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Modelling and Simulation of Traffic Light Control

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***Abstract*: *This study presents design of traffic light system with feedback control that considers a crossroad in an urban area. Two types of controllers are designed – fuzzy and analytical, which have been tested separately on Aimsun platform through a simulation. The aim of the study is to compare the performance of both controllers in terms of increasing traffic flow and decreasing queue length. The controllers manage the duration of the green light according to the traffic flow. Two different formal models are designed, tested, and compared. They have produced adequate solutions in terms of developing controllers for modeling and simulation of transportation tasks.*

***Keywords*: *Traffic light control, fuzzy logic, fuzzy controller, analytical controller, modeling, simulation, Aimsun platform.*

1. Introduction

Traffic in the urban environment is mainly controlled by the cycle lengths, green durations, and phases of traffic lights [1]. These three control mechanisms can be part of an optimization problem and respectively optimization functions that optimize traffic flows, queues in front of traffic lights, delays, and other traffic indicators. Depending on the urban setting traffic lights may have a significant role in control of traffic. The city area has points of interest with great density: buildings, offices, shopping centers, kindergartens, schools, etc. In the investigated urban areas, the proper optimization of traffic lights' settings may lead to additional benefits such as less air pollution.

The optimization of traffic lights for the investigated urban area has been performed through different approaches including bi-level optimization, classical optimization, and numerical approach for optimization [2-6].

The selected approach for solving the problem is using a fuzzy logic-based controller as the problem has stochastic characteristics, and uncertainties and is dealing with changes in the traffic flow [7-13].

The goal of this study is to develop an intelligent approach leading to decreasing the queue lengths at intersections in order to improve traffic behavior. To achieve this goal several tasks must be fulfilled: to design and compare two types of controllers, simulate and separately test them, with the purpose of controlling urban traffic plan. In this study, the basic idea is to apply different control impacts on the subject (in our case the transport intersection) depending on the changing traffic dynamics reflected by the system feedback and introduced as input to the controller.

The emphasis of the research is integration between principles of the control theory, intelligent methods for traffic light management, modeling, and computer simulations.

2. Overview of intelligent traffic light control

Intelligent Traffic Light Control (ITLC) utilizes information technologies and intelligent algorithms for solving optimization problems related to traffic light control of a single intersection or a network of intersections. Such intelligent algorithms are fuzzy logic, evolutionary algorithms, reinforcement learning, etc, [14, 15]. ITLC is part of Intelligent Transportation Systems (ITS) which is a broader term including in-car safety systems, simulation of infrastructure changes, and optimization of transport, smart infrastructure, and other transportation-related applications of information technology. With the rise of the capabilities of information technologies and computational power, the interest in ITS and ITLC is increasing on behalf of governments and companies.

As the optimization of traffic lights is a complex problem, there is no obvious solution even when only one intersection is considered. Respectively, if there are several intersections involved, the problem is more complex. Moreover, a considerable complication and characteristic of traffic, in general, is its stochastic nature as well as unpredicted events such as accidents and predicted events such as roadwork. Thus, different approaches are investigated and the problem with traffic light control remains a current issue with even more complications in regard to human health, environmental pollution, and the economy.

The present study investigates the fuzzy approach to ITLC. Research in this direction has been conducted worldwide in the past and present. More recent research in the field is done in [1] and [16]. Both studies reveal improved results of the fuzzy approach in comparison to traditional traffic light control strategies such as fixed traffic light control.

This difference is a prerequisite for different results and additional conclusions about the use of fuzzy logic for the purpose of traffic control.

3. Description of the problem

The paper presents traffic control modeling of one crossroad in an urban area in Sofia, Bulgaria with three input flows (three sections) and two outputs (duration of the green light for each section). The simulation environment is the Aimsun platform for transportation tasks [17].

Fig. 1 presents the studied crossroad with the three inputs – x_1, x_2 and x_3.

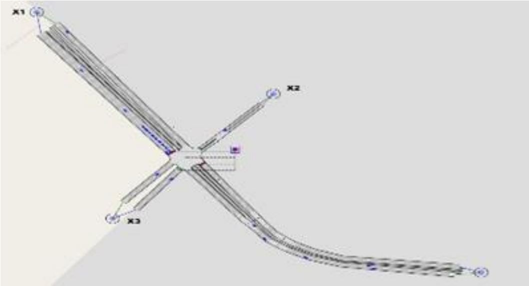


Fig. 1. Crossroad with three inputs

In this case, x_1 presents the main road and it uses separated green light duration u_1, while x_2 and x_3 use the same green light duration u_2. The simulation is implemented by setting the control variables u_1 and u_2, which represent the outputs of using two types of controllers at the same initial traffic flow values.

4. Proposed methods of the research

This research presents a design of a traffic light system with feedback control, where the control subject is the urban traffic passing through an intersection. The experiment targets the evaluation of traffic light plans for five hours during a day and the duration of the plan is one hour. Two types of controllers have been designed – fuzzy and analytical in order to reflect the stochastic traffic nature. These two types of controllers have been tested separately on the Aimsun platform through a simulation.

The idea behind the study is to use the Aimsun software environment to compare the two controllers. The implemented methods are: an initial number of vehicles for three sections of one intersection is given to the controller as three inputs (x_1, x_2, x_3). In the case of the fuzzy controller, the duration of the green light of the main road is given as an output (u_1), whereas the duration of the green light for the crossing roads (u_2) is calculated as a difference between the cycle duration (equal to 100 s) and the output u_1. In the case of the analytical controller, two equations are solved to define the duration of u_1 and u_2 based on the three inputs (x_1, x_2, x_3). The analytical controller is designed under the assumption that the ratio between the green light durations for the two sections (u_1 for Section 1, and u_2 for Section 2) is equal to the ratio between the traffic flows of the two sections. The outputs of the Controller (u_1 and u_2) become inputs for the Junction (simulation in Aimsun environment) and define the traffic control settings. After simulating the traffic flow of the intersection for the duration of one hour, the new traffic flow values have been calculated. These values are entered as inputs for the controller. The process of tuning the controllers and simulation in the Aimsun platform continues until the values of the controllers have been established.

The traffic light system with feedback control, including a controller (fuzzy or analytical) and control subject/Junction (Aimsun simulation platform) is presented in Fig. 2.

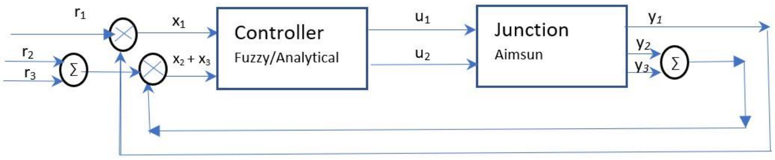


Fig. 2. Traffic light system with feedback control

Here: r_1, r_2, r_3 are the number, of cars from the urban network. In this case, we accept them for 0, because we described the ideal case without any other cars from the network; x_1, x_2, and x_3 are the initial number, of cars for the three inputs; u_1 and u_2 are the outputs of the controller measured in seconds; y_1, y_2, y_3 are the simulated number, of cars in Aimsun environment. They represent the outputs of the junction.

The two controllers have been designed and described further in this section.

4.1. Fuzzy controller design

The novelty in the current paper, as part of a series of experiments dedicated to the use of fuzzy logic for traffic control, is the use of three inputs, each with two linguistic values. The total number of rules that are based on expert knowledge is eight. The number of rules is defined by the inputs and linguistic values according to the fuzzy rules definition.

The fuzzy controller is designed as Fuzzy Mamdani System using MATLAB fuzzy toolbox [18]. The system consists of three inputs and one output.

Section 2 is calculated as the difference between the fixed duration of the full cycle of the green light and the duration of u_1. In this case, the fixed duration of the full cycle of the green light is 100 s and the following equation holds:

$$u_1 + u_2 = 100. \tag{1}$$

A triangular membership function is presented for modeling the fuzzy system with three inputs and one output.

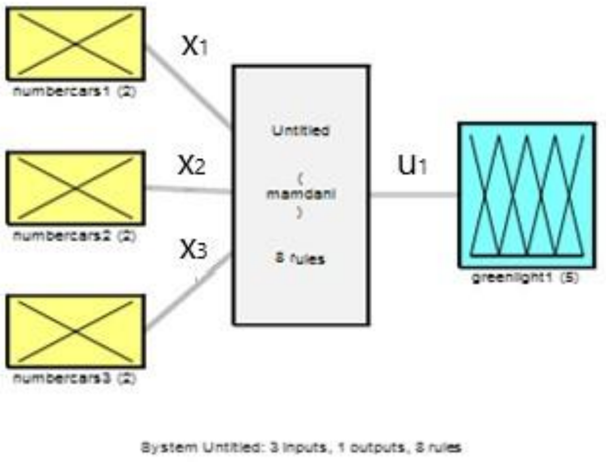


Fig. 3. Mamdani fuzzy system with three inputs, one output, and eight fuzzy rules

The inputs of the fuzzy controller are designed with two linguistic values for the different number of vehicles per hour.

The output (greenlight1) from the fuzzy controller consists of five linguistic values in Fig. 3.

The following heuristic fuzzy rules, which are based on expert knowledge, are:

1. If (the numbercars1 is short) (the numbercars2 is short) and (the numbercars3 is short), then (the greenlight1) is average.
2. If (the numbercars1 is short) (the numbercars2 is short) and (the numbercars3 is long) then (the greenlight1 is short).
3. If (the numbercars1 is short) (the numbercars2 is long) and (the numbercars3 is short) then (the greenlight1 is short).
4. If (the numbercars1 is short) (the numbercars2 is long) and (the numbercars3 is long) then (the greenlight1 is very short).
5. If (the numbercars1) is long, (the numbercars2) is short, and (the numbercars3) is short, then the (greenlight1) is very long.
6. If (the numbercars1 is long) (the numbercars2 is short) and (the numbercars3 is long) then (the greenlight1 is long).
7. If (the numbercars1 is long) (the numbercars2 is long), and (the numbercars3 is short) then (the greenlight1 is long).
8. If (the numbercars1 is long) (the numbercars2 is long), and (the numbercars3 is long) then (the greenlight1 is average).

It is follows the explanation of the fuzzy rules and MATLAB program using fuzzy toolbox.

The developed MATLAB program for the fuzzy controller uses triangular membership functions.

For all inputs, there are developed two membership functions, because it uses two-degree fuzzy logic named the program “short” and “long”.

For the first input x_1 named “numbercars1” the range is between 0 and 1000 cars, where the membership function “short” takes values [0 0 500] and the membership function “long” takes values [0 500 1000].

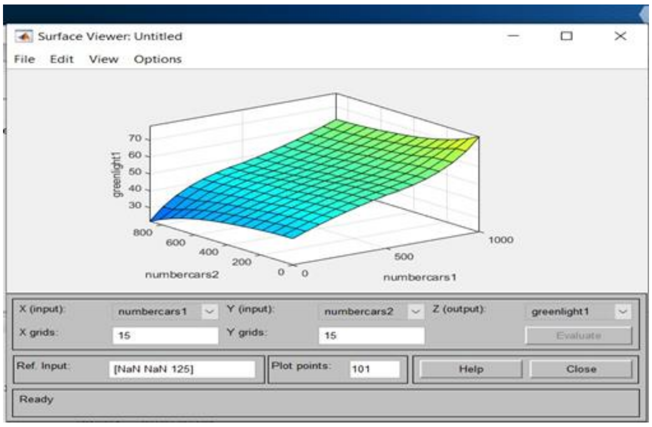
Analogically for the second input x_2 called “numbercars2”, the range is between [0 870] cars. For the second input membership function “short” is described as [0 0 435] and membership function “long” is described as [0 435 870].

Analogically for the third input x_3 called “numbercars3”, the range is between [0 250] cars. For the third input the membership function “short” is described as [0 0 125] and the membership function “long” is described as [0 125 250].

The first output is developed as five-degree logic and describes the green light for the first output named “greenlight1” measured in seconds. The range is between 0 and 100 s for the output.

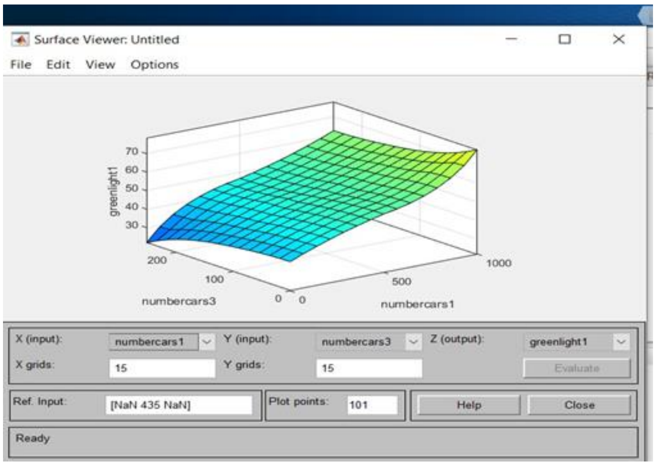
There are developed five membership functions in MATLAB program respectively “very short” with the range [0 0 25], “short” with the range [0 25 50], “average” with the range [25 50 75], “long” with the range [50 75 100] and “very long” with the range [75 100 100].

Figs 4-6 show the surfaces of the fuzzy controller in 3D format as a function of the two inputs and the output.



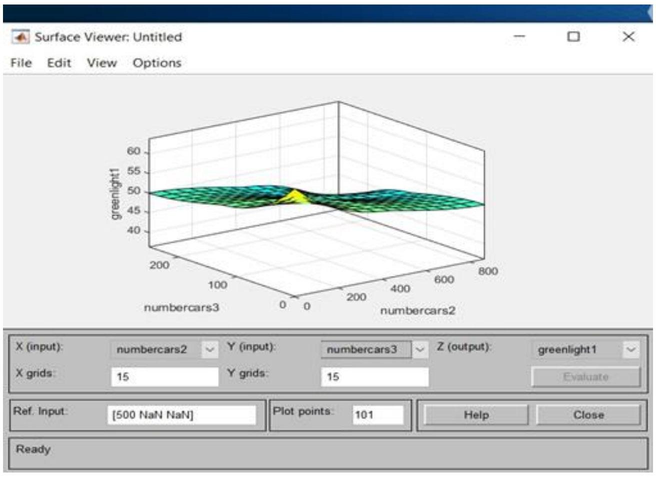
X (input): numbercars1
Y (input): numbercars2
Z (output): greenlight1
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 125]
Plot points: 101
Ready

Fig. 4. Surface of fuzzy controller with input1 and input2 and the output



X (input): numbercars1
Y (input): numbercars3
Z (output): greenlight1
X grids: 15
Y grids: 15
Ref. Input: [NaN 435 NaN]
Plot points: 101
Ready

Fig. 5. Surface of fuzzy controller with input1 and input3 and the output



X (input): numbercars2
Y (input): numbercars3
Z (output): greenlight1
X grids: 15
Y grids: 15
Ref. Input: [500 NaN NaN]
Plot points: 101
Ready

Fig. 6. Surface of fuzzy controller with input2 and input3 and the output

4.2. Analytical controller design

The analytical controller is designed analytically under the assumption that the ratio between the green light durations for the two sections u_1 for Section 1 and u_2 for Section 2. However, the presentation format used in this section shows the way in which the system of algebraic equations could be solved, i.e., by replacing u_2 in the next equation from Equation (3),

(2) $x_1/(x_2 + x_3) = u_1/u_2$,

(3) $u_1 + u_2 = 100$,

where x_1, x_2, and x_3 are the inputs measured in a number of cars for the analytical controller and u_1 and u_2 are the outputs measured as greenlight in seconds for the analytical controller.

The two controllers have equal initial inputs (number of cars), for the fuzzy controller (Table 1) and for the Analytical controller (Table 3).

5. Results and discussion

Table 1 presents the traffic flow for the fuzzy controller in regard to traffic flow measured in vehicles per hour. The first column presents the number of iterations. Under iteration is considered a control cycle which has a duration of one hour of simulation. The columns with x_1, x_2, and x_3 present the inputs, measured in the number of cars. The last two columns u_1 and u_2 present the outputs. Output1 (u_1) is for the main road with higher traffic flow and output2 (u_2) is for the crossing road.

The last two rows of Table 1 and Table 3 present sums of all iterations/control cycles of the traffic flow.

Table 1. Traffic flow for fuzzy controller

Number of iterations	x_1 – input1, numbercars	x_2 – input2, numbercars	x_3 – input3, numbercars	u_1 – output1, s	u_2 – output2, s
1	1000	870	250	50	50
2	964	872	250	41	59
3	960	872	250	41	59
4	960	872	250	41	59
x_1, x_2+x_3	3884	4486			
x_1+x_2+x_3	8370				

Table 2 presents the mean queue per section (z_1, z, z_3) for the fuzzy controller. The first column presents the iterations. The next three columns present the values of the mean queue for each approach. The fifth column presents the mean queue of the three approaches (sections). Output1 and output2 present the duration of the green light for the main road and the crossing road.

The last two rows of Table 2 and Table 4 present sums of all iterations/control cycles of the mean queue length.

Table 3 presents the traffic flow for the analytical controller in regard to traffic flow measured in vehicles per hour. The first three columns present the approaches – x_1, x_2, x_3. The last two columns u_1 and u_2 present the duration of green light for the main road and the crossing road.

Table 2. Mean queue per section Fuzzy controller

Number of iterations	z_1 – input1, mean queue	z_2 – input2, mean queue	z_3 – input3, mean queue	Mean value, mean queue	u_1 – output1, green light for Section 1, s	u_2 – output2, green light for Section 2, s
1-2	1.54	1.76	0.51	1.270	50	50
2-3	2.10	1.41	0.35	1.286	41	59
3-4	2.10	1.41	0.35	1.286	41	59
z_1, z_2+z_3	5.74	5.79				
$z_1+z_2+z_3$	11.53					

Table 3. Traffic flow for Analytical controller

Number of iterations	x_1 – input1, numbercars	x_2 – input2, numbercars	x_3 – input3, numbercars	u_1 – output1, green light for Section 1, s	u_2 – output2, green light for Section 2, s
1	1000	870	250	47	53
2	962	872	250	46	54
3	960	872	250	46	54
4	960	872	250	46	54
x_1, x_2+x_3	3882	4486			
$x_1+x_2+x_3$	8368				

Table 4 presents the mean queue length for the analytical controller, measured in vehicles. The first column presents the iterations, The following three columns present the queue for each approach. The fifth column presents the mean value for the three approaches. The last two columns present the duration of the green light for the main road and the crossing road.

Table 4. Mean queue per section analytical controller

Number of iterations	z_1 – input1, mean queue	z_2 – input2, mean queue	z_3 – input3, mean queue	Mean value, mean queue	u_1 – output1, green light for Section 1, s	u_2 – output2, green light for Section 2, s
1-2	1.70	1.66	0.46	1.273	47	53
2-3	1.80	1.60	0.43	1.276	46	54
3-4	1.80	1.60	0.43	1.276	46	54
z_1, z_2+z_3	5.3	6.18				
$z_1+z_2+z_3$	11.48					

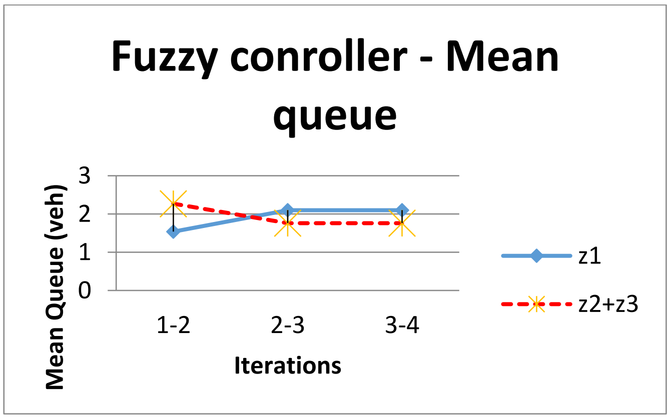


Fig. 7. Fuzzy controller – mean queue

Figs 7 and 8 present the mean queue for the fuzzy and analytical controllers, respectively. The *x* axis presents the iterations/control cycles and the *y* axis presents the values in number of vehicles for the main road z_1) and the crossing road ($z_2 + z_3$). The values are presented in Table 2 and Table 4.

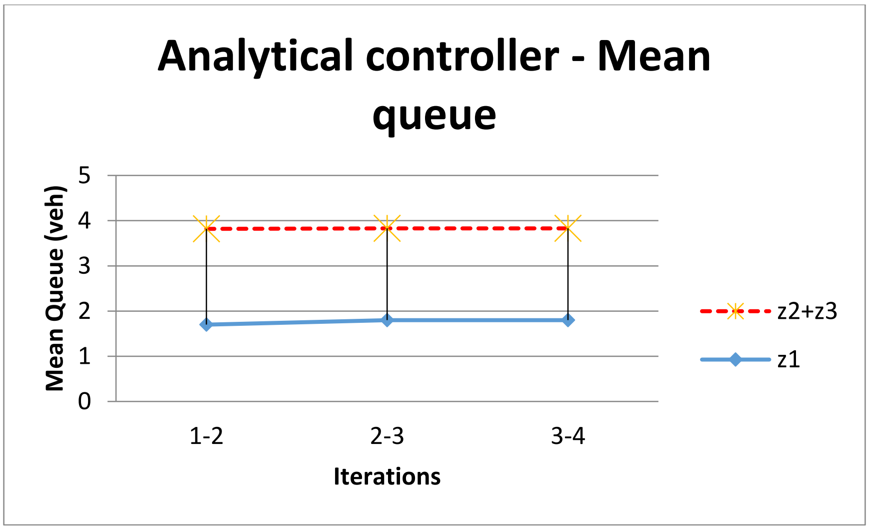


Fig. 8. Analytical controller – mean queue

Figs 9 and 10 present the traffic flow for the fuzzy and the analytical controllers, respectively. The traffic flow on both figures is presented on the *y* axis and is measured in vehicles per hour. The *x* axis on both figures presents the iterations/control cycles. The solid line presents the traffic flow for the main road (x_1) and the dashed line presents the crossing road, which is a sum of the two approaches (– x_2 and x_3). The values are presented in Table 1 and Table 3.

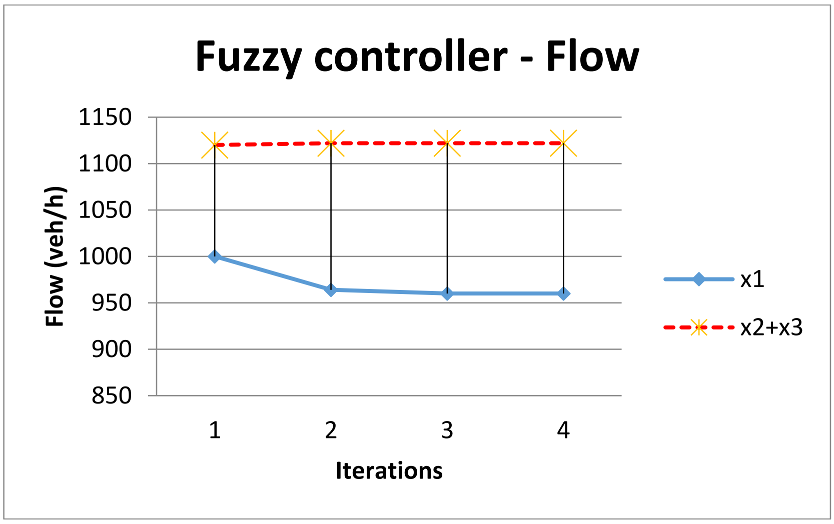


Fig. 9. Fuzzy controller – flow

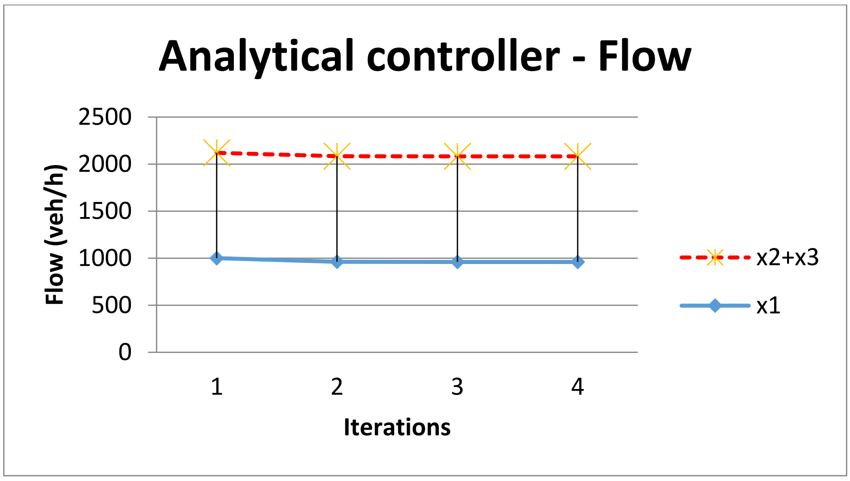


Fig. 10. Analytical controller – flow

Figs 11 and 12 present another representation of the mean queue and traffic flow for the fuzzy and the analytical controller where the overall performance of both controllers is more visible.

Fig. 11 presents a comparison between the fuzzy and the analytical controller in regard to the mean queue. It is visible from Fig. 11 that the fuzzy controller has a slightly higher mean queue. Thus, in terms of mean queue, the analytical controller performs slightly better.

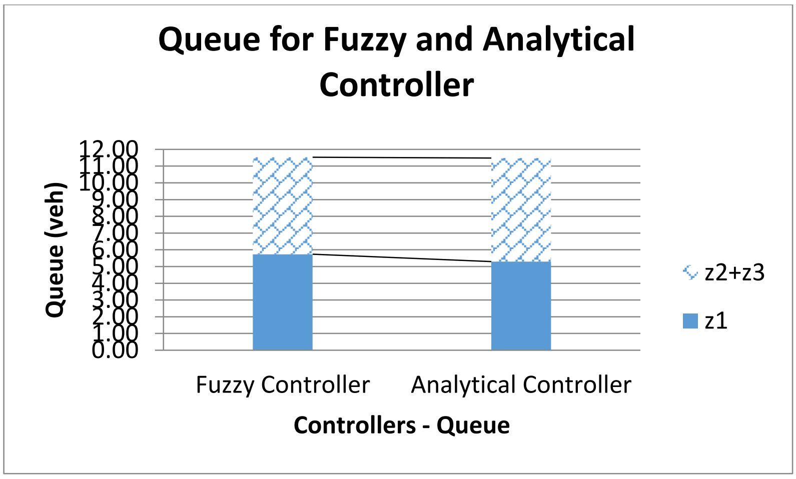


Fig. 11. Fuzzy and analytical controllers – comparison by queue

Fig. 12 presents a comparison between the fuzzy and the analytical controllers in regard to traffic flow. It is visible from Fig. 12 that both controllers behave adequately for the modelling and simulation of urban traffic flow.

Fig. 13 shows a comparison between the fuzzy and analytical controllers in terms of traffic flow and number of iterations. The fuzzy controller has a slightly bigger throughput compared to the analytical controller.

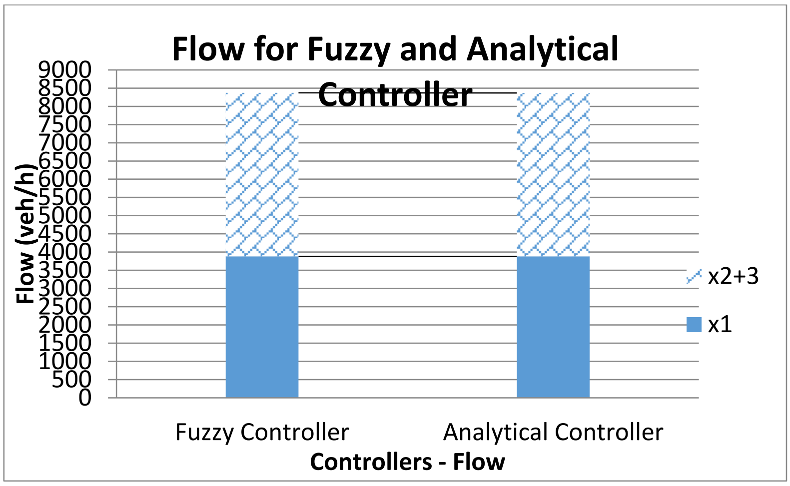


Fig. 12. Fuzzy and analytical controllers – comparison by flow

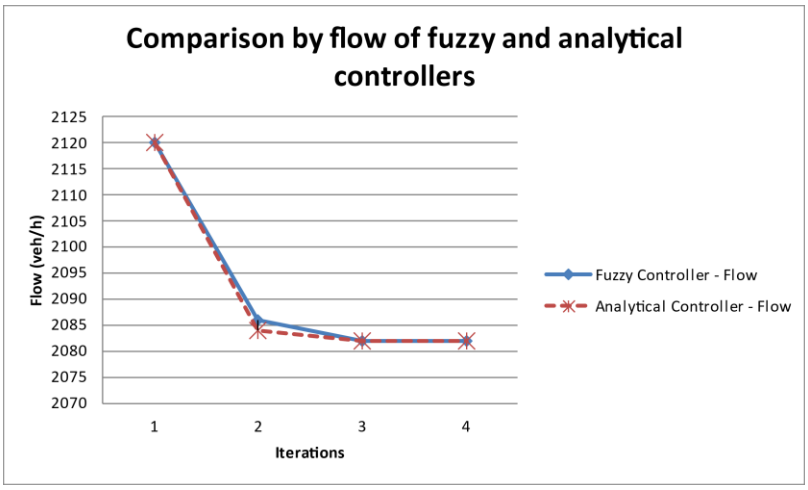


Fig. 13. Flow comparison of fuzzy and analytical controllers

6. Conclusion

This research emphasizes on development of a traffic light system with feedback control for the purpose of traffic plan in urban areas. The goal has been achieved by designing and comparison of two types of controllers, which have been separately modeled and then simulated and tested in Aimsun environment. The proposed designed controllers are fuzzy and analytical. The developed controllers manage the duration of the green lights/control variables according to the simulated traffic flow. They have produced adequate solutions in terms of developing a control of traffic light system with feedback and in that manner, the goal of the study is fulfilled. The added value of the research is the appropriate integration of the principles of the control theory, intelligent methods, and computer simulation.

The results of the study can be applied to control the traffic light system in an urban area in order to improve traffic behavior (to increase the flow and reduce the queue lengths).

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