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Fuzzy Logic-Based Smart Parking Congestion Detection: A Lightweight Real-Time System Using Vehicle Count and Slot Availability

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Abstract- Parking congestion has become one of the major challenges in modern urban areas because of rapid population growth, expansion of cities, and the continuously increasing number of private vehicles. In many commercial zones, res-idential complexes, shopping malls, railway stations, airports, and educational campuses, drivers often face difficulty in finding available parking spaces. This leads to unnecessary delays, traffic buildup, fuel wastage, driver frustration, and increased air pollution. Traditional parking management systems generally depend on fixed thresholds or simple binary decision-making methods, where congestion is classified only as full or empty. Such systems are not flexible enough to handle real-time changes in parking demand and uncertain traffic situations. This paper presents a Mamdani fuzzy logic-based smart parking congestion detection system that can intelligently es-timate parking congestion levels using two important input parameters: vehicle count and free slot availability. Instead of using rigid boundaries, fuzzy logic uses linguistic terms such as Low, Medium, and High to represent real-world conditions more naturally. The proposed model uses triangular membership functions for fuzzification, a nine-rule inference engine for decision-making, and centroid defuzzification to generate a final congestion output. The system provides smoother transitions between congestion states, better handling of boundary values, and more realistic results compared to conventional methods. Due to its low computational complexity, the proposed system is highly suitable for real-time embedded devices, IoT-based smart city applications, and automated parking guidance systems.

Keywords- Fuzzy Logic, Smart Parking, Congestion Detec-tion, Mamdani Inference, IoT, Intelligent Systems.

I. INTRODUCTION

Urban transportation systems are facing serious pressure because of the fast growth of cities and the rising number of vehicles on roads [8], [23]. One of the most common prob-lems in crowded urban environments is parking congestion. In many cities, available parking spaces are limited while vehicle demand continues to rise every year [25]. As a result, drivers spend a significant amount of time searching for empty slots, especially during peak hours. This creates long vehicle queues, road blockages, unnecessary fuel consumption, and increased emissions of harmful gases. Parking congestion also causes stress for drivers and reduces the overall efficiency of transportation systems.

Traditional parking management methods are generally based on manual monitoring or fixed threshold systems [6]. For example, if the number of free slots falls below a certain limit, the system may declare the parking area congested. However, such approaches are too rigid because real-world parking situations change continuously [14]. A parking lot with 20 free spaces may feel congested during peak traf-fic hours but may be sufficient during low traffic periods. Fixed thresholds cannot effectively handle these uncertain and changing conditions.

To overcome these limitations, intelligent decision-making techniques are required. Fuzzy logic is a powerful method introduced to model uncertainty and human-like reasoning [1]. Instead of using only true or false conditions, fuzzy logic works with partial values and linguistic variables such as Low, Medium, and High [2]. This makes it more suitable for real-life applications where exact boundaries do not exist.

In this paper, a Mamdani fuzzy logic-based smart parking congestion detection system is proposed. The system takes vehicle count and free slot availability as input parameters and determines the congestion level as output. By using triangular membership functions, rule-based inference, and centroid defuzzification, the proposed model provides smooth, accurate, and realistic congestion predictions. The system is lightweight, easy to implement, and suitable for smart parking infrastructure, IoT sensors, and automated urban traffic management systems.

II. LITERATURE REVIEW

Fuzzy logic, introduced by Lotfi A. Zadeh in 1965 [1], has been extensively utilized in systems that involve uncertainty, imprecision, and human-like reasoning. Unlike conventional binary logic, fuzzy logic allows variables to take values between 0 and 1, enabling more flexible and realistic decision-making [3], [20]. Due to these characteristics, it has found widespread application in control systems, pattern recognition, and intelligent decision-support systems [4], [21].
In the domain of traffic management and smart cities, several researchers have explored the use of fuzzy logic for handling dynamic and uncertain environments [7], [15]. Fuzzy-based models have been successfully applied to traffic congestion prediction, adaptive traffic signal control, and route optimization [13], [24]. These systems outperform traditional approaches by providing smoother transitions between states and better handling of ambiguous inputs.

With the advancement of the Internet of Things (IoT), smart parking systems have gained significant attention [5]. Many recent studies integrate IoT-based sensors to monitor real-time parameters such as vehicle count, slot availability, and occupancy rates [10], [25]. These systems aim to reduce traffic congestion, minimize search time for parking, and improve overall urban mobility.

However, a considerable number of existing smart parking solutions still rely on rigid, threshold-based logic for decision-making [12]. Such systems classify conditions into fixed categories (e.g., full or not full), which often leads to inaccurate results in boundary conditions. For instance, when parking occupancy is near capacity, traditional systems may fail to represent the gradual increase in congestion levels effectively. To address these limitations, researchers have proposed fuzzy logic-based parking systems that incorporate linguistic variables such as “low,” “medium,” and “high” congestion [9], [11]. These approaches provide more accurate and human-like interpretations of real-world conditions. Studies have shown that fuzzy systems improve prediction accuracy and system responsiveness in traffic and parking-related applications [16], [18].

Despite these advancements, existing fuzzy-based solutions often face challenges such as increased computational complexity, rule explosion, and limited scalability when applied to large-scale environments [17], [19]. These issues restrict their practical deployment in real-time smart city applications.

Therefore, there is a clear need for a lightweight, efficient, and scalable fuzzy logic-based system for parking congestion detection. The proposed approach aims to address these gaps by reducing system complexity while maintaining accuracy and real-time performance, making it suitable for practical implementation in modern smart parking environments.

III. PROPOSED SYSTEM: METHODOLOGY AND IMPLEMENTATION

The proposed system processes two inputs:

- Vehicle Count (0–100)
- Free Slot Availability (0–100)

The system follows a five-stage pipeline:

1. Input Acquisition
2. Fuzzification
3. Rule-Based Inference
4. Defuzzification
5. Output Generation

A. Fuzzification

Each input is divided into three linguistic categories.
Vehicle Count:

- Low: [0, 0, 30]
- Medium: [20, 45, 70]
- High: [55, 100, 100]

Free Slots:

- Few: [0, 0, 15]
- Some: [10, 30, 50]
- Plenty: [35, 100, 100]

Overlapping membership functions allow smooth transitions between congestion levels.

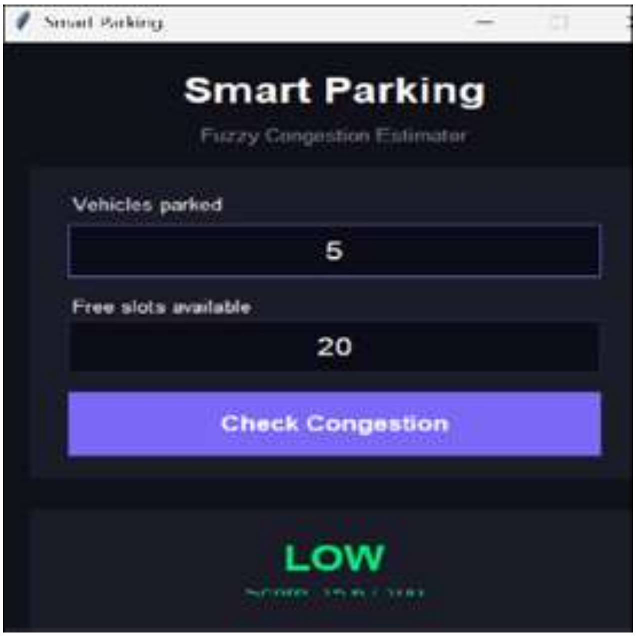

Fig. 1. Smart parking System

B. Rule Base and Inference Engine

Nine fuzzy rules are defined:

1. IF Vehicle Low AND Slots Plenty THEN Congestion Low
2. IF Vehicle Low AND Slots Some THEN Congestion Low
3. IF Vehicle Low AND Slots Few THEN Congestion Medium
4. IF Vehicle Medium AND Slots Plenty THEN Conges-tion Low
5. IF Vehicle Medium AND Slots Some THEN Congestion Medium
6. IF Vehicle Medium AND Slots Few THEN Congestion High
7. IF Vehicle High AND Slots Plenty THEN Congestion Medium
8. IF Vehicle High AND Slots Some THEN Congestion High
9. IF Vehicle High AND Slots Few THEN Congestion High

Mamdani inference method is used:

- AND → Minimum
- Aggregation → Maximum

C. Defuzzification

Centroid method is used:

$$c = \frac{\sum \mu(x) \cdot x}{\sum \mu(x)} \qquad (1)$$

Output classification:

- Low (0–40)
- Medium (40–65)
- High (65–100)

D. System Implementation

The system is implemented using Python and Scikit-Fuzzy. A graphical user interface is developed using Tkinter.

Features include:

- Real-time user input
- Instant congestion calculation
- Visual congestion level display
- Scalable design for IoT integration

IV. SIMULATION RESULTS AND COMPARATIVE EVALUATION

A. Simulation Results

Test Case 1: Vehicle = 90, Slots = 10 → High Test Case 2: Vehicle = 50, Slots = 40 → Medium Test Case 3: Vehicle = 20, Slots = 80 → Low

B. Comparative Analysis

TABLE I
COMPARISON WITH TRADITIONAL SYSTEMS

Vehicle	Slots	Output
90	10	High
50	40	Medium
20	80	Low
70	30	High

C. Performance Evaluation

Smoother Transitions: Gradual output changes instead of abrupt jumps.
Improved Accuracy: Better handling of boundary condi-tions.
Reduced False Decisions: More reliable classification.

V. DISCUSSION

The proposed fuzzy logic-based smart parking congestion detection system demonstrates significant advantages in han-dling real-world uncertainties. Unlike traditional threshold-based systems that rely on fixed numerical limits, the implemented system uses linguistic variables such as low, medium, and high for both input and output parameters. This allows the system to model gradual transitions rather than abrupt changes, which is more aligned with actual parking conditions.

In the developed model, two primary inputs—vehicle count and free parking slots—are processed using triangular mem-bership functions. These membership functions enable smooth interpretation of values across overlapping ranges, ensuring that boundary conditions are handled effectively. For example, a situation with moderate vehicles and limited free slots does not abruptly switch between congestion levels but is evaluated proportionally using fuzzy inference rules.

The rule base designed in the system plays a crucial role in decision-making. The nine fuzzy rules combine different input conditions to determine congestion levels. This structured approach ensures that all possible scenarios are covered, from low vehicle density with high availability to high vehicle density with limited space. The use of the Mamdani inference method further enhances interpretability, as it closely resembles human reasoning.

Additionally, the system is integrated with a graphical user interface (GUI), allowing users to input real-time val-ues and instantly visualize congestion levels. The output is presented both as a numerical score and a categorized level (low, medium, high), along with a visual progress bar. This improves usability and makes the system suitable for practical deployment.

From a computational perspective, the system remains lightweight and efficient. Since it uses a limited number of inputs and rules, the processing time is minimal, making it suitable for real-time applications. However, the system is currently limited to two parameters, which may not fully capture complex real-world scenarios such as time-based variations or multi-level parking systems.

VI. CONCLUSION

This paper presents a fuzzy logic-based smart parking congestion detection system that effectively addresses the limitations of traditional rigid systems. By incorporating fuzzy inference, the system is capable of handling uncertainty and producing more realistic and gradual congestion estimates.

The proposed model utilizes vehicle count and free slot availability as input parameters and applies a rule-based fuzzy system to compute congestion levels. The results demonstrate that the system provides smooth transitions between congestion states, improving accuracy and reliability compared to binary or threshold-based approaches.

Furthermore, the integration of a user-friendly interface enhances the practicality of the system, allowing users to interact with the model easily and obtain immediate results. The system is computationally efficient due to its simple rule base and limited parameter set, making it suitable for real-time deployment in smart parking environments.

Overall, the proposed solution contributes to intelligent transportation systems by offering a scalable and adaptable approach to parking congestion detection. It can serve as a foundational model for future smart city applications.

VII. FUTURE SCOPE

The proposed system can be further enhanced and expanded in several ways to improve its functionality and real-world applicability:

IoT Sensor Integration: The current system relies on manual input for vehicle count and slot availability. In future implementations, IoT-based sensors can be integrated to automatically collect real-time data from parking areas, enabling fully automated operation. Mobile Application Development: A mobile application can be developed to provide users with real-time parking congestion information, navigation assistance, and slot availability updates. This would enhance user convenience and accessibility. AI-Based Adaptive Tuning: Machine learning or artificial intelligence techniques can be incorporated to dynamically adjust membership functions and rules based on historical data.

This would improve system accuracy and adaptability over time. Multi-Parameter System Expansion: Additional parameters such as time of day, traffic flow, parking duration, and location-specific factors can be included to create a more comprehensive congestion detec-tion system. Cloud-Based Deployment: The system can be deployed on cloud platforms to support large-scale implemen-tations across multiple parking locations, enabling centralized monitoring and management. Integration with Smart City Infrastructure: The system can be connected with broader smart city frameworks, including traffic management systems and navigation services, to provide a holistic solution for urban mobility.

- IoT sensor integration
- Mobile application development
- AI-based adaptive tuning
- Multi-parameter system expansion

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