Research and application of dimming control system for highway tunnel lighting on demand

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Abstract—Aim at the widely used energy—saving lamp in highway tunnel, in accordance with the relevant requirements in JTG/T D70 /2— 01−2014” Design Details of Highway Tunnel Lighting” ,traffic prediction theory and multi-source information fusion method, internet of things technology was applied to tunnel lighting control. Taking a highway tunnel as background, this paper carried out application study on the on-demand lighting technology of highway tunnel, and it built LED tunnel lighting system on demand and developed dimming control system for highway tunnel based on the Internet of things, and it achieved networked and intelligent management of lighting energy saving.

1. INTRODUCTION
With the rapid development of one's economy, especially one belt, one road, the construction and maintenance of highway tunnels have entered a high-speed development period. By the end of 2019, there were 19067 highway tunnels, 18.966 million meters, an increase of 1329 and 1.7305 million meters. Among them, 1175 extra long tunnels, 5.2175 million meters, 4784 long tunnels, 8.2631 million meters [1,2]. If the previous decades were the period of large-scale construction of highway tunnels in China, the current stage of highway tunnel operation and management has entered. It can be seen that China has ushered in the national highway tunnel operation management peak. Now, China is the country with the largest number of tunnels and underground projects, the most complex and the fastest-growing in the world. At the same time, in the highway tunnel operation and maintenance costs, tunnel lighting power consumption accounts for a considerable part. According to incomplete statistics, tunnel lighting energy consumption accounts for more than 50% of the operation energy consumption, but about 70% of the tunnel lighting energy consumption is wasted in the "lighting transition" [3]. Therefore, on the premise of ensuring the safety and efficiency of tunnels and providing safe and convenient high-quality services for public travel, reducing tunnel transport energy consumption and saving operating costs, how to achieve tunnel operation on-demand lighting through intelligent management and fine control has become an urgent demand of the industry and society. At present, most of the tunnel lighting in China is controlled by time sequence. According to different seasons and
time periods, the lighting control scheme is prefabricated. This control method is very easy to cause excessive or insufficient lighting, thus affecting the safety of tunnel traffic [4]. According to the requirements of the current "highway tunnel lighting design rules", the lighting control should be combined with the brightness outside the tunnel, time, Traffic volume, design speed, power supply voltage, weather conditions, light source characteristics and other factors. In this paper, combined with the actual tunnel engineering case, according to the relevant theoretical requirements of highway tunnel lighting design specifications, traffic prediction theory, multi-source information fusion method, taking the right line of a tunnel as the actual engineering background, this paper designs and develops a highway tunnel on-demand lighting control platform based on the Internet of things, that realizes the intelligent infinite control of the tunnel LED lighting lamps by the platform software The safe, efficient, green and energy-saving operation of road and tunnel provides decision support.

2. KEY FACTORS OF TUNNEL LIGHTING

2.1. Brightness outside the cave
The brightness outside the tunnel L20 (s) refers to the average brightness measured at the starting point s of the approaching section of the highway tunnel, 1.5m above the ground and 20 ° cone angle field of view in the direction of the portal. For the tunnel under construction, the value of the brightness outside the tunnel can be obtained according to the actual field measurement. The test methods include environmental sketch method, blackness method, digital camera method and look-up table method. Considering the convenience of operation and the accuracy of the test results, the digital camera method is the mainstream test method for the brightness outside the tunnel at present. External luminance L20 (s) is one of the important design reference parameters of tunnel lighting system, which has a great impact on the project investment, operation cost and safety operation of subsequent tunnel lighting [5].

![Fig 1. angle of 20 Field](image)

2.2. Energy saving lighting
At present, Tunnel lighting in China has experienced incandescent lamps, fluorescent lamps, low-pressure sodium lamps, high-pressure sodium lamps, LED lamps and other light sources [6]. In the actual project, according to the characteristics of the actual tunnel engineering, according to the light efficiency, luminous flux, light attenuation, life, light color, color rendering, reliability and cost requirements of the light source, the brightness requirements suitable for the specific environment of the tunnel should be selected, and at the same time, the good visibility in the smoke formed by automobile emission should be ensured. A large number of studies show that: compared with the traditional high-pressure sodium lamp, LED lamps can save about 50% in energy consumption. At the same time, the traditional highway tunnel lighting design lamps basically use loop control to meet the lighting requirements in the tunnel, while LED lights can adjust the brightness according to the speed, traffic volume and brightness outside the tunnel, which has strong advantages in energy saving and operation safety of tunnel lighting [7 ~ 9].

2.3. Lighting control
At present, the domestic tunnel lighting control mode mainly includes three modes: manual control, time sequence control and intelligent control [10]. Manual control mode is a traditional lighting control mode, mainly including switch control and dimming control, which has the advantages of simple, intuitive and effective. The basic principle of timing control mode is to use the control center to send
control signals, and control the opening and closing of lighting power supply and distribution circuit through digital to analog conversion controller, so as to control the switch of lighting system. However, timing control can not control the change of lighting brightness according to the actual situation inside and outside the tunnel, which is easy to cause "excessive lighting" and "insufficient lighting". It is necessary to conduct long-term data monitoring based on the field environment and weather conditions in different seasons to determine the control plan. Intelligent control refers to the application of intelligent control technology such as artificial intelligence, expert system, fuzzy control, neural network, genetic algorithm and other intelligent control technologies on the basis of automatic control mode, according to the lighting design brightness adaptation curve, dynamic dimming is achieved to achieve safe, comfortable, funny and economic lighting effect, and finally achieve on-demand lighting.

3. CONTROL PARAMETERS AND ALGORITHM OF DIMMING FOR TUNNEL ON DEMAND LIGHTING

The input factors that affect the lighting control of highway tunnel are complex. The main actual factors are: traffic volume, brightness outside the tunnel, average speed, visibility inside the tunnel, special events and time factors. The greater the traffic volume and the faster the average speed, the greater the lighting demand. In addition, the greater the brightness outside the tunnel, the greater the brightness demand inside the tunnel. As shown in Fig. 2 is the dimming control schematic diagram of on-demand lighting.

3.1. Selection of dimming control index

Referring to the current "detailed rules for lighting design of highway tunnel", the design speed of highway tunnel is divided into 5 grades from 40km / h to 120km / h, as shown in Table 1.

| Parameter Division  | gradation |
|---------------------|-----------|
|                      | A | B | C | D | E |
| Vehicle speed (km / h) | 120 | 100 | 80 | 60 | 40 |

The traffic volume grade of highway tunnel is divided into 6 grades, as shown in Table 2.

| Parameter Division | Traffic Volume Grade Of Highway Tunnel |
|--------------------|---------------------------------------|
|                     | gradation |
|                     | A | B | C | D | E | F |

Fig 2. dimming control schematic diagram of on demand lighting
One way traffic flow (veh/(h ꞏ ln))

| Traffic Flow | ≤1200 | 990≤N < 1200 | 780≤N < 990 | 570≤N < 780 | 350 < N ≤570 | ≤350 |
|--------------|-------|--------------|--------------|--------------|--------------|-----|

Two way traffic flow (veh / (h ꞏ ln))

| Traffic Flow | ≥650 | 535≤N < 650 | 420≤N < 535 | 305≤N < 420 | 180 < N ≤305 | ≤180 |
|--------------|------|--------------|--------------|--------------|--------------|-----|

VI visibility of highway tunnel is divided into four grades, and the relationship between each level and illuminance is shown in Table 3.

| Parameter Division | gradation |
|--------------------|-----------|
| In tunnel / VI visibility transmittance (%) | A normal traffic | B Slight obstruction | C Block | D close the tunnel |
| ≥60 | 50 | 40 | 30 |

| Attenuation coefficient K (10⁻³ m⁻¹) | 5 | 7 | 9 | 12 |
| Range of illuminance increase | - | 10% | 20% | 30% |

Referring to the "design rules for highway tunnel lighting" JTG / TD70 / 2-01-2014, the enhanced section lighting can be automatically turned off and turned on according to the brightness outside the tunnel. According to the light control coefficient, it can be seen that when the brightness outside the tunnel is greater than 0.13L₂₀ (s), the lighting control is carried out in the daytime; when the brightness outside the tunnel is less than 0.13L₂₀ (s), the dimming control is carried out according to the nighttime. 0.13L₂₀ (s) is the dividing point between daytime and nighttime lighting dimming control.

3.2. On demand lighting calculation of entrance section

The entrance section should be divided into two lighting sections, Th1 and Th2. The brightness of each section is calculated as follows:

\[ L_{th1} = k \times L_{20}(S) \]  
\[ L_{th2} = 0.5 \times k \times L_{20}(S) \]

Where: \( L_{th1} \) ——Brightness of entrance section Th1 (cd/m²) ; \( L_{th2} \) ——Brightness of entrance section Th2 (cd/m²) ; \( k \) ——Brightness reduction system of entrance section, \( L_{20} (S) \) ——Real time brightness outside the tunnel (cd/m²) ; The value of luminance reduction coefficient \( K \) in the entrance section is related to the speed, traffic flow and length of the tunnel.

Given the speed, traffic flow and traffic form, the values of \( L_{th1} \) and \( L_{th2} \) in the entrance section of Th1 and Th2 can be calculated by the reduction coefficient \( K \).
3.3. Brightness calculation of transition section
Referring to the current design rules for highway tunnel lighting, the transition section should be divided into three lighting sections: TR1, TR2 and TR3 according to the gradual decreasing principle, and the corresponding brightness shall be calculated according to the following formula:

\[ L_{tr1} = 0.15 \times L_{th1} \]  
\[ L_{tr2} = 0.05 \times L_{th1} \]  
\[ L_{tr3} = 0.02 \times L_{th1} \]

3.4. Calculation of basic segment brightness
Referring to the current "highway tunnel lighting design rules", the following table can be obtained.

| Design speed vt (km/h) | Lin (Basic segment brightness) |
|------------------------|--------------------------------|
| **One way traffic N (veh/(h.ln))** | | |
| ≥1200 | 990≤N < 1200 | 780≤N < 990 | 570≤N < 780 | 350 < N < 570 | ≤350 |
| 120 | 10.0 | 8.9 | 7.8 | 6.7 | 5.6 | 4.5 |
| 100 | 6.5 | 5.8 | 5.1 | 4.4 | 3.7 | 3.0 |
| 80 | 3.5 | 3.1 | 2.7 | 2.3 | 1.9 | 1.5 |
| 60 | 2.0 | 1.8 | 1.6 | 1.4 | 1.2 | 1.0 |
| 40 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

| **Two way traffic N (veh/(h.ln))** | | |
| ≥650 | 535≤N < 650 | 420≤N < 535 | 305≤N < 420 | 180 < N < 305 | ≤180 |
| 120 | 10.0 | 8.9 | 7.8 | 6.7 | 5.6 | 4.5 |
| 100 | 6.5 | 5.8 | 5.1 | 4.4 | 3.7 | 3.0 |
| 80 | 3.5 | 3.1 | 2.7 | 2.3 | 1.9 | 1.5 |
| 60 | 2.0 | 1.8 | 1.6 | 1.4 | 1.2 | 1.0 |
| 40 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

When the traffic volume is in the middle value, the following relationship between Lin value and traffic volume can be obtained by linear interpolation.

3.5. Exit lighting
Referring to the current "detailed rules for lighting design of highway tunnels", the exit section should be divided into two lighting sections EX1 and EX2, and the length of each section should be 30m. The corresponding brightness should be calculated according to the following formula:

\[ L_{ex1} = 3 \times L_{in} \]  
\[ L_{ex2} = 5 \times L_{in} \]

4. ANALYSIS ON DIMMING CONTROL FUNCTION OF TUNNEL ON DEMAND LIGHTING
Based on the Internet of things, on-demand lighting dimming control system includes brightness detector, vehicle detector, VI detector, transmission network, control algorithm, dimming controller management platform. Among them, the LED tunnel lamp needs to integrate a single lamp control module, and the tunnel intelligent lighting control cabinet can realize the control of single LED tunnel light. Tunnel intelligent lighting control and management platform is installed in the management station server. The system can collect field data through high-precision imaging luminance meter,
vehicle detector and VI detector. The data collected on site is analyzed by designing advanced control algorithm to judge whether some preset control conditions are met, and then the on-demand control of LED tunnel light is completed by lighting controller.

According to the main functions of on-demand lighting control system, it is divided into five functional modules: parameter configuration management, real-time monitoring management, energy consumption evaluation management, information query management and user rights management. As shown in Figure 3, the system function model is divided.

Parameter configuration management module: it is responsible for inputting initialization data of on-demand lighting control system, such as portal form, one-way / two-way traffic, design speed, etc. the input parameters are the basis of on-demand lighting control system.

Real time monitoring and management module: according to the actual data of brightness, traffic flow and speed outside the tunnel, the on-demand lighting control of the lighting system in the tunnel can be realized through the algorithm, which can realize the functions of intelligent control, manual control and equipment status monitoring. Intelligent control includes automatic control and time sequence control, while manual control includes group control and emergency control. The equipment condition monitoring has the function of monitoring and displaying the lamp running state, dimming parameters, front-end acquisition equipment status, and fault monitoring, alarm and fault response functions.

Energy consumption evaluation management module: responsible for energy consumption collection, energy consumption statistics, energy consumption comparative analysis and energy saving expectation analysis.

User rights management module: it is the basic component of the system, which is used to manage the user information of the system and assign permissions to users, so that users with different permissions can use the functions within the scope of their permissions in the system.

The main functions of specific function modules are shown in Table 5.

| Primary menu | Secondary menu | explain |
|--------------|----------------|---------|
| Parameter configuration management | Configuration management of tunnel design parameters | Tunnel portal form, one-way / two-way traffic, design speed |
| | Intelligent parameter configuration | Add, modify and delete the control level in the intelligent control module, mainly for |

Figure 3. system function module division
### Real time monitoring management

| Manual control | The control of lamps and lanterns in tunnel can be realized and batch operation can be realized |
|----------------|----------------------------------------------------------------------------------|
| Intelligent control | The intelligent adjustment of background tunnel lamps can be realized; the real-time traffic volume in the tunnel, the brightness inside and outside the tunnel, and the required brightness in the tunnel can be inquired |
| Condition monitoring | Query the operation status of lamps in the tunnel: on, off and fault (when the lamp status is on, it indicates the power percentage of the lamp) |

### Energy consumption assessment management

| Statistical analysis of lighting energy consumption | Query the energy consumption of lamps and lanterns in different time sections, and realize the operation evaluation of tunnel lighting system |

### Information query management

| - | Inquiry of equipment operation status, history, etc |

### User rights management

| - | User information and user rights allocation |

According to the design requirements of the current "highway tunnel lighting design rules", the lighting design parameters of the tunnel entrance section, transition section, basic section and exit section are calculated. According to the calculated design parameters, the tunnel management center workstation issues the light adjustment instructions of the lamps, and the dimming control cabinet realizes the stepless control of the on-site lamps. As shown in Figure 4, it is the control system diagram of tunnel lighting on demand.

![Figure 4. Tunnel on demand lighting control system](image-url)
5. PRACTICAL ENGINEERING APPLICATION

5.1. Engineering situation
A high-speed tunnel is a two-way six lane Expressway with a design speed of 100km/h, a net width of 14.75m, a clear height of 5.0m, a left line of 3191m and a right line of 3192m. The pavement type is imported asphalt with the remaining part of cement. The mixed traffic volume is 36645 (vehicles/day), and the peak hour traffic volume is $350 < V < 1200$ (vehicles/h/Lane).

According to the actual tunnel portal test, the brightness value of tunnel lighting design is 3500 cd/m², and the brightness reduction of entrance section is $Zhang \text{ San, Vol. 6, issue 2.}$ The structure and layout template of this paper are calculated according to the traffic volume of tunnel opening for 10 years, and the value is 0.041. The average brightness of the middle section of the tunnel: $Lin \geq 2.5$ cd/m². The maintenance coefficient $M = 0.7$. The conversion relationship between average brightness and plane illumination is $15 \text{ lx/cd} \cdot \text{m}^2$ for asphalt pavement and $10 \text{ lx/cd} \cdot \text{m}^2$ for cement pavement. See Table 6 for lighting fixture setting of each functional section of tunnel.

| project        | Entrance section 1 | Entrance section 2 | Transition section I | Transition section II | Middle section | Exit section 1 | Exit section 2 |
|----------------|--------------------|--------------------|----------------------|-----------------------|----------------|----------------|----------------|
| brightness (cd/m²) | 144                | 72                 | 21.6                 | 7.2                   | 2.5            | 7.5            | 12.5           |
| spacing (m)    | 1                  | 1                  | 2                    | 2                     | 6              | 2              | 1.2            |
| length (m)     | 71                 | 71                 | 106                  | 111                   | 2772/277       | 30             | 30             |

5.2. Engineering application
As shown in Figure 5, the on-demand lighting control platform of highway tunnel based on Internet of things is used. Different control modes are used for different application situations and environments. Each control mode has corresponding algorithm structure and independent trigger conditions, so as to realize intelligent infinite control of highway tunnel lighting.
In the practical engineering application of the on-demand lighting control platform of highway tunnel based on the Internet of things, under different seasons, different weather and different traffic volume, the field test records the current value of the brightness requirements of 75 cd/m², 80 cd/m², 90 cd/m², 95 cd/m², 110 cd/m², 120 cd/m², 144 cd/m² in the reinforced section of the tunnel 24 hours a day. As shown in Table 7, it is the entrance of the right tunnel. The required luminance value corresponds to the current value, as shown in Figure 6, which is the current value at 75 cd/m². Compared with the traditional time sequence control, the system can save about 15% energy, has better timeliness and obvious energy saving effect.

| Brightness (cd/m²) | 75  | 80  | 90  | 95  | 110 | 130 | 144 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|
| Right line entrance transition strengthened1 (A) | 45.4 | 45.9 | 46.4 | 46.8 | 47.7 | 50.6 | 50.6 |
| Right line entrance transition strengthened2 (A) | 44.6 | 45.3 | 46.5 | 47.1 | 49.0 | 54.2 | 54.1 |

Figure 6. 75 cd/m² current value

6. CONCLUSION

In this paper, aiming at the lighting lamps widely used in the highway tunnel lighting system, according to the relevant theoretical requirements of highway tunnel lighting design specifications, traffic prediction theory, multi-source information fusion method, based on the Internet of things technology, this paper designs and develops a highway tunnel on-demand lighting control platform based on the Internet of things:

(1) The traffic volume, brightness inside and outside the tunnel, visibility and other elements are obtained through the on-site sensing equipment, and the multi-source data fusion algorithm is used in
combination with the highway tunnel lighting design specification to realize the on-demand brightness of tunnel lighting. The energy-saving effect is remarkable, which can reach about 15%.

(2) The application of on-demand lighting control platform for Highway Tunnel Based on Internet of things can effectively guide highway tunnel management units to improve operation management level, realize intelligent management and fine control of tunnel lighting, and provide decision-making basis for lamp maintenance.

(3) The application of on-demand lighting control platform of highway tunnel based on Internet of things can effectively improve the driving environment of tunnel portal section

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