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ANALYSIS OF CARBON EMISSION CHARACTERISTICS AND REDUCTION POTENTIAL ON TUNNEL LIGHTING

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Abstract: The problem of global warming caused by excess carbon emission has aroused great concern of all countries in the world. As an important part of underground space, road tunnels produce a large amount of carbon emissions in the operation process. In this study, the carbon emission of the tunnel life cycle was calculated and evaluated, and the role of lighting was analyzed. The eye movement characteristics and carbon emissions ratio of each lighting section were studied for the tunnel graded lighting. The carbon emission uncertainty analysis of tunnel lighting was carried out considering the influence of multiple factors such as traffic volume and design speed, and the carbon reduction potential was studied based on particle swarm optimization algorithm. The results show that the carbon emission of tunnel lighting is closely related to the length of tunnel, and the sum of carbon emission of the entrance section and the middle section exceeded 80%. With the increase of tunnel length, the proportion of lighting carbon emission in the middle section of the tunnel continues to increase. In addition, the carbon reduction potential of tunnel lighting was analyzed.

Keywords: Carbon emission, Tunnel lighting, Optimization method, Reduction potential analysis

1. INTRODUCTION

Under the backdrop of global warming, low-carbon and sustainable development have become the recognized development trends of the international community (Chen et al, 2016; Yuan et al, 2011). At the Global Climate Change Conference on December 12, 2015, the heads of state of many countries adopted the Paris Agreement, calling on all countries around the world to work together to address climate change. The goal is to keep the global average temperature range within 2℃ and strive to limit the temperature rise to within 1.5 ℃ (Zou et al, 2023).

Infrastructure construction has significant practical significance in expanding domestic demand, improving people's livelihood and promoting industrial development in various regions (Melo et al, 2013). Large-scale transportation infrastructure construction and subsequent operation are believed to generate a large amount of carbon emissions (Wang et al, 2015). Among them, tunnels are regarded as the most energy-intensive part of transportation infrastructure and should be given particular attention (Zhan et al, 2018). At present, there are still relatively few studies on carbon emissions from tunnel engineering. Guo et al. (2019) selected eight highway tunnels in southwest China as the research objects, conducted research on the influencing factors of carbon emissions in each process of tunnel construction, and used statistical analysis methods to identify the key influencing factors of carbon emissions from tunnel construction. However, these studies mainly focus on the

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carbon emissions during the construction of tunnels. To ensure the safety and efficient operation of highway tunnels, various electromechanical facilities such as monitoring, ventilation and lighting need to be installed in the tunnels. The carbon emissions during the operation of the tunnels are also very huge (Peeling et al, 2016). In addition, for the same tunnel, different lighting design schemes can lead to significant differences in the carbon emissions from the tunnel's lighting. Therefore, the carbon emissions throughout the entire life cycle of a tunnel should also be carried out in combination with the characteristics of tunnel lighting. In recent years, research on carbon emissions based on the LCA(Life Cycle Assessment) theory has received increasing attention.

Based on tunnel cases, this study conducted a quantitative analysis of tunnel carbon emissions, studied the characteristics of carbon emissions at each stage of the tunnel, and focused on analyzing and evaluating the carbon emissions of tunnel lighting. The research results can provide data support for exploring the emission reduction potential at each stage of the tunnel.

2. METHODS

2.1. Calculation boundary

When assessing the carbon emissions throughout the entire life cycle of a tunnel, it is necessary to first analyze and classify the CO2 sources of the tunnel at different stages and define a reasonable calculation boundary. Based on the previous life cycle assessment theories and the division of stages (Dou et al, 2024), this study divides the entire life cycle of the tunnel into the construction stage, the operation stage and the demolition stage. Specifically, the carbon emissions in the construction stage include those generated from the three processes of material production, transportation and on-site construction. For carbon emissions during the operation stage, tunnels consume various types of energy during operation, thereby generating carbon emissions. Additionally, for structures with a relatively short natural lifespan, maintenance and replacement will be carried out during operation, which also leads to carbon emissions. Carbon emissions during the demolition stage refer to the carbon emissions caused by the energy consumed when using equipment to dismantle the tunnel at the end of its service life. The detailed stage division and boundary definition are shown in Figure 1.

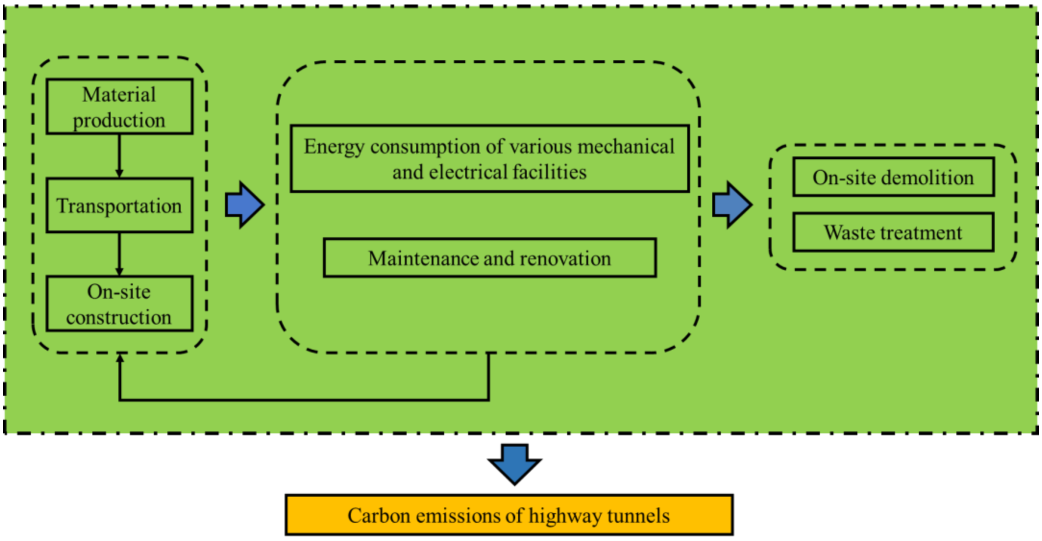


Figure 1. *Life cycle carbon emission assessment boundary of highway tunnel.*

2.2. Inventory analysis

This study adopts the process-based inventory analysis method. Inventory analysis is the most time-consuming stage in the entire LCA (Life Cycle Assessment) research and is the process by which LCA collects and organizes basic data. The bill of quantities for the tunnel construction stage can be obtained from the survey and design data and construction drawings of the tunnel in the early stage. The energy consumption during the construction process can be obtained from the on-site measured data and the national stipulated quota system for highway engineering. For various energy consumption data during the tunnel operation period, they can be obtained by combining the quantity table of various equipment during the operation period and the operation plan. For the carbon emission factors of various related materials and energy sources, based on previous studies (Li et al, 2018; Shao et al, 2014), this study established a carbon emission factor database suitable for tunnels. After completing the inventory analysis, calculate the carbon emissions of each stage of the tunnel based on the carbon emission calculation model, and finally obtain the carbon emissions of the entire life cycle of the tunnel.

2.3. Tunnel carbon emission calculation model

The IPCC(Intergovernmental Panel on Climate Change) has provided a calculation method for carbon emissions, which indicates that the carbon emissions generated by energy activities can be calculated with the help of carbon emission factors. By combining the data of activities that affect carbon emissions with the emission coefficient per unit activity, the carbon emissions corresponding to energy activities can be obtained.

2.3.1. Construction stage

During the construction stage of the tunnel, the carbon emissions from the material production refer to the carbon emissions generated by the consumption of coal, oil, electricity and other energy sources during the production process of various major building materials such as steel and cement. For the carbon emissions of tunnel material production, the calculation method is as shown in equation (1) :

$$C_m = \sum_i^n mf_i \times m_i \tag{1}$$

where, i represents the type of material, mf_i is the carbon emission factor corresponding to the *i-th* material, and m_i is the consumption of the *i-th* material.

During the transportation of raw materials for highway tunnels from the production site to the construction site, the transportation equipment will consume fuels such as gasoline and diesel, thereby generating carbon emissions. The calculation method is shown in equation (2) :

$$C_t = \sum_i^n tf_i \times L_i \times m_i \tag{2}$$

where, i represents the type of material, tf_i is the carbon emission factor corresponding to the transportation mode of the *i-th* material, L_i is the transportation distance of the *i-th* material, and m_i is the transportation volume of the *i-th* material.

For the carbon emissions during the on-site construction stage of highway tunnel, the calculation method is as shown in equation (3) :

$$C_c = \sum_i^n cf_i \times (M_p / M_i) \times c_i \tag{3}$$

where, i represents the category of construction equipment, cf_i is the carbon emission factor corresponding to the energy consumption of the *i-th* type of construction equipment, M_p is the amount of work that the *i-th* type of construction equipment needs to complete, M_i is the amount of work completed by the *i-th* type of construction equipment within a unit of time, and ci is the energy consumption of the *i-th* type of construction equipment within a unit of time.

2.3.2. Operation stage

After the tunnel is completed, various types of energy need to be consumed to ensure its normal use and the safety of vehicle operation. The carbon emissions during the operation of the tunnel can be derived from equation (4)：

$$C_o = \sum_i^n q_i \times w_i \times t_i \times ff_i \tag{4}$$

where, i represents the type of operational equipment, q_i is the quantity of specific operational equipment, w_i is the power demand of a specific facility in watts, t_i is the operating time of the equipment, and ff_i is the carbon emission factor corresponding to the energy consumption of the *i-th* type of operational equipment.

For the carbon emissions during the tunnel renovation period, the calculation method of carbon emissions during the tunnel construction stage can be referred to for assessment.

2.3.3. Demolition stage

When a highway tunnel is out of use, various types of mechanical equipment need to be used for demolition. Therefore, the carbon emissions during this period mainly came from the energy consumption of dismantling equipment. However, for the demolition stage, there is currently a lack of accurate calculation models, and most of them are mainly estimated (Zhang and Wang, 2015). Based on relevant studies, this study takes the carbon emissions of the demolition stage as 90% of the carbon emissions during the on-site construction process of the tunnel.

$$C_d = 0.9 \times \sum_{i}^{n} cf_i \times (M_p / M_i) \times c_i \tag{5}$$

For the treatment of tunnel waste after demolition, the carbon emissions in this study are considered as the carbon emissions caused by the energy consumption of transportation equipment to transport the waste to the landfill, and the calculation method is carried out with reference to equation (2).

2.3.4. Total carbon emissions

In summary, the calculation method for the total carbon emissions of highway tunnels throughout their life cycle can be derived from equation (6).

$$C_{tot} = C_m + C_t + C_c + C_o + C_d \tag{6}$$

where, C_{tot} represents the total carbon emissions throughout the entire life cycle of a highway tunnel, C_m represents the carbon emissions generated during the material production, C_t represents the carbon emissions generated during the transportation, C_c represents the carbon emissions generated during the on-site construction, C_o represents the carbon emissions generated during the operation stage, C_d represents the carbon emissions generated during the demolition stage.

2.4. Tunnel driving eye movement test

While analyzing the carbon emissions of tunnel lighting, it is necessary to analyze the impact of different tunnel lighting sections on drivers from the perspective of engineering safety. This study carried out eye movement tests for tunnel driving. The test vehicle selected was an ordinary small car. During the driving process, the driver wore a wireless eyeglass-type eye tracker to record the eye movement data and psychological parameters of the driver in real time when driving the vehicle through the tunnel. As shown in Figure 2, At the beginning of the test, the driver wore the eye tracker as required for the test and drove the vehicle through the tunnel under normal lighting. The test recorder used the software provided with the instrument to record the physiological parameter data of the driver. Afterwards, the physiological indicators collected under the lighting environment will be analyzed.

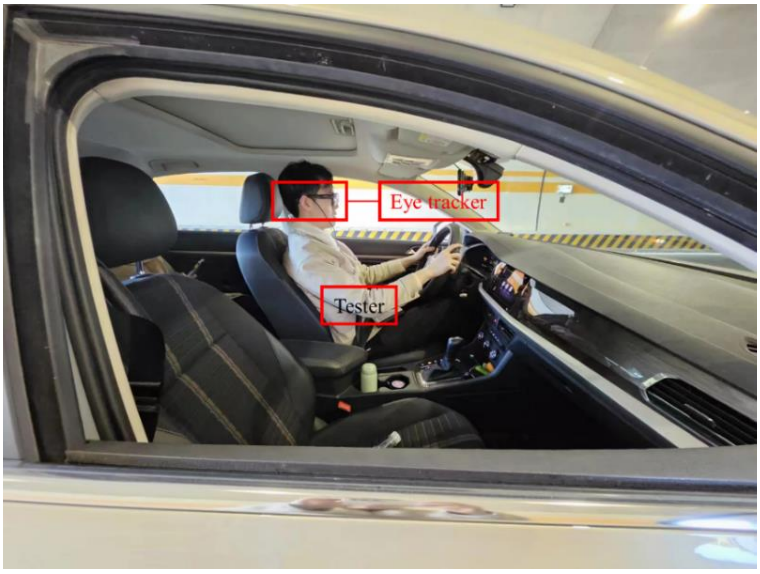


Figure 2. *Driver's eye movement test under tunnel lighting.*

3. CASE ANALYSIS

3.1. Project overview

Taking four types of tunnels of different lengths in a certain area in southern China as examples, including one extra-long tunnel, one long tunnel, one medium tunnel and one short tunnel, the specific length data are shown in Table 1.

Table 1. *Overview of each highway tunnel.*

Type	**Name**	**Length/m**
Extra-long tunnel	Tuochuan tunnel	4650
Long tunnel	Wuyuan tunnel	1670
Medium tunnel	Wangpingtan tunnel	619
Short tunnel	Ziyang tunnel	417

According to the carbon emission calculation model proposed in this study, the carbon emissions throughout the life cycle of these four tunnels were calculated. The design life cycle of the tunnels was considered to be 100 years. For various bill of quantities data, this study gives priority to obtaining them from on-site construction units. For the missing transportation distance and other relevant data, certain assumptions need to be made. This study is supplemented based on China's "GBT 51366-2019 Calculation Standard for Building Carbon Emissions".

3.2. Refined assessment of energy consumption in tunnel operation stage

For highway tunnels, the energy consumption during operation is huge. Existing studies show that the current electricity consumption of highway tunnels mainly occurs in lighting facilities and ventilation facilities (Qiu et al, 2020). Therefore, the carbon emission calculation in this study mainly focuses on the two parts of tunnel lighting and ventilation. The lighting of the tunnel studied in the case is more scientific and reasonable. Dimming strategies as shown in Table 2 are set according to different seasons and weather conditions. In order to accurately assess the lighting energy consumption during the operation of each tunnel in the case, this study obtained the local weather information of the past year and calculated the lighting carbon emissions during the operation period considering the weather. For the ventilation of tunnels, under conditions where the tunnel length, traffic mode and local weather conditions are suitable, fan equipment is not necessary. It is entirely dependent on the combined effect of the movement of car pistons and natural wind to expel harmful gases and smoke from the tunnel. When natural ventilation fails to meet the ventilation requirements, mechanical ventilation is then selected. In this case, mechanical ventilation is provided for the extra-long and long tunnels, while natural ventilation is adopted for the medium and short tunnels. Based on the fan configuration and equipment parameters of each tunnel, combined with equation (4), the ventilation carbon emissions during the operation stage of each tunnel can be calculated.

Table 2. *The standards for dimming classification of case tunnel lighting.*

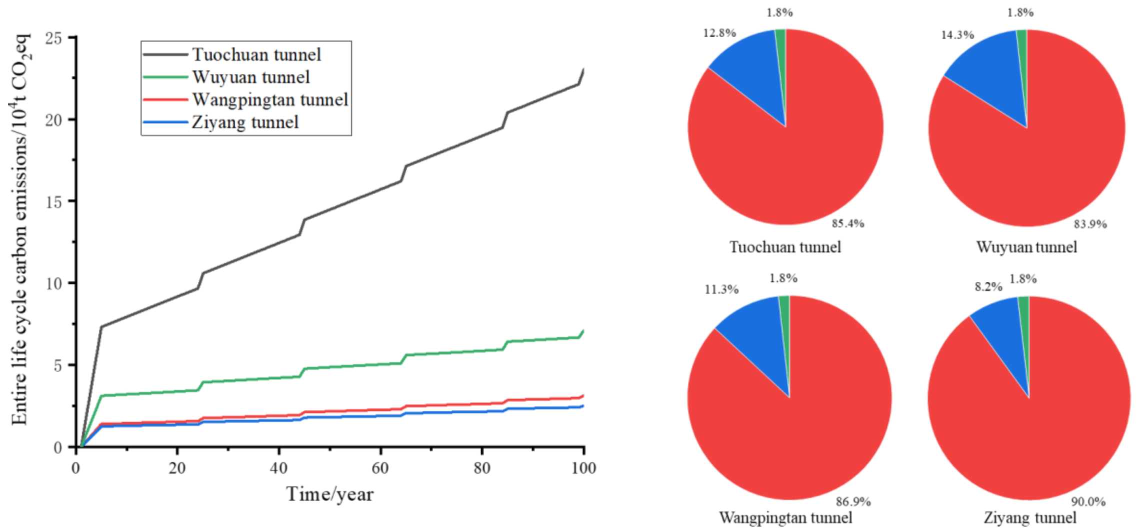
<table>
<tr><th>Lighting type</th><th>Season and weather</th><th>Brightness outside the tunnel</th><th>Explanation</th></tr>
<tr><td rowspan="4">Enhance lighting</td><td>Summer sunny day</td><td>L20（S）</td><td rowspan="4">Closed at night</td></tr>
<tr><td>Sunny days in other seasons/Cloudy days in summer</td><td>0.5 L20（S）</td></tr>
<tr><td>Cloudy days in other seasons/Cloudy days in summer</td><td>0.25 L20（S）</td></tr>
<tr><td>Overcast or heavily overcast days in other seasons</td><td>0.125 L20（S）</td></tr>
<tr><td>Basic lighting</td><td>Day/Night</td><td></td><td>Brightness 2.5cd/m^2</td></tr>
</table>

The renovation work during the tunnel operation mainly focuses on the maintenance of the road surface, and the service life of the road surface is considered to be 20 years. The demolition work of the tunnel is considered to be completed within one year, and the transportation distance of the demolition waste is considered to be 20 km.

4. RESULTS

4.1. Growth trend and characteristics of carbon emissions

Based on the calculation of carbon emissions at each stage of the tunnel, the changes in carbon emissions throughout the entire life cycle of each tunnel are shown in Figure 3. The carbon emission results throughout the entire life cycle of the tunnel show that there is a relatively large carbon emission in the initial stage of the tunnel's construction. After entering the operation stage, the carbon emissions of the tunnel rise steadily. The longer the tunnel, the greater the carbon emission rate during the operation stage. During the operation stage, as the renovation project progresses, the carbon emissions of the tunnel will also experience a short-term increase.



(a) Trend of carbon emissions throughout the entire life cycle of tunnels (b) Carbon emissions during the construction stage of each tunnel

Figure 3. *The changing trend and characteristics of carbon emissions throughout the life cycle of tunnels.*

In addition, as shown in Figure 3, during the tunnel construction period, the carbon emissions of the material production part were the highest, and those of the material transportation part were the lowest. From the perspective of total emissions, as the length of the tunnel increases, the carbon emissions during the tunnel construction stage increase significantly, and the carbon emissions during the construction stage are directly proportional to the length of the tunnel.

4.2. Growth trend and characteristics of carbon emissions

According to the carbon emission results throughout the entire life cycle of the tunnel, it can be known that the carbon emissions during the operation stage of the tunnel account for a relatively high proportion. Among them, tunnel lighting has always been regarded as a high-energy-consuming part and has huge potential for emission reduction. Unlike external lighting, as a semi-enclosed space, there is a significant difference in the brightness of the environment inside and outside the tunnel. When drivers pass through the tunnel, they have the problem of adapting to light and dark. To meet the drivers' visual adaptation needs in high and low brightness environments and ensure the safety of tunnel driving, tunnel lighting is generally set up in the entrance section, transition section, middle section and exit section according to different design brightness levels. In tunnels of different lengths, the settings of each lighting section are also not the same. In order to assess the lighting carbon emissions of each section of the tunnel, it is necessary to calculate the energy consumption of each lighting section of tunnels of different lengths.

Based on the lighting fixture settings of each tunnel in the case, the carbon emissions of different lighting sections of the four tunnels in the highway tunnel were analyzed. The proportion of carbon emissions of each section is shown in Figure 4. It can be known from the results that the carbon emission proportion of the entrance sections of these four tunnels is the highest, accounting for approximately 50% to 80%. The proportion of carbon emissions in the middle section increases with the increase of the tunnel length. Therefore, the entrance section of the tunnel has extremely high carbon reduction potential. During the subsequent operation stage, relevant measures can be taken to reduce the carbon emissions caused by lighting in the entrance section of the tunnel.

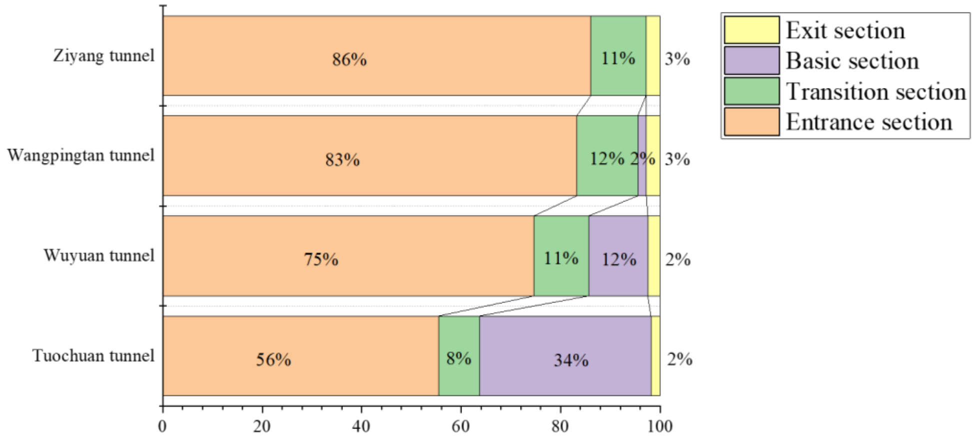


Figure 4. *The proportion of carbon emissions in each lighting section of the case tunnel.*

4.3. Driver's eye movement characteristics

As shown in Figure 5, before approaching the tunnel entrance, the pupil area fluctuates between 2.0 and 2.5 mm². At the moment of entering the tunnel (the 0m coordinate point), the pupil area shows a sharp increase and remains at a high level continuously in the middle section of the tunnel, with the peak reaching 4.8 mm² and the average value stabilizing above 4.0 mm². This regular feature confirms that the relatively dim environment inside the tunnel prompts the pupil to expand the amount of light intake to enhance the sensitivity of retinal imaging. It is worth noting that the data of this section still shows slight oscillations, which may be due to the periodic distribution of lighting fixtures inside the tunnel or the alternation of light and shadow caused by vehicle movement. When the vehicle approaches the exit, the pupil area shows a gradual downward trend and falls back to about 3.3mm ² at 1600m. This physiological response reflects the driver's pre-adaptation mechanism to the high-intensity natural light outside the tunnel - iris contraction to reduce glare interference and provide a buffer for the visual function transition after the exit.

The changes in pupil area during tunnel passage reveal the psychological adaptation characteristics related to the driver's cognitive load and emotions. The pupil area shows an accelerating dilation trend when approaching the entrance of the tunnel. This reflects the driver's instinctive vigilance towards the semi-enclosed space and a certain degree of anxiety at the entrance section.

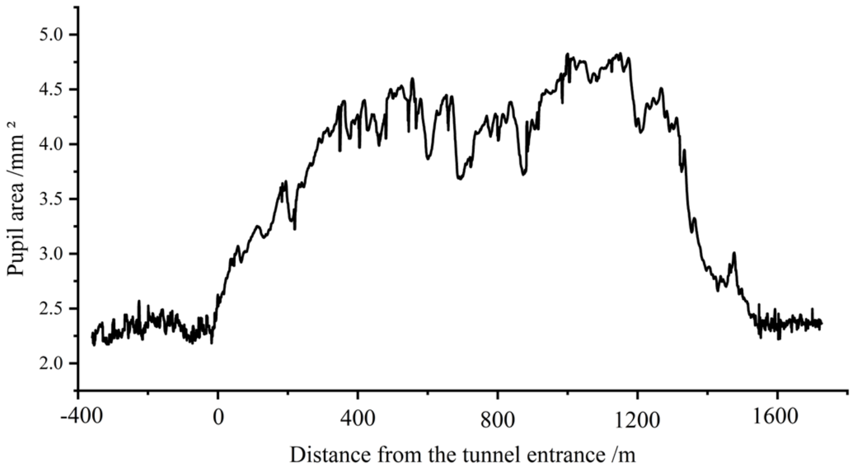


Figure 5. *The variation characteristics of the pupil area of the driver when passing through the tunnel.*

5. CONCLUSIONS

This paper analyzes the carbon emissions of highway tunnels throughout their entire life cycle and divides the boundaries, establishing carbon emission calculation models for each period. And based on the case of each tunnel, case calculations were carried out, and the following main conclusions can be obtained:

(1) During the tunnel construction stage, the carbon emissions from the material production section are the highest, accounting for approximately 70%. Therefore, various low-carbon materials have a very promising application prospect. The carbon emissions of the material transportation section are the lowest, while those of the on-site construction section are in the middle.

(2) Regarding the total carbon emissions throughout the entire life cycle of a tunnel, there will be a significant increase in carbon emissions as the tunnel length increases. Moreover, the relative magnitudes of carbon emissions during the construction stage and the operation stage also vary due to the different lengths of the tunnels.

(3) Based on life-cycle assessment, tunnel entrance sections account for 50%-80% of lighting-related carbon emissions due to high-intensity illumination requirements. Meanwhile, pupil area monitoring shows that the driver's pupils dilate faster and anxiety intensifies at the entrance. The research indicates that the design of entrance lighting not only imposes an ecological burden but also a cognitive burden. By optimizing the lighting scheme in the entrance area, there is huge potential for carbon emission reduction.

6. ACKNOWLEDGMENTS

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