Current Situation and Prospect of Low Carbon Lighting in Highway Tunnel

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Abstract. Highway This paper discusses the current situation and future prospects of low-carbon lighting in highway tunnels, with emphasis on technological progress and renewable energy. The study pointed out that the current system has achieved remarkable results in improving energy efficiency and reducing carbon emissions, but the energy saving potential is not fully tapped. The future development direction is proposed, such as improving the luminous efficiency of LED lamps and promoting intelligent control systems. The key point of this paper is to provide specific measures for realizing low carbon energy saving in tunnel lighting. Specific examples can be added to illustrate the current situation and potential for improvement, to discuss in detail the challenges and limitations of implementing low carbon lighting, and to elaborate on the economic and environmental benefits of adopting low carbon lighting to provide a more balanced perspective and help readers understand the broad implications of the research and the potential implications for society.

Keywords: Tunnel lighting; low-carbon, current situation; prospects

1 Introduction

China is the country with the largest number of tunnels in the world, with the total length and number of tunnels ranking first in the world. By the end of 2023, there will be 27,297 highway tunnels covering 30,231,800 meters, including 2,050 extra-long tunnels covering 9,240,700 meters, and 7,552 long tunnels covering 13,213,800 meters [1]. At the same time, the Chinese government has put forward the ambitious goal of carbon peak and carbon neutrality, requiring carbon peak before 2030 and carbon neutrality before 2060, which puts higher requirements on energy conservation and emission reduction of transportation infrastructure.

As an indispensable part of tunnel operation, the energy consumption of tunnel lighting is becoming increasingly prominent. The energy consumption of tunnel lighting accounts for about 70-80% of the total energy consumption of the tunnel. High energy

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consumption not only increases carbon emissions, but also puts tremendous pressure on the costs of operating units, which are facing an increasing financial burden in their daily operations. Therefore, how to effectively reduce the energy consumption of tunnel lighting system is not only the need to achieve the national carbon peak and carbon neutrality goals, but also the key to reduce operating costs and improve economic benefits [2,3].

At present, the tunnel lighting system has made some progress in the selection of lamps, lighting control and renewable energy utilization, but the problem of extensive management and energy saving potential has not been fully tapped still exists. Energy-efficient tunnel lighting systems not only help reduce energy consumption and carbon emissions, but also significantly reduce operating costs and improve the overall operating efficiency of the tunnel.

In this context, it is of great significance to further study the low-carbon energy-saving technology of tunnel lighting system, explore new energy-saving measures and optimize the existing lighting scheme for promoting the sustainable development of tunnel lighting system. This paper will analyze the current situation and existing problems of the tunnel lighting system, propose specific strategies and suggestions to improve lighting efficiency, reduce energy consumption and carbon emissions, and provide scientific basis and technical support for the realization of low-carbon and efficient tunnel lighting.

2 Current Situation of Tunnel Lighting

2.1 LED Iuminaire

With the rapid development of LED technology, the application of LED lighting in tunnel lighting has basically replaced traditional high-pressure sodium lamps, gold halide lamps, fluorescent lamps and other traditional lamps. With its excellent performance and many advantages, LED lamps have become the first choice for modern tunnel lighting. In recent years, the luminous efficiency of LED lamps has been significantly improved, close to 200lm/W. High light efficiency is mainly achieved by using larger chips, such as the 5050 chip instead of the traditional 3030 chip, or installing two 3030 chips behind the lens. By increasing the luminous surface area and decreasing the chip current, the total luminous efficiency is significantly improved. This technical improvement allows LED lamps to provide higher light output for the same power consumption, thereby improving lighting effects and reducing energy consumption [4,5].

Another significant advantage of LED lamps is their high color rendering index and tunable color temperature function. The high color rendering index makes the light in the tunnel more natural, and can restore the color and material of the vehicle, obstacle and other objects, which helps the driver more clearly identify the road conditions and find obstacles, and improve driving safety. In addition, the color temperature adjustable function of the LED lamp can adjust the color temperature of the light according to the needs of different environments and times, providing the most appropriate lighting effect, which can improve the comfort and safety of driving, and enhance the visual experience in the tunnel.

2.2 Lighting Control

In the control mode, part of the tunnel adopts the loop + stepless dimming mode, that is, the lighting intensity is adjusted by controlling the luminous flux output ratio of a set of lamps. For example, a set of lamps can simultaneously output 50% of the luminous flux. This approach simplifies the complexity of the control system and is more suitable for the actual needs of tunnel lighting [6].

Loop and stepless dimming have several advantages. First of all, the tunnel environment is usually linearly distributed, and the overall brightness can be uniformly adjusted through partition control to meet the lighting needs of different areas in the tunnel. Second, the loop + stepless dimming system has a simple structure, is easy to maintain and manage, and can reduce the system failure rate and maintenance costs. In contrast, single-lamp stepless dimming requires independent adjustment of each fixture, which not only increases the complexity of hardware and software, but also significantly increases the initial investment and maintenance costs. In fact, the light change needs in the tunnel do not need to reach the fine level of independent adjustment of each lamp. Loop + stepless dimming by controlling the luminous flux output of a set of lamps, has been able to meet the lighting needs in most cases. Although single-lamp control can provide higher dimming accuracy and energy-saving effect in theory, it is not suitable for tunnel lighting system in practical application. On the one hand, the single lamp control technology is complex, and the installation and maintenance workload is large. On the other hand, the high cost and complexity of single lamp control limit its application in tunnel lighting [7].

Loop and stepless dimming is the best choice for tunnel lighting dimming because of its strong adaptability, low cost and easy maintenance. Although single-lamp control performs well in some fine lighting needs, its high cost and complexity limit its practical application in tunnel lighting.

Although the tunnel lighting control technology can realize intelligent and energy-saving management in theory, in practical application, the lighting control effect of many tunnels is not ideal. This is mainly due to the following reasons:

First, the awareness of energy conservation is weak. Some tunnel managers do not know enough about the importance of energy conservation, for example, the enhanced lighting is still turned on at night, while the code requires that the enhanced lighting should be turned off at night and only the basic lighting should be turned on. This practice not only wastes energy, but also increases operating costs.

The second is not familiar with the lighting control system. Many tunnel managers lack a sufficient understanding of the lighting control system and do not know how to operate and control the system. This technical unproficiency, resulting in the inability to flexibly adjust according to the actual situation, affecting the overall efficiency of the lighting system.

Third, equipment maintenance is not in place. For example, the installation of the luminance meter outside the tunnel is not standardized, resulting in the control system can not obtain accurate luminance data outside the tunnel, which directly affects the precise control of strengthening the lighting, and the system may mistakenly run the lamp at the maximum power, further increasing energy consumption. Take the design value of the brightness outside the hole as 3000cd/m2, as shown in Formula 1, when the brightness meter outside the hole fails and the real-time brightness outside the hole cannot be measured L20, no matter how the ambient brightness outside the hole changes, the enhanced lighting will run at the maximum installed power.

$$L_{th1} = \frac{L_{20}}{3000} \times 75 \tag{1}$$

2.3 Current Situation of Lighting Computing

At present, the calculation of tunnel lighting mostly adopts the utilization coefficient method. This method is mainly based on the principle of conservation of luminous flux, and the illumination scheme is designed by rough estimation of the illumination of tunnel pavement. The utilization coefficient method simplifies the lighting design process, but there are significant limitations. The calculation formula of the utilization coefficient method is as follows:

$$\boldsymbol{E_{av}} = \frac{\eta \cdot \Phi \cdot \mathrm{M}.\omega}{\mathrm{W.S}} \times 75 \tag{2}$$

Where: ω-- luminaire arrangement coefficient, 2 for symmetrical arrangement, 1 for staggered, center line and central side biased single light strip arrangement; H-- utilization coefficient, obtained from the graph of the utilization coefficient of the luminaire; W -- tunnel pavement width (m);S -- luminaire spacing (m).

When using coefficient method to calculate the tunnel lighting, the relationship between the total luminous flux emitted by the luminaires and the road area is mainly considered, but the complexity of the tunnel structure and environment is ignored. This method does not calculate the brightness of the tunnel pavement directly, but deduces the brightness from the approximate value of illumination. This simplified calculation ignores the influence of the specific shape and size of the tunnel section on the light distribution, and does not consider the reflection characteristics of the tunnel wall.

The reflected light of tunnel wall and road surface has an important influence on the lighting effect. The different reflectance of different materials and surfaces can cause the distribution of light within the tunnel to change significantly. If these reflection characteristics are not taken into account, the calculated results will not accurately reflect the actual lighting effect. In particular, the diffuse light reflected from the tunnel walls will make an important contribution to the illumination and brightness of the road surface. In addition, the reflective characteristics of the road surface are also ignored. Factors such as reflectivity, color and texture of pavement materials will directly affect the distribution of light and the driver's visual perception. If these factors are not taken into account, the coefficient method cannot provide accurate brightness calculation, which may lead to poor lighting effect and affect driving safety.

The light intensity distribution of lamps is another important factor that is ignored. The light intensity distribution curve of different lamps is different, which has a direct influence on the direction and intensity of light projection. If the specific light intensity distribution of the luminaire is not considered, the calculation only by the total luminous flux will lead to the lack of pertinence and accuracy of the lighting design.

Because the utilization coefficient method neglects many key factors, it can not accurately configure the luminaire. For the sake of safety, designers usually prefer to configure a larger lamp power, which leads to the actual brightness of the tunnel lighting system after it is put into operation. Too high brightness not only can not improve the actual use effect, but will lead to waste of resources. The result of excessive lighting is a large initial investment, while increasing the later operating electricity costs, bringing huge economic waste. This situation obviously runs counter to the goal of low-carbon energy saving.

3 The Development Trend of Tunnel Lighting

3.1 Further Improvement of Light Efficiency

High efficiency and energy saving has become one of the important trends in the development of tunnel lighting. With the increasing tension of global energy resources and the enhancement of environmental protection awareness, tunnel lighting systems are gradually developing in the direction of high efficiency and low energy consumption. First of all, the wide application of high-efficiency LED lamps is the main driving force behind this trend. Modern LED technology continues to innovate, the whole lighting effect has been close to 200lm/W, under the same power consumption, LED lamps can provide higher light output, significantly reducing energy consumption. Compared with traditional lighting technology, LED lamps improve light efficiency at the same time, but also have a longer service life and lower maintenance costs, making it the first choice for energy-efficient lighting. In addition, LED technology still has room for further improvement, and the light efficiency of LED lamps in the future is expected to be further improved, thereby further reducing energy consumption and achieving higher energy efficiency. Through the widespread adoption of high-efficiency LED fixtures, tunnel lighting systems can achieve significant energy savings and operational cost reductions, providing strong support for achieving sustainable development goals [8-10].

3.2 Intelligent Control of Lighting System

Intelligent control system is the key to realize high efficiency and energy saving tunnel lighting. By sensing changes in vehicles and the environment, these systems can dynamically adjust lighting brightness, minimize ineffective lighting, and achieve on-demand lighting and follow lighting [11]. When there are no cars in the tunnel, the system can automatically reduce the lighting brightness and maintain only the basic safe lighting level, thus significantly reducing energy consumption. For example, using vehicle detection sensors installed in the tunnel, the system can monitor the traffic situation in the tunnel in real time. When no vehicle is detected in the tunnel, the system automatically reduces the lighting brightness to the minimum, and once a vehicle enters the tunnel, the lighting brightness is quickly increased to the appropriate level to ensure that the driver's vision is clear.

This way of on-demand lighting can not only effectively save energy, but also extend the service life of lighting equipment and reduce maintenance costs. In addition, at night when there is less traffic or during the day when there is sufficient light, the system can also adjust the lighting intensity according to actual needs to avoid unnecessary high brightness lighting. Through these intelligent control measures, the tunnel lighting system can achieve significant energy saving effects on the premise of ensuring driving safety and comfort, and promote the development of tunnel lighting in a more efficient, intelligent and environmentally friendly direction.

In the development of tunnel lighting, the utilization of new energy technologies is also gradually becoming an important trend. By introducing renewable energy sources such as solar and wind, tunnel lighting systems can not only reduce dependence on traditional energy sources, but also significantly reduce carbon emissions and achieve more environmentally friendly and sustainable development goals.

3.3 Trends in Lighting Computing

Three-dimensional space lighting calculation method is becoming an important development trend in tunnel lighting design. Different from the traditional methods, the 3D spatial lighting calculation method can simulate and analyze the light distribution in the tunnel more comprehensively and accurately. Its advantage is that it can consider many factors such as the geometry of the tunnel section, the reflection characteristics of the wall and road surface, and the light intensity distribution of the luminaire, so as to provide more accurate illumination and brightness distribution prediction.

The 3D space lighting calculation method includes the following key steps: First, a 3D model is established according to the actual structure and size of the tunnel, including the tunnel section, wall material and pavement reflection characteristics, as shown in Figure 1. Next, the light source is precisely positioned in the model, and the light intensity distribution curve and optical characteristics of the luminaire are input to simulate the actual lighting effect. Then, through the ray tracing algorithm, the propagation path of light in the tunnel is simulated, and the illumination and brightness distribution in each area of the tunnel is calculated by considering multiple reflections and scattering phenomena, as shown in Figure 2. Finally, the calculation results are analyzed and visualized, the areas with uneven light distribution are identified, optimization suggestions are put forward, and verification and adjustment are carried out.

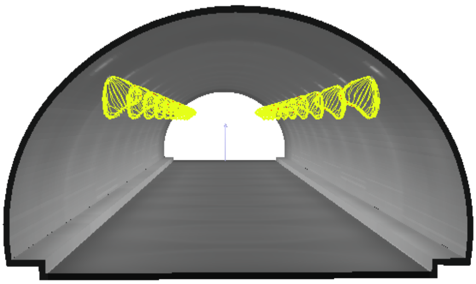

Fig. 1. Tunnel three-dimensional space lighting model

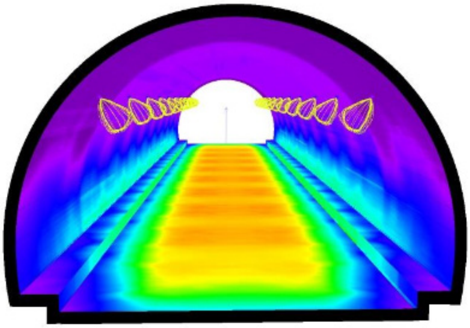

Fig. 2. Tunnel spatial brightness distribution

The precision of the three-dimensional space lighting calculation method is higher, and the power of the lamp can be accurately configured to avoid excessive lighting configuration, so as to achieve more efficient energy use. This approach not only significantly improves the accuracy and reliability of lighting design, but also enables more efficient energy use and better lighting results. For example, by accurately calculating the light distribution in the tunnel, the number and power configuration of lamps can be optimized, reducing unnecessary energy consumption, in line with the overall trend of low-carbon energy saving. The application of three-dimensional space lighting calculation method makes the tunnel lighting design more scientific and fine, ensuring driving safety while achieving the goal of energy saving and environmental protection. This trend will lead the development of future tunnel lighting technology and push the industry to a higher level.

3.4 Utilization of New Energy

In the development of tunnel lighting, the utilization of new energy technologies is gradually becoming an important trend. By introducing renewable energy sources such as solar and wind energy, tunnel lighting systems can not only reduce the dependence on traditional energy sources, but also significantly reduce carbon emissions and achieve more environmentally friendly and sustainable development goals [12-13].

First of all, the application of solar photovoltaic technology in tunnel lighting is gradually expanding. By installing solar panels at the tunnel entrance or the surrounding area, solar energy is converted into electricity during the day and stored in batteries for use at night or when light is low. This technology can not only make the best use of natural resources, but also reduce the load on the grid and reduce energy costs. The efficiency of modern photovoltaic technology continues to improve, making solar power generation in a variety of climate conditions have a high economy and reliability.

The construction of solar photovoltaic power stations outside the tunnel has significant advantages and conditions. As shown in Figure 3, the left and right width of highway tunnels are generally separated, and between the left and right width holes are generally open fields with an area of 3000~6000m2 and good sunshine conditions. Solar photovoltaic power stations can be established after simple site flattening.

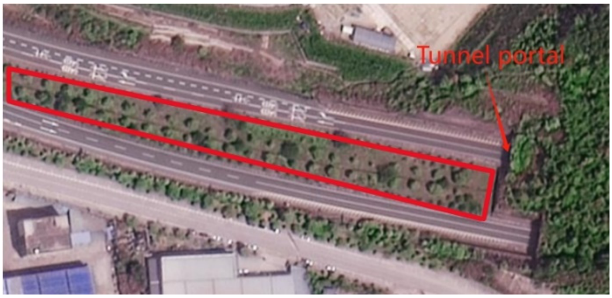

Fig. 3. Site outside the tunnel

3.5 Brightening Pavement

Brightening pavement is an important development direction in tunnel lighting design. By improving the reflectivity of pavement, higher pavement brightness can be obtained under the same illuminance condition, thus realizing low carbon and energy saving [14]. Traditional pavement materials have low reflectivity, resulting in the need for higher lighting intensity to achieve the desired brightness level. The brightening road surface uses high-reflectivity materials to make the light reflect better on the road surface and significantly improve the brightness of the road surface, as shown in Figure 4. Under the condition of the same illumination, the brightness of the yellow road surface is 3 times that of the black asphalt road surface, and about 2.2 times that of the red road surface and the gray road surface.

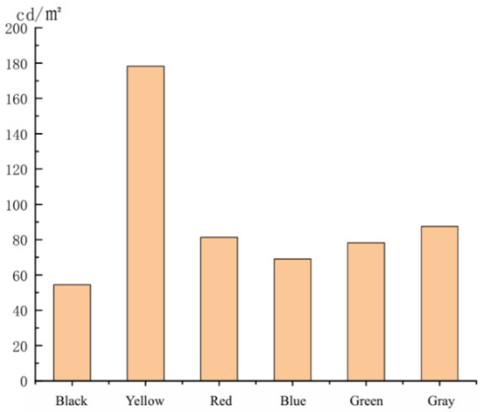

Fig. 4. Brightness comparison of different pavement materials

The advantage of this technology is that it can improve the lighting effect in the tunnel without increasing energy consumption. High-reflectivity materials can effectively utilize existing light sources, reduce reliance on high-power lamps, and reduce energy consumption and operating costs. At the same time, the ming-colored pavement can also reduce the layout density of the light source, and further save the construction cost. The use of brightening road surface technology not only conforms to the trend of low-carbon environmental protection, but also improves the visual comfort and driving safety in the tunnel.

The application of brightening pavement is expected to be widely promoted in tunnel lighting. As materials science advances, more highly reflective, durable and affordable pavement materials will be developed. These new materials can not only improve the light reflectivity, but also maintain good performance and long service life under various environmental conditions.

4 Conclusions and Suggestions

The fundamental purpose of tunnel lighting is to ensure driving safety. On this basis, the current tunnel lighting has made remarkable progress in LED lamps, intelligent control, three-dimensional space lighting calculation and new energy utilization, but the energy saving potential is still not fully tapped. Future trends include further improvement of LED light efficiency, promotion of intelligent control systems, realization of on-demand lighting, application of three-dimensional spatial lighting calculation methods to optimize lamp configuration, comprehensive use of solar energy, wind energy and energy storage technology, promotion of brightening pavement technology to improve pavement reflectivity. Through these measures, the goal of low-carbon energy saving is achieved, operating costs are reduced, and driving safety is improved.

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