A review of researches on lighting energy saving technology methods for highway tunnels

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Abstract: Lighting accounts for a large proportion of energy consumption in highway tunnels. In the context of the "low-carbon economy" and "energy conservation and emission reduction" strategies, this article starts from designing energy conservation, and discusses energy saving of light sources, lamp arrangement, control system, and auxiliary lighting. It summarizes the related research results, and puts forward some insights on the future energy saving design of highway tunnel lighting in China, and provides a reference for highway tunnel lighting design.

1. Introduction

The transportation industry is an important context of economic development and has important strategic significance. However, China's highway construction started late, and it is quite different from developed countries. China is a country with a vast territory and ravines. The demand and quantity of highway tunnel transportation are increasing day by day, and the coverage is more extensive. However, the proportion of highway network is low, the regional demand is large, the traffic volume in the initial stage of tunnel construction is small, and the operating expenses are not enough. The problems are endless. Although China has become a major transportation country, it still has a long way to go.

China has many landforms, plenty of hills, and a great number of plateau areas. The mountain area accounts for about 69.24% of the total area of the country [1]. By the end of 2018, the number of highway tunnels in China was 17,738, with a mileage of 1,7236.1 km, which increased by 15098 and 1951.0 km respectively compared with 2017 [2]. The statistics of the number and total mileage of China's highway tunnels from 2009 to 2018 are shown in Figure 1. In the past ten years, the mileage of China's highway tunnels increases more than 1,100 km per year. China is a country with the most complicated geological conditions and topographic structure. But China is acknowledged to have the largest number of highway tunnels and grow very fast in these years. As a large number of highway tunnels are put into operation, the importance and urgency of energy saving in highway tunnels is increasingly highlighted.

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Taking the case of Xulingguan Extra-long Tunnel in Sichuan\cite{3}, the design and construction of the tunnel lighting system of the Xulingguan Tunnel complies with relevant national standards and specifications. After calculation, the electricity cost of the lighting system occupies more than 60% of the tunnel operating load. Therefore, it is of great significance to reduce lighting power consumption. It not only provides efficient and energy-efficient tunnel lighting sources but also effective control measures reasonably. This article mainly reviews the changing process of tunnel light sources, summarizes the lighting arrangements, lighting control measures and auxiliary lighting methods of highway tunnels. Finally, it looks forward to the development trend of highway tunnel lighting technology in China, and aims to provide references for in-depth research on highway rapid-tuning lighting technology.

2. Energy saving of light source

The choice of light source is the most direct link in energy saving in highway tunnel lighting design. Incandescent lamps, high-pressure mercury lamps, low-pressure sodium lamps, mixed lights, fluorescent lamps and metal halide lamps have all been used in highway tunnel lighting in China \cite{4}. At present, the lamps commonly used in China are high-pressure sodium lamps and LED lamps. High-pressure sodium lamps are used because of their long life, high light efficiency, and excellent color rendering. However, the new energy-saving lamps LED have more obvious energy-saving advantages. They have the advantages of high color rendering index, low power consumption, high light source utilization, short startup time, wide operating voltage range, and low comprehensive cost\cite{5}. "Intermediate vision theory" and "Visual effect method of response time to target objects" were applied to highway tunnel lighting design. Relevant experimental data shows that\cite{6} the lighting system designed with the energy-saving light source LED can save more than 35% of energy than the traditional high-pressure sodium lamp lighting system. In addition, LED lights are often used for stepless dimming. They can receive dimming control signals and change the current to adjust the brightness of the light. Road tunnel lighting application of LED lights has significant energy saving effects.

3. Energy saving through lighting arrangement

Highway tunnel lamps are mainly arranged in the form of central lighting, centerline side biased lighting, symmetrical lighting on both sides, and staggered lighting on both sides. Different lighting methods have different characteristics, thus the number of lamps used and the degree of maintenance are also different. Road tunnel lighting needs to be designed according to the actual situation. On the
premise of meeting the lighting requirements and ensuring safety, the lighting energy consumption is minimized to improve the energy saving efficiency. Actual situations include optimizing the arrangement of lamps, the distance between lamps, the installation angle, and the installation height.

Engineering practice has shown that arranging lighting fixtures on one side of a highway tunnel and an installation height of 6.3 meters is a highly efficient energy-saving arrangement[7]. Wu Shaoming used DIALux simulation software to establish three-lane tunnel lighting fixtures on both sides of symmetrical and staggered layout models. Comprehensive analysis and comparison showed that the lighting environment was best when the staggered layout of lighting fixtures, the angle between the light-emitting axis and the vertical plane was 15°[8]. According to the special environment of the West Sichuan Plateau Tunnel, Li Ke proposed the arrangement and spacing of the lamps and lanterns in the secondary and tertiary tunnels of the West Sichuan Plateau[9]. It can be seen that rationally arranging lamps according to tunnel engineering and environmental characteristics is of great significance to reduce lighting energy consumption.

4. Energy-saving control system

China's highway tunnel lighting control methods are divided into manual control, automatic control, and intelligent control. Most of the tunnels in China have adopted the lighting control method mainly based on automatic control and supplemented by manual control. However, with the development of intelligent technology, intelligent control technology is now more widely used in tunnel lighting control.

Intelligent control is based on automatic control and applies intelligent control technology to dynamically dim the tunnel lighting to achieve the purpose of economical energy saving and achieve on-demand lighting according to the actual traffic flow and environmental conditions[4]. When using control technology for control, the control center controls the system based on the real-time information collected inside and outside the tunnel by the detection equipment and the monitoring center, including vehicle speed, traffic volume, and illuminance outside the tunnel. Among them, to detect the driving conditions of vehicles in the tunnel, such as vehicle speed and traffic volume, common sensing technologies are video, microwave radar, and induction coils[10]. In the process of inputting information to the control center, wireless sensor network technology is often used[11-12], and the control center applies intelligent control technologies such as artificial intelligence, expert systems, fuzzy control, neural networks, genetic algorithms[13-14]. The control center outputs information to perform dynamic dimming on the LED lights. This dimming mode is stepless dimming, which gradually changes the brightness of the tunnel lamps[15-16]. Not only has it created a good driving environment, but also achieved energy-saving effects. The structure of control system is shown in Figure 2.

![Figure 2. Structure of control system.](image)

5. Energy-saving auxiliary lighting

Tunnel lighting energy-saving auxiliary facilities mainly include tunnel retro-reflective arch and LED induced lights. Tunnel retro-reflective arch are mainly installed in long tunnels and extra-long tunnels, and are arranged horizontally along the longitudinal direction of the tunnel. They can effectively absorb the light from the vehicles entering, and exert a strong retroreflective effect to improve the contrast between light and dark inside and outside the tunnel. In some short tunnels, LED induction lights can be added to control the scale of the lighting system[1].

Both the tunnel reflective rings and the LED induction light can improve the inductivity of the traffic in the tunnel and make the outline of the highway clearer, as shown in the Figure 3. And they
both have good economic and social value[17]. Not only can they save a lot of construction investment costs, but also reduce maintenance costs and power consumption. At the same time, under the premise of satisfying road tunnel driving safety, the road tunnel lighting illuminance can be appropriately reduced (especially at night). In addition to tunnel reflective rings and LED induction lights, using materials to design and develop energy-saving signs is also indispensable in the energy saving of highway tunnel lighting.

![Figure 3.Auxiliary facilities for tunnel lighting.](image)

6. Suggestions and prospects
With the rapid development of related technologies such as automatic control and electronic technology, China's highway tunnel lighting technology will break new ground. With the introduction of the National Highway Network Plan and under the opportunity of western development and the “Belt and Road” initiative, under the background of the global “low-carbon economy” and the national “energy-saving and emission-reduction” strategy, the goal of energy conservation, safety and comfort has been continuously advanced in highway tunnel lighting in China.

1) The improvement of the lighting quality of highway tunnels is of great significance to China's transition from a "big country of highway tunnels" to a "powerful country of highway tunnels." We should adhere to high standard, high quality, and high-level construction and management operations.

2) Existing highway tunnels should be upgraded. Based on national strategy, industry needs and people's needs, China should carry out effective actions based on appropriate tunneling, rational use of old, put forward the concept of innovative development, carry out classification transformation, and batch implementation. In addition, we need to pay more attention to the problems of tunnel lighting, ventilation, fire protection, and traffic safety.

3) It is recommended to carry out basic theoretical research in a timely manner. It is necessary to summarize the successful experience of improving the quality of highway tunnels across the country and reasonably learn from advanced foreign research and technology. After that, it is time for China to apply it in highway tunnels and carry on the standard consummation and the revision according to the actual situation.

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