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KNOWLEDGE BASED TRAFFIC SIGNAL CONTROL MODEL FOR SIGNALIZED INTERSECTION

Henrikas Pranevičius[1], Tadas Kraujalis[2]

[1]Dept of Business Informatics, Kaunas University of Technology, Studentų g. 56, LT-51424 Kaunas, Lithuania
[2]Dept of Applied Informatics, Vytautas Magnus University, Vileikos g. 8, LT-44404 Kaunas, Lithuania
E-mails: [1]henrikas.pranevicius@ktu.lt (corresponding author); [2]t.kraujalis@if.vdu.lt

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Abstract. Intelligent transportation systems have received increasing attention in academy and industry. Being able to handle uncertainties and complexity, expert systems are applied in vast areas of real life including intelligent transportation systems. This paper presents a traffic signal control method based on expert knowledge for an isolated signalized intersection. The proposed method has the adaptive signal timing ability to adjust its signal timing in response to changing traffic conditions. Based on the traffic conditions, the system determines to extend or terminate the current green signal group. Using the information from its traffic detectors of isolated intersection, the proposed controller gives optimal signals to adapt the phase lengths to the traffic conditions. A comparative analysis between proposed control algorithm, fuzzy logic (FLC) and fixed-timed (pre-timed) controllers has been made in traffic flows control, with varying traffic volume levels, by using simulation software 'Arena'. Simulation results show that the proposed traffic signal control method (EKC) has better performance over fuzzy logic and conventional pre-time controllers under light and heavy traffic conditions.

Keywords: intelligent transport system (ITS), simulation, traffic signal control, fuzzy logic, fuzzy controller, signalized intersection.

1. Introduction

The increasing number of vehicles is becoming a major problem in many countries. With the ever increasing number of vehicles, the problems such as congestion and accidents happen more frequently. So the signal control of traffic intersection is becoming more important because such control directly affects the efficiency of urban transportation systems.

The conventional fixed-time traffic control system is one of the most popular and oldest in the world. This controller repeats preset signal timings derived from historical traffic patterns. As it is well known, the traffic system is a dynamic system, with great variation in real-time traffic; so the pre-timed control hardly adjusts to the different traffic conditions. The optimum cycle time procedure was first proposed by (Webster 1958) and had been extensively used by traffic engineers for the design of fixed signal plans based on known traffic volumes or expected demands for each junction link. This system is not effective for oversaturated intersection or rush hours. With the development of technologies, many adaptive methods have been developed to adjust signal timings according to the real-time traffic data (vehicle actuated control, semi-actuated control, green wave control and etc.). Adaptive control is designed on account of the traffic conditions in real-time at all approaches in the whole intersection. With rapid development of computer technology, the artificial intelligence methods have become an important control method for traffic operation. Intelligent traffic signal control systems have been recently developed as a part of an effective means to resolve the traffic problem of the crowded areas. There are many intelligence approaches used to manage the flows of traffic at intersections (Liu 2007), such as: fuzzy logic, fuzzy-neural network, evolutionary algorithms, reinforcement learning.

One of the most widely spread traffic signal control approach based on expert knowledge is fuzzy logic. Several methods have been developed based on fuzzy logic to handle signalized intersection. The Niittymäki and Pursula (2000) simulated an isolated traffic signal control intersection. The fuzzy controller worked on two levels. The upper level identified traffic conditions and the lower level defined green light cycle time. It was shown that fuzzy traffic controller reduced delays and stops when the traffic volume was heavy. The fuzzy logic controller was developed to control isolated and over-saturated intersections during special events (Zhang *et al.* 2005). Given real-time traffic information, the FLC controller decides on whether to extend or terminate the current green phase. The decision making process is based on a set of fuzzy rules which take into account the traffic conditions with the current and next phases. The proposed strategy was compared with fixed-time and actuated control strategies. The Nair and Cai (2007) proposed a new fuzzy traffic controller that can optimally control traffic flows under both normal and exceptional traffic conditions. The Azimirad *et al.* (2010) also proposed a novel fuzzy traffic control method for a single intersection to control the traffic light timings and phase sequence under the typical traffic conditions and exceptional traffic cases, such as roadblocks and road accidents. The state – space equations to formulate the average waiting time of vehicles in traffic network at fixed time control were applied too. An adaptive fuzzy logic signal controller for a single four-approach intersection suitable for mixed traffic was described by Sharma *et al.* (2010). These traffic control systems use several detection stations along the road, such as: signal analysis at induction sensors, field equipment supervision, incident detection, weather condition detection, speed limit control. A central traffic control computer collects the data transmitted from the section stations and derives an adequate speed limit for every section. A fuzzy control method for complex junction was proposed by Khalid *et al.* (2004). It has ability to communicate with neighbour junctions and manages phase sequences and phase lengths adaptively. Three modules were proposed in the design of the fuzzy traffic lights controller: next phase module, a green phase module and a decision module. The first module selects the most urgent phase except the green phase. The green phase module observes the conditions of traffic flows of the green phase only. The decision module decides the urgency degree between the next phase and the green phase modules. It also decides by how long to extend the green phase signal or whether to change it to other phases.

Our recent research in the area of modeling and simulation of complex systems led us to study expert system. Expert systems can be defined as practical computer programs that use heuristic strategies developed by humans to solve specific classes of problems. Expert systems are developed through cooperation between an expert who provides expert knowledge in a problem field and a knowledge engineer who codes the expert knowledge into a form that a computer program can utilize to solve problems in that field.

This paper describes a traffic control method based on expert knowledge to regulate traffic flows for single intersections. All above mentioned researches used fuzzy logic to control traffic flows; we suggest a traffic control algorithm based on expert knowledge using fuzzy set. The proposed controller concludes to terminate the current green signal group or extend it for some period. These assessments are made using the following fuzzy sets: 'extend green' or 'terminate green'. Each membership function of fuzzy set considers the queue length of current green and next green, the higher grade of membership functions means higher partial association to corresponding fuzzy set which denotes the control action. The model is developed using 'Arena' modeling software. A comparative analysis between proposed controller and fuzzy logic, fixed-time controllers have been made in traffic flows control, with varying traffic volume levels.

This paper is organized as follows: the proposed controller algorithm is described in Section 2. In Section 3 the performance of proposed controller is evaluated by simulator. The conclusion is presented in Section 4.

2. Description of Proposed Method

Fuzzy set is an extension of the classical set (Zadeh 1965). In traditional set theory, an object either completely belongs to a set or does not at all. No partial membership is allowed. Nevertheless, there exist countless vague and subjective concepts that we humans can easily describe, understand and communicate with each other but conventional mathematics fails to handle in a rational way. Traffic flow is usually characterized by randomness and uncertainty. To extend or terminate the relating green phase can be difficult and confusing. Fuzzy set theory generalizes 0 and 1 membership values of a classical set to a membership function of a fuzzy set ranging from 0 to 1; 0 means no association, 1 indicates complete association, and any number in between means partial association.

The proposed traffic signal control method works as a police man who uses his expert opinion in controlling the traffic. The concept of this method is to authorize an element to belong, more or less strongly, to a class. Suppose the expert wants to describe the class of current green signal having the property of being extended by considering vehicles queue length at current green phase. If the queue is very long, the green signal should be extended (complete association of fuzzy set); in the case of medium queue, the current green could be extended (partial association) and the current green should not be extended if there is no car in the queue.

There are two parameters used as an input. The first is the average queue length at green (Q_{green}) which is the number of vehicles that did not pass the intersection during the green phase. The second parameter (Q_{red}) is the average queue length at next green. This parameter is calculated by the following expression:

$$Q_{red} = RV + AV, \quad (1)$$

where: *RV* is the residue of vehicles since the last green signal; *AV* is the number of vehicles arrived during the red signal.

Using a fuzzy set, the fuzzy set of 'extend green' can be described as depicted in Fig. 1. The membership function for fuzzy set 'extend green' is defined in equation (2):

$$\mu_E\left(Q_{green}\right)=\begin{cases}0, \text{ if } Q_{green}\le 0;\\ 0.125\cdot Q_{green}, \text{ if } Q_{green}\in\left(0;8\right);\\ 1, \text{ if } Q_{green}\ge 8.\end{cases} \quad (2)$$

A fuzzy set of 'terminate green' by considering average vehicles queue lengths at a red traffic light can be defined as a fuzzy set depicted in Fig. 2. The membership function for fuzzy set 'terminate green' is defined by the following equation:

$$\mu_T\left(Q_{red}\right)=\begin{cases}0, \text{ if } Q_{red}\le 0;\\ 0.0625\cdot Q_{red}, \text{ if } Q_{red}\in\left(0;16\right);\\ 1, \text{ if } Q_{red}\ge 16.\end{cases} \quad (3)$$

Of course, no standard characteristic function of fuzzy set exists; it depends on the problem being solved and expert knowledge. The controller makes the decision by comparing the degrees of membership functions; the one with the highest membership grade is chosen as the control action:

$$y=\begin{cases}\text{extend, if } \mu_E\left(Q_{green}\right)\ge\mu_T\left(Q_{red}\right);\\ \text{terminate, if } \mu_E\left(Q_{green}\right)<\mu_T\left(Q_{red}\right).\end{cases} \quad (4)$$

For instance, the parameters of current traffic condition are the following: average queue length at green-end (Q_{green}) is 2, and the average number of vehicles waiting in the lanes at a red traffic light (Q_{red}), which will receive green light in the next phase is 8. Then the membership grade of fuzzy set 'extend green' is 0.25 ($\mu_E(Q_{green})$ = 0.25) and the membership grade of fuzzy set 'terminate green' is 0.5 ($\mu_T(Q_{red})$ = 0.5)), thus the control action is to terminate current green and switch to the next green signal group ($\mu_E(Q_{green}) < \mu_T(Q_{red})$).

Based on the traffic conditions, the system decides whether to extend the current green signal or to terminate it. The current traffic situation data is collected from traffic detectors; these data are fuzzified in fuzzifications module. The outputs of the fuzzification module are the possibility of extending the green phase and the possibility of switching to the next green phase; these membership grades go to the decision module. The decision module compares membership grades of traffic conditions in the current green phase and the next candidate green phase, and determines the urgency degree. If the current green phase is more urgent to extend than to terminate, the green signal will be extended. The system control architecture is depicted in Fig. 3.

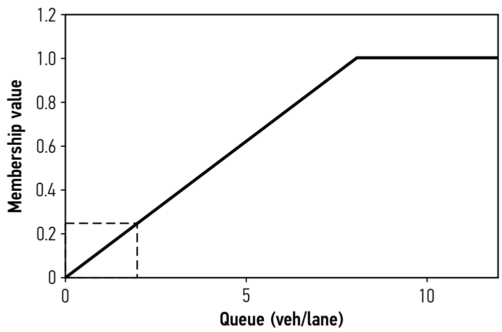

Fig. 1. Fuzzy set of 'extend green signal'

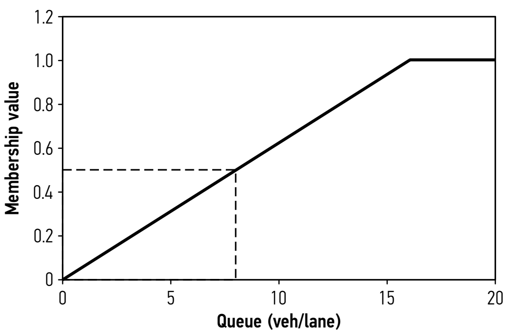

Fig. 2. Fuzzy set of 'terminate green signal'

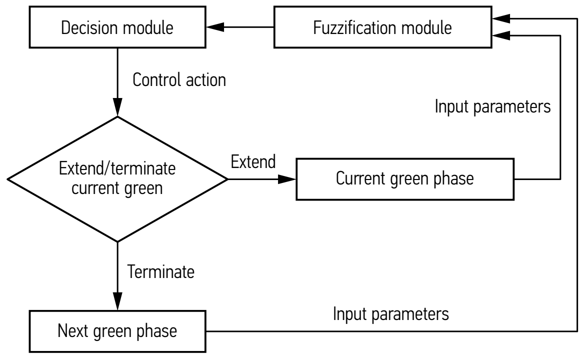

Fig. 3. System control architecture

3. Simulation Results

A proposed traffic control approach like the fuzzy logic method after green time period determines whether to stay in the current green phase or switch to the next phase. A green time of 10 second is given for the first time. If the fuzzy controller concludes to switch to the next phase, then the current green will be terminated. Otherwise, the current phase will be extended for the time interval of 6 seconds and so forth until the maximum green time is reached (40 seconds).

A case study is done involving a three-approach junction. The geometry of the intersection is illustrated in Fig. 4. Fig. 5 presents the phase order of the intersection model. The cycle sequence is 1–2–3–1– ....

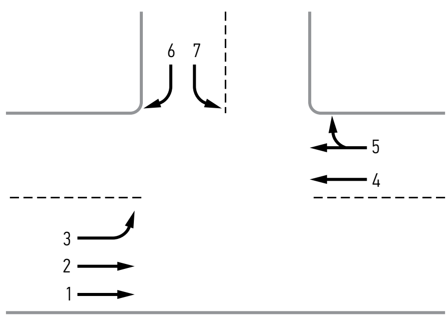

Fig. 4. The geometry of simulated intersection

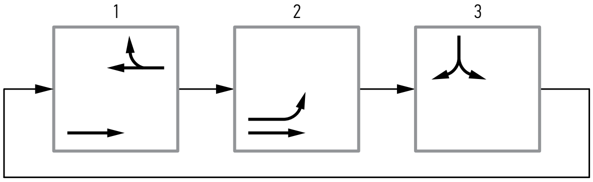

Fig. 5. Phase sequence of the tested intersection

To evaluate the ability of proposed algorithm to control traffic effectively in real-time at an isolated intersection, its performance is compared against the performance of a fixed-time signal operation and against fuzzy logic control.

Fuzzy logic controller. In this approach (Zhang *et al.* 2005) input parameters for the fuzzy logic system are as follows:

- average number of vehicles in the lanes of current green phase;
- arrival rate of current green phase;
- average number of vehicles in the lanes of the next green phase.

The number of vehicles of current green phase and the number of vehicles in next green phase are divided into four fuzzy sets: 'short', 'medium', 'long' and 'very long'. Arrival rate has three fuzzy sets: 'low', 'medium' and 'high'. The decision making process is based on a set of fuzzy rules proposed by Zhang *et al.* (2005); total of 48 rules are used in this approach.

In the first stage, the input parameters (most often crisp values) are fed to the fuzzification part of fuzzy logic controller. Then the fuzzified input data are entered into the fuzzy inference system where the most appropriate rules are selected from the fuzzy rule base. The control action is chosen by using *max min* fuzzy inference. To extend or terminate the current green phase is the output parameter of the fuzzy logic system.

Pre-timed signal control. Pre-timed control is the earliest and simplest control method that is still widely used. The control system uses a timer (fixed-time): each phase lasts for a specific duration before next phase. The optimization of these parameters to minimize the total delay or maximize the intersection capacity is a hot research spot in this field. One of the most important pieces of research was done by Webster (1958) whose delay formula was the basis of the pre-timed traffic signal settings. The optimum cycle length was approximated with the well-known Webster's equation (5) when traffic flow density is close to peak hour:

$$C_0 = \frac{1.5 \cdot L + 5}{1 - \frac{1}{X_c} \cdot \sum_{1}^{n} \frac{v_i}{s_i}}, \qquad (5)$$

where: C_0 is the optimum cycle length; L is the sum of lost times for all the phases (yellow and all-red); n is the number of critical lane groups (a critical lane group is a group of movements that can access the intersection concurrently); v_i/s_i is the maximum flow ratio for the critical lane group i; $1/X_c$ is the desired degree of intersection utilization (usually 0.95).

The signal timing plan for different traffic volume at each approach is designed as follows: 1st phase – green light time 42 sec., 2nd phase – 30 sec., 3rd phase – 22 sec. The signal timing plan with the same traffic volume at all approaches is 32 sec. for all phases.

The accuracy of traffic control model of signalized intersections strongly depends on the saturation flow rate and total lost time for each phase (start-up and clearance lost time). The additional time required starting the queue to move, known as the start-up lost time, it is the time when the drivers react to the green light and accelerate to free flow speed. In our approach 2 sec. is selected. At the end of each green time interval, there is a portion of the clearance that is not used for vehicle movements. This time is referred to as clearance lost time, and it is the same as start-up lost time (2 sec.). The number of vehicles per hour that could enter the intersection known as the saturation flow rate. This parameter varied according to the driver behavior between geographic locations, the geometry of intersection and etc. In our simulation model the saturation flow rate was selected 1800 veh/hr for all approaches based on field measurement and recommendation (Zhang, Chen 2009).

In the experimental part of this study, traffic signal controllers are tested using simulation runs. The simulation was carried out using simulation software 'Arena'. Graphical user interface of the traffic simulator is depicted in Fig. 6. During the simulation the arrival rate of vehicles in the lane varying from 0.08 to 0.19 vehicles per second (288÷680 veh/hr). The proposed method based on expert knowledge and the two existing methods – FLC and fixed time (Zhang *et al.* 2005) – were simulated under the same conditions without pedestrian crossing. Comparisons were made by considering two cases of traffic volumes: equal and different (not equal) at approaches of intersection.

The criterion used for the evaluation is the average stopped delay (Darma *et al.* 2005), i.e. the delay which occurs when a vehicle is fully immobilized. The best control strategy is the one that provides the lowest delays.

When traffic volumes at each approach of intersection are the same, the average delays per vehicle of each control model are shown in Table 1. Table 2 represents the average delays when traffic volumes at each approach of intersection are different. The first row of the table shows the lanes of intersection depicted in Fig. 4. The arrival rate in the lane is shown in the second row of the table. The rest rows of the table shows the results of case

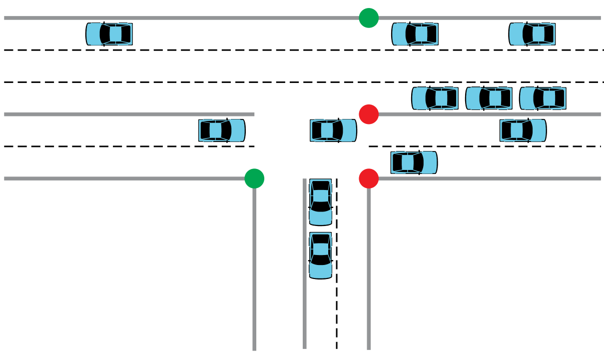

Fig. 6. Screenshot of 'Arena' graphical user interface

Table 1. Average delays with the same traffic volumes

Arrival rate (veh/hr)	Average delay (sec) when used		
	Pre-timed control model	FLC control model	EKC control model
370	34.99	16.57	16.36
410	36.62	21.48	21.22
475	38.00	27.29	22.60
515	39.91	44.44	34.40
580	69.48	77.50	62.71

Table 2. Average delays with different traffic volumes

Lane	Arrival rate (veh/hr)	Average delay (sec) when used		
		Pre-timed control model	Pre-timed control model	Pre-timed control model
1, 2, 3	470			
4, 5	360	32.84	18.12	17.76
6, 7	288			
1, 2, 3	470			
4, 5	470	33.77	19.81	19.67
6, 7	288			
1, 2, 3	600			
4, 5	470	36.52	28.15	26.54
6, 7	360			
1, 2, 3	680			
4, 5	510	37.70	50.78	37.45
6, 7	360			
1, 2, 3	680			
4, 5	600	82.92	80.94	65.28
6, 7	470			

study. The results for the proposed controller and FLC are almost identical since the arrival rate is low. Both FLC and fuzzy controllers produced lower delays than pre-timed in the first three-volume-level cases at equal and different traffic flows. During high traffic volume, all controllers are able to control the traffic flows quite well; however, applying the fuzzy logic method, the average delay is higher than EKC and pre-timed controllers at equal traffic volumes for all approaches. For different traffic volumes the pre-timed controller produces small improvement compared to FLC control strategy at heavy traffic flows because the fixed time controller was optimized to control the intersection under heavy traffic conditions.

The overall average delay with different arrival rate was 18.67% lower employing the proposed controller as compared with FLC and 34.23% lower as compared with pre-timed. With the same arrival rate in each lane, the EKC produced 19.06% and 39.23% lower overall average delays compared to FLC and pre-timed controllers respectively.

4. Conclusions

This paper has presented an algorithm based on the expert's knowledge to control traffic flows at isolated intersection. In order to evaluate the performance of the proposed algorithm, it has been compared with the fuzzy logic controller (Zhang *et al.* 2005) and the fixed time controller for three-phased controlled intersections with respect to average delays. The proposed controller has been tested in two cases: with different and equal traffic volume levels at each approach.

The results of the experiments indicate that the proposed approach can provide effective real-time traffic signal control at individual isolated intersections with varying traffic volume level. The simulation showed that proposed signal controller is better when traffic volumes are high. When traffic streams are low or close to medium, the results are almost the same as with the fuzzy logic controller. The proposed EKC control strategy has some advantages over the FLC control strategy; it decreases the delays of vehicles and increases performance. EKC was compared with pre-timed control strategy and showed significant improvements too.

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