

## FUZZY-LOGIC ADAPTIVE CONTROL OF TRAFFIC IN AN URBAN JUNCTION

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*Traffic light system plays a critical role in solving congestion in current urban traffic environment, where moving from pre-programed traffic lights systems to traffic adapted systems is a natural development. In this paper we present a new traffic control concept using fuzzy logic adaptive control for traffic light timing strategies to minimize the time vehicles spend in the intersection, as an optimization criteria in an Intelligent Transportation System. We also propose simulation tools to enable in-detail analysis for adaptive traffic light system based on road sensing and several strategies for pre-programed and adaptive stroke concepts.*

**Keywords:** traffic light simulation, fuzzy logic control, urban traffic congestion, adaptive traffic light systems, road sensing, intelligent transportation systems

### 1. Introduction

Controlling traffic with traffic signals/lights is a concept that was first used in London in 1868, followed by the first three color light signals installed in New York starting 1918, however still controlled by a human operator. This proved to be very efficient and therefore has been largely deployed all over the world. Modern different concepts started to be developed based on this type of control as the key element for ITS – Intelligent Transportation System infrastructure, integrating more and more sophisticated technologies, leading to current computational intelligence methods for controlling traffic signal timing [1].

Currently there are two main categories/types of traffic lights: pre-programed/timed traffic lights, which works based on constant time sequences and intervals and adaptive/traffic-driven and actuated traffic lights, which use sensing technologies like electronic sensors and/or cameras to assess traffic conditions/workload and actuate accordingly. In a pre-programed/timed traffic light system, as initially introduced by Webster [2], all vehicles have to wait for their turn to enter into the junctions, not considering the situation when no vehicles are moving from the green-lighted lane. This leads to long waiting times,

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independent of real traffic conditions. Using traffic sensors and introducing some intelligent control techniques for the sensor-type traffic light, the time for vehicles to wait in the traffic light can be minimized if the intelligent control system takes into account local traffic properties, as presented [3, 4].

Several studies have been presented on implementation of new generation sensors in traffic light systems: intrusive type (e.g. induction loop detectors, pneumatic road tube) and non-intrusive type (e.g. video image processing, microwave radar, lasers). It is generally accepted that intrusive type provides better accuracy compared to the non-intrusive type, but with higher installation and maintenance cost. However, sensors may solve the problems only integrated with control systems, as already presented in [4]. One of the most promising technologies to further improve this concept relies on fuzzy logic control systems to mimic human intelligence in controlling traffic conditions, combined with the implementation of smart sensors in multi-phase traffic light systems [3, 13].

In this paper we provide an adaptive fuzzy logic control model and a simulation environment for realistic multi-phase/stroke traffic light system at four-way intersection (Fig. 1), a comparison between time-based traffic light system and sensor-based traffic light system in normal and busy traffic condition and concept extension towards congestion mitigation in urban traffic. We start from modeling techniques to optimize current/older implemented timing-based strategies, with the goal of minimizing both the length of car queues at the stoplight as well as average time spent in the system. Then we introduce fuzzy logic adaptive control based on road sensing and find the most appropriate timing adaptation strategy. Moving from three stroke sequence to a four stroke sequence is then proposed to fully explore optimization potential from the simulation.

## **2. State of the art in traffic light system simulation**

Various control strategies and mathematical methods have been applied to obtain an optimized scheduling model for the traffic light system, able to meet the requirements for an ITS, as presented in [4, 11, 12]. One of the first traffic theories has been developed by Webster [2] taking into account traffic volume on streets and an objective function for cycle time optimization. The implementation of sensors in real traffic environments was possible starting late 1980s with simplified models, as presented by Albagul [4], followed by new conceptual developments, including fuzzy logic control system to mimic human intelligence in controlling traffic conditions of two phase systems [13, 14, 16].

Traffic optimization was already analyzed taking into account the influence of queue length and green time on the traffic system. Queuing theory methods have been introduced by Babicheva [5], considering the growth of the queue length in time aiming to find an optimal traffic light switching scheme in

order to minimize queues. Genetic algorithms have been introduced by Teo [9] using the queue length as the input data and Zhao [10] extended this introducing machine learning concepts. As an alternative, Yanguang and Hao [6] developed a dynamic model for traffic light scheduling and applied a hybrid chaotic quantum evolutionary algorithm to solve the traffic congestion problem, where minimization of the queue length is the major objective.

For direct applications towards ITS, the real traffic situation with different scenarios has been considered in studies which apply simulation methods and software simulation tools. Howell [7] introduced a smoothed perturbation analysis to simulate and optimize traffic light timing by minimizing queue and Wen [8] developed a framework for a dynamic and automatic traffic light control system which benefits from a simulation model and Arena Platform (Rockwell Automation, <https://www.arenasimulation.com/>).



Fig. 1 – Bucharest/Lujerului Junction

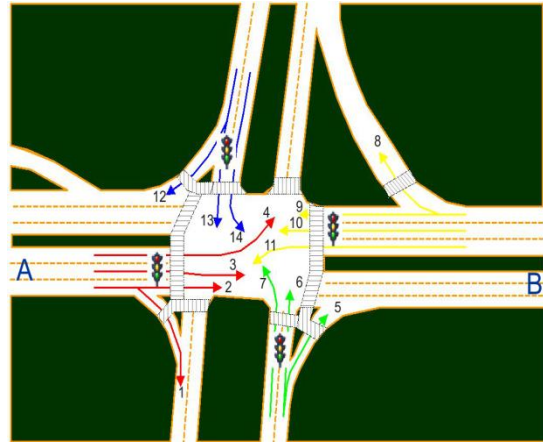


Fig. 2 –Reference Simulation Domain

Advanced simulation platforms have been used in simulations on multiple intersections featuring two-phase/stroke system and to determine the best green light timing on certain traffic condition. This is the case for simulation platforms like CELLSIM, FRESIM/CORSIM, FUSICO/HUTSIM, Arena, using various models including cellular automata, car-following, fuzzy signal control or mimic human thinking, proving real capabilities in solving traffic congestion by advanced simulation and determine the best green light timing on certain traffic condition [8, 14, 15].

### 3. Problem definition for traffic light fuzzy control

In this paper we aim to provide an alternative concept for an adaptive fuzzy logic controller and a new simulation model, aiming to minimize the average time that a vehicle spends in a complex junction. Our reference case is a

junction with two two-way streets in relevant urban environment (Fig. 1 - Bucharest/Lujerului junction), with the actual queueing logic presented in Fig. 2. This environment is of significant interest since large waiting times/delays, heavy congestion conditions and several car accidents are statistically reported almost every day.

We start from this basic configuration with a three-stroke pre-timed traffic signal as already installed (a two-stroke cycle is also an option for low traffic conditions), but a four-stroke adaptive traffic signal concept will be also considered for implementation and analyzed for potential benefits. We generate input traffic flows as statistical distributions. This mirrors the difficulty in modeling of complex real-life traffic where the actual measurements would be provided from sensors that determine the number of cars approaching the surveyed zone via the respective entry points. These inherent incertitude leads to a heuristic approach because classical solutions are not effective enough in this case and therefore we chose to implement an adaptive Fuzzy Logic Control (FLC) system in an open loop adaptive control (Fig. 3) as this would allow further integration into an intelligent transportation system in the urban area.

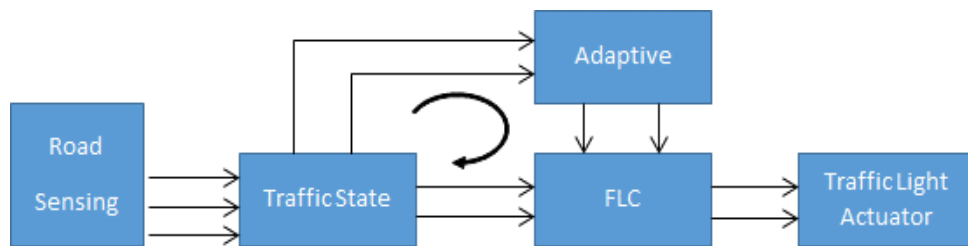


Fig. 3 – Adaptive FLC process

### 3.1 Global rules in junction area

Since our goal is to set up a new concept and to implement this in a powerful existing simulation environment (Arena), we do not consider at this moment pedestrians and potential induced conflicts generated by them. This is a very important element in the overall process leading towards a real implementation, since left/right lane changes are always associated with specific needs for pedestrians crossing and therefore additional delays and potential blockage for those trajectories. However, since we are currently investigating the adaptive FLC concept based on road sensing (traffic flows and queues), we will only address this implementation. The influence of the pedestrian time for the road crossing and associated problems will be addressed in future work.

For simplicity in the simulation environment, here we assume 3 lanes on each street from the junction, as one may derive from Fig. 2. Lanes are assigned on normal rules as follows (*Lane Rule*):

- All vehicles should wait for green light if they want to go straight or turn left. This is the case for Lane 2 (straight) and Lane 3 (straight and/or left turn);
- Lane 1 is for vehicles going straight and/or turn right. Turning to the right is always possible and leave the junction without waiting for green light.
- Vehicles from Lane 1 are not allowed to turn left. Also, vehicles from lane 3 are not allowed to turn right!

For the reference case, for the three-stroke scenario derived from Fig. 2, timing stroke sequence in this intersection is as follows:

- Stroke 1: green light for straight movements and left-turning vehicles in Up-Down street are allowed (blue arrows), but any other movements for other streets are not permitted;
- Stroke 2: green light for straight and left-turning movements of vehicles in Down-Up street (green arrows) and red for all directions of other streets;
- Stroke 3: green light for straight and left-turning movements of vehicles in Left-Right and Right-Left streets are allowed simultaneously (red arrows); but it is prohibited for all directions of other streets.

Vehicles are considered “logged” into the simulation/analysis domain once we define their trajectory in the junction area. For the reference junction we can use statistical data in order to estimate probability for cars selecting one of the three possible directions and driver behavior. As a general logic, we consider the following scenario for a vehicle entering to the junction system:

- First option: the driver chooses the lane where the queue is minimum, if not contradicting the *Lane Rule*, or;
- Second option: in case of equal queues, the driver chooses the lane closer to the direction of travel and compatible with the *Lane Rule*.

A fuzzy logic adaptive control is proposed (Fig. 3) taking into account a number of parameters that may influence the overall time needed for a car entering into the junction system to exit to the desired trajectory. In this paper we will use the traffic intensity, as defined by the number of vehicles entering into the junction in a specific time unit, and the traffic congestion, as defined by the length of a queue in front of the traffic light.

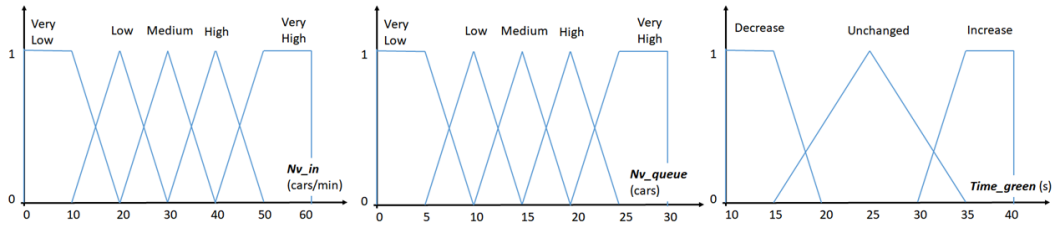
### 3.2 Fuzzy traffic light signal control

General rules and conditions for traffic light signal control are somehow vague and difficult to define in precise words, mainly if we would like to characterize the traffic condition or the queue length as *high* or *low*. If we introduce fuzzy logic concepts and membership functions, we have the possibility to define *short-queue* and *long-queue* terms and insert them in logical sentences such as: “*if queue = high then increase Time\_green*” and to apply this theory for traffic light control. Also, in the case of fuzzy inference, all rules are considered

once the rule set is used, compared to the binary logic case where decision trees are generated and only one branch is to be followed based on a specific part of the rules. As a result, fuzzy inference enables transitions from one state to another in a smoother way. The output is a fuzzy membership function and a de-fuzzification method is then applied to generate the output value from a fuzzy algorithm.

Table 1

The membership function for the traffic light system



The proposed fuzzy logic controller (Fig. 3) is able to determine whether to increase or decrease the reference *Time\_green* phase based on a set of fuzzy rules. At each sequence, the fuzzy rules compare actual road traffic conditions with the current settings for green light phase and traffic conditions with the next green-light phase to be defined. Proposed fuzzification (Table 1) process uses two input fuzzy variables chosen as follows:

- the number of vehicles entering the junction (*Nv\_in*). This is possible to monitor using dedicated sensors, used to characterize overall traffic conditions and communicate to a centralized command and control center/traffic authority. One may also consider this as the output from a statistical model for each junction, using specific databases;
- the number of vehicles waiting in the queue at the traffic lights (*Nv\_queue*). This is possible to monitor using sensors embedded into the junction infrastructure and communicated to the control center. This is the critical parameter to characterize traffic condition and may be subject to very specific technological implementations (sensing and communication included).

Table 2

The fuzzy relation matrix and entry probabilities for the reference junction

		Nv_queue				
		Very Low	Low	Medium	High	Very High
Nv_in	Very Low	1	R1	R1	R1	R2
	Low	2	R1	R1	R1	R2
	Medium	3	R1	R1	R2	R3
	High	4	R1	R2	R2	R3
	Very High	5	R2	R2	R3	R3
Intersection point		Entrance probability		Exit probability		
Point A		100%		0%		
1		0%		20%		
2		20%		0%		
3		40%		0%		
4		20%		25%		
5		0%		0%		
6		35%		0%		
7		40%		0%		
8		0%		15%		
9		15%		0%		
10		50%		0%		
11		20%		0%		
12		0%		20%		
13		25%		0%		
14		55%		0%		
Point B		0%		100%		

Here we consider the output fuzzy action as the green light time set into the system (*Time\_green*). We use a 5 stages description (very low, low, medium, high, very high) for both *Nv\_in* and *Nv\_queue* variables and a 3 level output for *Time\_green* in 3 basic rules (R1 – decrease, R2 – unchanged and R3 - increase), where basic functionality is considered from pre-defined timed regime and min/max boundaries, with membership functions presented in Table 1. There are 25 fuzzy logic rules in our case, defined as follows (Table 2):

- if *very low* number of the vehicles waiting in queue and *medium* number of vehicles which arrive, then *Time\_green decrease* (R1);
- if *low* number of the vehicles waiting in queue and *medium* number of vehicles which arrive, then *Time\_green decrease* (R1);
- if *medium* number of the vehicles waiting in queue and *medium* number of vehicles which arrive, then then *Time\_green unchanged* (R2);
- if *high* number of the vehicles waiting in queue and *medium* number of vehicles which arrive, then then *Time\_green unchanged* (R2);
- if *very high* number of the vehicles waiting in queue and *medium* number of vehicles which arrive, then then *Time\_green increase* (R3).

Fuzzification is carried out using the Zadeh min-max AND and OR operations [10]. For the de-fuzzification process, the following strategy is used: each fuzzy output is multiplied by its corresponding singleton position; the sum of this product is then divided by the sum of all fuzzy output. The result from this calculation is the final single output, which can be used to control the green light duration in the Arena Software Platform.

### 3.3 Reference boundary conditions

For the reference junction simulation, realistic input data need to be collected for vehicles arrival behavior and the distribution function for vehicles crossing the intersection. Such data is available from statistics on Bucharest/Lujerului junction and may also be compared to some literature data [14]. Also, Input Analyzer Tool from Arena Software Platform may be applied to find the behavior (distribution function) which most fits the data and fitting tests (e.g. Kolmogorov-Smirnov and square error with *P*-value like factors) are applied to analyze the relevance for the estimated distributions.

For more realistic simulations, traffic intensity is measured on a 3 to 5 intensity level scale (e.g. high/heavy traffic, medium and low/light). Vehicles entering to the system may be generated from one source using a single parameter  $\lambda$ , to separate vehicles in time (sec/car). Using specific probabilities as given in Table 2 the vehicles enter the intersection and an attribute representing the index of the intersection exit is assigned to the vehicle. Here we consider the exponential distribution as optimum to represent the system inputs, using  $\lambda$  values

for heavy, medium and light traffic as 0.8 sec/car, 1.0 sec/car and 2.0 sec/car respectively.

#### 4. Case study

The reference traffic system (Fig. 2) is a three-stroke cycle light. This is a development from the “classical” two-stroke cycle, blamed for large and dense bustle of the cars and pedestrians, accidents, vehicles long waiting times, etc. Simulation methods make it possible to assume different sequences of traffic lights for the system and consider animations in the Arena framework to show that how the system behaves. The first implementation (pre-timed –Fig. 4) has been simplified so that phases only allow one junction to move.

The configuration of traffic light system (pre-timed reference) has been done as follows:

- The green light sequence is based on clockwise movement, starting with right junction, followed by up, left and down;
- For time-based system, the green light is always be 40 seconds for each junction;
- Sensors are used to scan the condition on the road, if there are three or less vehicles waiting in the junction, indicating that system is not busy and allowing for 10 seconds of green light;
- If there are more than 7 vehicles waiting in junction, indicating that road is busy, 60 seconds of green light is allowed;
- All entrances to the systems are generated from the same inter-arrival time and then distributed with specific probabilities (Table 2)

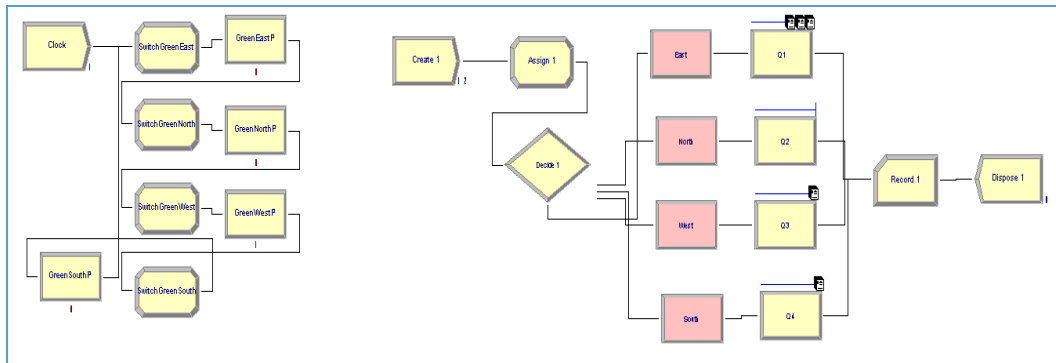


Fig. 4 – Basic model for the traffic light system – pre-timed system

Based on configuration above, algorithms have been developed for time-based and sensor-based system, where only fixed values are possible (10, 40 and 60 sec.). For the adaptive fuzzy logic controller, we allow incremental variation in 5 sec. steps between 10 to 40 sec., from the 40 sec. reference. With the algorithms



developed, the simulation model can be done and validated, using up to 30 cycles (1.200 sec.) to enable proper statistical evaluation.

#### 4.1 Simulation framework

The simulation models developed in Arena can be seen in Fig. 4 and 5 for basic pre-timed and adaptive conditions. Fig. 4 is a representation of the basic model using four Create modules that were used to represent the arrival of vehicles at the intersection. In addition, four Process modules represent traffic lights and branching possibilities as represented by four Decide modules. The last four modules are the Dispose modules that are used for capturing cars that are exiting the traffic system. Model of sensor-based, adaptive FLC system is constructed as in Fig. 5. The difference between systems is the timing of green lights and the fuzzy logic control is implemented as a sub-model for decision on the same structure as for the sensor-based model.

The arrival rate of the vehicles is determined by the arrival rate of  $\lambda$  seconds/car. Also, we consider that exits from the junction system can only be made from the exit points defined in Table 2 with corresponding probability. For this global scenario we measure the performance of the traffic light system as the average time spent in the system by a generic vehicle, as statistically derived from data recorded in the simulation model.

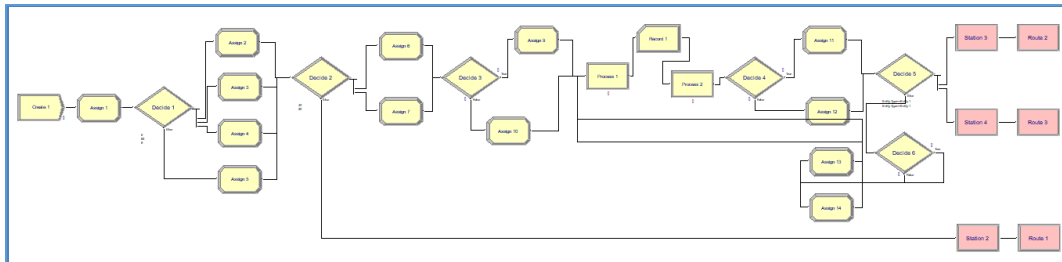


Fig. 5 – Adaptive model for the traffic light system at Lujerului Junction

Since the simulation generates vehicles in random arrival time based on exponential distribution, average waiting time is different in different simulation runs. Therefore, the simulation has the run length of 1.200 seconds for each run and is replicated to 15 runs for statistical purpose. This leads to a total significant 18.000 seconds simulation total time for each scenario in the Arena framework.

#### 4.2 Adaptive fuzzy logic model implementation

In this paper we propose to implement time-based system and the sensor-based system using the same simulation model of the state of traffic light with a configuration added for the inclusion of the sensor-based system, changing the duration of traffic light (Fig. 5) due to sensing and a specific decision algorithm. For the basic adaptive sensor-based case, if sensor detects three or less vehicles in

the system, it changes duration down to 10 seconds, if more than 7 vehicles detected, it changes up to 60 seconds, by fixed 5 second increment on each cycle. The adaptive fuzzy logic sub-module is then implemented as an alternative process to change *Time\_green* with a different strategy.

### 4.3 Verification and validation Results

A dedicated simulation experiment was carried out to compare the performance of the models with a fixed-cycle time (conventional) control system and adaptive “classical” sensing, where the traffic lights change at constant cycle times (e.g. from 10 to 40 or 60 sec.). Simulation has been run for 1.200 seconds, replicated for 15 runs, for time-based and sensor-based system in normal and busy condition. Data from the reports generated in Arena is mean queues length and waiting times values for the reference three stroke sequence (Fig. 6 and 7).

For heavy traffic, a vehicle goes from Point A to B in 32.12 seconds on the reference situation (three-stroke scenario, averaged). From detail simulations we also report that, for normal traffic conditions, this number fluctuate from 48.45 seconds to less than 27 seconds, so these values have to be associated to statistics in order to make them possible to compare with real life data.

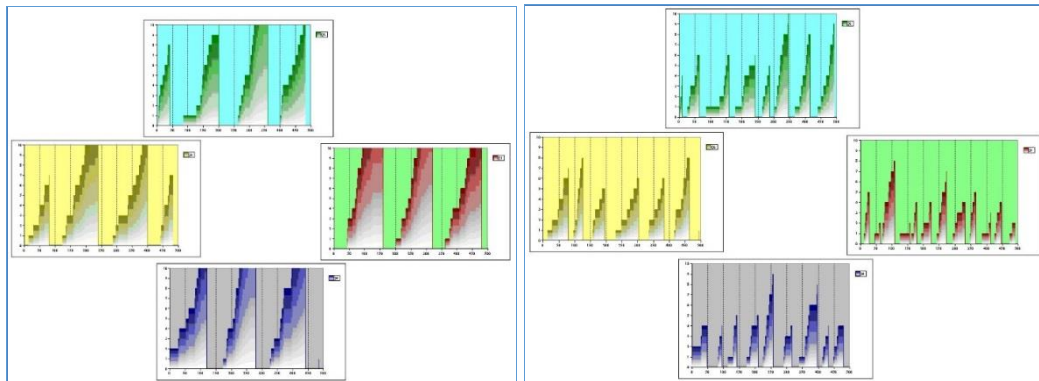


Fig. 6 – Queue length from simulation models a) - time based and b) - sensor-based

In our simulations, for three-stroke and four stroke sequence, we also compare waiting time of vehicles in the junctions for the case when we use traffic light control system with 40 sec fixed time-based system and the sensor-based system with 10-40-60 sec. timing sequence. The goal is to identify if, from the simulation modeling perspective, there is room for improvement with respect to vehicles waiting time and time to pass from point A to point B if *Time\_green* is decided on the presented adaptive logic, then introducing adaptive FLC.

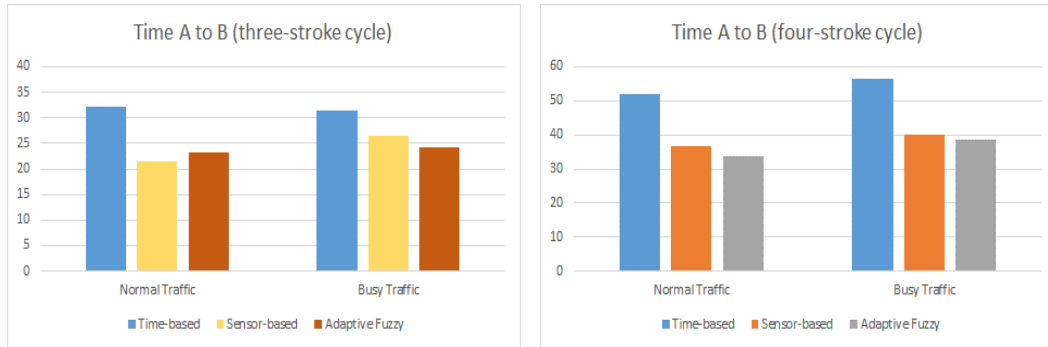


Fig. 7 - Mean waiting time for different traffic light system control strategies

Preliminary obtained values for mean waiting time are for around 32 sec. for fixed time-based traffic light system, almost identical for normal and busy traffic conditions (31.47 sec. vs. 32.12 sec.), as one might expect since only small queues (1 to 2 cars) are generated in these scenarios. The mean waiting time for vehicles in the junctions for the sensor-based traffic light system is case more sensitive to traffic conditions, about 21.57 seconds for normal traffic and about 26.48 sec. for busy traffic conditions, being dependent on the queues generated (up to 12 cars in a queue). The focus is however on the usage of adaptive fuzzy control, where we get 23.18 seconds average waiting time in normal conditions and 24.32 sec for busy traffic conditions, and real benefits in reducing the waiting queues as presented in Fig. 7.

A preliminary conclusion from these simulations is that, in case of three-stroke cycle scenario, the adaptive fuzzy control is not efficient compared to “classical” road sensing approach, mainly due to fact that we have considered a case where limited queue are generated as reference. However, when traffic is “busy”, the adaptive fuzzy control shows clear benefit with respect to other control strategies, reducing waiting time and queue by more than 6 cars compared to non-adaptive case, and with 2 cars compared to “classical” road sensing case.

## 5. Conclusions

In this paper we report on the capability to simulate urban congestion and control strategies for enhanced urban mobility. We presented a new concept for traffic light timing adaptation with respect to a sensing capability and a new decision-making algorithm using adaptive fuzzy logic to minimize the average time that cars spend in the crowded junction. Different scenarios were proposed and numerically tested in the proposed model and the one with lowest average time spent in the system is selected and proposed for further development.

We did not consider pedestrians and their impact in the real implementation. We have assumed that pedestrians are crossing the street in a

sequence coupled with the normal operation of the traffic lights on the parallel lane. This is not valid in case of left/right turns, where pedestrians induce significant delays in the overall traffic. One direct effect is that car speed for these trajectories may be decreased, based on some statistical values. This will be part of a dedicated future work, where we will introduce a dedicated model in the Arena simulation.

Table 3

**Time spent in the traffic system (three-stroke sequence)**

	three-stroke		four-stroke	
	Normal Traffic	Busy Traffic	Normal Traffic	Busy Traffic
Time-based	32.12	31.47	52.12	56.26
Sensor-based	21.57	26.48	36.78	40.12
Adaptive Fuzzy	23.18	24.32	33.63	38.75
$\lambda$ [sec/vehicle]	1	0.8	1	0.8

Our models and simulations considered the implementation of sensors in the traffic light control system in order to improve the waiting time of vehicles in the junction system. From our results, this was not a direct and optimal solution for the improvement of the waiting time of vehicles in junctions, since key parameters such as arrival rate of vehicles at the intersection, the average number of vehicles waiting in the junction and optimal traffic light duration is different from one intersection to another. However, clear benefit from adaptive fuzzy logic control has been presented for all scenarios. This work will continue towards optimization, with the implementation in a broader environment, considering adjacent junctions towards presented reference. This very complex model will strongly benefit from the Arena software capability towards complex dynamic simulations.

As a practical conclusion, moving from a three-stroke sequence to a four-stroke sequence needs special attention. In a simplified approach it is clear that a four-stroke sequence leads to longer waiting times in a junction. However, if we consider problems associated to the real traffic conditions and congestions in busy traffic case, we propose the four-stroke cycle scenario, with adaptive fuzzy logic control, able to lower waiting time close to fixed pre-times case, but with higher performance in terms of safety and resilience.

Directions for future research are based on optimization methods to be used in order to obtain better/efficient solutions according to cycle strokes and lights cycle time. Also, issues like the implementation of heuristic and learning algorithms in obtaining better traffic light scheduling, or advanced formulation for the optimization problem under a dynamic condition, as well as the need for pedestrian models will be considered in future work.

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