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Improving Traffic Light Control by Means of Fuzzy Logic

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***Abstract*—In urban areas, the traffic demand grows every year due to the constantly increasing number of vehicles. The consequence is a capacity drop of the roads followed by traffic problems like congestion, reduced travel time, increased fuel consumption, etc. This paper presents an adaptive traffic light controller based on fuzzy logic for improving the traffic flow on an isolated intersection. A set of fuzzy rules has been made that, using the collected information from road detectors (queue length, arrival flow, and exit flow), computes the amount of time for which the next phase should be shortened or extended. The proposed fuzzy control system is constituted of two parts: one for the primary driveway (with a higher volume of vehicles) and for the secondary driveway (with a lower volume of vehicles). The proposed controller is compared with a fixed signal program in three scenarios with different traffic demand proofing the effectiveness of the developed decision rules.**

***Keywords*— Intelligent transport systems; Traffic light control; Microscopic simulation; Urban intersections; Fuzzy logic**

I. INTRODUCTION

With the increasing number of vehicles in urban areas, many urban networks have problems with the capacity drop of roads and corresponding Level of Service (LoS). Many traffic-related problems occur because of control systems on intersections that use fixed signal programs. They repeat the same phase sequence and its duration with no changes. Increased demand for road capacity also increases the need for new solutions for traffic control that can be found in the field of Intelligent Transport Systems (ITS). ITS provides information transparency, manageability of the transport network, and an improved response of the transport system. In the framework of ITS, there are many solutions for today's traffic problems and for the future development of intelligent vehicles, intelligent roads, wireless smart cards, dynamic navigation systems, adaptive traffic control systems, efficient public transport, etc.

One solution to the problem of traffic congestion is the traffic actuated control that shows an improvement over fixed time control. But according to [1], the effectiveness of this control approach deteriorates with heavy traffic demand. On the other hand, the application of adaptive traffic light control, by which signal programs can be adapted according to the current traffic situation, shows significantly better results. According to [2], in relation to fixed time control (uses a fixed sequence and duration of traffic light phases), the adaptive system is more complex but is significantly more efficient because of the reduction of travel times and other Measures of Effectiveness (MoE).

The main objective of this research is to design a traffic light controller based on fuzzy logic that can adapt to the current traffic situation. The proposed system consists of two fuzzy controllers, one for the main (primary) and one for the secondary driveway. The controllers gather information about the current traffic conditions and decide whether and for what amount of time to shorten or extend the next phase in the signal program. The proposed traffic light controller is made with a traffic controller containing a fixed signal plan in different traffic scenarios ranging from small to large traffic demand.

This paper is organized as follows. The second section describes similar solutions of adaptive traffic control including using fuzzy logic as a solution for many traffic problems. The third section describes the proposed fuzzy logic control approach that was made for the purpose of this research. The fourth section presents the obtained traffic parameters, simulation model, scenarios and framework, and obtained simulation results including their evaluation. The last section contains the conclusion and possibilities for future work.

II. STATE OF THE ART

There are many contributions to traffic light optimization using various methods that can significantly improve traffic light control. The main principle of optimal traffic control is a real-time response to dynamic traffic flow changes in urban environments. According to [3], optimization of signal timing in the urban network is usually done by minimizing the delay times or queue lengths of an intersection.

The queue time ratio algorithm shows significant improvement of the traffic parameters such as increased flow, and reduced delay time and density of the urban network in which it was tested. In [4], this algorithm was used for the purpose of automated planning for traffic signal control. It is implemented as an autonomic system that uses automated planning techniques. The proposed system monitors the current traffic state, detects if the system is degrading its performance, creates new sets of goals, triggers the planner that generates plans with control actions, and executes the selected courses of actions. With the implementation of artificial urban networks, which perform monitoring and execution of such plans, all vehicles were able to finish their journey with a decreased average travel time and CO_2 emissions.

The study [5] shows that start-up lost time is an important parameter regarding the performance of traffic light control. The parameters that were used in this study are start-up lost time, saturation flow, and start response time with the behavior of Turkish drivers. All parameters are used in regression analysis and results showed that with the application of the relationship between queue discharge headway, start response time and start-up time for traffic light control results in a decrease in saturation headways while the start response time increases. Also, start-up lost time decreases as the lane width increases, and increases as the duration of the traffic light cycle gets prolonged.

In the last few decades, there is an increased popularity present in using Artificial Intelligence (AI) as an approach for obtaining a better throughput of signalized intersections in urban traffic areas. In [6], traffic light optimization by application of the Q-learning algorithm is shown. The proposed approach was verified on a small urban road network with three intersections and it outperforms the actuated signals controllers. There are also solutions where multiple methods using various AI methods are combined for obtaining a better optimization of traffic light control. In [7], the traffic light signals were synchronized with the implementation of fuzzy logic and Q-learning. The main focus in [7] was enhancing fuzzy logic with the help of a Q-learning module that can learn on its own by updating a set of fuzzy decision rules (classic fuzzy logic based approach has a set of rules that remain unchanged once defined). Similar projects have involved multiple methods and various AI-based systems for getting better results. In [8–12], the application of AI algorithms and fuzzy logic as a solution to traffic problems that occur in urban areas is also described.

Even though combining fuzzy logic and one of the methods from the area of AI can alleviate today's traffic problems, one can also use fuzzy logic alone in order to improve the current traffic state that occurs on isolated intersections in the urban city road network. According to [13] and [1], using a fuzzy rule set one can design a traffic controller for an isolated intersection that is responsive to real-time changes of traffic demand. According to [14], adaptive traffic light control can reduce the response time of emergency services. In the mentioned paper, preemptive traffic light control based on vehicle tracking and queue lengths was applied to reduce the travel time of emergency vehicles.

III. PROPOSED FUZZY LOGIC CONTROL APPROACH

With time a demand for control systems, which would represent a wide range of input and output values different from the crisp 0 and 1 values used in the classic Boolean logic, appeared. The possibility of the system's inputs and outputs being able to adapt to a wide set of values assures a smooth transition between all subsequent states and was achieved by means of fuzzy logic. Thus, a lot of opportunities emerged for creating fine-tuned control systems. Fuzzy logic has also shown its significant importance when it comes to designing dynamic and complex control systems, such as control systems for adaptive traffic light control [15].

In this paper, three inputs and one output were used in order to design a fuzzy traffic light controller. Parameters, which were recognized as most important, for the control systems inputs were queue length, arrival flow, and exit flow. The urgency of a particular phase is used as a single output. Queue length was identified as the most important factor when designing the rules in MATLAB's Fuzzy Inference System as it was the prime indicator of the degree to which the traffic was congested. Other two inputs, arrival and exit flow, are informing what capacity is being currently used (arrival flow) and freed up after one signal phase (exit flow). Since the main goal of this research was to ensure the maximum effective use of the capacity on an isolated signalized intersection, it is necessary to emphasize the importance of the correlation among fuzzy inputs in question. Especially, as certain input combinations provide unwanted results, while some, on the other hand, enable better optimization.

A part of the fuzzy rules set used in this paper can be seen in Table I. They were created using expert knowledge about the traffic flows on isolated intersections. One of the situations important to be taken into account, while setting up fuzzy rules, is high arrival flow and high exit flow. In cases of short queue lengths, this situation ensures maximum traffic flow and identifies the need for a further extension of the respective phase duration. This way of designing an adaptive traffic system, using the three above explained inputs, gives full control over the traffic flow by applying two fuzzy controllers as stated before. By choosing the inputs of queue length, exit flow, and arrival flow, there is a constant overview of the degree of congestion of the controlled traffic flow and the rate at which vehicles leave and arrive at the intersection respectively. In Fig. 1, a selected set of representative fuzzy rules is presented in MATLAB's graphic interface for monitoring of the fuzzy decision process. The output (colored blue) shows the significance of the combination the inputs create in each rule. In this way, it is possible to track which sets of rules make the most difference in the final outcome when it comes to obtaining the urgency of an examined driveway.

One important information for the design of the traffic light controller comes from the capacity of the roadways (maximum number of vehicles per hour) which creates two categories: primary and secondary driveways. The difference becomes apparent when designing fuzzy rules, as there is a clear distinction in the way the fuzzy system behaves according to the type of driveway being examined. The proposed fuzzy logic controller was designed to give an advantage to the primary driveway in general and this is visible in the results section. In this way, it is ensured that all lanes belonging to the category of primary driveways will always have a clear advantage in terms of being extended by the fuzzy rule set as they have lower input values needed to achieve higher urgency states. As the data on input values are being collected throughout the simulation process, they are being stored in a table where all of the lanes sorted by the driveway category are being evaluated to obtain their respective urgency levels.

Calculation of the current phase duration is done by taking all the currently active lanes into account. Lane urgency can adopt any value between -1 and 1. Here -1 denotes no traffic and the respective lane contributes to shortening the phase for

TABLE I. EXCERPT FORM THE DESIGNED SET OF FUZZY RULES

	$Queuelength$		$Arrivalflow$		$Exitflow$		$Urgency$
IF	$QL = high$	AND	$AF = low$	AND	$EF = low$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = low$	AND	$EF = middle$	$THEN$	$MEDIUM$
IF	$QL = high$	AND	$AF = low$	AND	$EF = high$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = low$	AND	$EF = very\ high$	$THEN$	$MEDIUM$
IF	$QL = high$	AND	$AF = middle$	AND	$EF = low$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = middle$	AND	$EF = middle$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = middle$	AND	$EF = high$	$THEN$	$MEDIUM$
IF	$QL = high$	AND	$AF = middle$	AND	$EF = very\ high$	$THEN$	$MEDIUM$
IF	$QL = high$	AND	$AF = high$	AND	$EF = low$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = high$	AND	$EF = middle$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = high$	AND	$EF = high$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = high$	AND	$EF = very\ high$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = very\ high$	AND	$EF = low$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = very\ high$	AND	$EF = middle$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = very\ high$	AND	$EF = high$	$THEN$	$HIGH$
IF	$QL = high$	AND	$AF = very\ high$	AND	$EF = very\ high$	$THEN$	$HIGH$

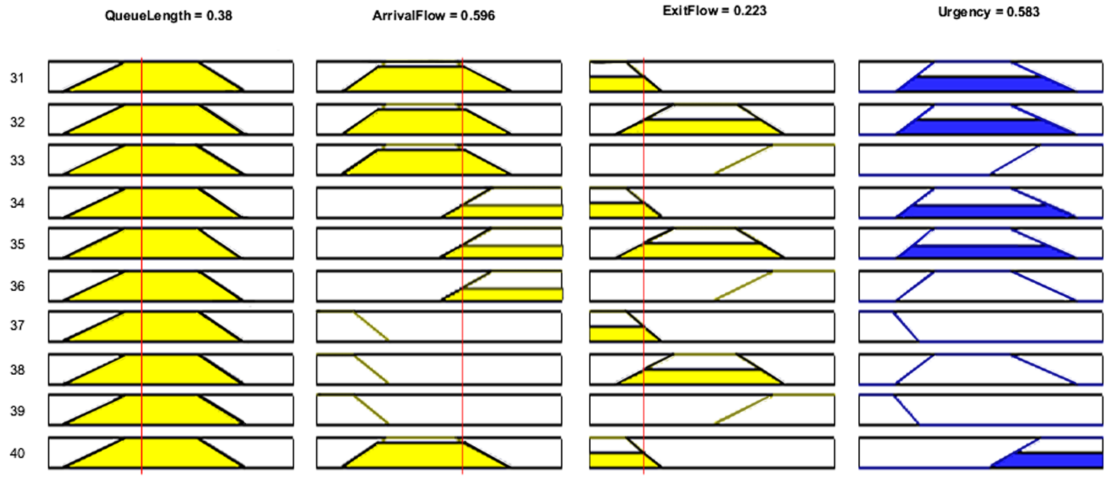

Figure 1. Activation of the chosen representative set of rules in MATLABs Fuzzy Inference System

the maximum percent, 0 denotes a medium traffic demand and the phase time should stay like in the fixed signal program, and 1 denotes that the respective lane capacity is full and the respective phase needs to be extended for the maximum possible amount. Individual lane urgencies are summed using:

$$U_{phase} = \frac{\sum_{i=1}^{n} U_{lane_i}}{n}, \tag{1}$$

where U_{phase} is phase urgency, n is the number of currently active lanes, and U_{lane_i} is urgency of the ith active lane. The maximum amount by which a phase can be shortened or prolonged ΔT_{max} is obtained as:

$$\Delta T_{max} = T_{phase} \cdot CDC, \tag{2}$$

where CDC is maximum change of duration coefficient (0.25 as recommended in [16]), and T_{phase} is the fixed phase duration. Final change of the original fixed duration of a phase ΔT is obtained by taking the respective phase urgency into account:

$$\Delta T = U_{phase} \cdot \Delta T_{max}. \tag{3}$$

IV. SIMULATION RESULTS AND EVALUATION

Performance of the proposed traffic light control system was analyzed in three different traffic scenarios using chosen traffic parameters. The proposed fuzzy controller was simulated using a framework consisting of the microscopic traffic simulator VISSIM and MATLAB software environment connected using the integrated Component Object Model (COM) interface [14].

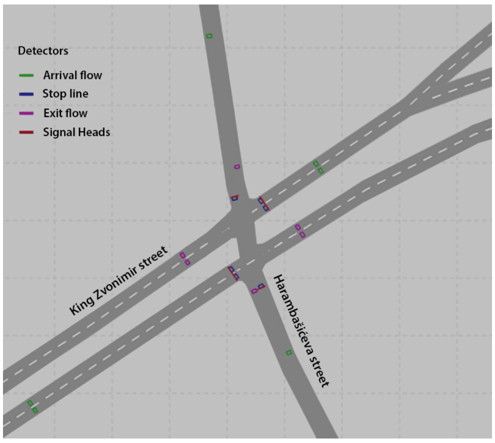

Figure 2. Model of the isolated intersection simulated in VISSIM

TABLE II. TRAFFIC DEMAND FOR EACH SCENARIO

Scenario	Traffic demand [veh/h]			
	King Zvonimir Street		Harambašićeva Street	
	West	East	South	North
1	432	660	90	132
2	720	1100	150	220
3	1008	1540	120	308

A microscopic simulation was chosen to simulate every vehicle in the network as an independent entity so that the proposed system can be tested in an environment similar to the real world. Traffic data processing and fuzzy decision making were done in MATLAB. The processed data were interchanged with VISSIM using the mentioned COM interface.

A. Simulation model and scenarios

In order to evaluate the proposed traffic light control system, a model of an isolated intersection has been made in VISSIM. The chosen intersection of the King Zvonimir street and Harambašićeva street is located in Zagreb, Croatia, and can be seen in Fig. 2. Signal program of the mentioned intersection contains two signal phases. The first is the East-West through phase (King Zvonimir street) and the second phase is the North-South through phase (Harambašićeva street). This intersection was chosen because of the significant difference in primary and secondary traffic demand during a working day since it is part of a green wave corridor in the mentioned city. That difference gives the possibility to significantly differ the phase duration's to demonstrate better the adaptation of the signal program to the current traffic demand. Three different scenarios were made with representative traffic demands using realistic traffic data from [17]. The first and the third scenario present a modification of the second scenario that was obtained by counting the traffic on the modeled intersection [17]. Traffic demand of the first scenario is 40% less than the second one, and the third scenario has 40% higher. Such change of traffic demand was made in order to realistically simulate congested and free flow traffic situations that reoccur daily on this intersection. Traffic demand for each scenario is shown in Table II. Each simulation lasted for one hour.

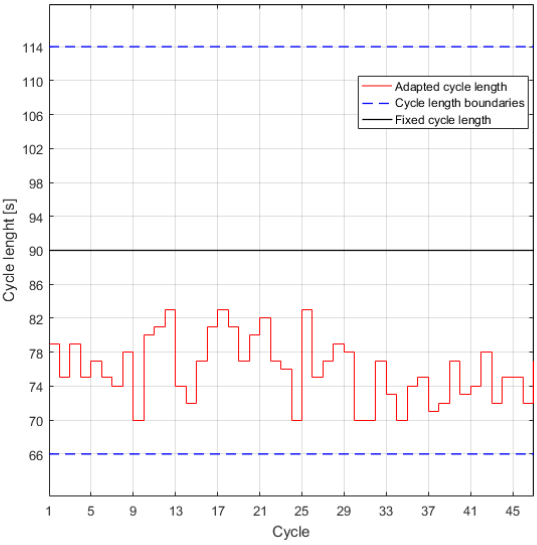

Figure 3. Variable cycle length obtained using the adaptive and fixed traffic light control for the first scenario

B. Obtained traffic parameters

Traffic data were obtained from 20 simulations of each scenario. The first ten simulations were done with a fixed signal program and the other ten were done utilizing the proposed controller for adapting the phase duration. Average results from all simulation runs are shown in Tables III, IV and V. The following MoEs were obtained for every scenario: QL as average queue length, MQL as average maximum queue length, and VS as the average number of vehicle stops.

Furthermore, in Table VI average values of emissions contributed by all vehicles in every scenario are shown. The following emissions are shown: CO as carbon monoxide, NO_x as nitrogen oxides and VOC as volatile organic compounds. The fuel consumption, denoted as GAS, is shown also.

C. Discussion

It can be seen from the obtained results that QL is reduced in every scenario for the primary flow (East-West) reaching the maximum improvement of 33% for the East driveway in the third scenario. While the values of QL are improved for the primary flow using adaptive control, the same is not true for the secondary flow. This was expected because of giving priority in fuzzy rules for the primary flow. The results for the secondary flow (North-West) are worse in the third scenario but are still better than the fixed time control in the first and the second scenarios.

Overall, the biggest improvement in MQL can be seen in the first scenario on the primary traffic flow (24% and 10%). This can be explained by the fact that in the first scenario with a smaller traffic demand the phases shift faster due to

TABLE III. Average values of obtained MoEs for scenario 1

MoE	North			South			East			West		
	Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control	
		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]
QL [m]	3.3	3.1	3	2.7	2.4	10	8.5	6.9	18	9.7	8.5	12
MQL [m]	40.9	36.8	10	32.1	30.6	5	63.8	48.5	24	69.4	62.1	10
VS	73	76	−4	58	58	0	319	298	6	336	325	3

TABLE IV. Average values of obtained MoEs for scenario 2

MoE	North			South			East			West		
	Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control	
		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]
QL [m]	7.7	7.4	3	5	4.9	1	18.7	16.8	10	20.0	18.5	7
MQL [m]	70.2	64.8	8	43.7	46.3	−6	97.5	93.5	4	111.9	106.8	5
VS	139	143	−3	98	100	−2	653	613	6	639	629	2

TABLE V. Average values of obtained MoEs for scenario 3

MoE	North			South			East			West		
	Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control	
		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]
QL [m]	14.7	15.1	−2	10.1	11.1	−10	101.1	68.2	33	72.1	50.1	31
MQL [m]	110.4	93.2	16	69.2	69.1	0	208.4	187.8	10	184.8	181.4	2
VS	232	227	2	157	161	−2	2075	1595	23	1632	1290	21

TABLE VI. Emission values from all scenarios

MoE	Scenario I			Scenario II			Scenario III		
	Fixed time control	Adaptive control		Fixed time control	Adaptive control		Fixed time control	Adaptive control	
		Value	Reduction [%]		Value	Reduction [%]		Value	Reduction [%]
CO	280.3	274.1	2	512.0	473.2	8	1224.2	1008.6	18
NO$_x$	54.5	53.3	2	99.6	92.0	8	238.2	196.2	18
VOC	65.0	63.5	2	118.7	109.7	8	238.7	233.8	18
GAS	4	3.9	2	7.3	6.8	8	17.5	14.4	18

the reduction of phase times, and the maximum number of accumulated vehicles is smaller. Two other scenarios also show improvement in the primary flow and mixed results for the secondary flow because of the stated reason.

Regarding the value of VS for the primary flow, improvement also exists through all scenarios peaking in the third scenario with 23% and 21% respectively. Values for the secondary flow show a small decline or no change in most of the simulated scenarios.

In addition to the already mentioned traffic parameters, in Table VI vehicle emissions are shown including fuel consumption. These data are obtained as values without measurement units from the microscopic simulator VISSIM. Hence, only relative change can be examined in the analysis of the influence of the fuzzy traffic light controller. All parameters show improvement in all simulated scenarios. As expected, the biggest improvement is shown in the third scenario which showed the best results beforehand. It should be noted that CO, NO$_x$, VOC, and GAS show the same amount of improvement in every scenario due to the way how VISSIM calculates them since all data for analysis were extracted from VISSIM.

Fig. 3 shows the adaptation of the cycle length of a selected simulation in the first scenario. The average cycle length is 76 seconds which is 14 seconds shorter than the fixed cycle length. The resulting cycle lengths are a product of shortening both the first and the second phase due to the low traffic demand. Shorter cycles mean more cycles in comparison with the second scenario that has an average of 42, and the third scenario with an average of 38 cycles since the average number of cycles in the first scenario is 47.

V. CONCLUSION AND FUTURE WORK

In this paper, a fuzzy logic traffic light controller for an isolated traffic intersection has been created. The results show that in the scenario with low traffic demand there has been an improvement in average and maximum queue lengths for both primary and secondary driveways. A rise in the number of vehicle stops in secondary driveways has been registered with the rise in average traffic flow. Such behavior was expected due to the shortened cycle duration because of a low traffic demand scenario. In the fixed control scenario, both average and maximum queue length have been reduced including both primary and secondary driveways. Results showed improvement in the number of vehicle stops in primary driveways, but slightly worse results were shown when it comes to secondary driveways. In the case of the high traffic demand scenario, the results have shown a major improvement over the examined traffic parameters in primary driveways. Regarding the secondary driveways, the results were slightly worse compared to the fixed control of the same traffic demand. Such results in secondary driveways were expected, considering that the fuzzy adaptive control system was designed in favor of the primary driveways, due to their larger capacity and, therefore, higher traffic demand. With only two signal phases in the isolated intersection, the disproportion in fuzzy rules favoring the primary driveways was inevitable.

This system of adaptive control was designed in a way that, with small changes specific to the traffic network model it can still perform its function, no matter the complexity regarding the number of traffic intersections or signal phases, as well as traffic demand. In the end, the results did not show improvements only traffic-wise, but in terms of pollution reduction as well, when compared to the fixed signal program.

By using fuzzy logic in adaptive traffic light control systems, it is possible to accomplish much better results when it comes to traffic parameters compared to fixed signal programs. The use of fuzzy logic is especially justified when it comes to optimizing traffic flow because of its ability to evaluate data in real time providing a traffic control system with high level of efficiency. This can be seen in the results of this paper for the case of an isolated intersection. This kind of adaptive control improves the MoS of current traffic networks by reducing the maximal queue lengths providing a better use of the existing roads capacity with the reduction of the level of congestion.

The further improvement of this system comes in the shape of cooperative control. With it, multiple mutually connected signalized intersections (traffic network) can be controlled on the network level. Additionally, the possible application of the genetic algorithm for the optimization of the fuzzy rule sets will be investigated.

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