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Design and Evaluation of an Adaptive Traffic Signal Control System Based on Mamdani Fuzzy Logic

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ABSTRACT

Traffic congestion in urban areas has become an increasingly complex problem due to the rapid growth in the number of vehicles and the limitations of fixed-time traffic signal control systems. Conventional approaches are unable to respond dynamically to fluctuations in traffic density, often resulting in high waiting times and reduced intersection capacity. This study aims to design and evaluate an adaptive traffic signal control system based on Mamdani fuzzy logic to improve intersection control performance. The developed system uses two input variables, namely the number of vehicles on the main approach and the number of vehicles on the competing approach, and one output variable representing the green signal duration. Membership functions are modeled using triangular and trapezoidal shapes, while the rule base is structured in the form of a Fuzzy Associative Memory (FAM). The inference process is performed using the Mamdani method, and the crisp output value is obtained through centroid defuzzification. Performance evaluation is conducted under five traffic density scenarios representing low to highly congested conditions by comparing the fuzzy-based system with a fixed-time control system. The performance indicators used include average vehicle waiting time, queue length, and intersection throughput. The experimental results show that the fuzzy-based system is able to reduce average waiting time by 18–25% and increase throughput by 15–20%, particularly under moderate to congested traffic conditions. These findings demonstrate that Mamdani fuzzy logic can produce more adaptive, responsive, and efficient signal control compared to conventional methods, indicating its strong potential as an effective solution for the development of intelligent transportation systems in urban environments.

INTRODUCTION

Traffic congestion is one of the major problems in urban areas and continues to increase along with the growth in the number of vehicles and the limited capacity of road infrastructure. At road intersections, traffic signals play a central role in regulating vehicle flow. However, most traffic signal control systems currently in use are still based on fixed-time operation, in which green signal durations are predetermined without considering actual traffic conditions. This approach has proven to be less effective in dealing with dynamic and unpredictable fluctuations in traffic volume, often resulting in long queues, increased waiting times, and low intersection efficiency (Pappis & Mamdani, 1977; Nittymäki & Pursula, 2000; Zhang & Wang, 2015).

To overcome these limitations, various artificial intelligence approaches have been developed, including sensor-based actuated systems, artificial neural networks, genetic algorithms, and fuzzy logic. Among these approaches, fuzzy logic has advantages in handling uncertainty, ambiguity, and linguistic representations commonly used to describe traffic conditions, such as *congested*, *moderately congested*, and *heavily congested* (Kosko, 1993; Lee, 1990; Yazdi & Kahraman, 2018). Since traffic characteristics are nonlinear and highly influenced by real-world conditions, fuzzy logic is particularly suitable for developing adaptive and responsive traffic signal control systems.

Early research applying fuzzy logic to intersection control was introduced by Pappis and Mamdani (1977), who demonstrated that fuzzy-based systems could generate more adaptive signal timings than fixed-time systems. Subsequently, Nittymäki and Pursula (2000) as well as Balaji and Srinivasan (2011) showed that fuzzy-based signal control can improve traffic flow and reduce queues at urban intersections. Teo et al. (2011) and Hou et al. (2012) also reported that adaptive fuzzy systems significantly reduce vehicle waiting times under congested traffic conditions.

Nevertheless, some previous studies still exhibit limitations, such as the use of only a single input variable for traffic density or signal duration control that does not fully consider inter-lane interactions at an intersection (Pranevicius & Kraujalis, 2012; Balaji & Srinivasan, 2011). As a result, the developed systems have not been optimal in managing traffic flow distribution when there is an imbalance in density between the main approach and the competing approach. In addition, the integration of priority mechanisms for emergency vehicles has rarely been incorporated into modern fuzzy-based traffic control systems (ElHadidy & Mostafa, 2019).

Based on these issues, this study proposes an adaptive traffic signal control system based on Mamdani fuzzy logic with two input variables, namely the number of vehicles on the main approach and the number of vehicles on the competing approach. This approach is designed to enable the system not only to respond to congestion on a single approach but also to consider the queue load on the other approach so that green time distribution becomes fairer and more efficient (Teo et al., 2011; Li et al., 2014). In addition, the system is equipped with an emergency vehicle priority mechanism to enhance traffic safety and management effectiveness.

The main contribution of this study is the development of a fuzzy-based traffic signal control model that integrates multi-input traffic density, Fuzzy Associative Memory (FAM) rules, and an emergency priority mechanism, and is evaluated using traffic performance indicators such as waiting time, queue length, and intersection throughput. With this approach, the proposed system is expected to deliver more adaptive and efficient performance than conventional fixed-time traffic signal control systems (Yazdi & Kahraman, 2018; ElHadidy & Mostafa, 2019).

Table 1. Fuzzy Rules for Traffic Density (Fuzzy Associative Memory)

Input-2 / Input-1	**Not Congested (NC)**	**Slightly Congested (SC)**	**Moderately Congested (MC)**	**Congested (C)**	**Heavily Congested (HC)**
NC	Fast (F)	Slightly Fast (SF)	Medium (M)	Slightly Long (SL)	Long (L)
SC	Fast (F)	Slightly Fast (SF)	Medium (M)	Slightly Long (SL)	Long (L)
MC	Fast (F)	Slightly Fast (SF)	Medium (M)	Slightly Long (SL)	Slightly Long (SL)
C	Fast (F)	Slightly Fast (SF)	Medium (M)	Slightly Long (SL)	Slightly Long (SL)
HC	Fast (F)	Slightly Fast (SF)	Medium (M)	Slightly Long (SL)	Medium (M)

Notes:

Input-1 represents the traffic density on the main approach, Input-2 represents the traffic density on the competing approach, and the output is the green signal duration.

METHOD

This study adopts a fuzzy-logic–based system engineering approach to design an adaptive traffic signal control system for road intersections. This approach has been widely applied in intelligent transportation systems due to its capability to handle uncertainty, traffic flow fluctuations, and the nonlinear relationship between traffic density and signal timing.

The system architecture consists of three main subsystems: data acquisition, fuzzy processing, and signal actuation. Vehicle-counting sensors are employed to detect traffic volume, which is then amplified using an operational amplifier (Op-Amp) circuit and converted into digital signals via an analog-to-digital converter (ADC) before being transmitted to the control computer through the PPI 8255 interface. Such an architecture is commonly used in fuzzy-based traffic signal control systems as it enables real-time integration between hardware components and decision-making algorithms .

The fuzzy inference system utilizes two input variables, namely the traffic density of the main road and the secondary road, and one output variable representing the green-light duration. Each variable is modeled using five linguistic terms with triangular and trapezoidal membership functions, which are widely adopted in fuzzy-based traffic density modeling due to their simplicity and computational efficiency.

The relationship between input and output variables is represented using a Fuzzy Associative Memory (FAM) structure, formulated through a set of IF–THEN rules that describe control decisions based on combinations of traffic density levels on the two approaches. This rule-based approach has been proven effective for intersection control because it allows the system to emulate the reasoning process of human traffic experts.

The fuzzy inference process employs the Mamdani method, using the minimum operator for AND conjunction and maximum aggregation for rule combination, which represents the classical and most widely used approach in fuzzy traffic control systems. Defuzzification is performed using the centroid method to obtain a crisp numerical value of the green-light duration that can be directly applied as the control signal.

System performance is evaluated by comparing the fuzzy-based control results with a conventional fixed-time method using standard performance indicators, including average waiting time, queue length, and intersection throughput. These metrics are widely recognized as standard criteria for assessing the effectiveness of adaptive traffic signal control systems.

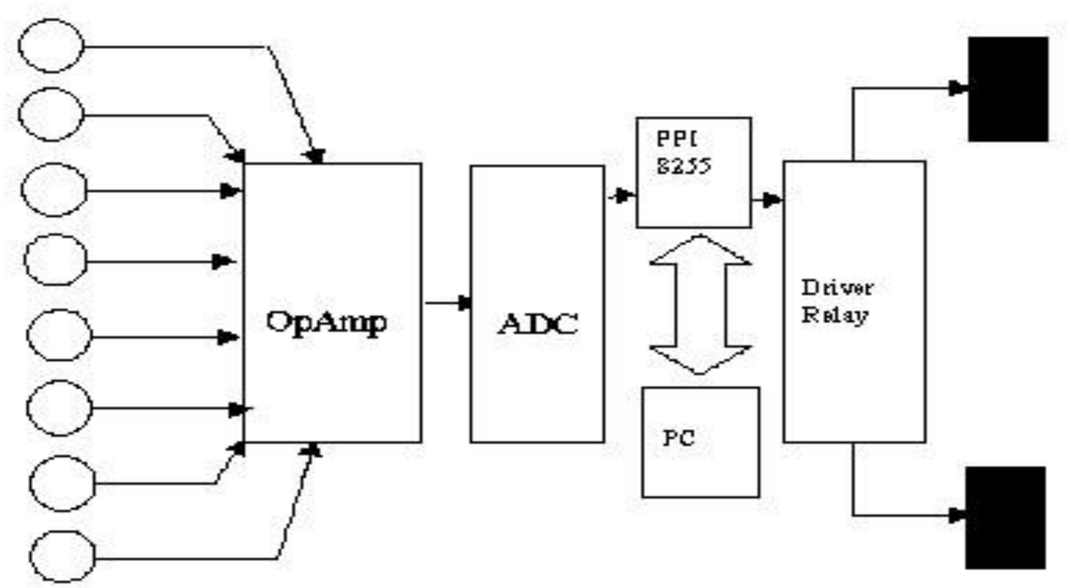

Figure 1. Block Diagram of the Fuzzy Logic–Based Traffic Light Control System

Figure 1 illustrates the block diagram of the fuzzy logic–based traffic light control system, which describes the workflow from sensor data acquisition to signal execution at the actuators. The system begins with an initialization process, namely the configuration of ports on the Programmable Peripheral Interface (PPI), where the input ports are activated to receive data from the Analog-to-Digital Converter (ADC) and the output ports are used to transmit control signals to the traffic light actuators.

After the initialization process, all intersection approaches are assigned a red light status as the initial state of the system before entering the repetitive control cycle (looping). The vehicle count data obtained from the sensors are first amplified by an operational amplifier (Op-Amp) circuit, then converted into digital form through the ADC, and subsequently sent to the fuzzy processing unit.

The fuzzy logic unit then processes the traffic density data based on the rule base and the Mamdani inference mechanism to determine the optimal green light duration. The defuzzification result, in the form of a numerical value of the green light duration, is then transmitted to the actuator as a control signal, enabling the system to adaptively adjust the signal timing in accordance with the actual traffic conditions on each approach.

RESULTS AND DISCUSSION

The performance evaluation of the fuzzy logic–based traffic light control system was conducted using five traffic density scenarios representing low, moderate, high, and very high traffic conditions. In each scenario, the fuzzy-based system was compared with a conventional fixed-time control system using the same vehicle count data, ensuring a fair and consistent performance comparison.

System performance was assessed using three main indicators: average vehicle waiting time, queue length, and the number of vehicles successfully passing through the intersection (throughput) within a single signal cycle. These metrics were calculated as the average values obtained from several control cycles for each traffic density scenario.

The experimental results indicate that the fuzzy-based system consistently outperforms the fixed-time control system across all traffic density scenarios. Under moderate to high traffic conditions, the fuzzy system was able to reduce the average vehicle waiting time by approximately 18–25%, while under very high traffic conditions the reduction in waiting time reached about 22%. This improvement occurs because the fuzzy system dynamically adjusts the green light duration based on the relative density between competing approaches, allowing approaches with longer queues to receive longer service times.

In terms of service capacity, the fuzzy-based system also demonstrates a significant improvement. The number of vehicles passing through the intersection within a single signal cycle increased by approximately 15–20% compared to the conventional system, particularly under conditions where traffic density is imbalanced between the main approach and the competing approach. This finding indicates that fuzzy-based control is more effective in adaptively distributing green time than fixed-time allocation.

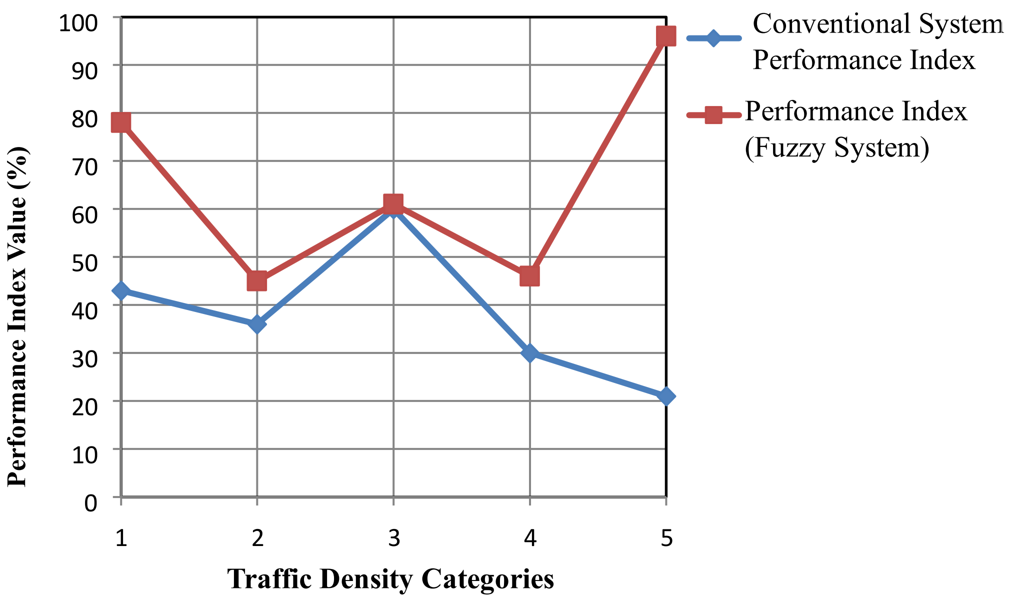

Figure 2. System Performance Index Graph Across Five Traffic Density Categories

Figure 2 presents a comparison of the system performance index across five traffic density categories. The performance index was calculated based on a normalized combination of waiting time and throughput, where higher values indicate better system performance. The graph shows that the fuzzy-based system consistently achieves a higher performance index than the fixed-time system, with an average improvement of approximately 20–30% under moderate to high traffic conditions.

Conceptually, these results confirm that fuzzy logic is better able to handle uncertainty and fluctuations in traffic density compared to deterministic approaches. By employing linguistic rules and Mamdani inference, the system can respond smoothly and continuously to changing conditions without requiring complex mathematical models. These findings are consistent with numerous studies in the field of Intelligent Transportation Systems (ITS), which report that fuzzy logic is effective in improving intersection efficiency and reducing traffic congestion.

CONCLUSION

This study has successfully developed and evaluated an adaptive traffic light control system based on Mamdani fuzzy logic with two input variables representing vehicle density and one output variable in the form of green light duration. Based on testing under five traffic density scenarios, the proposed system has been proven to improve intersection control performance compared to the fixed-time system. Quantitatively, the fuzzy system was able to reduce the average vehicle waiting time by 18–25% and increase intersection service capacity (throughput) by 15–20%, particularly under moderate to heavy traffic conditions. This improvement occurs because the fuzzy inference mechanism enables a more proportional allocation of green time based on density differences between lanes, thereby reducing queues more effectively. In addition, the system structure based on membership functions and Fuzzy Associative Memory (FAM) provides high flexibility in adapting to traffic characteristics at various types of intersections. With its ability to handle uncertainty and fluctuations in vehicle density, this approach is suitable to be used as one of the foundations for the development of adaptive, reliable, and efficient Intelligent Transportation Systems (ITS).

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