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An Intelligent Street Lighting Scheduling Optimization Algorithm Based on Fuzzy Logic

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Abstract: *With the construction of smart cities, the intelligent streetlight system has become an important part of modern urban management. However, the traditional scheduling method is difficult to dynamically adapt to complex traffic flow and environmental changes, leading to energy waste and low efficiency. This paper proposes a smart streetlight scheduling method based on fuzzy logic, which uses traffic flow and vehicle speed as input variables and achieves dynamic control of streetlight brightness and time through a fuzzy inference system and custom rules. Specifically, this paper designs fuzzy domains and membership functions for vehicle numbers and vehicle speeds, dividing them into five fuzzy subsets: VS (very few/very short), S (few/short), M (medium), L (many/long), and VL (many/very long). Based on the logic that "the longer the time and the more vehicles, the longer the time; the shorter the time and the fewer vehicles, the shorter the time," 25 fuzzy rules are formulated. The experimental results show that the method can dynamically adjust the brightness and time of streetlights based on real-time traffic conditions, achieving an energy-saving efficiency rate of 59% and ensuring traffic safety. This method has good extensibility and can provide reference for intelligent streetlight scheduling in complex traffic environments.*

Keywords: *intelligent street lights; Fuzzy logic; Energy saving optimization; Fuzzy control; smart city*

1. Introduction

With the rapid development of the economy and society, urban road lighting has become one of the important indicators to measure the level of modernization. With the expansion of lighting facilities and the continuous increase in electricity consumption, society has put forward higher requirements for urban public lighting. The intelligent streetlight system, as a key technology for improving urban management efficiency and achieving sustainable development, is receiving widespread attention. However, traditional control methods that rely on static schedules or manual operations are difficult to adapt to dynamic traffic and environmental changes, resulting in energy waste, increased operating costs, and environmental issues, which urgently require more intelligent solutions.

In recent years, intelligent street light control technology has made significant progress in energy conservation and efficient management. [1]Tian et al. proposed an automatic monitoring system for street lamps based on LoRa wireless communication technology. The system collects street lamp parameters through STM32 MCU and uses LoRa network and 4G module to achieve data transmission and remote control. Combined with PWM dimming, it can save about 45.74% of electricity.[2] Zheng et al. designed a smart street light control method based on road visibility using Long Short Term Memory (LSTM) neural network, utilizing PM2.5 PM10, Modeling humidity and cumulative wind speed, optimizing street light brightness and color temperature through adaptive dimming, improves visibility and driving safety in foggy weather while saving energy, and its model prediction accuracy is better than the comparison model.[3]Shao et al. developed a distributed energy-saving control method based on ZigBee network and adaptive PSD algorithm, combined with neural network to improve signal processing efficiency, and dynamically adjusted street lamp power through adaptive signal detection, achieving more stable energy-saving control.[4]Han et al. put forward an energy saving strategy based on multi-source information fusion and edge computing, which uses multi-sensor and convolutional neural network to count the traffic flow, optimizes the control cycle of street lights in combination with the visual statistics system, realizes real-time brightness adjustment through edge computing, and significantly reduces power consumption.[5]Chen et al. designed an intelligent street light control algorithm with high energy consumption ratio, which collects real-time environmental lighting and traffic flow data, dynamically

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adjusts brightness through a predictive model, and achieves a balance between energy consumption and lighting effect, reducing energy consumption by about 35%. Although the above methods perform well in terms of energy efficiency, some methods are still limited by complex environmental changes and real-time requirements, and there is still room for optimization.

Some studies combine fuzzy logic with intelligent algorithms (such as particle swarm optimization, moth to flame optimization, etc.) to further optimize rule library design and parameter adjustment. For example, [6] Zhang et al. proposed an intelligent dimming street light system that integrates deep learning and fuzzy control, using an improved MFO algorithm to optimize GRU hyperparameters for enhanced visibility prediction accuracy. The system collects environmental data via sensors, predicts visibility in real-time, and adjusts street light brightness accordingly, achieving energy savings. Although the method has improved prediction accuracy and energy-saving effects, its adaptability in complex environments still has limitations.

Based on the above issues, this paper proposes an intelligent street light scheduling optimization method based on fuzzy logic. By defining language variables for traffic flow, vehicle speed, and lighting time, and establishing membership functions and fuzzy rule libraries, the street light system dynamically adapts and regulates to different traffic conditions. Through MATLAB simulation experiments, it has been verified that the energy-saving efficiency of our proposed method is around 59%. This method significantly improves the energy-saving effect while ensuring traffic safety, demonstrating its enormous potential and practical value in smart city construction.

2. Related work

2.1 Fuzzy Control Theory

Fuzzy control theory originates from fuzzy concepts that are difficult to accurately describe in daily life, such as height, short, fat, and thin, in contrast to clearly expressed attributes such as age and date. In 1965, American scholar Zadeh L.A. proposed fuzzy theory and developed fuzzy logic control, abbreviated as fuzzy control. This is a digital control technique based on fuzzy set theory, fuzzy linguistic variables, and fuzzy reasoning, which achieves adaptive control through imprecise mathematical models and is suitable for uncertain and nonlinear systems. Compared with traditional control theory, fuzzy control does not rely on precise controlled object models, significantly simplifies system design, and fully utilizes experience and knowledge in rule base establishment, resulting in higher development efficiency.

2.2 Membership Function in Fuzzy Control

In fuzzy control, the membership function is a core component used to quantify the degree to which an element belongs to a fuzzy set. It maps a specific value x from the universe of discourse U to a value $\mu A(x)$ between 0 and 1, representing the extent to which x belongs to the fuzzy set A; this value is known as the membership degree. The function satisfies normalization ($0 \leq \mu A(x) \leq 1$) and boundary conditions, where $\mu A(x)$ equals 0 when x completely does not belong to A, and equals 1 when x fully belongs to A.

As fuzzy control theory has evolved, various types of membership functions have been developed, each offering particular advantages suited to different scenarios. These include triangular, trapezoidal, Z-shaped, S-shaped, and Gaussian membership functions. The triangular membership function is characterized by linear changes, with slopes that gradually decrease to zero on both sides, providing an intuitive method for describing membership degrees. The Z-shaped membership function maintains a constant value of 1 on its left side, making it suitable for representing fuzzy sets of extremely low values. Conversely, the S-shaped membership function holds a constant value of 1 on its right side, ideal for characterizing fuzzy sets of extremely high values.

2.3 The Method of Resolving Fuzzy in Fuzzy Control

In fuzzy control, deblurring is the process of converting the output of a fuzzy set into specific numerical values for generating operable control signals. Common methods include centroid method, maximum membership degree method, weighted average method, and median method.

Center of gravity method: Using the center of gravity of the area enclosed by the membership curve and the horizontal axis as the output result to achieve ambiguity resolution.

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Maximum membership degree method: Select the maximum value of the membership degree curve as the output result to achieve fuzzy resolution, which is easy to calculate.

Weighted average method: By assigning weight coefficients to different function values and performing weighted averaging, the final output result is obtained to achieve ambiguity resolution. The difference in weight coefficients directly affects the output results.

3. The proposed fuzzy control algorithm

This article proposes a street lamp scheduling system based on fuzzy control, which dynamically adjusts the lighting time of street lamps by inputting the number and speed of vehicles. The system first fuzzifies the number and speed of vehicles, establishes a domain and fuzzy rule table, and after fuzzy reasoning, deblures the results to obtain the initial lighting time t1. In addition, the system considers dynamic traffic factors and increases t2=20/vehicle speed and t3=20 × N/vehicle speed (where N is the number of vehicles). The total time for the final streetlights to light up is t1+t2+t3. This method achieves precise control and optimization for different traffic conditions. The fuzzy control system is shown in the figure 1.

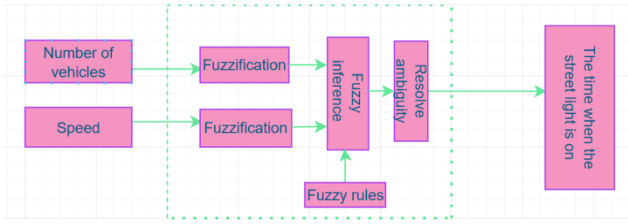

Figure 1: Fuzzy Control System Diagram

3.1 Fuzzy input and output indicators

In fuzzy control, the input quantity needs to be fuzzified first. The input variables in this article include the number of vehicles N and the vehicle speed S (km/h). The domain of the number of vehicles is set to [0,50] and divided into five fuzzy subsets: very small (VS), small (S), medium (M), large (L), and large (VL). According to the actual situation, when the number of vehicles is less than 10, it belongs to the "very small" subset; When the number of vehicles is greater than 40, it belongs to the "very large" subset. Considering the complexity of the number of vehicles, a triangular membership function is used for fuzzification, which has the advantages of simplicity, high computational efficiency, and good control performance. As shown in figure2.

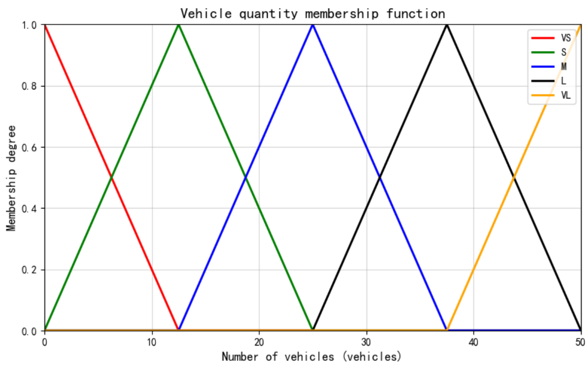

Figure 2: Schematic diagram of membership function for the number of vehicles

The domain of vehicle speed is set to [0, 50] and divided into five fuzzy subsets: very slow (VS), slow (S), medium (M), fast (L), and very fast (VL). A vehicle speed less than 5 is considered "very slow", greater than 45 is considered "very fast", and the rest is a fuzzy area. The vehicle speed adopts a triangular membership function to reflect the complex vehicle speed distribution in real life. The vehicle speed membership function is shown in the following figure 3.

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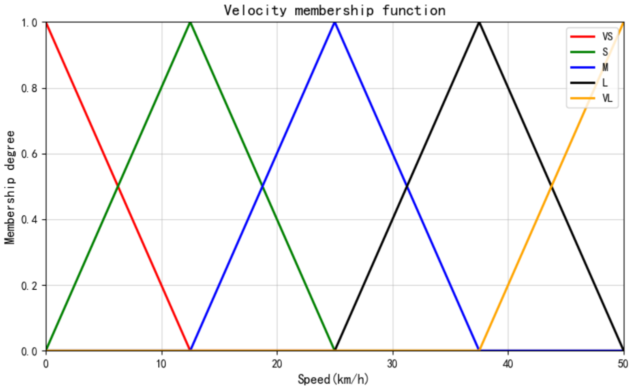

Figure 3: Schematic diagram of vehicle speed membership function

The time domain for streetlights to illuminate is set to [0,120] and divided into five fuzzy subsets: very short (VS), short (S), medium (M), long (L), and very long (VL). Due to the irregular timing of street lights, all fuzzy subsets are defined using triangular membership functions, as shown in the following figure 4.

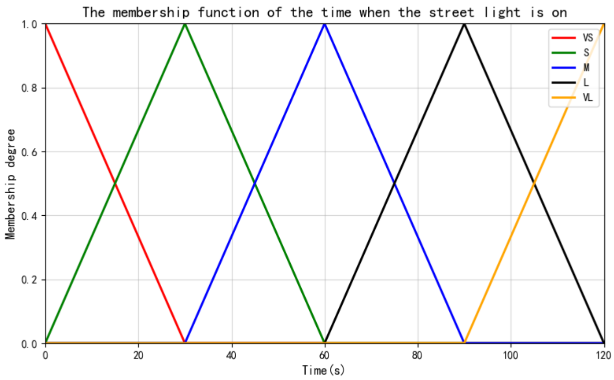

Figure 4: Schematic diagram of membership function for the time when the street light is on

3.2 Fuzzy rule setting

The rationality of fuzzy rules determines the effectiveness of fuzzy controllers. The rules in this section are based on practical situations: the faster the vehicle speed, the fewer the number, the smoother the traffic, and the shorter the time when the street lights are on; On the contrary, slow vehicle speeds, large numbers of vehicles, traffic congestion, and longer street lights are on. The fuzzy rules set in MATLAB are shown in the table 1.

Table 1: Fuzzy rule representation intention

		Fuzzy Rule Control Table				
The time when the street light is on			**Speed**			
		VS	S	M	L	VL
	VS	M	M	S	S	VS
Number of vehicles	S	L	M	M	S	S
	M	VL	L	L	M	S
	L	VL	VL	L	L	M
	VL	VL	VL	VL	L	L

3.3 Fuzzy controller for solving problems

After completing the setting of fuzzy input, output, and fuzzy rules, fuzzy reasoning adopts the following methods: for the "AND" operation of fuzzy sets, the minimum method is used; for the "OR" operation, the maximum method is used; for the implication operation, the minimum method is also used; for the synthesis calculation of output, the maximum method is used; for solving fuzzy sets, the centroid

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method is used. By following these steps, the corresponding relationship between input and output can be obtained, and the time when the exit light is on can be solved. The fuzzy reasoning setting is shown in Figure 5, and the input-output correspondence is shown in the figure 6.

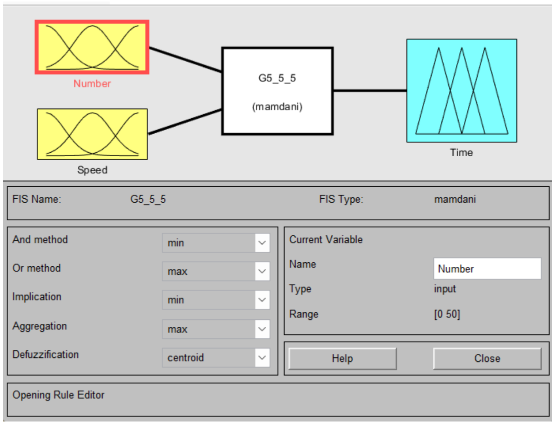

Figure 5: Schematic diagram of fuzzy reasoning setting

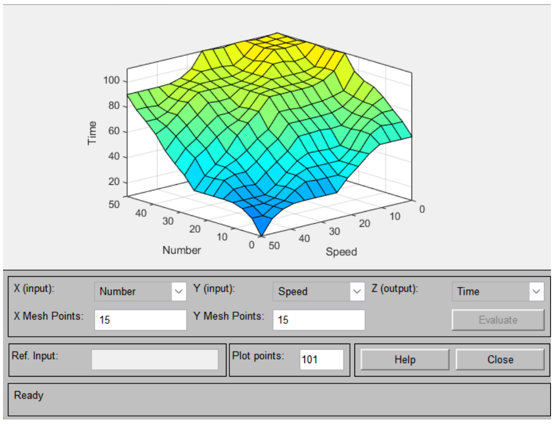

Figure 6: Schematic diagram of input-output correspondence

4. Experiment

This experiment utilized MATLAB for modeling and simulation, and designed and validated a street light dimming system based on fuzzy control. The simulation time was from 23:00 in the evening to 6:00 in the morning. The experimental input parameters include the number of vehicles ([0,50]) and vehicle speed ([0,50]), and the output is the brightness time of the street lamps ([0,120]). The experiment is set to have a vehicle every 10 minutes, with a randomly generated speed range of 20 to 40 km/h and a total of 0 to 10 vehicles. Through fuzzy analysis of the relationship between traffic flow and vehicle speed, the experiment uses the minimum and maximum methods for fuzzy inference and output synthesis, and uses the center of gravity method to solve the fuzzy problem, obtaining the corresponding street light illumination time for each group of vehicles under the condition of vehicle speed. In addition, assuming a light bulb power of 0.1 kWh, the experiment further verified the effectiveness of the system in improving traffic smoothness and energy efficiency under different traffic scenarios. The results indicate that the system can dynamically adjust the brightness time of street lamps based on real-time traffic conditions, achieving the goals of energy conservation and optimized lighting. Input the corresponding output as shown in the figure 7.

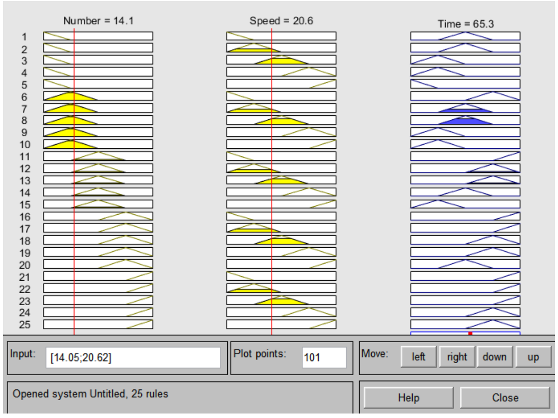

Figure 7: Input corresponding output diagram

By conducting ten simulation experiments on a single light bulb, the experimental results are shown in table 2. In the table, En represents the experiment number ,FCte(kwh) represents the total energy consumption of street lamps controlled by fuzzy controllers, Ecl(kwh) represents the total energy consumption of the constantly lit street lights, Es(kwh) represents the saved energy consumption, ηs represents the saved energy consumption rate.

$$\mathrm{Es} = \mathrm{Ecl} - \mathrm{FCte}$$

$$\eta\mathrm{s} = \mathrm{Es}/\mathrm{Ecl} * 100\%$$

Table 2: Schematic diagram of experimental data

En	FCte	Ecl	Es	ηs
E1	0.30707	0.7	0.39293	56.13%
E2	0.3135	0.7	0.3865	55.21%
E3	0.27489	0.7	0.42511	60.73%
E4	0.27401	0.7	0.42599	60.86%
E5	0.27419	0.7	0.42581	60.83%
E6	0.29196	0.7	0.40804	58.29%
E7	0.28537	0.7	0.41463	59.23%
R8	0.2687	0.7	0.4313	61.61%
E9	0.24438	0.7	0.45562	65.09%
E10	0.27799	0.7	0.42201	60.29%

The maximum saved energy consumption (kwh) is 0.45562kwh, the minimum is 0.3865kwh, and the average is about 0.42kwh; The maximum energy saving rate is 65.09%, the minimum is 55.21%, and the average is about 59.83%.

Based on this, it can be inferred that on a 1-kilometer-long road, a set of street lamps (each set containing two lamps, located on both sides of the road) is installed every 20 meters, with a total of 100 lamps. The energy saved is about 42kWh, and the energy saving rate is about 59.83%.

5. Conclusion

This article studies an intelligent street light scheduling method based on fuzzy logic, and verifies its performance by simulating different traffic scenarios at night. The experiment shows that this method can dynamically adjust the brightness time of street lamps based on the real-time number and speed of vehicles, achieving significant energy-saving effects and traffic safety guarantees. In ten simulated experiments, the average energy saving of a single lamp was 0.42 kWh, with an energy saving rate of 59.83%. Further calculations show that 100 street lights on a 1-kilometer road can save approximately 42 kWh of energy consumption. Compared with traditional fixed time control and simple sensor triggering logic, this method is more intelligent and adaptable, can effectively cope with traffic flow fluctuations, improve energy utilization efficiency, and provide important reference and practical application value for intelligent street light control in the context of smart cities. This study demonstrates the potential of fuzzy logic in optimizing resource allocation in complex traffic environments and has good prospects for promotion.

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