The Evolution and Future Trends of Tunnel Design: Enhancing User Experience and Safety

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Abstract

With the rapid development of transportation infrastructure, ultra-long high-speed tunnels are increasingly used in complex terrain areas, but their closed environment poses new challenges to driving experience and safety. This study takes the ultra-long high-speed tunnel in Nujiang Prefecture, Yunnan Province as the object, and analyzes "the consideration of user experience in tunnel design and its development trend". Through literature review, case study and interviews, the evolution of tunnel visual landscape design and the key factors affecting user satisfaction are summarized. The results show that light environment adaptation, spatial perception, visual guidance and cultural element integration are the core factors affecting user experience. The research results provide a theoretical basis and practical guidance for the design of ultra-long tunnels.

Keywords: Super Long Tunnel, Driving Experience, Landscape Design, User Satisfaction, Safety

1. Introduction

Nujiang Lisu Autonomous Prefecture in Yunnan Province is located in the southwest of China. It has complex terrain and rich ethnic culture. The construction of ultra-long high-speed tunnels has become an important support for regional economic development. However, the closed environment of the tunnel can easily cause visual fatigue and psychological pressure on drivers, affecting driving safety. Traditional tunnel design focuses more on functionality and engineering safety, and pays less attention to user experience（Hung, C. J., Wisniewski, J., Monsees, J., & Munfah, N. 2009）. In recent years, visual landscape design has gradually become a key means to improve driving experience. This study aims to analyze the evolution trend of user experience needs in tunnel design, explore the core factors that affect user satisfaction and safety, and provide optimization directions for the design of the Nujiang ultra-long tunnel.

1.1 Research Objective

This research aims to sstudy the development and trends of tunnel design considering user experience, and analyze the factors affecting user satisfaction and safety.

2. Literature Review

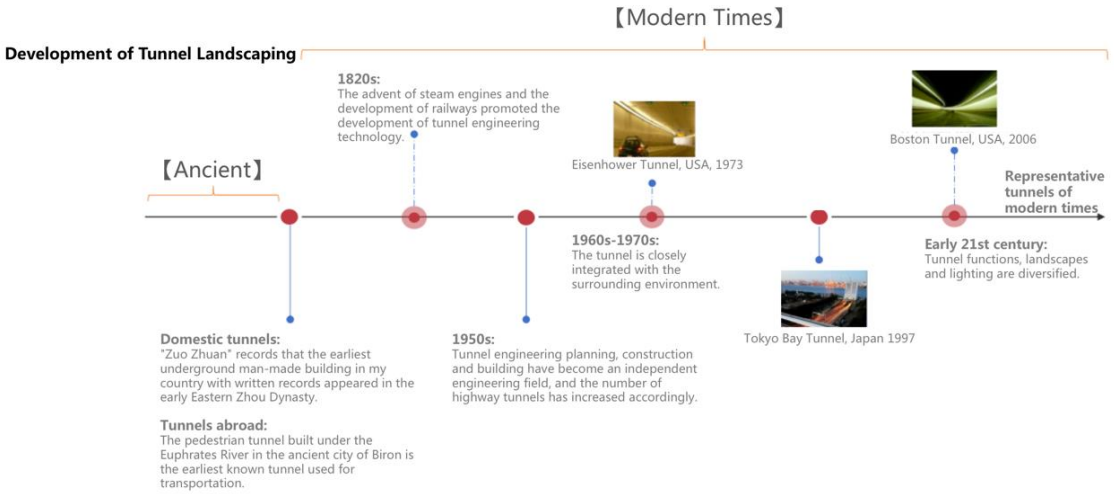
1. Development of Tunnel Design

The development of tunnel design is closely related to human history. In ancient times, primitive society used natural caves as habitats. With the progress of society, the artificial excavation of tunnels gradually emerged. The earliest tunnel design mainly served basic functional needs, such as water extraction and transportation, and the construction technology was relatively primitive. During the Spring and Autumn Period and the Warring States Period, the Qin State excavated stone cave plank roads in order to open up the Shu Road. Among them, the famous "Shimen Tunnel" was a milestone in the history of Chinese tunnels. The Shimen Tunnel in the Eastern Han Dynasty was excavated by fire and water quenching, which was a preliminary exploration of tunnel construction technology. Although its specific operation method is still controversial, its historical significance cannot be ignored.

With the evolution of the times, the functions of tunnels have gradually diversified, especially in modern times, design of tunnels is no longer limited to simple transportation functions (Chapman, Metje, & Stark, 2017). China's tunnel construction has experienced a process of development from slow to rapid, especially after entering the 21st century, with the development of the western region and the rapid construction of highways and high-speed railways, the number and scale of tunnels have achieved a leap. By 2017, the total length of China's highway tunnels has exceeded 15,000 kilometers, of which 902 are longer than 3 kilometers. Many world-class tunnel projects, such as Qinling Zhongnanshan Tunnel and the Hong Kong-Zhuhai-Macao Undersea Tunnel, have demonstrated China's outstanding achievements in tunnel construction.

While tunnels are being built, the landscape design inside tunnels has also gradually come into view. Since tunnels have no sunlight for a long time, traditional landscape elements are difficult to apply, and artificial light sources in tunnels have become the main design method. With the increase in the popularity of cars, drivers' demand for tunnel landscapes has gradually increased, and the experience of landscape design has begun to be valued. In the past, the focus of tunnel design was functionality. With the changes of the times, it has gradually begun to take into account both ornamental and user experience. For example, the Port of Miami Tunnel in the United States has improved driving comfort through LED lighting and artistic entrance design; Japan's Tokyo Bay Underwater Tunnel combines natural elements with earthquake-resistant technology to take into account safety and aesthetic expression. In China, for example, the Qinling Zhongnanshan Highway Tunnel divides the long tunnel into multiple short tunnels through "imitation outdoor" lighting design to alleviate visual monotony. (Figure 1)

Figure 1: The development history of tunnel landscaping



Source: Author

However, with the gradual innovation of landscape design, the visual effects in super-long tunnels are too complex, leading to increased safety hazards. For example, in 2022, Chongqing's first 4D landscape highway tunnel caused multiple traffic accidents due to complex visual effects. Statistics show that most traffic accidents in super-long tunnels are closely related to the complex visual design in the tunnel.

The views and concepts of people in developed countries are relatively advanced. The combination of roads and landscapes has been developed for a long time abroad, and it also provides us with a lot of things worth learning from. Many countries and regions have formulated relevant specifications and guidelines (Table 1)

Table 1: Sanxingdui incense burner

Nation	Time	Issuer	Regulatory guidelines or regulatory resolutions
America	1999	AASHTO	Guide for the Design of Roadway Lighting
Britain	2012	Institution of Lighting Professionals (ILP)	Code of Practice for Road Lighting
Germany	2004	DIN (German Institute for Standardization)	DIN 67524: Road Tunnel Lighting
Japan	1988	Japan Road Corporation	Standard for Road Tunnel Lighting
Switzerland	2001	Swiss Society of Engineers and Architects (SIA)	SIA 197/1: Tunnel Lighting Guidelines
Australia	2014	Austroads	Guide to Road Tunnel Operations
France	2011	LCPC (Central Laboratory of Roads and Bridges)	Tunnel Design and Safety Guidelines
Canada	2003	Transport Canada	Canadian Road Tunnel Design Guide

Source: Author

2. Factors affecting user experience

As a closed tubular structure, the driving conditions of super-long highway tunnels are significantly different from those of ordinary roads, resulting in unique characteristics of the internal traffic environment. The internal space of the tunnel is narrow and closed, the light

environment inside and outside the tunnel is very different, the internal brightness level is uneven, and dust is difficult to spread. The overall driving environment of the tunnel is composed of space, signs, etc., which work together with artificial light sources. The driver's experience in the tunnel environment is affected by multiple factors:

2.1 Adaptation to the light environment: The change in illumination at the entrance and exit of the tunnel has a significant impact on the driver's visual adaptation ability, especially during the day when the weather is clear (He, Liang, Pan, Wang, & Cui, 2017). At this time, the illumination outside the tunnel can reach tens of thousands or even hundreds of thousands of Lux, while after entering the tunnel, the illumination drops sharply to tens to hundreds of Lux. When the driver enters a relatively dark tunnel from a bright external environment, or drives from a tunnel into a bright external environment, the human eye's sensitivity to light decreases due to the large difference in the internal and external light environments, and it takes a certain amount of time to adapt. The visual adaptation process caused by this sudden change in light environment includes "dark adaptation" and "light adaptation" (Baker, 1963).

Dark adaptation refers to the gradual increase in the sensitivity of the retinal photoreceptor cells (mainly rod cells) when the driver enters the dark area of the tunnel from a bright environment to adapt to the dark environment. In the case of weak light, the cone cells stop working, and only the rod cells that are sensitive to weak light work. This process is relatively slow. Studies have shown that after staying in the dark for 5 minutes, about 60% of rhodopsin (the light-sensitive substance in rod cells) will be synthesized, and rhodopsin will be completely generated after 30 minutes, thus completing the dark adaptation process. In contrast, light adaptation occurs when the driver enters the bright external environment from the dark area in the tunnel. At this time, rhodopsin quickly decomposes and cone cells begin to work. It usually takes only about 1 minute to complete the adaptation.

Due to this visual adaptation lag phenomenon, drivers may face significant visual impairment at the entrance and exit of the tunnel. For example, when a vehicle approaches the entrance of a tunnel, the brightness of the sky, open road surface and surrounding buildings in the driver's field of view is much higher than that in the tunnel, which causes the tunnel entrance to become very dark in the driver's field of view, making it difficult to identify the situation near the entrance of the tunnel, and even unable to detect obstacles in time. This phenomenon is called the "black hole effect". Similarly, when a vehicle exits a long tunnel, the driver will see a dazzling bright white hole due to the huge difference in illumination inside and outside, causing vertigo, a temporary decrease in vision, and thus causing short-term visual impairment. This phenomenon is called the "white hole phenomenon." The visual effect when driving at night is the opposite of that during the day, but the sudden change in illumination can still make it difficult for drivers to discern road traffic conditions, especially when responding to sudden changes in brightness in a short period of time. This can lead to visual blind spots and increase the risk of accidents. The change in illumination at the entrance and exit of a tunnel has a direct and significant impact on the driver's visual perception. Reasonable lighting design must be used to reduce these potential visual obstacles and ensure driving safety. Long-term tunnel driving can also cause visual fatigue, which affects the driver's reaction speed and attention (Kircher & Ahlstrom, 2012).

2.2 Spatial perception: The width, height and sidewall design of the tunnel directly affect the psychological feelings of the driver. If the width of the tunnel is too narrow or the height is too low, the driver may feel depressed or even fearful during driving. This negative emotion will cause the driver to lose concentration, which will affect driving safety. A reasonable tunnel space layout can effectively alleviate this discomfort and improve the driver's comfort (Han, Du, Wang, & He, 2024).

2.3 Visual guidance: Reasonable visual guidance design is crucial to ensure that the driver drives correctly in the tunnel. Clear road signs, markings and reflectors can effectively guide the driver and reduce driving errors caused by insufficient visual information. This design helps to improve the driver's road cognition and ensure driving safety (Babić, Fiolić, Babić, & Gates, 2020).

2.4 Integration of cultural elements: Visual landscape design not only helps to improve functionality, but also enhances aesthetic value of tunnel. The introduction of art and design elements can significantly improve the viewing and attractiveness of the tunnel, making it a visually attractive traffic environment (Ji, 2024). This design enhances the image and value of the tunnel as a landmark building.

The integration of regional culture is an important aspect of visual landscape design. By incorporating local cultural and historical elements into the design, the regional characteristics and cultural identity of the tunnel can be enhanced (Valdenebro & Gimena, 2018). This design not only enhances the cultural value of the tunnel, but also enhances the public's sense of identity with the local culture. For example, the traditional art and cultural symbols of the Nujiang region can be expressed through the visual elements of the tunnel design, such as wall decoration, lighting design, color matching, etc. The introduction of this cultural symbol can not only beautify the tunnel environment, but also allow drivers to feel the local cultural atmosphere when passing through the tunnel, reducing the psychological fatigue caused by long-term driving (Ye, He, Wang, & Zhang, 2012).

3. Research Methodology

Step 1: Literature review

Data collection: Select relevant literature on tunnel visual design in Web of Science and China National Knowledge Infrastructure (CNKI) from 2000 to 2023, covering fields such as engineering, psychology, and cultural studies, and collect relevant information on the theoretical basis, user experience, psychological research, visual design, and cultural elements of tunnel design.

Data analysis: Use VOSviewer to perform co-occurrence analysis on keywords in the literature to identify the evolution trend of keywords related to "lighting safety", "visual fatigue", "emotional regulation", etc. By analyzing the changes in keyword frequency in different time periods, the changes in experience needs in tunnel design are revealed. For example, "lighting safety" accounted for 82% before 2000, while psychological terms such as "visual fatigue" and "emotional regulation" increased by 320% after 2015, reflecting the increasing attention to user experience and psychological factors in tunnel design.

Step 2: Case comparative analysis

Data collection: Select 5 typical domestic and foreign tunnel design cases, covering tunnels in different regions, cultural backgrounds, and technical levels, and collect the design concepts, implementation details, and their impact on user experience of these tunnels.

Case analysis: Compare the design strategies of each case in detail, analyze their innovative applications and effects in visual design, user experience, safety, etc., and evaluate the success and shortcomings of their design concepts. By summarizing the successful experiences and lessons from failure, summarize which design strategies can effectively improve the visual aesthetics and user experience of the tunnel, and provide optimization suggestions for future tunnel design.

Step 3: Expert interview

Data collection: Invite 5 experts who have been engaged in tunnel environment design for more than 10 years to conduct semi-structured interviews. The interviews revolve around the theme of "evolution trend of user experience" in tunnel design, and design open questions such as "How does intelligent technology reconstruct tunnel landscape design?" The interview aims to gain an in-depth understanding of the key technology applications in tunnel design, the changing trends of user experience, and the potential and challenges of future design development.

Data analysis: Use Nvivo12 to conduct qualitative analysis of the interview content, extract key node vocabulary, classify and code interview data, and identify the core issues, design challenges and future development directions that affect tunnel design. Through the analysis of interview data, summarize the key factors of tunnel design and how technological development and social needs drive changes in design trends.

4. Research Results

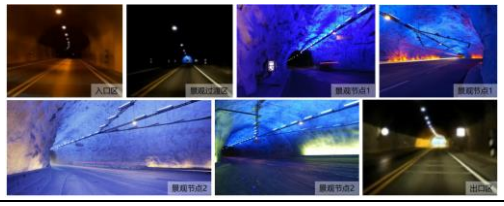
1. Tunnel Design Trend Analysis

1.1 The evolution of user experience-oriented tunnel design: Through literature review, it is found that in the early stage (1970s-2000s): functionality and safety are the absolute core (such as tunnel clearance section standards, lighting intensity specifications, ventilation efficiency), and users are regarded as passive passers-by. Modern stage (2010s to present): interdisciplinary integration of psychology and cultural research promotes the transformation of design from "passing efficiency" to "psychological comfort". Tunnel design has gradually shifted from focusing on functionality and safety (such as lighting and ventilation) in the early stage to focusing on the driver's psychological experience (visual comfort and emotional regulation). User experience needs show a trend from "functional compliance" to "psychological comfort optimization".

Early reliance on static lighting and color schemes, modern design emphasizes dynamic light and shadow technology (such as LED variable color temperature), the scenario application of cultural symbols, and the practice of visual corridor theory in space segmentation. Intelligent lighting systems (such as dynamic color temperature adjustment)

have become the mainstream tool for optimization design. The application of intelligent lighting systems has become an important trend in tunnel design. Intelligent lighting systems, especially dynamic color temperature adjustment technology, can automatically adjust the lighting intensity and color temperature according to the light changes in the environment inside and outside the tunnel, thereby reducing the driver's visual fatigue and improving emotional comfort. According to the adaptability of the light environment, reasonable lighting design can significantly improve the driver's emotional experience and reduce the psychological pressure caused by long-term driving. The lighting can be automatically adjusted according to different time periods, weather conditions and changes in brightness inside and outside the tunnel, avoiding the negative impact of excessive or dark lighting on the driver's emotions and safety. Through case analysis, it can be concluded (Table 2).

Table 2: Excellent Cases at Home and Abroad

Case	Highlights	Successful Experience	Lesson & Picture
Maluansh an Extra Long Tunnel	4 landscape sections, with signs and reminders	The theme paragraph design can effectively reduce driver fatigue and improve driving safety, and enhance the driving experience through landscape signs and lighting.	The visual transition of the landscape section needs to be further optimized to avoid overly simple designs that affect the overall aesthetics. 
Qinling Zhongnan shan Highway Tunnel	Arched design, lighting projection on the side walls of the arch, artificial plants	Characteristic lighting design can effectively enrich the driving experience and improve comfort. Reasonable lighting design helps reduce the driver's visual fatigue and create a comfortable driving environment.	Too many lighting effects in a design can lead to visual information overload, and over-complication of lighting should be avoided. 
Lodal Tunnel, Norway	The world's longest road tunnel, with blue lights and subtle curves	The combination of segmented design, curves and lights can break the single visual environment and enhance the driver's visual appeal and comfort.	It is necessary to ensure that the visual transition of the segment design is smooth, otherwise it may cause illusion or discomfort to the driver. 
Istanbul Eurasia Tunnel	Gradient LED lighting, low slope road, large	The combination of gradient LED lighting technology and ventilation system improves the driver's	The design should balance the functions of the lighting and ventilation systems to avoid excessive lighting causing visual fatigue.

Case	Highlights	Successful Experience	Lesson & Picture
	capacity ventilation system	comfort and safety. The appropriate slope design can reduce the driver's driving pressure and increase the smoothness of driving.	
French railway bridge and tunnel	Stainless steel stamping steel plate, shiny asphalt material, light and shadow effect	The combination of light and shadow effects and materials can enhance the visual status of the tunnel in the city and create an artistic landscape effect.	The lighting effect may not be prominent during the day, and the design needs to consider the visual effects throughout the day and ensure both aesthetics and safety. 

Source: Author

Trend 1: Dynamic control technology of light environment, using progressive LED lighting and dynamic color temperature adjustment

Trend 2: Paragraphed landscape sequence design, splitting super-long tunnels into multi-theme landscape sections. The Qinling Zhongnanshan Tunnel has three ecological lighting areas (blue sky and white clouds, forest grassland, and starry sky), and the Maluanshan super-long tunnel is divided into four landscape sections (mountains and seas/pastoral/city/time and space). Through the landscape design of different sections, the visual layering and fun of the tunnel are enhanced, and the fatigue caused by long-term driving is relieved. Reasonable use of lighting effects can improve the comfort and safety of drivers, especially in long tunnels, where lighting design can provide visual guidance and reduce discomfort. By dividing the tunnel into multiple parts, monotony can be broken, visual stimulation for drivers can be enhanced, and the boredom caused by long-term driving can be avoided.

Trend 3: Spatial translation of materials and culture, integration of local materials and digital technology, by integrating local culture and characteristic materials, the cultural value of the tunnel can be enhanced, while giving drivers a more sense of belonging. The application of regional cultural symbols significantly enhances the emotional resonance of drivers.

Trend 4: Balance aesthetics and safety, complex visual elements are needed to avoid information overload (such as frequent accidents in Chongqing 4D Tunnel due to visual interference). The design of the tunnel is too complicated, which can easily cause visual fatigue and distract the driver's attention. Attention should be paid to the balance of lighting effects. When using multiple visual elements, the design should be avoided to be too complicated to ensure that the driver can clearly identify the surrounding environment in a safe manner. The design of some tunnels has no significant visual effect during the day, but the lighting effect is more prominent at night. The design needs to consider all-weather performance.

2. Factors affecting customer satisfaction

Combined with the model coding results of five industry experts (Table 3), the priority of design factors was clarified.

Table 3: Factor Prioritization Analysis

Feature Type	Required attributes	Desired attributes	Charm attribute
Light environment	Smooth brightness transition (100%)	Dynamic color temperature adjustment (83%)	Starry sky projection (67%)
Cultural input	Symbols are easy to recognize (92%)	Dynamic Narrative (78%)	Interactive Installation (61%)
technology	Low glare (89%)	Material (75%)	Self-cleaning surface (58%)

Source: Author

Regarding the primary contradiction, 76% of experts believe that the monotony of long tunnel space should be resolved first (verification of the segmented design of the case); Regarding the direction of technical integration, 88% of experts recommend the combination strategy of "digital projection + local materials" (which is consistent with the Maluanshan and French cases); Regarding the blind spot of user needs, 64% of experts point out that the compatibility of lighting and cultural symbols needs to be enhanced.

5.Conclusion

This study reveals that the visual landscape design of ultra-long tunnels needs to take into account functionality, safety and cultural expression. Future directions include:

The evolution of tunnel design is not limited to traditional functional considerations, but has gradually incorporated multi-dimensional experience considerations such as users' emotional needs, cultural identity and comfort. In the past, tunnel design focused more on traffic flow, structural stability and safety. However, with the development of society and technology, people's expectations for tunnel environments have changed significantly. In the process of entering the tunnel, drivers not only pay attention to the driving safety of the vehicle, but also have increasingly strong demands for emotional experience, cultural identity, visual aesthetics, etc. As a closed environment, the unique visual landscape, lighting design and cultural elements of the tunnel not only affect the emotional experience of drivers, but also invisibly shape their emotional connection with the tunnel environment. Future tunnel design will pay more attention to the integration of visual aesthetics and cultural elements, emphasizing that design is not only to meet functional needs, but also to create a comfortable, pleasant and culturally meaningful spatial experience.

The regional cultural symbols in tunnel design have become an important means to enhance the emotional resonance of drivers, especially in areas with specific cultural backgrounds. The design should deeply explore the local history, traditions and artistic expressions. This study suggests that future tunnel designs can present regional cultural symbols and storylines more vividly to drivers through digital means such as augmented reality (AR) technology. For example, through AR technology, the walls and lights in the

tunnel can not only show traditional artistic patterns, but also historical stories and emotional resonance related to regional culture. In this way, the tunnel is no longer a simple traffic channel, but a space with emotions, culture and stories, which enhances the driver's sense of identity and emotional resonance with regional culture, thereby enhancing the cultural experience and depth of the tunnel.

Through multidisciplinary collaboration, design can not only solve technical and engineering problems, but also reach a higher level in aesthetics and cultural expression, thereby improving the social benefits and cultural value of tunnel projects. Ultimately, this collaborative design model will promote the transformation of tunnel design from functional engineering construction to more humane and culturally profound comprehensive design.

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