methodology suitable for a control algorithm implementation, where the capacity of transport network is considered, exactly emerging negative reserves of capacity and their possible solutions. The described methodology was tested in AIMSUN-GETRAM simulation environment, which was chosen as suitable for these purposes. It offers an option of programming in C++ language. The results of simulation using the described algorithm have improvement approximately 15%, which can be considered as practically achievable results in real traffic. If we consider dynamic interventions that improve the capacity by 10-20% according to the defined area, we can reach even further increase of capacity by using the suitable algorithm.

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