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APPLICATION OF FUZZY LOGIC IN DECISION-MAKING SYSTEMS FOR URBAN TRAFFIC MANAGEMENT

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ABSTRACT

The rapid growth of urban populations and increased vehicular traffic have intensified congestion, pollution, and travel delays in cities. Traditional traffic management systems, often based on fixed-time signal control, fail to adapt to dynamic traffic conditions, necessitating more intelligent solutions. This study explores the application of Fuzzy Logic in urban traffic management, demonstrating its potential for optimizing real-time traffic signal control. Fuzzy Logic, an extension of classical logic, effectively handles uncertainties and imprecise data, making it particularly suitable for traffic environments where variables such as traffic volume, waiting time, and weather conditions fluctuate continuously.

By employing Fuzzy Logic, traffic light controllers can dynamically adjust signal durations to optimize vehicle flow. The system utilizes input variables such as real-time traffic volume, accumulated waiting time, and environmental factors to determine optimal signal timings through a fuzzy inference engine. This adaptive approach enhances mobility, reduces congestion, minimizes fuel consumption, and improves road safety.

Simulation results and case studies indicate that Fuzzy Logic-based traffic management significantly outperforms fixed-time signal control by reducing average waiting times and improving overall traffic efficiency. Furthermore, integrating reinforcement learning and game theory into Fuzzy Logic models shows promising results in cooperative multi-agent decision-making for large-scale urban traffic networks. Despite challenges related to data collection and implementation, the use of intelligent traffic control systems can play a pivotal role in achieving sustainable urban mobility

Keywords: Fuzzy logic. Urban traffic management. Decision-making. Traffic optimization.

INTRODUCTION

Population growth and rapid urbanization have led to a significant increase in urban traffic volume, resulting in congestion, pollution, and longer travel times. In this context, optimizing vehicle flow becomes a crucial challenge for authorities responsible for managing urban traffic. One of the emerging approaches to solving this problem is the use of systems based on Fuzzy Logic, which are capable of handling uncertainties and variabilities in dynamic data such as traffic volume, waiting time at traffic lights, and weather conditions. Real-time traffic light adjustment based on these variables can significantly contribute to improving traffic flow, minimizing congestion, and optimizing travel time.

Fuzzy Logic, first proposed by Lotfi Zadeh in the 1960s, is an extension of classical (Boolean) logic, allowing imprecise or vaguely defined information to be processed more effectively. Instead of using sharp, binary variables (true or false, 0 or 1), fuzzy logic works with degrees of truth, allowing the input and output variables of a system to be represented by continuous values ranging from 0 to 1. This makes it possible to model complex and unpredictable systems, such as urban traffic, where conditions vary constantly.

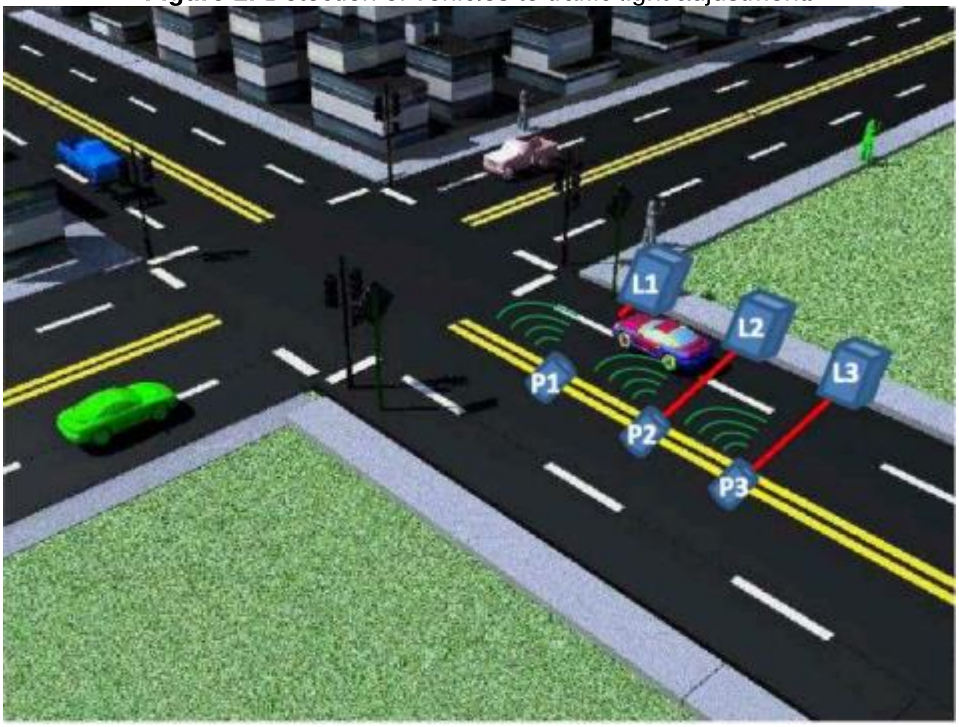
Traffic lights play a crucial role in regulating vehicle flow, but in many cities, their control is still fixed and does not take into account the temporal and seasonal variations in traffic. The use of Fuzzy Logic allows for real-time traffic light adjustment based on different input variables. Key parameters that can be used to optimize traffic management are discussed below:

Traffic Volume: The number of vehicles passing through a control point (traffic light) is one of the main indicators of traffic flow. Fuzzy Logic can adjust the traffic light timing based on traffic volume, increasing green light duration on streets with higher vehicle counts and decreasing it on streets with less traffic.

Waiting Time: The time vehicles wait at a traffic light is also a critical variable. Long waiting times can result in driver frustration and increased emissions. Fuzzy Logic can consider the accumulated waiting time to adjust the light duration in a way that balances traffic flow and reduces waiting times.

Weather Conditions: Climatic factors such as rain, fog, or snow can affect traffic safety and flow. For example, in reduced visibility conditions, it is necessary to increase the green light duration to allow vehicles to move more slowly and safely. Fuzzy Logic can integrate real-time weather information to adjust traffic light behavior based on these conditions.

Figure 1: Detection of vehicles to traffic light adjustment.



Source: Cavalheiro et al. (2020).

A Fuzzy Logic-based control system can be implemented through a model with three main components: input variables, a fuzzy rule set, and output variables.

Input Variables: As mentioned, input variables may include traffic volume, waiting time at traffic lights, and weather conditions. Each of these variables can be described by fuzzy terms such as "low," "medium," and "high" for traffic volume, or "rain," "fog," and "clear" for weather conditions.

Fuzzy Rules: The rules are formulated based on expert knowledge and consist of conditional statements. For example, a rule might be: "If traffic volume is high and waiting time is long, then increase the green light duration." These rules can be adjusted to reflect the complexity of interactions between the variables.

Output Variables: The output variable is the duration of the traffic light signals (green, yellow, and red), dynamically adjusted according to input parameters. Fuzzy Logic can calculate a continuous response for each output variable, considering all possible combinations of input variables.

Real-Time Adaptation: The main advantage of Fuzzy Logic is its ability to adapt the system to constant and unforeseen changes. This is especially useful in an urban environment where traffic can vary hourly or even minute by minute.

Congestion Reduction: The dynamic adjustment of traffic lights can help reduce congestion by optimizing the distribution of signal time, avoiding congestion on more crowded roads while still allowing green light on streets with lower traffic.

Greater Energy Efficiency: Intelligent traffic light systems can also reduce energy consumption by adjusting signals based on the actual need for vehicle passage, avoiding long signals during periods of low traffic.

Improved Safety: By considering adverse weather conditions, the system can improve safety by adjusting traffic lights to prevent accidents caused by poor visibility or road conditions.

Li et al. (2025) introduce FuzzyLight, a two-stage fuzzy logic-based approach to optimizing urban traffic signal control by integrating reinforcement learning (RL) and compressed sensing techniques. Addressing real-world challenges such as sensor noise, instability in RL training, and the lack of dynamic phase duration adjustments, FuzzyLight enhances decision-making by combining fuzzy rules for traffic signal phase selection with an RL-based module for determining phase duration. The model demonstrated a 48% increase in traffic efficiency compared to conventional expert-designed signal timings. The findings highlight FuzzyLight's robustness, adaptability to noisy traffic data, and its capacity to improve urban mobility in both real and simulated settings.

Tunc et al. (2021) explored different fuzzy logic control strategies for optimizing traffic signal timing at intersections, aiming to reduce congestion and improve traffic flow. Using the Simulation of Urban Mobility (SUMO) platform, the researchers compare a fuzzy logic controller (FLC) with queue length input and a fuzzy logic controller with state input, which considers vehicle positioning. The results indicate that the state-input-based method outperforms traditional fixed-time traffic light systems by dynamically adjusting signal durations based on real-time conditions. The findings contribute to intelligent transportation systems by demonstrating how adaptive traffic control can minimize waiting times and queue lengths, thereby enhancing urban mobility.

Tunc and Soylemes (2023) presented a novel approach for traffic signal control by integrating Deep Q-Learning (DQL) with Fuzzy Logic Systems (FLSI) to optimize green light durations at urban intersections. The proposed method dynamically adjusts phase sequences using reinforcement learning while employing fuzzy logic to determine signal durations based on real-time traffic conditions. Simulation results demonstrate that this hybrid approach significantly reduces vehicle queue lengths, CO_2 emissions, and overall delay compared to fixed-time and conventional deep learning-based strategies. Additionally, stability analysis confirms the robustness of the system, making it a promising solution for intelligent transportation systems.

Daeichian and Haghani (2029) introduced a multi-agent system for intelligent traffic control, integrating Fuzzy Q-learning and Game Theory to optimize signal timing and reduce vehicle delays. Each traffic light operates as an autonomous agent, learning from past experiences while considering decisions made by neighboring agents. By incorporating fuzzy logic, the system effectively handles uncertainty in traffic conditions, while game theory ensures cooperative decision-making across intersections. Simulations on a five-intersection network demonstrate that the proposed method significantly outperforms traditional fixed-time, fuzzy, Q-learning, and fuzzy Q-learning approaches in minimizing average delay times, highlighting its potential for improving urban traffic efficiency

Despite the benefits, the implementation of Fuzzy Logic-based systems faces some challenges, such as the need for real-time data collection with high accuracy, the integration of different data sources, and the requirement for advanced technological infrastructure. The application of Fuzzy Logic to optimize real-time traffic light control is a promising solution for improving urban traffic flow. By considering variables such as traffic volume, waiting time, and weather conditions, this system can dynamically adjust traffic light signals, providing significant benefits such as reducing congestion, increasing road safety, and enhancing energy efficiency. While there are technical and operational challenges to overcome, the evolution of technology and the implementation of intelligent transportation systems can transform how we manage traffic in cities, making them more efficient and sustainable.

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