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# An energy-saving fuzzy control system for highway tunnel lighting

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ABSTRACT

In order to achieve the goal of energy-saving and safety driving in tunnel, this paper proposes an energy-saving fuzzy control system for highway tunnel lighting. Firstly, a control system for highway tunnel lighting based on IoT technology is constructed. Then, by considering tunnel exterior environmental luminance, traffic volume and vehicle speed as inputs and tunnel interior luminance as output, a fuzzy control model is designed. Based on experts' experience and "Guidelines for Design of Lighting of Highway Tunnels (China)" (JTG/T D70/2-01-2014), membership functions and fuzzy control rules of different zones are designed. Furthermore, this system has been deployed at the Duan tunnel of Guangxi Province in China and stably operated for more than half a year. The operation results demonstrate that the proposed control method can effectively avoid the "black hole effect" and "white hole effect", and have a significant energy-saving effect (saving nearly 41% daily energy consumption).

## 1. Introduction

In recent years, highway construction is flourishing and gaining global attentions, which greatly benefits people's transportation and life [1]. Tunnels are special parts of highways because there are brightness differences between a tunnel interior and exterior [2]. In order to ensure the traffic safety and avoid the "black hole effect" and "white hole effect" [3] (the tunnel entrance appears to be a black hole and the tunnel exit appears to be a white hole), traditional highway tunnel lighting systems operate continuously (24 h a day and 365 days a year). However, energy waste is ubiquitous in these lighting systems because all tunnel lamps will be lit up regardless of the existence of vehicles and the changes of daylight, which can lead to a serious overlighting problem. Therefore, it is very significant to design an energy-efficient highway tunnel lighting control system under the premise of ensuring safety driving.

In response to this challenge, a wide range of researchers and experts are exploring all kinds of intelligent control system for highway tunnel lighting. Wang et al. [4] designed a kind of intelligent LED lighting system based on STC89C52 microcomputer. They realized light intensity control and infrared detection but ignored the analysis of experimental results. Lu et al. [5] adopted solar LED lighting technology to realize tunnel basic lighting and emergency lighting. Nevertheless, the solar tracking device and optical fiber lighting system were relatively expensive. Xu et al. [6] used DALI (Digital Addressable Lighting Interface) to develop a tunnel LED lighting control system. Their control system not only ensured operation safety of the tunnel, but also achieved remote and stepless dimming control. However, they only presented a small tunnel simulated model which may not be suitable for practical applications. Carni et al. [7] proposed a smart control method to automatically operate and tune the tunnel interior luminance according to the input signals of the external luminance, the climatic condition and the traffic intensity. Although the method can save energy to some

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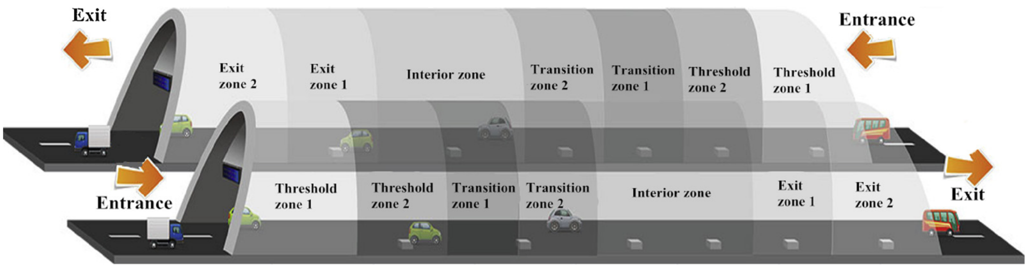



**Fig. 1.** Tunnel zone diagram.

extent, the uniformity and continuity of luminance in tunnels seemed poor, and the specifications of tunnel lighting cannot be satisfied. Yang et al. [8] proposed a fuzzy control method for tunnel lighting control system. The simulation results showed that the fuzzy system had a notable energy-saving effect and nice adaptability. However, their focus was on MATLAB simulation, while the method should be implemented in a real tunnel lighting system to analyze the effect of energy-saving. Qin et al. [9] proposed a "vehicle in, light brightens; vehicle out, light darkens" energy-saving control system based on incremental PID method. Although they contributed to energy conservation, they did not illustrate their proposed control mechanism and algorithm process in detail.

In this paper, we propose an enery-saving fuzzy control system for highway tunnel lighting. By using an adaptive fuzzy control strategy, the tunnel interior luminance is adjusted along with the changes of tunnel exterior environmental luminance, traffic volume and vehicle speed, which meets the basic requirements of tunnel lighting, avoids the "black hole effect" and "white hole effect" [3], and reduces the energy consumption significantly.

The rest of the paper is organized as follows. Section 2 introduces the architecture of the proposed system. Section 3 describes the design of fuzzy controller for tunnel lighting. Section 4 evaluates the experimental results. Finally, Section 5 concludes the paper.

## 2. Architecture of the proposed system

According to "Guidelines for Design of Lighting of Highway Tunnels (China)" (JTG/T D70/2-01-2014), the highway tunnel is divided into threshold zone, transition zone, interior zone and exit zone, as shown in Fig. 1.

In order to make sure that drivers can gradually adapt to the tunnel interior environment and avoid the "black hole effect" an "white hole effect" [3], the tunnel is divided into seven zones with different levels of required luminance, as shown in Table 1.

The architecture of the proposed energy-saving fuzzy control system is shown in Fig. 2. The control system can be divided into three layers:

1) Data acquisition layer: this layer can directly collect traffic flow, vehicle speed, illuminance and electricity usage by vehicle detector, luminance sensor and smart meter, respectively. High-voltage sodium lamps are controlled by electronic ballasts;
2) Data transmission layer: this layer consists of an ARM embedded system and DALI controllers. The ARM embedded system transfers the data collected by detectors and sensors to fuzzy control computer, and the DALI controllers send the control commands to electronic ballasts through DALI bus;
3) Data process and display layer: this layer includes a fuzzy control computer, using a given fuzzy logic to calculate the demand luminance of each zone of a tunnel, sending control commands to DALI controllers to adjust sodium lamps, showing the changes of luminance of each zone, and analyzing the statistics of energy consumption.

**Table 1**
Tunnel lighting specification.

| Tunnel zones | Minimum luminance ($cd/m^2$) |
|---|---|
| Threshold zone 1 | $L_{th1} = k \times L_{20}(s) = \begin{cases} (0.0005v - 0.013) \times L_{20}(s),\ N \le 350 \\ \frac{0.355v + 0.0002N(v-29) - 9.02}{850} \times L_{20}(s),\ 350 < N < 1200 \\ (0.0007v - 0.0188) \times L_{20}(s),\ N \ge 1200 \end{cases}$ |
| Threshold zone 2 | $L_{th2} = 0.5 \times L_{th1}$ |
| Transition zone 1 | $L_{tr1} = 0.15 \times L_{th1}$ |
| Transition zone 2 | $L_{tr2} = 0.05 \times L_{th1}$ |
| Interior zone | $L_{in} = \begin{cases} 0.007v^2 - 0.0693v + 2.6,\ N \le 350 \\ 0.0005v^2 - 0.0207v + 0.9,\ 350 < N < 1200 \\ 0.0012v^2 - 0.0732v + 2.1,\ N \ge 1200 \end{cases}$ |
| Exit zone 1 | $L_{ex1} = 3 \times L_{in}$ |
| Exit zone 2 | $L_{ex2} = 5 \times L_{in}$ |

**Notes:** $L_{th1}$, $L_{th2}$, $L_{tr1}$, $L_{tr2}$, $L_{in}$, $L_{ex1}$ and $L_{ex2}$ are minimun luminance of Threshold zone 1, Threshold zone 2, Transition zone 1, Transition zone 2, Interior zone, Exit zone 1 and Exit zone 2. $L_{20}(s)$ is the tunnel exterior environmental luminance, $k$ is the brightness reduction factor, $v$ is vehicle speed, and $N$ is traffic volume.

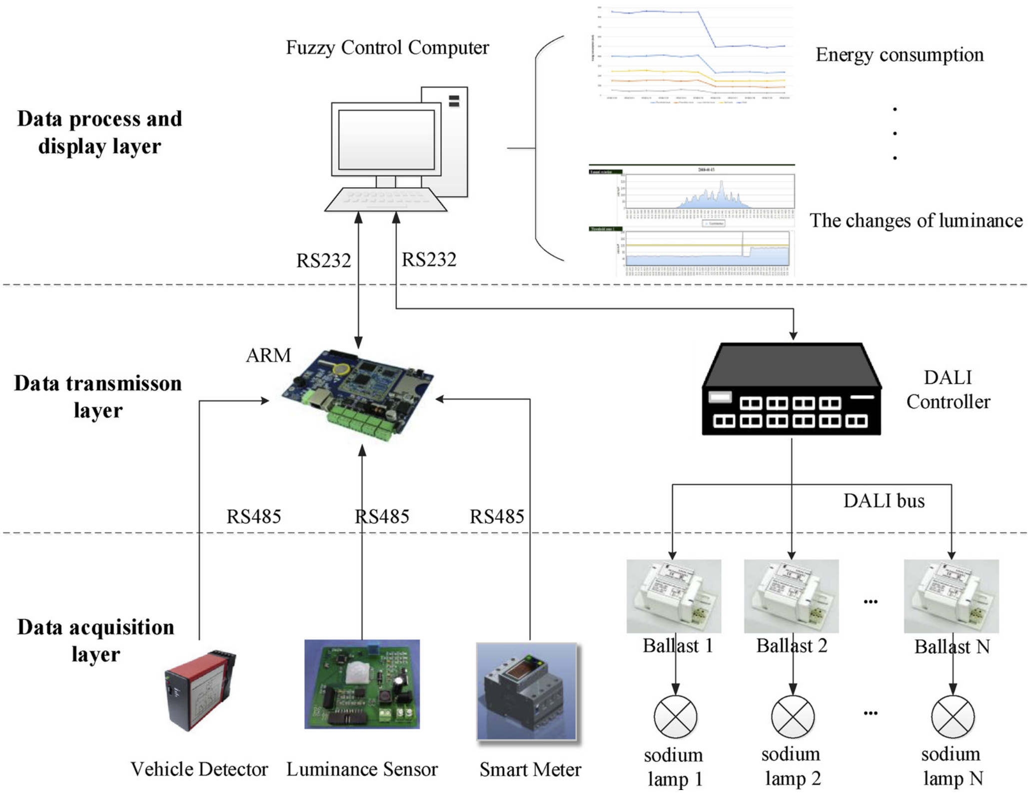



**Fig. 2.** The architecture of the proposed system.

## 3. Design of fuzzy controller for highway tunnel lighting

According to "JTG/T D70/2-01-2014" and features of deployment area, the $k$ is set as 0.035 and $L_{20}(s)$ is set as 3500 $cd/m^2$ in original tunnel lighting system. However, the $k$ should not be a constant because $v$ and $N$ are variables, and $L_{20}(s)$ is dynamical and even less than 3500 $cd/m^2$ in most of the daytime. Hence, original system causes an overlighting problem and wastes a lot of electricity energy. In order to solve this problem, a fuzzy control model for highway tunnel lighting is designed.

### 3.1. Fuzzy control model for highway tunnel lighting

As shown in Fig. 3, the inputs of fuzzy controller are tunnel exterior environmental luminance $L$, traffic volume $N$, and vehicle speed $V$. By fuzzification operation, these physical inputs can be translated into fuzzy inputs. The next step is to use fuzzy rules to realize fuzzy inference. After defuzzification operation, the output of fuzzy controller is tunnel interior luminance $Y$. Based on the error between required tunnel interior luminance calculated by the fuzzy controller and actual tunnel interior luminance measured by sensors, electronic ballasts are controlled through DALI bus to adjust sodium lamps. In this way, the required tunnel interior luminance can be satisfied.

Generally, there are two kinds of tunnel lighting lamps: ordinary LED lamps and high-voltage sodium lamps [10]. LEDs are used to maintain basic lighting, while sodium lamps are responsible for strengthened lighting. Considering high-voltage sodium lamps'

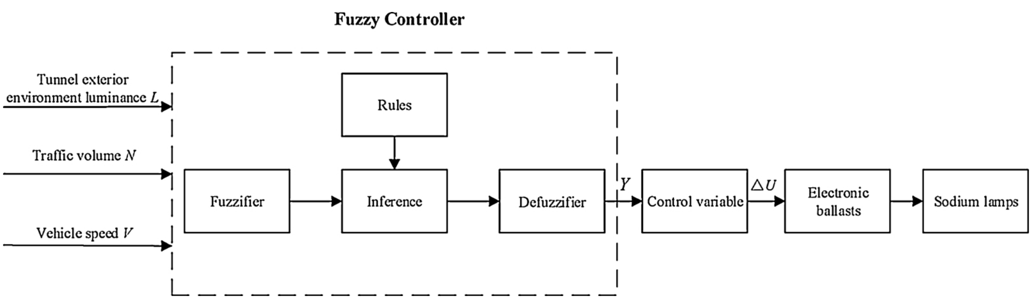



**Fig. 3.** Fuzzy control model for highway tunnel lighting.

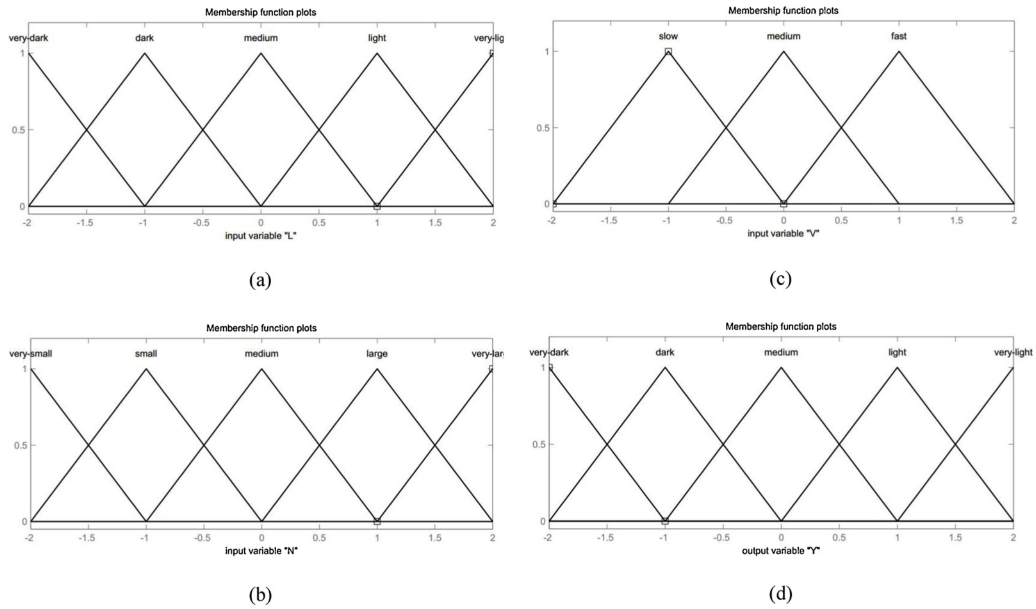



**Fig. 4.** Membership functions and universes. (a) Membership functions and universe of $L$, (b) Membership functions and universe of $N$, (c) Membership functions and universe of $V$, (d) Membership functions and universe of $Y$.

characteristics such as start-up time and durable years, it is harmful for them to frequently turn on or off. Therefore, a flexible fuzzy control strategy based on real-time $L$, $N$ and $V$ is very suitable for tunnel lighting.

### *3.2. Fuzzy control in threshold zone and transition zone*

#### *3.2.1. Transformation of input/output universes*

Actual input/output should be converted into fuzzy input/output by means of scale transformation. Supposing $x_{physical}$ is the actual physical input/output and its universe is $[x^*_{min}, x^*_{max}]$, if the corresponding fuzzy input/output universe is $[x^{min}, x^{max}]$, then the fuzzy input/output $x_{fuzzy}$ can be calculated with (1) by a linear transformation [8,11].

$$x_{fuzzy} = \frac{x^{min} + x^{max}}{2} + \frac{x^{max} - x^{min}}{x^*_{max} - x^*_{min}}\left(x_{physical} - \frac{x^*_{min} + x^*_{max}}{2}\right) \tag{1}$$

where $x_{fuzzy} \in [x^{min}, x^{max}]$ and $x_{physical} \in [x^*_{min}, x^*_{max}]$.

In this way, three kinds of input ($L$, $N$ and $V$) and one kind of output ($Y$) can be translated into $L_{fuzzy}$, $N_{fuzzy}$, $V_{fuzzy}$ and $Y_{fuzzy}$, and their quantificational universe is $\{-2, -1, 0, 1, 2\}$.

#### *3.2.2. Fuzzy language and membership functions of input/output*

Fuzzy languages to describe tunnel exterior environmental luminance $L$ are defined as {very dark, dark, medium, light, very light}, that is $\{L_{NB}, L_{NS}, L_{ZO}, L_{PS}, L_{PB}\}$, and their triangle membership functions (MFs) are shown in Fig. 4(a).

Fuzzy languages to represent traffic volume $N$ are defined as {very small, small, medium, large, very large}, that is $\{N_{NB}, N_{NS}, N_{ZO}, N_{PS}, N_{PB}\}$, and their MFs are shown in Fig. 4(b).

Fuzzy languages to describe vehicle speed $V$ are defined as {slow, medium, fast}, that is $\{V_{NB}, V_{ZO}, V_{PB}\}$, and their MFs are shown in Fig. 4(c).

Furthermore, fuzzy languages to describe tunnel interior luminance $Y$ are also defined as {very dark, dark, medium, light, very light}, that is $\{Y_{NB}, Y_{NS}, Y_{ZO}, Y_{PS}, Y_{PB}\}$, and their triangle MFs are shown in Fig. 4(d).

#### *3.2.3. Fuzzy control rules and fuzzy inference*

It is very significant to design fuzzy control rules between input and output because it greatly affects the performance of the fuzzy controller. Therefore, the integrity of control rules must be guaranteed and contradictory control rules must be avoided. Based on experts' knowledge and practical experience, a fuzzy control rule table describing the relationship between $L$, $N$, $V$ and $Y$ is established, as shown in Table 2.

The fuzzy controller consists of three input variables ($L$, $N$ and $V$) and one output variable ($Y$). The total number of control rules is 75 ($5 \times 5 \times 3$) becuase $L$, $N$ and $V$ have five, five, and three linguistic levels, respectively.

Every fuzzy statement corresponds to one fuzzy relationship $R_i$.

**Table 2**
Fuzzy control rules of threshold zone and transition zone.

| | | | $V_{NB}$ | | | | | | $V_{ZO}$ | | | | | | $V_{PB}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $L_{NB}$ | $L_{NS}$ | $L$ $L_{ZO}$ | $L_{PS}$ | $L_{PB}$ | $N$ | $L_{NB}$ | $L_{NS}$ | $L$ $L_{ZO}$ | $L_{PS}$ | $L_{PB}$ | $N$ | $L_{NB}$ | $L_{NS}$ | $L$ $L_{ZO}$ | $L_{PS}$ | $L_{PB}$ |
| $N_{NB}$ | $Y_{NB}$ | $Y_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $N_{NB}$ | $Y_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $N_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ |
| $N_{NS}$ | $Y_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $N_{NS}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $N_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ |
| $N_{ZO}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $N_{ZO}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $N_{ZO}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $Y_{PB}$ |
| $N_{PS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $N_{PS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $Y_{PB}$ | $N_{PS}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $Y_{PB}$ | $Y_{PB}$ |
| $N_{PB}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PB}$ | $Y_{PB}$ | $N_{PB}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PS}$ | $Y_{PB}$ | $Y_{PB}$ | $N_{PB}$ | $Y_{PS}$ | $Y_{PS}$ | $Y_{PB}$ | $Y_{PB}$ | $Y_{PB}$ |

**Notes:** If $V$ is $V_{NB}$ and $N$ is $N_{NB}$ and $L$ is $L_{NB}$, then $Y$ is $Y_{NB}$.
If $V$ is $V_{NB}$ and $N$ is $N_{NB}$ and $L$ is $L_{NS}$, then $Y$ is $Y_{NB}$.
If $V$ is $V_{NB}$ and $N$ is $N_{NB}$ and $L$ is $L_{ZO}$, then $Y$ is $Y_{NS}$.
If $V$ is $V_{NB}$ and $N$ is $N_{NB}$ and $L$ is $L_{PB}$, then $Y$ is $Y_{ZO}$.

$$R_i = [L_j \times N_m \times V_n]^{T_1} \times Y_k \tag{2}$$

where $L_j$, $N_m$, $V_n$ and $Y_k$ are linguistic levels of $L$, $N$, $V$ and $Y$, respectively; $T_1$ is the dimension of matrix $[L_j \times N_m \times V_n]$; $i = 0, 1, 2\cdots,74$; $j = m = k = 0, 1, 2, 3, 4$; $n = 0, 1, 2$.

By amalgamative computing, a fuzzy relationship matrix consists of 75 fuzzy relationships can be given by

$$R = \bigcup_{i=0}^{74} R_i \tag{3}$$

Then, the required tunnel interior luminance $Y$ can be calculated by

$$Y = [L \times N \times V]^{T_2} \times R \tag{4}$$

where $T_2$ is the dimension of matrix $[L \times N \times V]$.

#### *3.2.4. Defuzzification operation and fuzzy decision surface*

Applying centroid defuzzification method, fuzzy output can be tranlated into physical output by

$$U_Y = \frac{\sum_{i=0}^{74} Y_i \mu_Y(Y_i)}{\sum_{i=0}^{74} \mu_Y(Y_i)} \tag{5}$$

where $U_Y$ is the physical output of tunnel interior luminance $Y$; $\mu_Y$ is the membership function of $Y$; $Y_i$ is the linguistic level of $Y$.

When vehicle speed $V$ or traffic volume $N$ is constant, the corresponding fuzzy decision surface is shown in Figs. 5 and 6, respectively.

### *3.3. Fuzzy control in interior zone and exit zone*

Different from Section 3.2, the inputs of fuzzy controller of interior zone and exit zone are $V$ and $N$, while the output is still tunnel interior luminance $Y$. This is because $L_{in}$, $L_{ex1}$ and $L_{ex2}$ in Table 1 are only relevant to vehicle speed and traffic volume but not to tunnel exterior luminance $L$.

Another notable difference is that fuzzy languages to describe vehicle speed $V$ are defined as {very slow, slow, medium, fast, very fast}, that is {$V_{NB}$,$V_{NS}$,$V_{ZO}$,$V_{PS}$, $V_{PB}$}. Furthermore, Gauss MFs are used to represent $V_{NB}$,$V_{NS}$,$V_{ZO}$,$V_{PS}$ and $V_{PB}$ in linguistic levels of $V$; $N_{NB}$, $N_{NS}$,$N_{ZO}$,$N_{PS}$ and $N_{PB}$ in those of $N$; $Y_{NS}$,$Y_{ZO}$ and $Y_{PS}$ in those of $Y$. Z-shaped and S-shaped MFs are used to represent $Y_{NB}$ and $Y_{PB}$ in

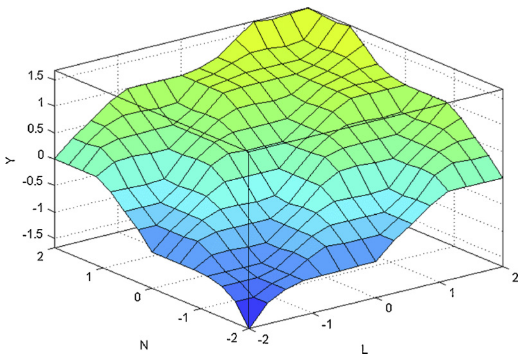



**Fig. 5.** Fuzzy decision surface of threshold zone and transition zone when $V$ is constant.

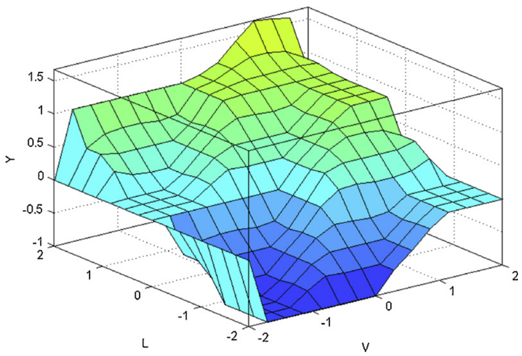



**Fig. 6.** Fuzzy decision surface of threshold zone and transition zone when $N$ is constant.

linguistic levels of $Y$, respectively, as shown in Fig. 7.

Similar to Section 3.2, another fuzzy control rule table describing the relationship between $V$, $N$ and $Y$ is established, as shown in Table 3.

Fig. 8 gives a fuzzy decision surface shows the relationship between input ($V$, $N$) and output ($Y$) based on the fuzzy control rules and universes. It can be seen from Fig. 8 that if $V$ is very fast and $N$ is very large, $Y$ will be very light to achieve required interior luminance. However, if $V$ is very fast but $N$ is very small, $Y$ will not be very light and even dark. When there are few cars in the tunnel, drivers tend to feel that traffic situation is good and accelerate the vehicle. Hence, the tunnel will not increase the interior luminance only for the sake of a small number of high-speed cars.

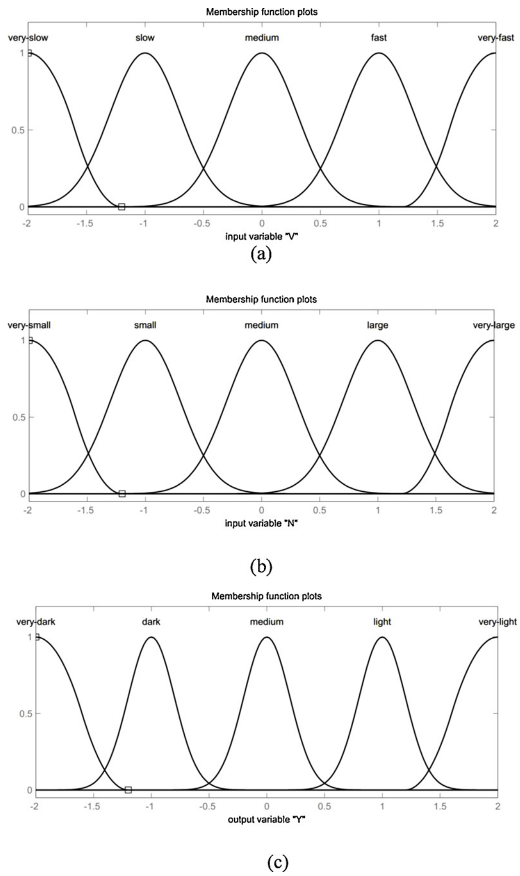



**Fig. 7.** Membership functions and universes. (a) Membership functions and universe of $V$, (b) Membership functions and universe of $N$, (c) Membership functions and universe of $Y$.

**Table 3**
Fuzzy control rules of interior zone and exit zone.

| $Y$ | | $N$ | | | | |
|---|---|---|---|---|---|---|
| | | $N_{NB}$ | $N_{NS}$ | $N_{ZO}$ | $N_{PS}$ | $N_{PB}$ |
| $V$ | $V_{NB}$ | $Y_{NB}$ | $Y_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{NS}$ |
| | $V_{NS}$ | $Y_{NB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ |
| | $V_{ZO}$ | $Y_{ZO}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ |
| | $V_{PS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PB}$ |
| | $V_{PB}$ | $Y_{NS}$ | $Y_{NS}$ | $Y_{ZO}$ | $Y_{PS}$ | $Y_{PB}$ |

**Notes:** If $V$ is $V_{NB}$ and $N$ is $N_{NB}$, then $Y$ is $Y_{NB}$.
If $V$ is $V_{NS}$ and $N$ is $N_{NB}$, then $Y$ is $Y_{NB}$.
If $V$ is $V_{ZO}$ and $N$ is $N_{NB}$, then $Y$ is $Y_{ZO}$.
If $V$ is $V_{PS}$ and $N$ is $N_{NB}$, then $Y$ is $Y_{NS}$.

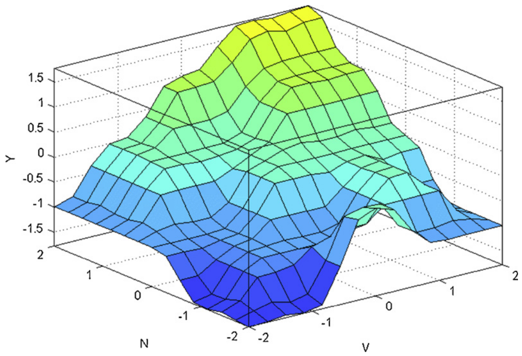



**Fig. 8.** Fuzzy decision surface of interior zone and exit zone.

**Table 4**
The relationship between $Y$ and sodium lamps.

| $Y$ | Ratio of lighted sodium lamps to the total |
|---|---|
| $Y_{PB}$ | 1 |
| $Y_{PS}$ | 3/4 |
| $Y_{ZO}$ | 1/2 |
| $Y_{NS}$ | 1/4 |
| $Y_{NB}$ | 0 |

**Fig. 9.** A STM32-based luminance sensor.

### 3.4. The relationship between output $Y$ and sodium lamps

During the tunnel construction period, the high-voltage sodium lamps were deployed in the tunnel based on $L_{20}(s) = 3500\ cd/m^2$ and $k = 0.035$. However, $L_{20}(s)$ and $k$ should not be constant because all input variables ($L$, $N$ and $V$) are dynamical. Therefore, the proposed system utilizes real-time inputs ($L$, $N$ and $V$) to figure out real-time output $Y$ and then uses it to adjust the number of lighted sodium lamps. The relationship between output $Y$ and sodium lamps is shown in Table 4. For example, if $Y$ is $Y_{PS}$, three quarters of sodium lamps should work, that is, three out of every four sodium lamps should be turned on.

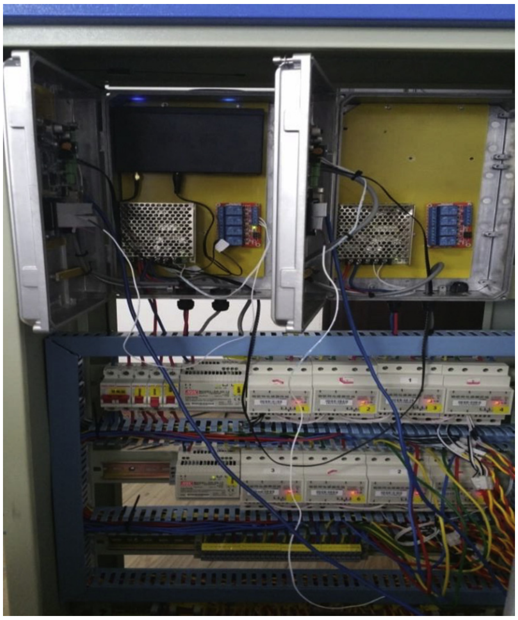


**Fig. 10.** ARM embedded system and smart electricity meters.

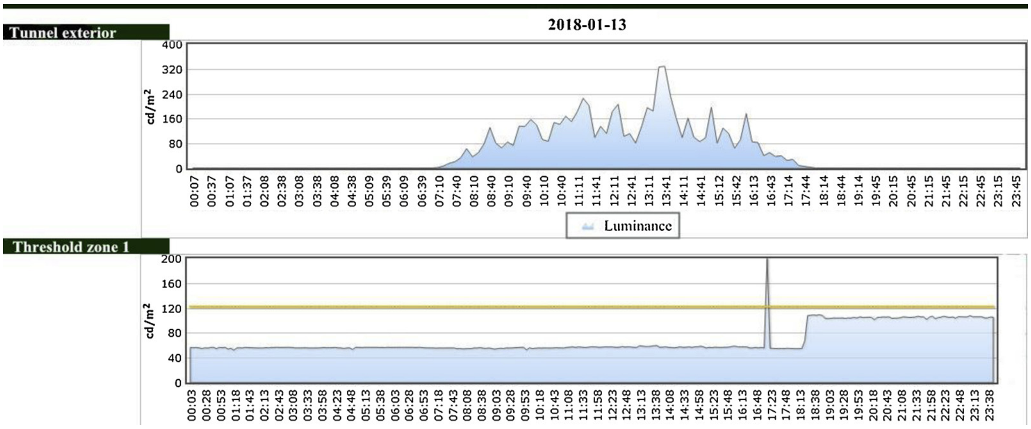



**Fig. 11.** The curve of tunnel exterior environmental luminance and threshold zone 1 luminance in 13 January 2018.

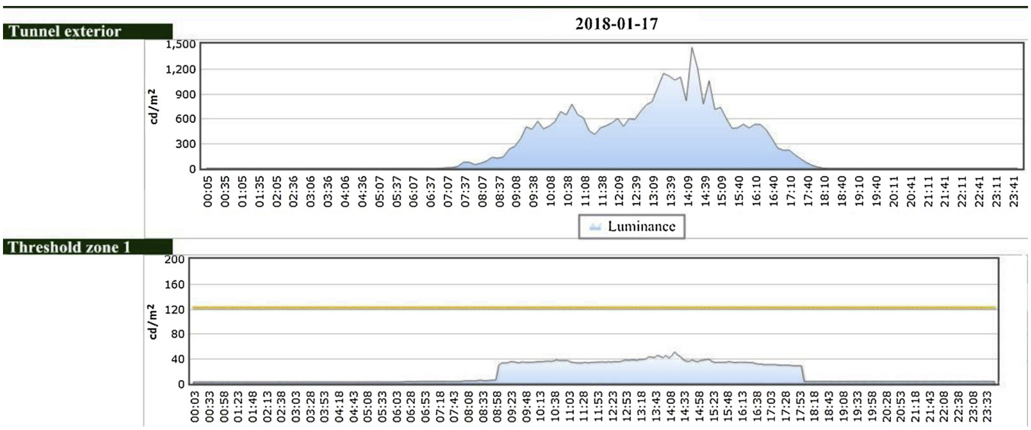
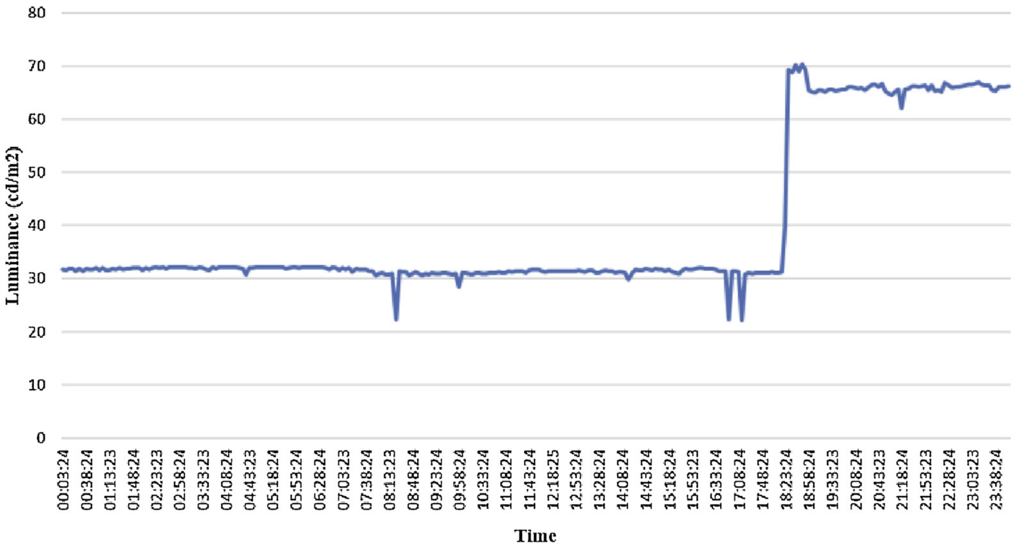
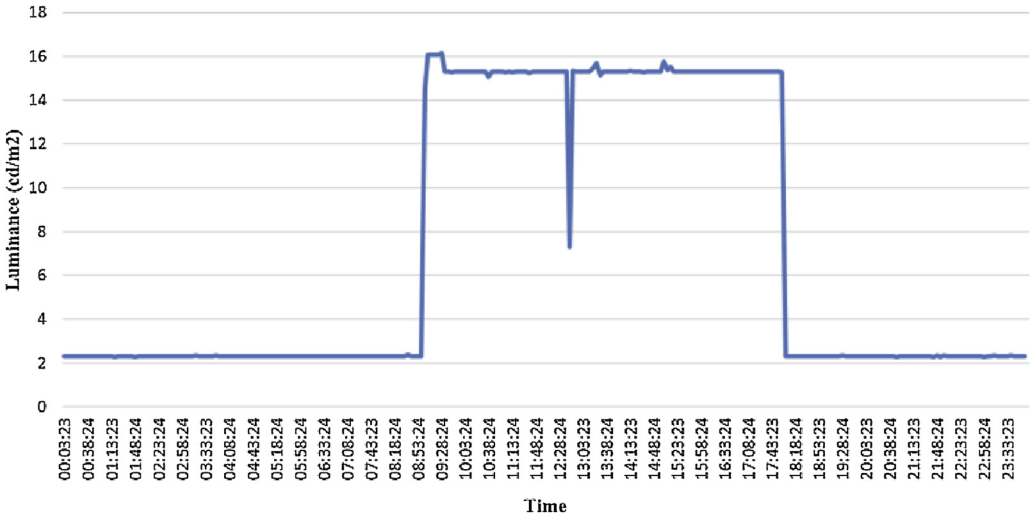



**Fig. 12.** The curve of tunnel exterior environmental luminance and threshold zone 1 interior luminance in 17 January 2018.




(a)




(b)

**Fig. 13.** Comparison of threshold zone 2 luminance before and after using fuzzy control. (a) Before using fuzzy control, (b) After using fuzzy control.

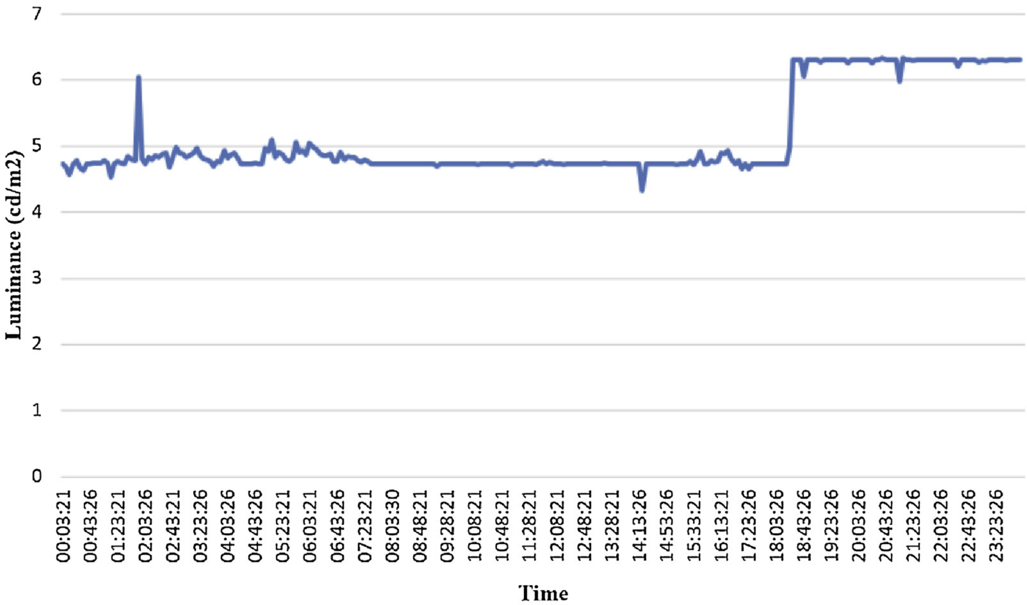
## 4. Results and discussion

In order to evaluate the effectiveness of energy-saving, the proposed system was implemented at the Duan tunnel of Guangxi Province in China since January 2018. As shown in Fig. 9, a STM32-based luminance sensor was designed and deployed in different zones of tunnel. While the ARM embedded system and smart electricity meters were installed in electricity cabinet, as shown in Fig. 10.

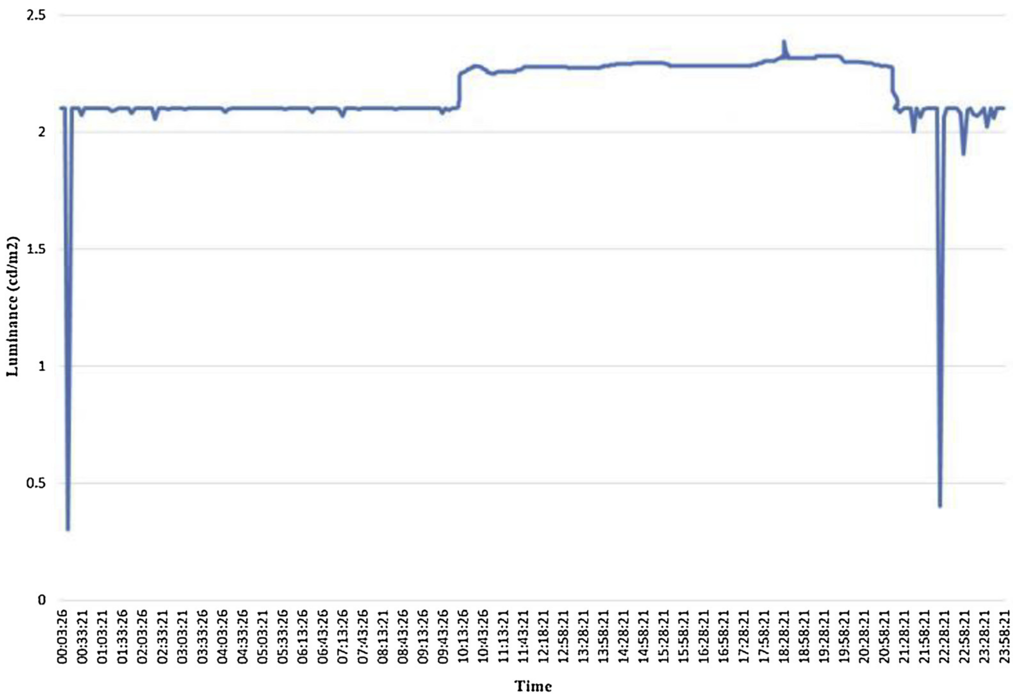
From 10 to 15 January 2018, the tunnel lighting system was controlled by original control method. But from 16 to 20 January 2018, the system was controlled by the proposed fuzzy control algorithm.

### *4.1. Luminance analysis in threshold zone 1 and tunnel exterior*

The comparison of tunnel exterior environmental luminance and threshold zone 1 luminance before and after using fuzzy control is given in Figs. 11 and 12, respectively.




(a)




(b)

**Fig. 14.** Comparison of interior zone luminance before and after using fuzzy control. (a) Before using fuzzy control, (b) After using fuzzy control.

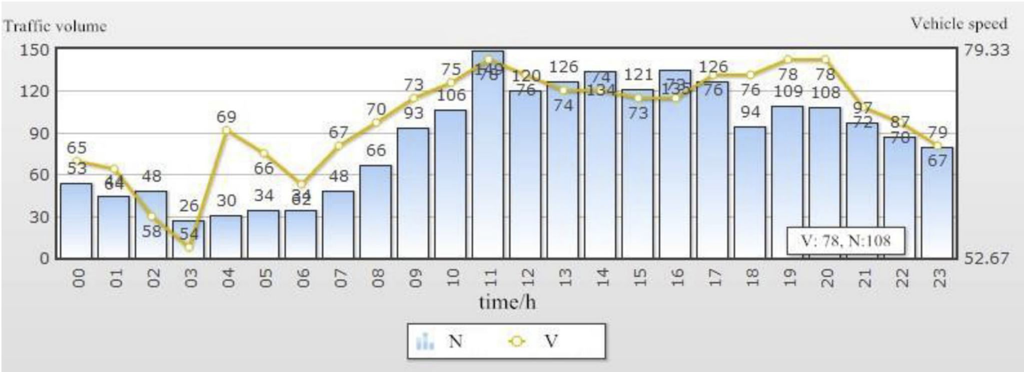



**Fig. 15.** The curve of vehicle speed and traffic volume in 17 January 2018.

Fig. 11 gives the curve of tunnel exterior environmental luminance and threshold zone 1 interior luminance in 13 January 2018 between 0:00 and 24:00. From the figure, the exterior environmental luminance between 00:00 to 07:10 and between 18:14 to 24:00 is less than 10 $cd/m^2$, and is relatively large between 07:10 to 18:14 because the sunlight is stronger during the daytime. However, the original system turns on half of the sodium lamps between 00:00 to 18:30 and turns on all of that between 18:30 to 24:00. This control method is unreasonable and wastes a lot of energy because the tunnel exterior environmental luminance in most of the daytime is less than 3500 $cd/m^2$ and even less than 320 $cd/m^2$.

Fig. 12 shows the curve of tunnel exterior environmental luminance and threshold zone 1 interior luminance in 17 January 2018 between 0:00 and 24:00. From the figure, the exterior environmental luminance between 00:00 to 07:07 and between 18:10 to 24:00 is less than 10 $cd/m^2$, which results in $Y$ is $Y_{NB}$. Hence, none of the sodium lamps will be turned on, but threshold zone 1 interior luminance is not 0 $cd/m^2$ because there are still some LEDs working for basic lighting. Furthermore, the tunnel exterior environmental luminance between 07:07 to 18:10 is more than 300 $cd/m^2$ and less than 900 $cd/m^2$, which results in $Y$ is $Y_{NS}$. Therefore, a quarter of the sodium lamps should be turned on. Also, it can be seen from Fig. 11 that threshold zone 1 luminance is around 30 $cd/m^2$ between 07:07 to 18:10 and is exactly a quarter of original luminance, which means that the proposed fuzzy control algorithm can not only ensure the actual interior luminance meet the requirements of tunnel lighting, but also achieve the goal of energy-conserving.

### 4.2. Luminance analysis in threshold zone 2

Similar to Section 4.1, Fig. 13 gives the comparison of threshold zone 2 luminance before and after using fuzzy control.

Fig. 13(a) shows that the variation trend of luminance is similar to the bottom half of Fig. 11. This is because in 13 January 2018, the lighting system was controlled by original control method. However, Fig. 13(b) shows that after using fuzzy control, the threshold zone 2 luminance in daytime is about 15 $cd/m^2$ and is almost a half of original luminance (31 $cd/m^2$).

### 4.3. Luminance analysis in interior zone and exit zone

Similarly, comparison of luminance in transition zone, exit zone 1 and exit zone 2 before and after using fuzzy control is shown in Fig. 14, Figs. 16 and 17, respectively.

Fig. 14 shows that before using fuzzy control, the interior zone luminance for the whole day is around 5 $cd/m^2$, while after using fuzzy control, the luminance can reduce to around 2.1 $cd/m^2$ (42% of original luminance). Furthermore, the luminance between 10:13 and 20:58 is a little bit larger because vehicle speed $V$ and traffic volume $N$ within this period are bigger than that in other time, as shown in Fig. 15.

Figs. 16(a) and 17 (a) also demonstrate that before using fuzzy control, the luminance between 18:08 to 24:00 in exit zone 1 and 2 is around 14 $cd/m^2$ and 22 $cd/m^2$, respectively. However, we can see from Figs. 16(b) and 17 (b) that after using fuzzy control, the daytime luminance in exit zone 1 and 2 is around 4 $cd/m^2$ and 10 $cd/m^2$, respectively, which contributes to energy-saving to some extent. Please note that daytime luminance in exit zone 2 is almost equal to original one because outside sunlight will enhance the brightness of exit zone 2.

### 4.4. Energy-saving analysis

For comparisons, the energy consumption of highway tunnel lighting under original control method and fuzzy control algorithm is shown in Fig. 18. It can be seen from Fig. 18 that the energy consumption of all zones drops a lot after using fuzzy control algorithm, and that the energy usage in threshold zone accounts for nearly a half of the total energy consumption, because the brightness requirement of threshold zone 1 and 2 is much higher than that of other zones. Furthermore, before using fuzzy control, the total energy consumption of original system is around 850 kwh every day, but after adopting fuzzy control, the daily energy consumption reduces to about 500 kwh. This means that the proposed fuzzy control strategy can save almost 41% energy than

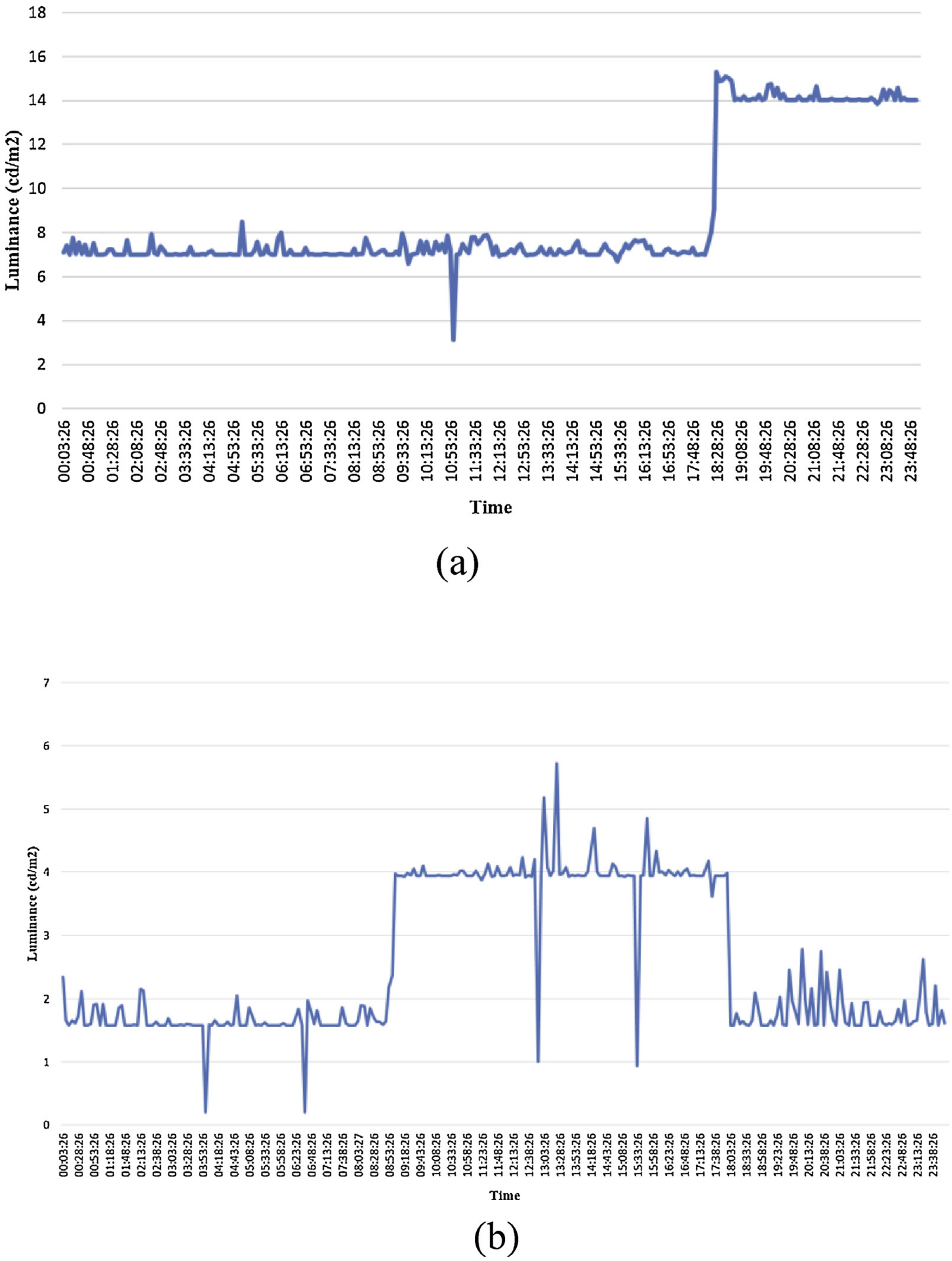


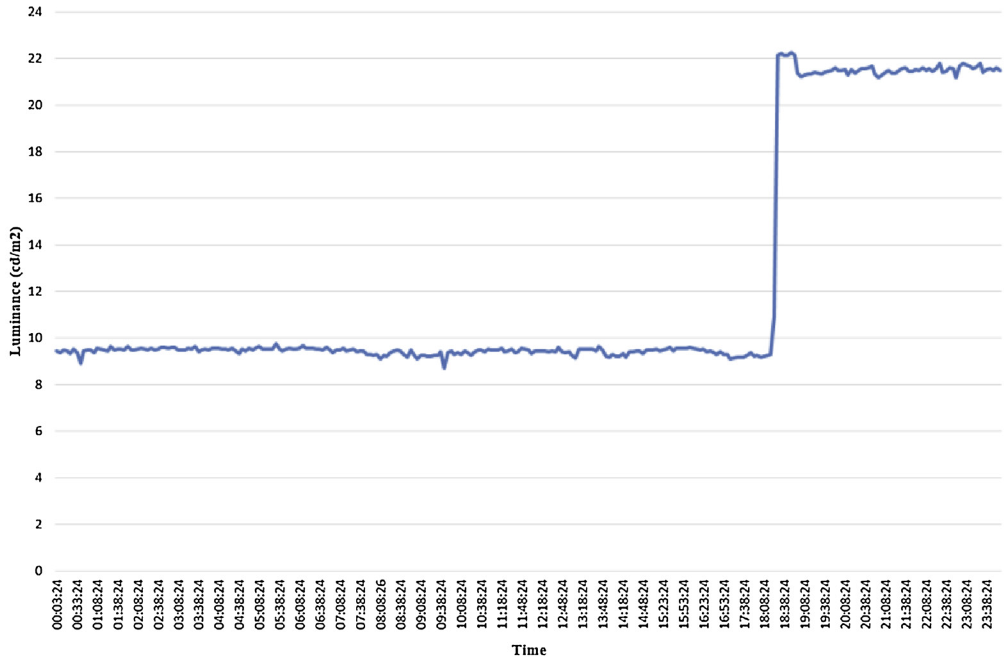

**Fig. 16.** Comparison of exit zone 1 luminance before and after using fuzzy control. (a) Before using fuzzy control, (b) After using fuzzy control.

traditional control methods do.

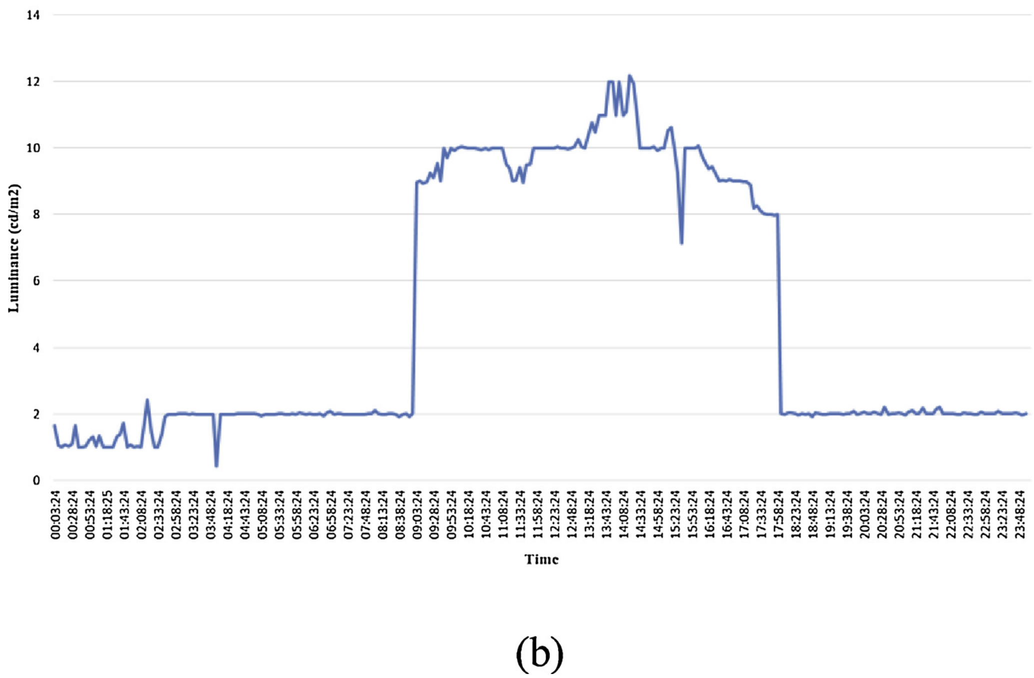
Based on above analysis, it can be concluded that the proposed system can not only ensure safety driving by avoiding “black hole effect” and “white hole effect”, but also greatly contribute to energy-saving and emission reduction.

## 5. Conclusion

This paper presents an energy-saving fuzzy control system for highway tunnel lighting based on IoT technology. Fuzzy control method is adopted to realize energy-saving by adjusting tunnel interior luminance according to real-time tunnel exterior environmental luminance, traffic volume and vehicle speed. The Duan tunnel, located at Guangxi Province of China, is used as the study case.




(a)




(b)

**Fig. 17.** Comparison of exit zone 2 luminance before and after using fuzzy control. (a) Before using fuzzy control, (b) After using fuzzy control.

The operation results from 16 to 20 January 2018 indicate that the proposed system has good adaptability to tunnel exterior environmental luminance and has a significant energy-saving effect (saving nearly 41% daily energy). In the future, deep learning will be taken into account to analyze the influence of the changes of traffic flow and vehicle speed, and to provide a more reliable, accurate and energy-efficient tunnel lighting control.

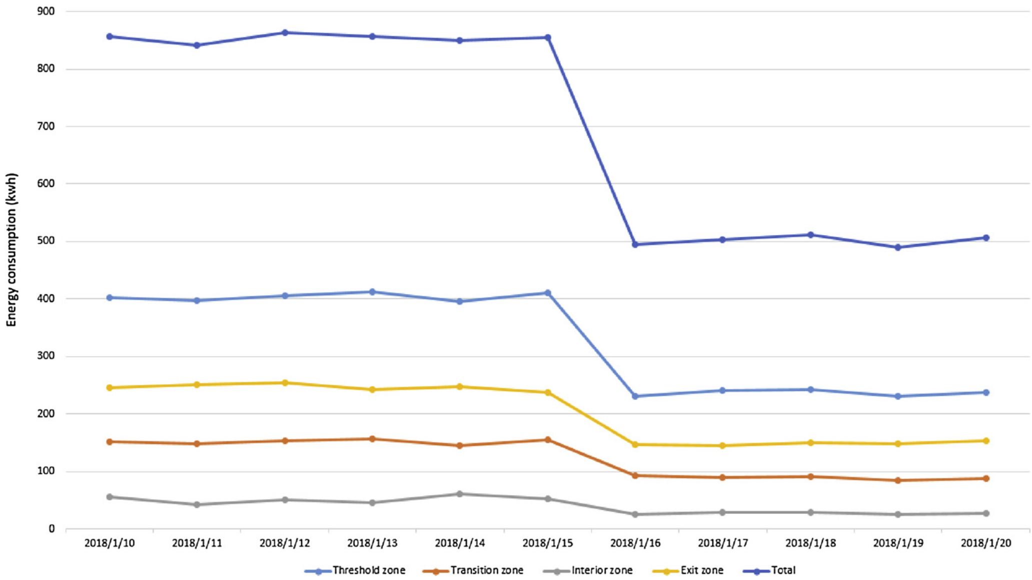



**Fig. 18.** Comparison of the energy consumption of highway tunnel lighting before and after using fuzzy control.

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