Fuzzy Logic Based Traffic Light Control System

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***Abstract*—Traffic congestion remains a critical problem in urban environments, necessitating advanced solutions for traffic monitoring and control. Traditional traffic light systems, which often operate on fixed cycles or predetermined schedules based on the time of day, fail to adjust to dynamic traffic volumes, leading to significant inefficiencies. This project introduces a novel approach using a fuzzy logic-based traffic light controller designed to optimize traffic flow and minimize delays, particularly effective under varied and heavy traffic conditions. The system smartly prioritizes emergency vehicles at intersections, significantly reducing their waiting times and enhancing overall traffic management.**

The methodology harnesses the capabilities of SciKit Fuzzy and the SUMO traffic simulation tool to integrate real-time traffic data into a fuzzy logic controller. This controller processes inputs such as vehicle count and the presence of emergency vehicles to dynamically adjust traffic light timings. The application of fuzzy logic allows for a more nuanced response to real-time traffic conditions, mimicking human decision-making processes in traffic control by extending or shortening green phases based on the volume of arriving vehicles and the queue length during red phases.

Initial results from the implementation of this system demonstrate a marked improvement in traffic flow and a significant reduction in wait times for prioritized vehicles. These outcomes highlight the potential of a fuzzy logic-based system to substantially enhance the efficiency of traffic light control at busy intersections. This project not only contributes to the field of intelligent transportation systems but also provides a scalable model for future enhancements in urban traffic management.

***Index Terms*—Fuzzy Rule Base, Membership Functions, Fuzzy Variables, and Fuzzy Logic Controller.**

I. Introduction

Traffic control systems are essential for managing the flow of vehicles and pedestrians in urban areas. Traditionally, these systems have used fixed-timer or time-of-day schemes where traffic lights change according to preset schedules. Such systems are based on average traffic flow data and do not account for real-time changes in traffic volume, leading to inefficiencies.

As urban populations have grown, the increase in vehicles has intensified the limitations of these traditional traffic systems. Congestion, long waiting times at intersections, and increased carbon emissions are common problems that cities face today. This situation calls for an intelligent traffic control system that can adapt to changing traffic conditions in real-time, ensuring smoother flow and reduced congestion.

One of the critical issues with traditional traffic systems is their inability to dynamically adjust to fluctuations in traffic volume. During off-peak hours, this can result in unnecessarily long waits at red lights when there are few vehicles on the road. Conversely, during peak hours, fixed timers often cannot handle the volume of traffic, leading to congestion and extended waiting times.

Fuzzy logic offers a promising solution to these problems. Unlike traditional binary logic, which operates under strict true/false parameters, fuzzy logic allows for degrees of truth. This means that it can handle uncertainty and partial truths effectively, making it ideal for complex environments like traffic control where traditional methods fail to capture the nuances of real-world scenarios.

The project aims to develop a fuzzy logic-based traffic light controller that prioritizes emergency vehicles and adapts traffic light phases in response to real-time traffic conditions. By integrating inputs such as vehicle count and emergency vehicle presence into a fuzzy logic controller, the system can make more informed decisions about signal timing. The objectives of the project are to improve vehicular throughput, reduce waiting times, and enhance overall intersection efficiency.

This new system will be developed and tested using tools such as SciKit Fuzzy for implementing fuzzy logic algorithms and SUMO (Simulation of Urban MObility) for traffic simulation. The results will provide insights into the effectiveness of fuzzy logic in traffic management and its potential to replace or augment existing traffic control systems.

By addressing the shortcomings of traditional traffic control mechanisms through the application of fuzzy logic, this project represents a significant step forward in the development of intelligent transportation systems. It aims not only to improve traffic efficiency but also to enhance the quality of urban life by reducing congestion and the environmental impact associated with it.

II. Related Work

Previous studies on traffic control systems have focused on optimizing traffic flow using various methods including signal timing adjustments based on fixed schedules, vehicle detection systems, and adaptive traffic control technologies. Research has extensively explored the limitations of conventional traffic light systems, especially under varying traffic densities and during emergency situations.

Methods such as the queue time ratio algorithm have shown significant improvements in traffic flow, reduced delay times, and decreased traffic density by adapting signal plans based on real-time traffic states. These approaches use advanced planning and execution systems to adjust goals and actions continuously, improving overall traffic performance.

The application of AI in traffic management has gained popularity for its ability to optimize traffic light control and improve intersection throughput. Fuzzy logic has been applied in numerous traffic systems to address the inadequacies of traditional binary logic controllers. It has been used for dynamic traffic light sequencing, pedestrian crossing signals, and real-time adjustments based on traffic density. Fuzzy systems are favored for their ability to handle uncertainty and provide decisions that mimic human reasoning, making them particularly suitable for complex environments like urban traffic.

Compared to traditional systems, fuzzy logic controllers show improvements in reducing wait times and increasing throughput at intersections. However, there are gaps such as the complexity of designing these systems and the computational demands of real-time data processing. While previous implementations of fuzzy logic in traffic control have demonstrated efficacy, they often require extensive calibration and tuning to perform optimally under diverse traffic conditions. This project aims to further refine these approaches, focusing on scalability and ease of implementation, to enhance their practicality for widespread adoption.

III. Methodology

The fuzzy inference system consists of input membership functions that classify the inputs (e.g., vehicle count, emergency vehicle detection) into fuzzy sets, a rule base that contains the fuzzy logic rules, and an inference engine that applies these rules to generate output decisions. The outputs are defuzzified into crisp values to set the specific timings of traffic lights. The decision-making process involves evaluating the current traffic conditions against predefined fuzzy rules, enabling the system to extend or shorten light phases dynamically based on real-time traffic demands.

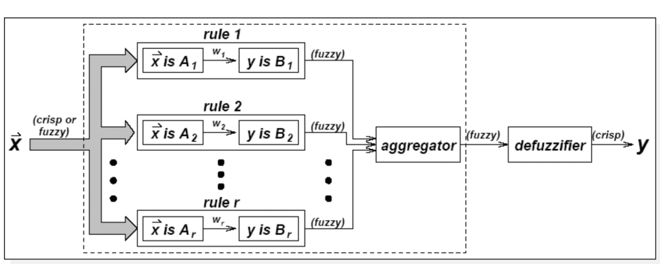

Fig. 1. Framework of the Proposed Approach

Fuzzy inference system involves:

A. Input Variables Identification

- Selection of Variables: The system begins by selecting critical variables that influence traffic control decisions. Key variables typically include vehicle density, queue length at the traffic signal, and emergency vehicle presence. These variables are chosen based on their relevance and availability from sensor data at intersections.
- Data Acquisition: Sensors deployed at intersections collect real-time data on traffic conditions, which is then transmitted to the fuzzy logic controller.
- Inputs Definition: The system considers five primary inputs to determine traffic light behavior:
  1) Number of vehicles on red lanes (0-12 vehicles)
  2) Number of vehicles on green lanes (0-12 vehicles)
  3) Maximum waiting time of vehicles on red lanes (0-50 seconds)
  4) Number of emergency vehicles on red lanes (0-2 vehicles)
  5) Number of emergency vehicles on green lanes (0-2 vehicles)

B. Development of Membership Functions

- Designing Membership Functions: Each input variable is associated with a set of membership functions that classify the input data into linguistic terms such as low, medium, or high.
- Implementation: Triangular and S-shaped membership functions are designed to capture the fuzzy nature of real-world inputs.
- Membership Functions for Inputs:
  1) Number of Vehicles: Defined with a range of 0 to 12 and categorized into four groups:
     - ”Too-small” (0-4 vehicles)
     - ”Small” (2-8 vehicles)
     - ”Much” (5-10 vehicles)
     - ”Too-much” (8+ vehicles)

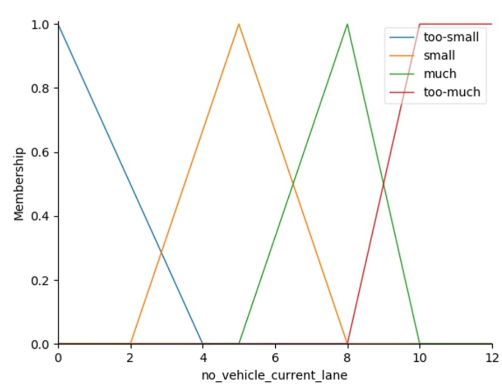

Fig. 2. Number of vehicles membership graph

2) Maximum Waiting Time: Defined with a range of 0 to 50 seconds and categorized into:
   - "Negligible" (0-12 seconds)
   - "Okay" (8-25 seconds)
   - "Much" (18-38 seconds)
   - "Too much" (28+ seconds)

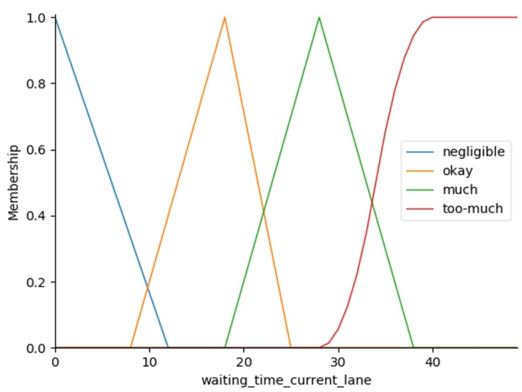

Fig. 3. Maximum vehicle waiting time membership graph

3) Number of Emergency Vehicles: Defined with a range of 0 to 2 and categorized into:
   - "Absent" (0 vehicles)
   - "Present" (1 vehicle)
   - "Much" (2+ vehicles)

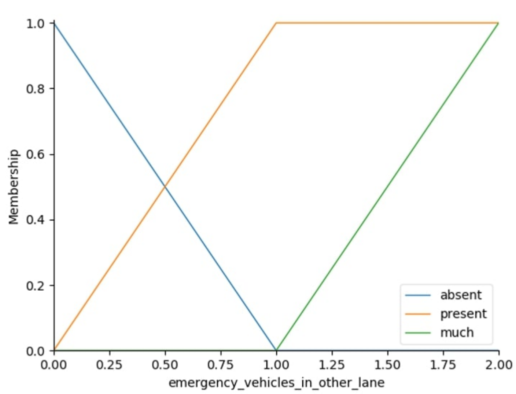

Fig. 4. Number of emergency vehicles membership graph

C. Rule Base Construction

- Rule Formulation: A comprehensive set of fuzzy logic rules is formulated based on expert knowledge and historical data. These rules dictate the controller's responses under various traffic conditions.
- System Integration: These rules are encoded into the fuzzy logic controller to guide the decision-making process dynamically.

- Fuzzy Rule Base -
  1) Rule 1: If the number of vehicles on red lanes is "Too-much" and the maximum waiting time is "Too much," then extend the green light significantly.
  2) Rule 2: If the number of vehicles on red lanes is "Much" and there are emergency vehicles ("Present" or "Much") on red lanes, then extend the green light.
  3) Rule 3: If the number of emergency vehicles on green lanes is "Much," then reduce the green light duration slightly.
  4) Rule 4: If the number of vehicles on green lanes is "Small" and the maximum waiting time is "Negligible," then reduce the green light duration.
  5) Rule 5: If the maximum waiting time is "Too much" and there are emergency vehicles on red lanes ("Present"), then extend the green light significantly.
  6) Rule 6: If the number of vehicles on red lanes is "Too-small" and the maximum waiting time is "Okay," maintain the green light duration.
  7) Rule 7: If the number of emergency vehicles on green lanes is "Present" and the number of vehicles on green lanes is "Too-much," slightly extend the green light.
  8) Rule 8: If the number of vehicles on red lanes is "Much" and the maximum waiting time is "Much," then extend the green light moderately.
  9) Rule 9: If the number of vehicles on green lanes is "Too-much" and there are no emergency vehicles ("Absent") on green lanes, then reduce the green light duration.
  10) Rule 10: If the number of vehicles on red lanes is "Small" and there are emergency vehicles ("Much") on red lanes, then extend the green light significantly.

D. Fuzzy Inference System

- Fuzzification of Inputs: Each of the input variables (number of vehicles on red lanes, number of vehicles on green lanes, maximum waiting time, and number of emergency vehicles on both lanes) is converted into fuzzy values based on the defined membership functions.
- Rule Evaluation: Apply the fuzzy rule base to the fuzzified inputs. Each rule determines if it is activated based on the input conditions. For example, if a rule states "If the number of vehicles on red lanes is 'Much' and there are emergency vehicles 'Present' on red lanes, then extend the green light," the degree to which this rule applies is calculated based on the fuzzified inputs.
- Aggregation of Rule Outputs: Once each rule's output is determined, these need to be combined to form a single fuzzy output set for each action. This is typically done using max method.
  This method is preferred for combining the outputs of multiple fuzzy rules because it effectively captures the highest degree of truth among the activated rules.

E. Defuzzification

- Converting to Crisp Outputs: The final step involves converting the fuzzy outputs into crisp, actionable commands for the traffic lights. centroid or Center of Gravity (CoG) method is used to calculate a precise output, such as the exact duration to extend a green light.

- Mathematically, the centroid C is calculated as:

$$C = \frac{\int x \cdot \mu_A(x)\, dx}{\int \mu_A(x)\, dx}$$

  where x is a point in the output space, and $\mu_A(x)$ is the membership value at x in the aggregated output fuzzy set.
  It computes the balance point of the area under the curve of the aggregated output membership functions, providing a single crisp value that represents the overall decision of the fuzzy logic system.

- Output Definition: The output, a crisp value between 0 and 1, is used to directly to make decisions, such as setting the threshold for action in traffic light system.
  - If the output is below 0.5, the traffic light remains unchanged.
  - If the output is 0.5 or above, the traffic light is switched.
- Execution: These crisp values are then sent to the traffic signal controllers, adjusting the light phases in real-time to optimize traffic flow and reduce congestion.

IV. SIMULATION RESULTS AND EVALUATION

A. Pre-Simulation (Building the road networks)

The process involved using the SUMO Graphical User Interface to create and link the road network. The intersections and lane connections were configured, and the resulting XML configuration was saved. Eight specific routes are defined, each with a clear starting point and destination.

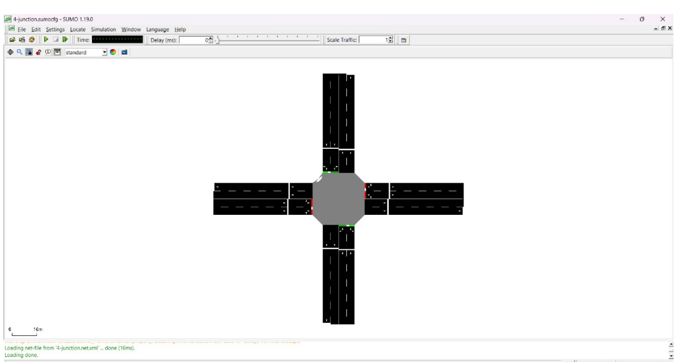

Fig. 5. Road network

B. Simulation model and scenarios

The simulation operated on a second-per-step basis, requiring around 16,000 steps in total. At each step, data was collected on the movement of vehicles and those halted at traffic lights, including the longest waiting time among them. The presence of emergency vehicles was also recorded.
The first program iteration ran with a standard 90-second fixed traffic light cycle, without adapting to real-time traffic conditions. This served as a benchmark.

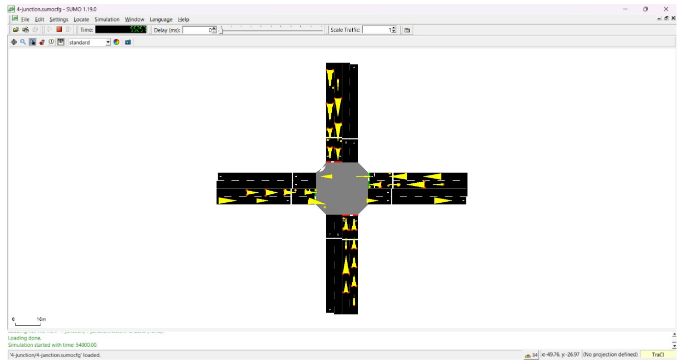

Fig. 6. Uncontrolled Simulation

The second iteration, employing fuzzy logic, assessed road conditions every seven seconds to decide if the traffic light should be changed, taking into account vehicle count, wait times, and emergency vehicle presence.

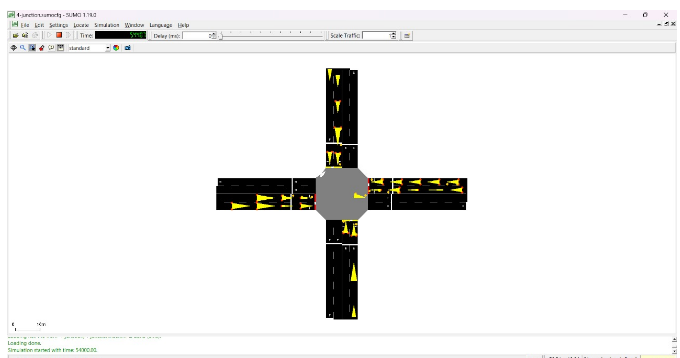

Fig. 7. Controlled Simulation

C. Discussion

The assessment of the developed fuzzy logic traffic controller revealed that a more intelligent system can indeed enhance intersection efficiency and reduce total traffic delays. It successfully improved non-emergency vehicle wait times by 25% and even more so for emergency vehicles, with a 77% decrease in waiting time. Additionally, the intersection saw a 6% increase in the number of vehicles moving through it, with a 7% decrease in vehicles stopped by traffic signals. This indicates that the system managed traffic flow effectively without adding extra delays for non-priority vehicles.

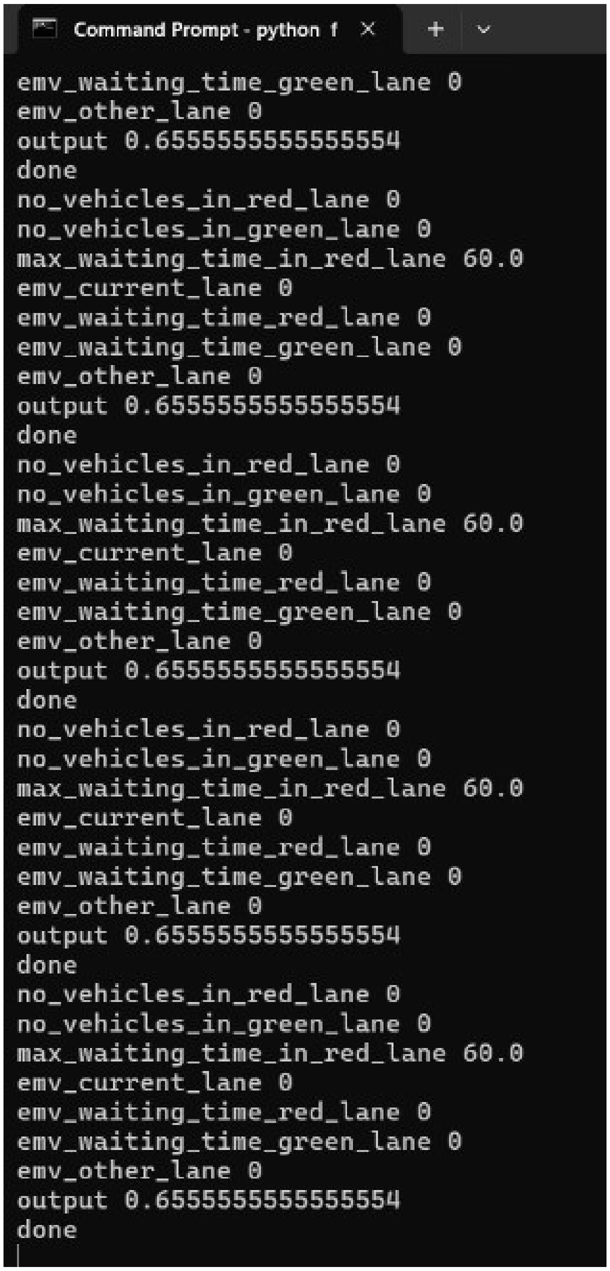

Fig. 8. Results

V. CONCLUSION

In this paper, we presented a fuzzy logic-based traffic light control system designed to optimize traffic flow at intersections. The implementation of the system using SciKit Fuzzy (skfuzzy) in Python demonstrates a promising approach to traffic management, acknowledging the variability and uncertainty inherent in real-world traffic scenarios.

The system's five inputs are effectively processed to make intelligent traffic light decisions. The membership functions and the fuzzy rule set are crafted to emulate human decision-making, providing a more adaptive and responsive traffic control system than traditional fixed-cycle traffic lights.

Through the employment of triangular and S-shaped membership functions, our system accurately reflects the nuances of traffic flow. The defuzzification process, while not explicitly outlined in terms of method, is crucial to convert fuzzy inferences into actionable outputs. Our simulated results indicate that the system operates within the expected bounds, with outputs ranging between 0.3 to 0.7, and utilizes a threshold of 0.5 to determine whether a traffic light should be switched.

The fuzzy logic controller demonstrates significant potential for reducing traffic congestion and waiting times, which can have far-reaching impacts on urban planning and environmental sustainability. By efficiently managing the time that vehicles spend idling at traffic lights, we can not only improve travel times but also contribute to reduced vehicular emissions – a significant concern in urban centers worldwide.

Furthermore, by prioritizing emergency vehicles through its rule set, the system ensures that these critical actors in urban safety can navigate traffic with increased ease, thereby potentially improving response times and outcomes in emergency situations. This highlights the system's ability to adapt to priority scenarios, an aspect where traditional systems often fall short.

One of the key findings of this study is that a fuzzy logic-based system can provide flexibility and adaptability to traffic light control, which are essential for managing the unpredictable nature of urban traffic. The outcomes suggest that such systems, when well-tuned and implemented, can substantially outperform conventional traffic control mechanisms.

The societal implications of this research are significant. By improving traffic flow, we can enhance the quality of life in urban areas, reduce the environmental footprint of transportation, and provide more reliable infrastructure for the mobility needs of citizens and services alike.

In conclusion, our research contributes to the growing body of knowledge in intelligent traffic management systems. The proposed fuzzy logic-based traffic light control system exemplifies how computational intelligence can be leveraged to address complex real-world problems such as urban traffic congestion. It is a step towards smarter, more sustainable cities that are responsive to the dynamic needs of their inhabitants and the environment.

VI. FUTURE WORK

Future discussions could explore the scalability of this approach, testing in varied urban settings, and integrating with other smart transportation technologies. This could include real-time data integration from multiple sources to further refine the traffic control decisions. Furthermore, adapting the fuzzy logic parameters based on different traffic patterns and special events could enhance system responsiveness and efficiency. This research opens avenues for extensive field trials and collaborations with city planners to explore practical implementations and the long-term impacts on urban mobility.

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