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Adaptive Traffic Signaling Control Using SUMO Simulator

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Abstract:- In today's world, transportation vehicles are essential for meeting mobility needs and moving goods efficiently. To reduce average waiting times across varying traffic flow rates, a two-stage, three-module fuzzy logic system has been developed for real-time management of signalized junctions. The first stage includes two modules: the "next phase selection module," which monitors traffic conditions of all red phases (except the current green) and selects the most urgent one based on 30 fuzzy rules. The "extension time module" assesses the green phase's traffic conditions to decide whether to stop or extend it, using 12 fuzzy rules. The second stage features a "decision module" with 10 fuzzy rules, which determines whether to replace or maintain the current green phase based on inputs from the previous modules. This system was implemented using the SUMO traffic simulation tool, utilizing real-world traffic data from a congested intersection in Kilis, Turkey. The fuzzy logic traffic management system outperformed conventional fixed-time control, achieving substantial reductions in average waiting times: 76.46%, 56%, 50%, and 60% for the four analyzed areas.

Keywords:- *Fuzzy Logic, Simulation Of Urban Mobility, Intelligent Traffic Control, Isolated Junction, Vehicles.*

I. INTRODUCTİON

Today, the number of vehicles is increasing rapidly. As a result, the problem of traffic congestion grows and in large cities, this problem is inextricably affecting people's quality of life. In recent years, high-speed living traffic has become an important part of the modern city [1]. As the number of road users, vehicles and pedestrians increases, light cycles controlled by traffic demand increase. Traffic congestion brings with it many problems; Besides environmental, social and economic losses, it causes time loss and directly affects production and fuel usage [2]. High rates of vehicle use; coupled with the lack of available space to build new transport infrastructure and public funds, it serves to further complicate the problem. Within this framework, it is necessary to develop smart and economical solutions to improve the service quality for road users [3]. In order to reduce all these problems in a relatively cheaper way and to ensure the best use of the existing road network, a traffic signaling system technique has been implemented. Many simulation models have been developed for traffic signaling, traffic situations can be simulated on the computer at reasonable cost and without danger, which is why the computer simulations are selected in the growth of traffic signal technology [4]. Traffic signal systems divide into three major categories: Human-controlled traffic light systems, fixed signal systems, and smart. The human-controlled method utilizes hand motions and voice commands. Static-time systems follow predetermined schedules based on historical data and lack the flexibility to make real-time changes. An intelligent traffic control system uses sensors to continually monitor traffic conditions. This allows for dynamic modification of signal timing and signal sequencing and improved intersection management. These approaches enhance the safety of both vehicles and pedestrians while increasing the capacity of the intersection at the same time [5].

This study discovers the improvement of an adaptive traffic signal management system for smart cities utilizing fuzzy logic and the SUMO simulation. The paper concentrates on an isolated intersection and compares the adaptive system performance based on fuzzy logic with a traditional fixed-time traffic signal controller. The adaptive system uses real-time traffic data, including vehicle density and queue length, to dynamically adjust signal timing strategically and enhance efficiency. The results indicate that the fuzzy logic system significantly reduces average waiting times compared to the fixed time method.

II. RELATED WORKS

This unit discusses traffic signal systems and presents recommendations for smart solutions:

Lee and Lee-Kwang (1999), the proposed traffic signal control system employs a fuzzy logic approach to manage multiple intersections adaptively. It dynamically adjusts signal phase sequences and durations to enhance performance. The system consists of three key modules: observation, next phase, and decision, all working together for real-time decision-making. Each module features its own fuzzy rule base, allowing for context-sensitive responses to traffic conditions. Results show that the fuzzy logic system significantly outperforms conventional vehicle-actuated methods, reducing average vehicle delays [6].

Askerzade and Mahmood (2010), fuzzy logic technology is utilized to control traffic lights, managing the duration of the green light based on traffic conditions. The fuzzy controller has three input variables: the number of vehicles arriving, the number of vehicles waiting, and those making right or left turns. Its output variable adjusts the green signal duration based on these inputs, demonstrating their influence on extension periods. The Tagaki-Sugeno method is employed to calculate these results, and its outcomes are compared with those of the Mamdani method under various traffic scenarios. The Tagaki-Sugeno method yields superior results in reducing total waiting and transportation times. Decreased waiting times lead to lower fuel consumption and reduced environmental pollution [7].

Azimi et al. (2010), present a new fuzzy logic controller for an isolated signalized intersection. The system consists of the following variables: the status of the signal, the number of vehicles leaving traffic and the number of changes in queue length. The exact value of the output was calculated by the centroid deviation technique. Simulation was carried out using fuzzy rules (81 in number), MATLAB 7.4 and fuzzy logic toolbox. The results of this method and the improvement percentage have shown us that the fuzzy control system reduces the average waiting time at any intersection compared to fixed time control [8,24].

Zaied and Al Othman (2011), This study introduces a fuzzy logic-based traffic signal control system designed for two-way intersections. The system dynamically adjusts signal timing intervals in response to current traffic conditions and vehicle movement levels. Implemented in MATLAB, the fuzzy logic control algorithm features a robust set of 78 fuzzy rules. These rules focus on optimizing signal cycle times and minimizing unused green light periods across different phases. When compared to traditional traffic control systems, this fuzzy logic approach shows enhanced performance by significantly reducing instances of unused green time [9].

Prasetiyo et al. (2015), this work outlines the design and implementation of an adaptive traffic light control system using the Sugeno-style fuzzy logic approach. The system leverages fuzzy logic to dynamically calculate the optimal duration of the green signal phase at intersections. Although the fuzzy logic-based adaptive control shows a slightly higher average waiting time than fixed-time traffic signals, it outperforms in reducing vehicle queues and increasing the overall number of vehicles departing the intersection. [10].

Dereli et al. (2018), This study introduces the design of a fuzzy logic-based traffic signal controller for a single intersection, aiming to dynamically adjust green light duration, reduce overall vehicle delays, and minimize waiting vehicles. The fuzzy logic system was implemented using the Fuzzy Inference System (FIS) in MATLAB. To assess its performance, the researchers compared it with artificial neural network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) models. The results indicate that the fuzzy logic approach effectively reduces total delay time and outperforms the other systems in terms of intersection efficiency [11].

Gündoğan et al. (2014), this study presents the ATAK system, a real-time adaptive traffic control method that manages signalized intersections through a combination of genetic algorithms and fuzzy logic. The ATAK system dynamically adjusts traffic signal timings based on variables like traffic volume and occupancy rates. Its performance was assessed against a conventional multi-plan traffic control system. The results show that the ATAK system can improve average travel times by up to 15%. Furthermore, it reduced carbon emissions by approximately 10% compared to the multi-plan control approach. [12].

III. TRAFFIC SIGNALING

The traffic light signal shown in Fig. 1, is a widely recognized signaling device typically installed at road intersections or pedestrian crossing points to regulate the flow of traffic through the use of colored lights. This type of traffic control system is widely implemented in cities across the globe to manage the movement of vehicles and pedestrians. All light signals are illuminated with two primary colors, red light means “stop” and green light means allowing passage. The first light signal was established in London in 1868, in 1913, tricolor (green, yellow, red) lights were invented in the United States. In 1922, the signal was found to be working mechanically and then states began to widely establish light signals to control traffic [16-17].

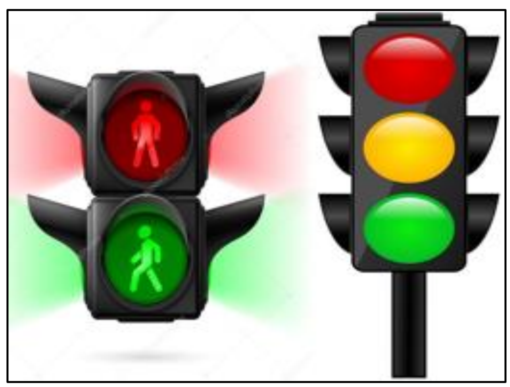

Fig. 1. Traffic Light Signals

➢ *Some Terms of Traffic Signaling*

Here, some basic concepts related to traffic signaling are briefly explained by making use of Fig. 2, and Fig. 3.

The most important concepts used in signaling:

- Junction: These are the areas where traffic flows coming from several roads are separated and intersected.
- Road: is a part that generally used by vehicles.

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- Lane: Each section of the road, separated by signs, for vehicles to travel safely.
- Traffic flow: The arrival and departure of vehicles on the road.
- Red time: The time at which a red light is given to a phase.
- Yellow time: Yellow light to signal phase is the known time.
- Green time: When the green light is given to the phase.

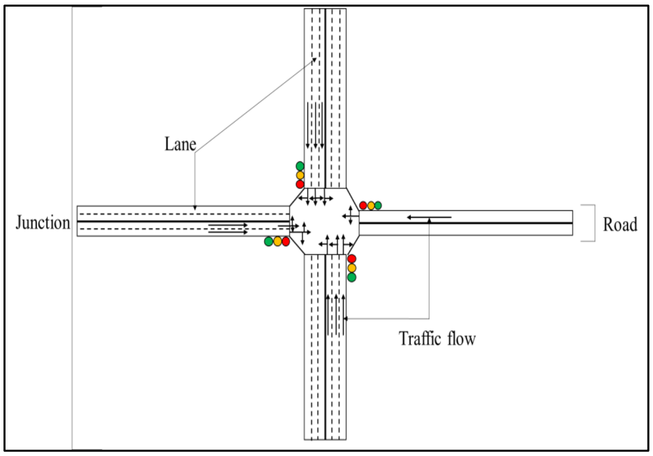


Fig. 2. Intersection, Road, Lane, Traffic Flow and Traffic Lights

- Phase: The time allowed to pass more than one flow at the junction. The time from the start of a current receiving the first green light to the next receiving a green signal is the phase.
- Cycle time: The total time during which each phase of the junction is allowed to pass once.

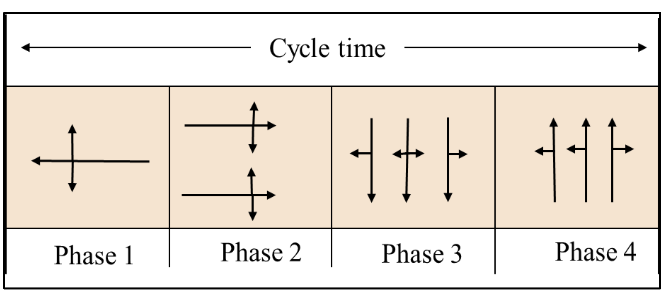


Fig. 3. Phase and Cycle Time

IV. FUZZY LOGIC

In a world dominated by the binary nature of traditional logic, where statements are either true or false, the concept of fuzzy logic emerges as a revolutionary approach to reasoning. Fuzzy logic, pioneered by the visionary mathematician Lotfi Zadeh in the 1960s, recognizes that many real-world phenomena defy the rigid constraints of classical logic [18]. Fuzzy logic is based on the concept of fuzzy sets unlike classical sets, where an element either fully belongs or does not belong, fuzzy sets allow for varying degrees of membership. This is represented by a membership function that ranges from 0 to 1. This flexibility is a key distinguishing characteristic of fuzzy logic compared to classical binary logic [19]. Its origins date back to Zadeh's groundbreaking work in the 1960s, where he questioned the limitations of traditional Boolean logic and paved the way for a new paradigm in mathematics and computer science. Zadeh's key insight was that many real-world problems involve imprecise or ambiguous information, which classical logical frameworks cannot effectively address [20]. Researchers such as Mamdani, Sugeno, and Takagi-Sugeno-Kang played pivotal roles in developing fuzzy control systems. These systems have been widely applied in fields like industrial automation, robotics, and consumer electronics. The ongoing advancements in fuzzy logic, coupled with its seamless integration with emerging technologies, suggest an exciting future where the power of imprecision will play an increasingly vital role in shaping the way we interact with and understand the world around us [21].

V. SIMULATION OF URBAN MOBILITY (SUMO)

Sumo was developed in 2001 by the German aerospace center (DLR). With the program, which was published in 2002, users gained a basic microscopic program that can be studied on traffic networks, it is open-source software [22]. With the TraCI module (Traffic Control Interface), this interface allows for interactive monitoring and control of various aspects of the traffic environment. All components can be manipulated in the simulation using the Python program. In this way, it is much easier to diversify than other simulation programs. SUMO can produce output data that can be used in various fields such as vehicle track data, vehicle type and number data passing through point, emission values of vehicles, lane change information at desired frequency as output with all specified features [23].

VI. APPLICATION AND RESULTS

Fuzzy logic-based traffic signal control provides a flexible alternative to conventional fixed-time traffic lights, adapting to various traffic patterns at intersections. This system employs detectors to sense vehicle presence and count the number of vehicles, effectively managing traffic density on individual lanes and improving the assessment of changing conditions. The fuzzy logic controller dynamically adjusts green light durations, and the sequence of signal phases based on current traffic conditions. In this two-stage traffic light system, the controller not only decides whether to extend or terminate the current green phase but also determines which red phase will become the next green phase and the appropriate extension time. As a result, the phase sequence remains uncertain. The performance of this fuzzy logic-based system will be evaluated using average vehicle waiting time as the primary metric. Fig. 4, shows the schematic diagram of the proposed controller.

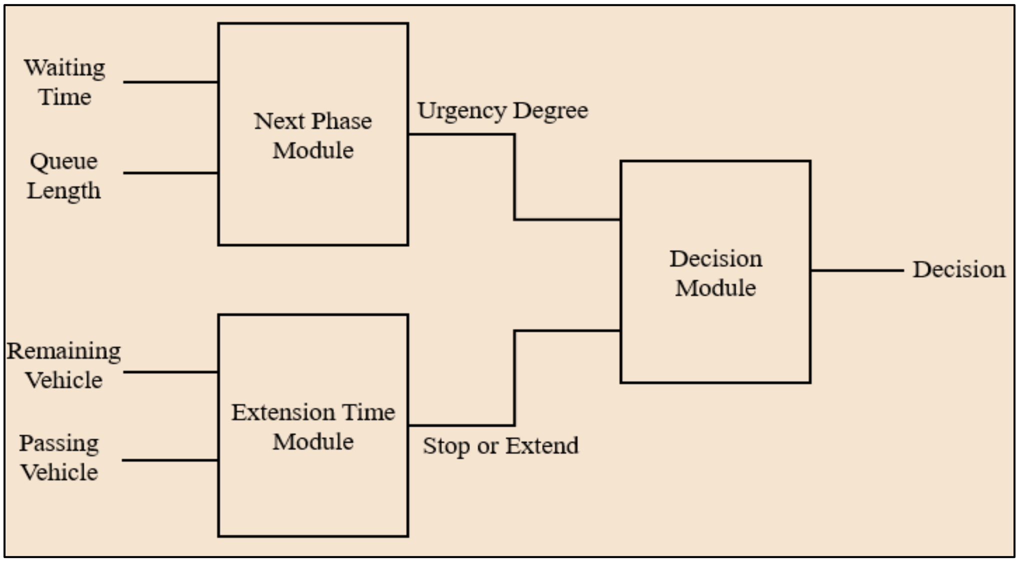
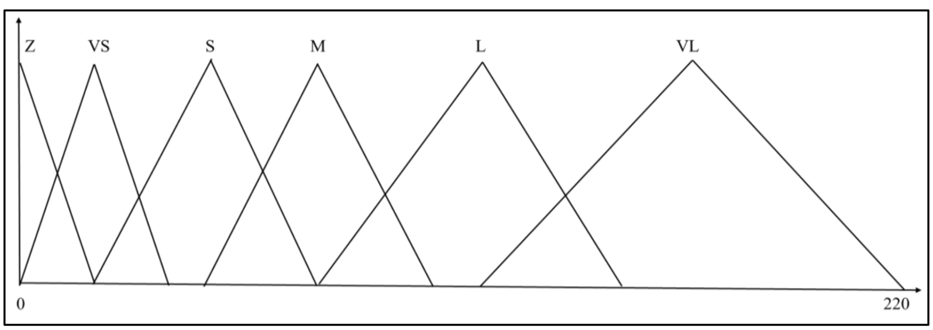


Fig. 4. Control unit diagram

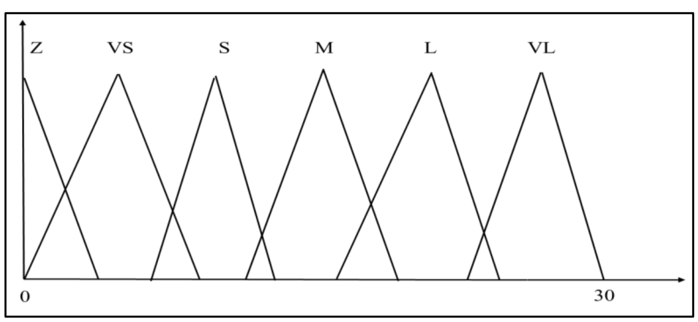
The first stage involves two distinct modules:

- *Next Stage Module*

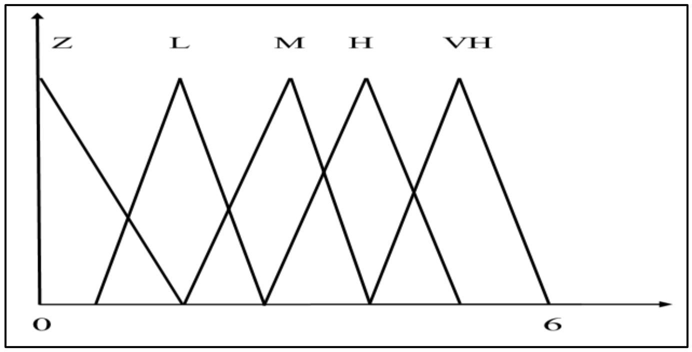
This module identifies the next candidate for the green phase by evaluating traffic conditions across all red phases, excluding the current green one. It uses waiting times and queue lengths from these phases as inputs. The output is the selected phase along with its urgency level. By comparing urgency levels of all input phases, the module determines the most urgent one. Inputs have six membership functions for waiting time and queue length, ranging from zero to very long. The Urgency Level output consists of five membership functions, from zero to very high, as shown in Fig. 5.



Waiting time
(a)



Queue length
(b)



Urgency degree
(c)

Fig. 5. The input parameters include waiting time and queue length, while the output parameter is the degree of urgency.

Table 1 outlines the 30 fuzzy rules governing the decision-making process within this module. As an example, if the waiting time is categorized as "Zero" and the queue length is deemed "Long", the corresponding urgency level would be determined as "Medium".

Table 1. Rules of the Next Stage Module.

Rule	**Waiting time**	**Queue length**	**Urgency level**
R1	Z	VS	Z
R2	VS	VS	L
R3	S	VS	M
R4	M	VS	M
R5	L	VS	M
R6	VL	VS	M
R7	Z	S	Z
R8	VS	S	M
R9	S	S	M
R10	M	S	H
R11	L	S	H
R12	VL	S	H
R13	Z	M	L
R14	VS	M	L
R15	S	M	M
R16	M	M	M
R17	L	M	H
R18	VL	M	VH
R19	Z	L	M
R20	VS	L	M
R21	S	L	H
R22	M	L	H
R23	L	L	VH
R24	VL	L	VH
R25	Z	VL	M
R26	VS	VL	H
R27	S	VL	H
R28	M	VL	VH
R29	L	VL	VH
R30	VL	VL	VH

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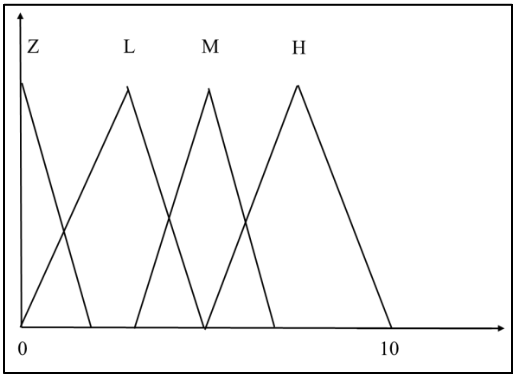
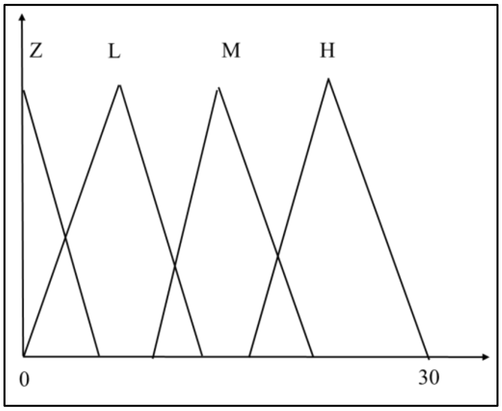
➢ *Extension time module*

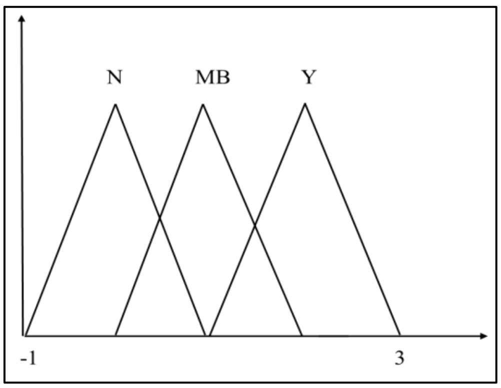
This module evaluates the traffic conditions during the current green phase. Using the collected data, it generates a stop degree to decide whether the controller should terminate or extend the green light duration. The inputs for this module include the number of remaining vehicles and the number of passing vehicles. The output consists of a decision to either stop or prolong the active green light phase. Each input parameter has four membership functions: remaining vehicles are categorized as (Zero, Short, Medium, Long), while passing vehicles are categorized as (Zero, Low, Medium, High). The output, or stop degree, features three membership functions: (No, Maybe, Yes), show Fig. 6.



Remaining vehicles number
(a)



Passing vehicles number
(b)



Stop or Extend
(c)

Fig. 6. The fuzzy sets for the number of remaining vehicles, passing vehicles, and the decision to stop or extend.

Table 2 presents the 12 fuzzy rules that govern the decision-making process within this module. As an example, if the number of remaining vehicles is assessed as "Short" and the number of passing vehicles is deemed "High", the resulting decision would be to either stop or extend the green light duration, which is classified as "No".

Table 2. Rules of Extension Time Module

Rule	Remaining vehicles	Passing vehicles	Stop or Extend
R1	Z	L	Y
R2	Z	M	MB
R3	Z	H	MB
R4	L	L	MB
R5	L	M	MB
R6	L	H	N
R7	M	L	N
R8	M	M	N
R9	M	H	N
R10	H	L	N
R11	H	M	N
R12	H	H	N

➢ *Second Stage Decision module*

The primary function of this module is to determine whether the current green phase should be changed or maintained based on the outputs from the preceding stages. The inputs to this decision module are the urgency degree and the stop/extend decision generated by the earlier modules. The output of this module is the final decision, which is represented using two membership functions: "No" and "Yes", as shown in Fig. 7.

This decision-making process takes into account the evaluated urgency degree as well as the recommendation to either stop or extend the green phase duration. By synthesizing these inputs, the Decision Module arrives at the appropriate course of action, whether to keep the existing green phase or initiate a change to the next phase. The flexibility of this two-stage approach ensures that the traffic signal control system can adaptively respond to the prevailing traffic conditions and optimize the signal timing accordingly.

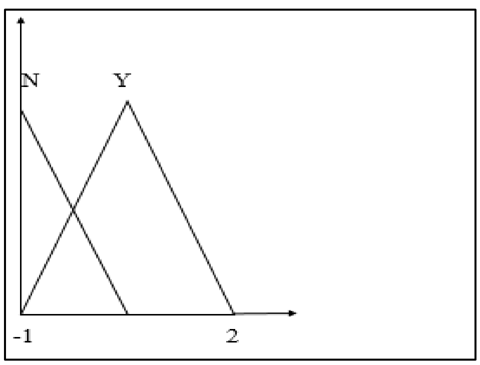


Fig. 7. The fuzzy sets of decision

Table 3 outlines the 10 fuzzy rules that define the decision-making process within this module. To illustrate, if the urgency degree is classified as "Very High" and the stop/extend decision is recognized as "Yes", the final output of the Decision Module would be "Yes", signifying the need to transition to the next green phase.

Table 3. Rules of the Decision Module

Rules	Urgency degree	stop/extend decision	Decision
R1	Z	MB	N
R2	L	MB	Y
R3	M	MB	Y
R4	H	MB	Y
R5	VH	MB	Y
R6	Z	Y	N

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R7	L	Y	Y
R8	M	Y	Y
R9	H	Y	Y
R10	VH	Y	Y

VII. WORKSPACE

The fuzzy logic and fixed-time methods we developed were implemented in simulations at four different intersections in Kilis city. Additionally, a 3-second transition time was allocated for each workspace to prevent accidents during phase changes. Our simulation studies are detailed as follows:

➢ *First Workspace*

As the first Workspace, in Fig. 8, the junction of Ali Metin Dirimtekin Street in Ekrem Çetin Quarter of Kilisili was selected and studied on 24-hour data.

Fig. 8. First Workspace

At a nine-lane, four-phase intersection, the first and second phases each have three lanes, the third phase has two lanes, and the fourth phase has a single lane. A detector is installed on the road for each lane, as illustrated in Fig. 9. Utilizing the SUMO program, the cycle time is set to 102 seconds to minimize the average waiting time in the fixed-time traffic control system. Specifically, the durations for phases 1, 2, 3, and 4 are 15, 15, 14, and 40 seconds, respectively.

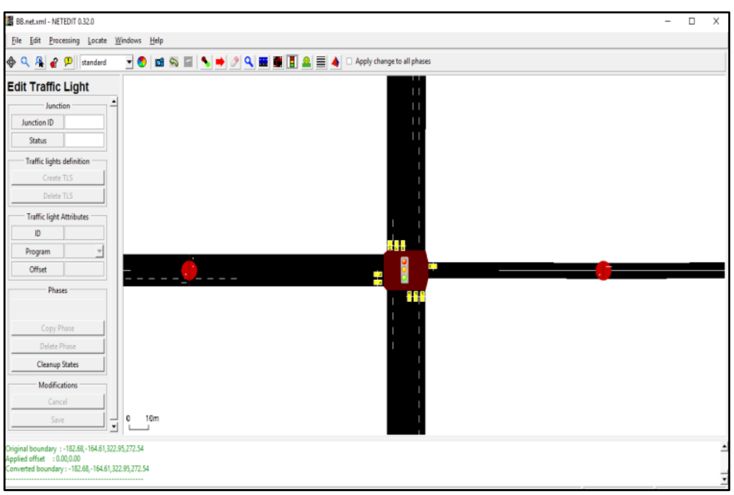

Fig. 9. Modeling the first workspace on Simulation

The results obtained from the simulation as shown in Table 4, fuzzy logic system reduces total waiting time from 996204 seconds to 234751 seconds compared to fixed time system, The total trip time is reduced from 1775617 seconds to 1037921 seconds,

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the average vehicle travel time is reduced from 92 seconds to 53 seconds, and the average vehicle waiting time is reduced from 51 seconds to 12 seconds. Fuzzy logic system has been observed to be better.

Table 4. Comparison of Results

Control Methods	Fixed Time Method	Fuzzy Logic Method
Total number of vehicles	19230	19230
Total Waiting Time (Sec)	996204	234751
Total Travel Time (Sec)	1775617	1037921
Average Vehicle Travel Time (Sec)	92	53
Average Vehicle Waiting Time (Sec)	51	12

- *Second Workspace*

As our second Workspace, the junction of Kilis Yaşar Aktürk Neighborhood, Vatan Street, which is seen in Fig. 10, was selected and studied on 24-hour data.

Fig. 10. Second Workspace

As illustrated in Fig. 11, the intersection features eight lanes organized into four phases, with each phase containing two lanes. A detector is positioned along the path for each lane. Using the SUMO program, the fixed-time traffic control system is configured with a cycle time of 56 seconds to minimize the average waiting time. Accordingly, the durations for phases 1, 2, 3, and 4 are set to 11 seconds each.

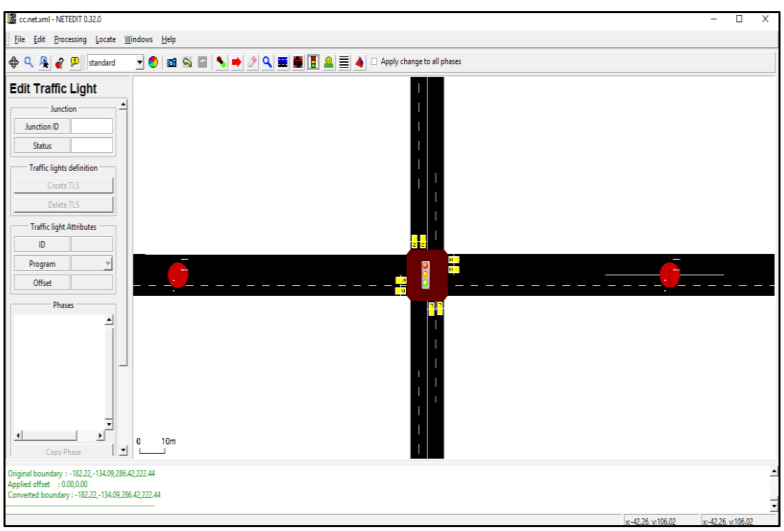

Fig. 11. Modeling the second workspace on Simulation

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The results obtained from the simulation in Table 5, fuzzy logic system compared to fixed time system the total waiting time is reduced from 421547 seconds to 185397 seconds, The total trip time is reduced from 1052305 seconds to 790478 seconds, the average vehicle travel time is reduced from 63 seconds to 47 seconds, and the average vehicle waiting time is reduced from 25 seconds to 11 seconds. Fuzzy logic system has been observed to be better.

Table 5. Comparison of results

Control Methods	**Fixed Time Method**	**Fuzzy Logic Method**
Total number of vehicles	16597	16597
Total Waiting Time (Sec)	421547	185397
Total Travel Time (Sec)	1052305	790478
Average Vehicle Travel Time (Sec)	63	47
Average Vehicle Waiting Time (Sec)	25	11

➢ *Third Workspace*

As the third Workspace, in Fig. 12, Kilis Mehmet Rıfat Kazancıoğlu Neighborhood, Gen. Safter Necioğlu Boulevard was selected and 18:30 hours data were studied.

Fig. 12. Third Workspace

As depicted in Fig. 13, the intersection consists of eight lanes divided into three phases: the first phase has three lanes, and the second phase has two lanes. A detector is installed in the path for each lane. Using the SUMO program, the fixed-time traffic control system is designed with a cycle time of 65 seconds to minimize the average waiting time. Specifically, the durations for phases 1, 2, and 3 are set to 20, 20, and 16 seconds, respectively.

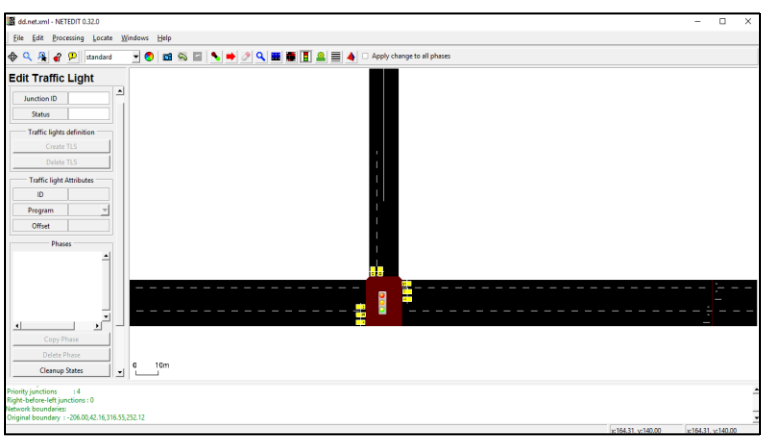

Fig. 13. Third workspace modeling on Simulation

Table 6 results obtained from the simulation, fuzzy logic system compared to fixed time system, the total waiting time is reduced from 269940 seconds to 131490 seconds, the total travel time is reduced from 977125 seconds to 826411 seconds, the average vehicle travel time is reduced from 61 seconds to 51 seconds, and the average vehicle waiting time is reduced from 16 seconds to 8 seconds. Fuzzy logic system has been observed to be better.

Table 6. Comparison of results

Control Methods	**Fixed Time Method**	**Fuzzy Logic Method**
Total number of vehicles	15977	15977
Total Waiting Time (Sec)	269940	131490
Total Travel Time (Sec)	977125	826411
Average Vehicle Travel Time (Sec)	61	51
Average Vehicle Waiting Time (Sec)	16	8

➢ *Fourth Workspace*

As the fourth Workspace, in Fig. 14, Kilis Ekrem Çetin Neighborhood, Doğan Güreş Pasha Boulevard was selected and 24-hour data were studied.

Fig. 14. Fourth Workspace

At an intersection with eleven lanes organized into five phases, the first phase has three lanes, while the second, third, fourth, and fifth phases each have two lanes. A detector is installed for each lane, as shown in Fig. 15. Utilizing the SUMO program, the cycle time is configured to 85 seconds to minimize the average waiting time in the fixed-time traffic control system. Specifically, the durations for phases 1, 2, 3, 4, and 5 are set to 16, 11, 16, 16, and 11 seconds, respectively.

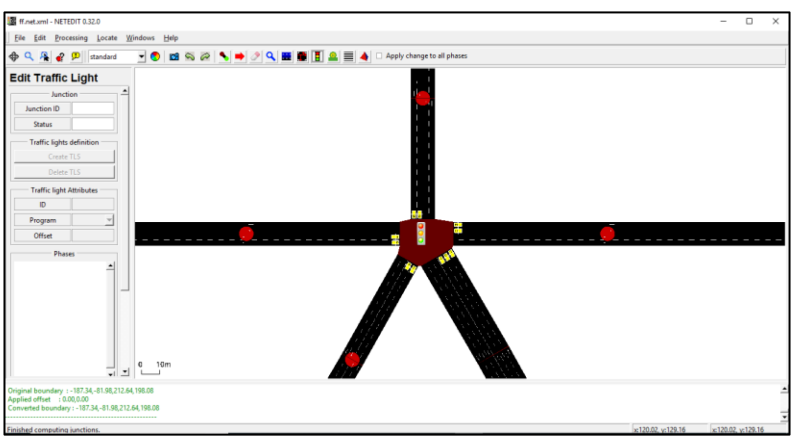

Fig. 15. Model workspace modeling on Simulation

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Table 7 results obtained from the simulation, the fuzzy logic system reduces the total waiting time from 413544 seconds to 165492 seconds, the total travel time decreases from 824562 seconds to 559979 seconds, the average vehicle travel time decreases from 61 seconds to 41 seconds and the average vehicle standby time decreases from 30 seconds to 12 seconds. Fuzzy logic system has been observed to be better.

Table 7. Comparison of results

Control Methods	**Fixed Time Method**	**Fuzzy Logic Method**
Total number of vehicles	13500	13500
Total Waiting Time (Sec)	413544	165492
Total Travel Time (Sec)	824562	559979
Average Vehicle Travel Time (Sec)	61	41
Average Vehicle Waiting Time (Sec)	30	12

VIII. CONCLUSION

We developed a two-stage traffic signal control system for an isolated intersection, utilizing fuzzy logic principles. The performance of this proposed system was compared to that of the traditional traffic control method. The traffic simulation was conducted using the SUMO platform. In this system, the traffic signal controllers manage the intersection based on the traffic information collected by their respective detectors. Using this real-time data, the fuzzy rule-based system determines the optimal phase sequence and timing for the traffic signals. The results obtained from the simulation showed significant improvements when compared to the conventional logic controller. Specifically, the proposed two-stage fuzzy logic-based system demonstrated 76.46%, 56%, 50%, and 60% enhancements in the respective working areas, as detailed in Table VIII. These findings suggest that the recommended fuzzy logic-based approach outperforms the traditional fixed-time control method in effectively managing the traffic flow at the isolated intersection.

Table 8. Average Vehicle Waiting Time İmprovement percentage

Variable	**Workspace**	**Fixed Time Method**	**Fuzzy Logic Method**	**İmprovement**
Average Vehicle Waiting Time (Sec)	First	51	12	%76.46
	Second	25	11	%56
	Third	16	8	%50
	Fourth	30	12	%60

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