Implementation of Fuzzy Logic Model to Solve Traffic Congestion Problem at Road Intersections

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Abstract- This research aims to tackle traffic congestion at intersections, primarily caused by static traffic light timings that don't adapt to changing traffic conditions. The proposed solution involves using adaptive fuzzy controllers, which can adjust their decisions based on fuzzy IF-THEN rules. These controllers employ both Mamdani and Sugeno fuzzy logic. The Mamdani method considers factors like the number of vehicles, queue length, emergency vehicle access, and road width to optimize traffic light timings and reduce unnecessary green signals. The Sugeno-type fuzzy logic enhances controller efficiency and decreases waiting times. The study also explores the application of direct adaptive fuzzy controllers to manage unstable systems, which is relevant in optimizing traffic control. Ultimately, the goal is to develop a simulator capable of predicting the right traffic light timings in real-time. This involves extending green light timings for lanes with high vehicle volumes and also for the emergency vehicles to alleviate congestion at intersections.

Keywords: Adaptive, Congestion, Mamdani, Sugeno, Alleviate

I. INTRODUCTION

Traffic congestion is a significant challenge for the growth of metropolitan areas worldwide, affecting both developed and developing nations. It leads to issues like restricted vehicle mobility, increased fuel consumption, longer travel times, and more. However, transportation engineers are actively working on solutions to alleviate congestion in road transportation systems[1]. One promising solution involves the use of advanced real-time monitoring tools like Inductive loop detectors and video image processors have been explored in prior research [3].These tools enable transportation researchers to track and predict traffic congestion accurately, providing valuable insights for better traffic management[4][5][6][7].

To alleviate traffic congestion, several strategies can be employed, such as building HOV lanes, responding quickly to road incidents, and creating fresh transportation systems. Nevertheless, it's apparent that these methods may not be sufficient to address the significant issue of traffic congestion. The main challenge is making better use of existing transportation resources to implement more effective traffic control measures.[1]

The notion of intelligent transportation systems (ITS)emerged in the early 1990s, ITS, with the goal of improving the efficiency of 'surface transportation systems,' sought to utilize advanced information and communication technologies to create effective solutions for tackling transportation issues [2].

Road transportation systems have two main goals: encouraging alternative transportation methods and improving traffic flow efficiency. To achieve these objectives, various strategies are employed, including Navigation systems such as GPS or Google Maps, improved traffic signal control, efficient accident handling, and the prediction and management regarding the movement of traffic.

All these transportation methods have two (2) similarities, as mentioned below:

(a) Understanding Traffic Flow: The first aim is to fully comprehend traffic flow in specific areas and manage its growth effectively.

(b) Challenges with Traditional Methods: To achieve these goals, both objectives share a common challenge: they heavily rely on Traditional mathematical approaches such as statistical regression may not fully account for the intricate nature of road traffic control elements and their interconnectedness [1].

Human drivers in non-autonomous vehicles primarily contribute to traffic congestion.. This arises from the fact that human drivers often base their decisions on incomplete information, ambiguity, and imprecision, which are vital factors in traffic-related choices. Consequently, it's important to account for the human element when creating equations for transportation models. However, this inclusion adds complexity and extends the time required for transportation calculations.

To address traffic congestion issues related to uncertainties in decision-making, varying traffic data, and uncertain transportation analysis, a global approach is crucial. Rather than relying solely on traditional analytical methods, dealing with real-world traffic congestion involves using subjective data, like language-based information. This approach is commonly used when developing knowledge-based strategies for controlling traffic at signalized road intersections in non-autonomous vehicles. For this study, the chosen model is based on the fuzzy Mamdani model. This model is renowned for its analytical and predictive capabilities, as well as its capacity to handle qualitative and linguistic data, making it well-suited for managing uncertainties, ambiguities, and stochastic information at signalized road intersections. It comprises two input variables for understanding of signalized intersections, one of the output variables is used to evaluate the severity of traffic congestion [1]

The use of the fuzzy Mamdani model showcases the efficacy of computational intelligence methods in addressing problems and enhances our understanding of addressing traffic congestion. Traditional analytical methods often fall short in dealing with traffic congestion issues because the variables in traffic statistics are often intricate or poorly defined. Real-life traffic incidents frequently involve subjective decision-making, making them challenging to evaluate using traditional mathematical approaches. Determining the best route depends on factors like traffic conditions, driver judgment, level of service (LOS), and parameters for alternate routing. To tackle this challenge, various approaches based on fuzzy set theory have been introduced. This is due to the limitations of existing computational traffic models in handling uncertainties in road transportation and the ambiguities of traffic congestion. Modern optimization methods, like fuzzy logic systems, excel at accurately approximating a wide range of complex, nonlinear functions found in the real world[8].

Traffic-related issues are often described using terms like ambiguity, uncertainty, and vagueness including those related to traffic congestion [9]claimed that ambiguous logical claims cause the development of algorithms that can be used to create complex inferences from ambiguous data. The idea that fuzzy logic may resolve actual traffic scenarios and issues with road transportation was initially proposed by [10], who were among the first transportation researchers to do so [11],[12],[13],[14][15],they used these techniques to develop a thorough solution to traffic flow issues.Thus, highlighting the importance of fuzzy set theory.

Fuzzy logic theory asserts that the core elements of human thought are fuzzy set labels rather than discrete numbers. Fuzzy facts, connectives, and rules of inference are all considered 'fuzzy' in this context. The prevalence of fuzzy logic in human reasoning suggests that traditional binary logic reasoning is not the primary foundation for human thinking [9]. In essence, fuzzy approaches such as fuzzy sets, fuzzy logic, and fuzzy inference help handle unclear and imprecise ideas. Let's denote 'X' as a nonempty set. In 'X', a fuzzy set A is represented by its membership function, denoted as μA: X $\rightarrow$ [0, 1]. This function measures the degree to which each element 'X' belongs to the fuzzy set A, with μA(X) indicating the degree of membership for each x∈X. This quantifies the extent of 'x' being a part of A, indicating how true this association is. Fuzzy sets go beyond traditional crisp sets, where elements are either in or out of the set. Fuzzy sets allow elements to possess varying degrees of membership, signifying partial belonging. Fuzzy logic excels in handling partial truth, encompassing truth values between complete truth and falsehood[16]. In the domain of fuzzy logic modeling, two key terms are Membership Functions (MFs) and Fuzzy Inference Systems (FIS). Membership functions describe the relationship between elements in the input space and a fuzzy set, determining their degree of membership within a closed interval from 0 to 1. Fuzzy inference systems commonly utilize five shapes for membership functions: Triangular, Trapezoidal, Gaussian, Generalized Bell, and Sigmoidal membership functions.

II. LITERATURE REVIEW

PC Hseih, YR Chen, and PA Hsiung introduced a smart traffic optimization system that employs a genetic algorithm for automatic adjustment of traffic light timings based on sensor and camera inputs [17].

M.A. Tank, A.S. Abdul Munem, and M.S. Croock proposed a smart traffic control system with an algorithm that prioritizes granting green lights to emergency vehicles, such as ambulances, as they pass through intersections [18].

D. Hartanti et al.'s research focused on crossroads, utilizing algorithms and data structures programmed in the Arduino control device system. The study observed increased traffic density during morning and evening hours, considering factors like maximum vehicle speed and length [19].

Hasan et al. employed image processing techniques for the detection of traffic congestion [20].

M. O. Okwu and A. N. Nwachukwu found that the Fuzzy Mamdani model outperformed the Takagi Sugeno model, actuated, and feed controller in various conditions [21].

Siswipraptini et al. utilized the Travelling Salesman Problem (TSP) to minimize the total trip length, using the detection results as inputs for the traffic regulation system [22].

According to Elsevier [23], urban population growth has led to an increase in transportation demand, resulting in a rise in the number of vehicles on the streets. This has a direct impact on traffic, especially at critical points such as intersections. To enhance mobility at these intersections, appropriate signal coordination and traffic light control are essential.

Mamdani's work is rooted in Zadeh's paper on fuzzy algorithms for complex systems and decision processes [24]. On the other hand, Sugeno-type systems are employed to model inference systems with linear or constant output membership functions. The simplification of computational requirements enhances the efficiency of the defuzzification process in this system. Unlike Mamdani's integration across a two-dimensional function, the Sugeno system employs a weighted average of data points to find the centroid. Currently, Mamdani's fuzzy inference method is the most commonly used fuzzy methodology.

III. METHODOLOGY

Traffic congestion represents a pervasive issue in cities worldwide, resulting in time wastage, heightened pollution levels, and decreased overall productivity.As a result, traffic congestion has become a major concern for policymakers and city planners, who are working to find effective solutions to this problem.

This section outlines the methodologies employed to achieve the research objectives, which involve enhancing traffic density simulation through the refinement of Fuzzy Mamdani logics, and incorporating an ambulance clearance simulation. Additionally, the Python Py-game library is used to visually showcase the model.

1. The enhancement of the Fuzzy Mamdani traffic logic system to accurately simulate traffic density patterns and optimize traffic flow. The focus was on modifying the membership functions, rule bases, and defuzzification methods, based on a comprehensive analysis of traffic behaviour data and expert domain knowledge.

2. Integration of Emergency Vehicle Management centres around the integration of an emergency vehicle management system. An algorithm has been developed that detects the presence of an ambulance on either side of the road. Once detected, the algorithm triggers a specialized traffic clearance mechanism for the corresponding side. This mechanism

prioritizes the passage of the emergency vehicle while ensuring the safety of both the vehicle and other road users. Upon the ambulance's successful passage, normal traffic conditions are gradually reinstated.

3. Utilization of Python Py-game Library for Visualization to visually illustrate the modified simulation model. This library provides a platform for creating interactive graphical representations of our traffic density and emergency vehicle management simulations. The visualization showcases road networks, vehicle movements, and the dynamic interaction between regular traffic and emergency vehicles. Now, there is implementation of Py-game's features to create a real-time and intuitive representation of our simulation model.

4. Simulation Workflow Our simulation workflow encompasses several key steps:

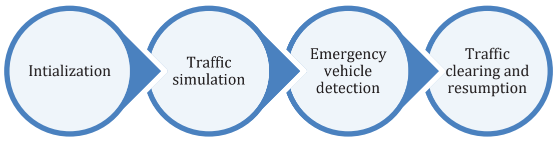

Fig. 1. Flowchart of simulation workflow

- Initialization: The simulation initializes the road network, traffic conditions, and simulation parameters, such as vehicle density and road layout.
- Traffic Simulation: The simulation progresses in time steps, with vehicles moving according to the Fuzzy Mamdani logic. Traffic conditions dynamically evolve based on this logic.
- Emergency Vehicle Detection: The algorithm continuously monitors the simulation to detect the presence of an ambulance. Detection triggers the activation of the emergency vehicle management system.
- Traffic Clearing and Resumption: When an ambulance is detected, the simulation clears traffic on the affected side of the road to create a path for the emergency vehicle. After passage, traffic gradually resumes its normal flow.

5. Data Collection and Analysis: Throughout the simulation runs, data is collected on various parameters, including traffic density, emergency vehicle response times, and clearance efficiency. The analysis of this data is done to assess the effectiveness of the modified simulation model in improving traffic flow and emergency vehicle management.

6. The enhanced simulation underscores the importance of ethical considerations when utilizing real-world traffic scenarios in simulations. It is designed for research purposes and does not involve real-time interactions with actual emergency services or road users.

IV. IMPLEMENTATION

The implementation features a traffic density simulation that leverages the Py-game library. The simulation is centred around an intersection, complete with traffic signals and various types of vehicles moving in different directions.

Traffic Signal Class: The system's implementation features a traffic density simulation centred around an intersection, utilizing the Py-game library. The simulation encompasses traffic signals and various vehicle types navigating the intersection. Within this, two distinct classes have been defined - "Traffic Signal" representing traffic signals, and "Vehicle" representing individual vehicles. The "Traffic Signal" class incorporates properties such as red, yellow, and green timers, while the simulation initializes default timer values for the traffic signals.

Vehicle Class: Complementing the simulation, the "Vehicle" class characterizes individual vehicles. The class holds attributes defining a vehicle's speed and position. This serves to simulate the movement of vehicles within the intersection accurately. Notably, the simulation accommodates special cases involving ambulances. When an ambulance approaches a side of the road, that road is promptly cleared, temporarily removing traffic. In instances of conflicting paths, the simulation adheres to the "first come, first serve" principle, prioritizing ambulances. Once the ambulance clears, traffic flow resumes as normal.

Simulation Operation: The simulation commences by configuring the initial intersection state and entering a continuous loop. During each iteration, the traffic signal timers are continuously updated, facilitating proper signal transitions. Similarly, vehicles' positions are recalculated according to their speeds. The simulation framework also incorporates data structures to manage information about vehicles and traffic signals. Notably, the Py-game library enhances the simulation's visual appeal through graphical elements. Background, traffic signal, and vehicle images are employed, mimicking a realistic intersection. This visual representation showcases traffic signals alongside timers and animates vehicles' movement, adhering to predefined rules and gaps. The simulation further ensures prioritized clearing of roads for ambulances and employs the Py-game library to foster an immersive experience. Overall, this implementation serves as a valuable tool for users to observe traffic dynamics and traffic signal behaviour. The Py-game integration offers an interactive and engaging platform, effectively supporting traffic density analysis.

Simulation Logic: Within the "Vehicle" class, we meticulously track the presence of an ambulance on either side of the road. This information is managed through a variable known as "Ambulance Containing Roads," which is effectively maintained as a queue data structure. Subsequently, during the execution of the "repeat" function, the system activates the green signal for the respective road sides present in the "Ambulance Containing Roads" variable. To illustrate, if the foremost element in the queue signifies the left side, the traffic signal controlling the left lane will transition to a green status, and subsequently, the left side will be dequeued from the variable to maintain an updated record.

```
    currentGreen = nextGreen # set next 
signal as green signal
    if Ambulance_Containing_Roads:
        if(Ambulance_Containing_Roads[0] 
== 'right'):
```

```
            currentGreen = 0
        elif(Ambulance_Containing_Roads[0]
== 'down'):
            currentGreen = 1
        elif(Ambulance_Containing_Roads[0]
== 'left'):
            currentGreen = 2
        elif(Ambulance_Containing_Roads[0]
== 'up'):
            currentGreen = 3
        Ambulance_Containing_Roads.popleft
()
    nextGreen =
(currentGreen+1)%noOfSignals    # set next
green signal
    signals[nextGreen].red =
signals[currentGreen].yellow+signals[curre
ntGreen].green    # set the red time of
next to next signal as (yellow time +
green time) of next
```

Fig. 2. Code for Simulation logic

The Fig 3 and 4. showcases the traffic density simulation control system featuring a four-way intersection with active traffic signals and timers. Mamdani implements fuzzy logic-based decision-making, while Sugeno uses mathematical models in traffic simulation systems for control and optimization. And this turns into basic flow of traffic on the roads.

Fig. 3. Traffic density simulation based on fuzzy logic (Scenario 1)

Fig. 4. Traffic density simulation based on fuzzy logic (Scenario 2)

In the modified traffic control logic, when an ambulance approaches from either side of the road, there is a activation of a special scenario depicted in Figures 5 and 6, where the traffic signal on the corresponding side of the road turns green, ensuring a rapid and safe passage for the emergency vehicle.

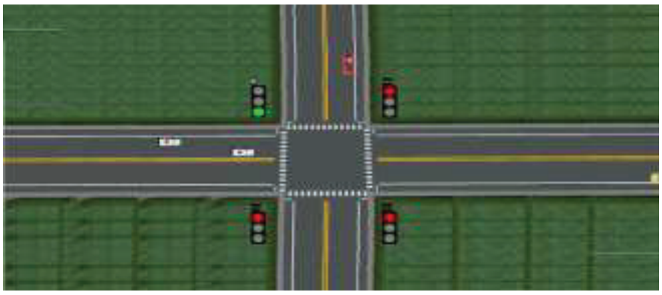

Fig. 5. Modified Traffic density simulation (Scenario 1)

Fig. 6. Modified Traffic density simulation (Scenario 2)

The system aims to ensure smooth vehicular flow by dynamically adjusting signal timings based on real-time traffic conditions. Cars navigate the intersection seamlessly, minimizing congestion. This research focuses on optimizing traffic management using advanced simulation techniques and intelligent signal control strategies.

V. EXPERIMENTATION

The dataset comprises four distinct instances, each with a modified direction, an indication of whether the modification resulted in an upward or downward change, and the older value associated with that direction as shown in Table 1. This dataset is integral to our study as it serves as a critical component for evaluating the performance of our proposed model. The modified directions encompass a range of changes, including upward, downward, leftward, and rightward adjustments, each with specific older values. Our model aims to analyse these modifications and predict the direction of change accurately. By utilizing this dataset, we can assess the model's ability to discern directional changes and contribute valuable insights to the field of predictive modelling and analysis as explained in Fig 7.

TABLE 1: COMPARATIVE TIMINGS OF MAMDANI LOGIC AND ENHANCED SIMULATION IMPLEMENTATION

Modified logic	direction	Mamdani logic
2.57	Up	6.35
5.05	Down	4.33
4.34	Left	4.98
4.98	Right	5.13

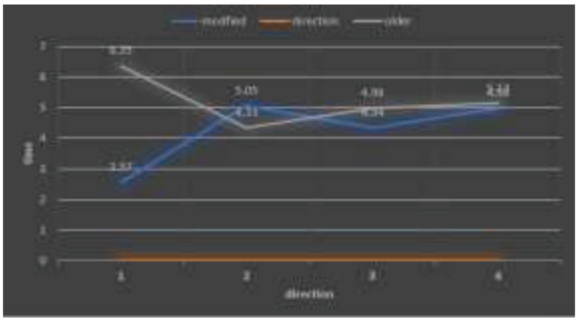

Fig. 7. Time comparison of Mamdani and Modified logic

VI. Conclusion

Traffic congestion is a significant problem in urban areas, with significant impacts on travel time, economic productivity, and the environment. While there is no single solution to this problem, various strategies have been proposed to mitigate its impacts. These strategies include the implementation of public transportation systems, road pricing, and congestion charging. It is important to continue researching this issue to develop more effective solutions to address traffic congestion in urban areas.

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