Virtual simulation technology for the design of the interior environment in an ultralong tunnel

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Abstract: Long-term driving and monotonous internal environment increase the safety hazard of driving in ultralong tunnels. Therefore, methods to alleviate the driving fatigue caused by long-term driving are of great significance to promote the safety of ultralong tunnel driving. Firstly, the environmental factors influencing driving fatigue of ultralong tunnel were analyzed, which can be divided into light environment and interior environment. Then, a driving fatigue detection system based on virtual reality technology was built which can integrate different hardware and software. Finally, based on Laoying ultralong tunnel in Yunnan Province, tunnel models under different environments were established, fatigue relief zone was set up and simulation tests were carried out. The experimental results show that setting a fatigue relief zone in the middle of the long tunnel, in the form of the combination of a “blue sky and white clouds” pattern on the inner wall and a high-color-temperature light source, can make drivers more attentive and effectively alleviate driving fatigue. This paper proposes a virtual simulation technology for fatigue relief zone settings; this technology can be adopted for other similar projects.

1 Introduction

The safety hazards of driving in ultralong tunnels increase because of the monotonous interior environment and long-term driving. According to the “Statistical Bulletin on the Development of the Transport Industry in 2019” issued by the Ministry of Transport of China [1], by the end of 2019, there were 19067 road tunnels in the country with a total length of 18.9666 million meters. Ultralong tunnels comprised 1175 of these road tunnels and had a length of more than 5.20 million meters, accounting for 27.51% of the total extent of highway tunnels. Methods to ensure driving safety, and especially, to alleviate the driving fatigue caused by long-term driving in the tunnel, are critical to promote the driving safety and reduce casualties.

Previous studies have shown that tunnel design (such as the design of the tunnel portal and lighting) has a great impact on driver safety [2]. When a driver enters the tunnel, the drastic changes in illumination and space can easily affect driving behavior [3]. Therefore, many researchers conducted studies on the design of the tunnel portal. Wang et al. [4] designed the landscape at the tunnel portal of Baoteng Tunnel in Yunnan Province to promote driving safety. Du et al. [5] proposed setting up a shading shed and a multifrequency marking system at the entrance and exit of the tunnel to enhance traffic safety in the tunnel. For ultralong tunnels, the monotonous interior environment, poor air quality [6], and driving fatigue caused by long driving time are more likely to cause traffic accidents. Lai et al. [7] counted 2193 traffic accidents in 156 tunnels (20 of which were ultralong tunnels) and found that with
an increase in tunnel length, the number of traffic accidents increased gradually. Wu et al. [8] found that drivers in an ultralong tunnel gazed longer and had dilated pupils, implying that long-term driving can easily lead to driving fatigue. Dong et al. [9] found that to alleviate long-term driving fatigue, using a light source with the optimal color temperature can reduce the reaction time and driving fatigue. In addition, Huang [10] proposed using colored asphalt concrete to relieve driving fatigue, and Chen [11] studied the design form of a visual fatigue relief zone from the perspectives of lighting, landscape, etc.

In summary, driving safety in ultralong tunnels is gaining research attention. Previous studies had the following shortcomings: (1) Many studies focused on the tunnel portal and ignored the impact of the middle section of the tunnel on driving safety. (2) Research on the design of the visual environment of the tunnel interior is lacking. (3) Using eye movement data as an indicator to reflect driving fatigue is susceptible to other factors.

To overcome these shortcomings, this study focused on the setting up of driving fatigue relief zones in ultralong tunnels. The factors contributing to the driving fatigue in ultralong tunnels were analyzed, and a driving fatigue detection system that can display different tunnel environments was developed based on virtual reality (VR) technology [12]. Using the data from simulation experiments, the optimum form of the driving fatigue relief zone was determined. Finally, the results were applied to the Laoying ultralong tunnel in Yunnan Province.

### 2 Influencing factors of driving fatigue in ultralong tunnels

Analysis of the influencing factors of driving fatigue in ultralong tunnels is helpful in the design of driving fatigue relief zone. Qin et al. [13] classified driving fatigue in ultralong tunnels into two types: drivers’ own conditions (for instance, sleep and mood) and driving environment. This study focused on the influence of the tunnel environment on driving fatigue.

The environment in the tunnel includes the lighting environment and decoration environment. As shown in Table 1, the lighting environment is mainly created by using lamps, and their types (e.g., light-emitting diodes and high-pressure sodium lamps), brightness, illuminance, color temperature, and spacing will affect long-term driving fatigue. The decoration environment in the tunnel refers to the signs, landscapes, or other color stimuli on the sidewalls or the roof of the tunnel. Suitable types of such decoration (enameled steel plates, gradient patterns, natural landscapes, etc.) plus reasonable length and spacing of the layout can alleviate long-term driving fatigue.

| Factors influencing driving fatigue | Type | Brightness | Illuminance | Color temperature | Space |
|---|---|---|---|---|---|
| Lighting environment | Type | Brightness | Illuminance | Color temperature | Space |
| Decoration environment | Type | Length | Spacing |

### 3 Driving fatigue detection system based on VR

Currently, actual vehicle test is the main method used for driving fatigue detection. However, because it is not easy to replace the light sources and decorations in an actual ultralong tunnel, VR technology was adopted to conduct a simulation test.

#### 3.1 System architecture

The driving fatigue detection system is divided into four layers: a basic layer, a data layer, an application layer, and a user layer, as shown in Figure 1. The basic layer refers to the hardware of the system, including the VR equipment, analog driving equipment and physiological signal acquisition equipment. The data layer stores the test data obtained from the simulation test, including tunnel design parameters,
and physiological data of test personnel. In the application layer, the test data are used for designing the fatigue relief zone, including the design of lighting and decoration. The user layer contains the users of the system, including tunnel designers, construction personnel, operation and maintenance personnel, test personnel, and scientific research personnel.

| User layer       | Design | Construction | Maintenance | Test | Research |
|------------------|--------|--------------|-------------|------|----------|
| Application layer| Fatigue relief zone | Location | Length | Lighting | Decoration |
| Data layer       | Tunnel data | Test data | Fatigue data |
| Basic layer      | VR equipment | Analog driving equipment | Physiological signal Acquisition equipment |

**Fig.1 System architecture**

### 3.2 Hardware and software composition

Figure 2 shows the completed driving fatigue detection system. The headband, BrainCo’s Focus ring (produced by BrainCo. Company), was used as the brainwave acquisition equipment to collect the signals of changes in the attention of the participants; a decrease in attention was used to reflect the driving fatigue during driving in real time. To create an immersive environment, HTC Vive Pro (dual AMOLED 3.5-inch diagonal screen, 1440 × 1600 pixels per eye, and 90 Hz refresh rate, produced by HTC Company) was used to enhance the driving immersion and experience. In addition, a steering wheel, a throttle and other equipment (a set of Logitech Momo Driving Force which was produced by Logitech Company) were also used to control the vehicle operation during simulated driving to better simulate the feeling of real driving.

**Fig.2 Set up of the virtual experiment**

The software interface of the system is shown in Fig. 3. Unity game engine was used to integrate and visualize data. Several algorithms were developed in Unity to collect and store data in real time. For example, in the case of attention data, the data collected by the Focus ring were stored in a .txt file in a
specific folder; simultaneously, the algorithm to read the .txt file in real time was written in Unity using C# language to allow visualizing and analyzing the data. VR scenarios were shown in the head-mounted display (HMD) by using Steam VR plug-in in Unity, and the analog driving equipment was integrated into Unity by using Logitech Driving Force plug-in. In the software interface, the upper left panel shows the tester information, including the tester's name and test number; the lower left panel shows the test VR scene; and the panel on the right shows the test parameters, including the type of the fatigue relief zone, test duration, and current attention value.

4 Setting of fatigue relief zones in an ultralong tunnel

4.1 Project overview
The optimal design method for fatigue relief zones was applied to the Laoying tunnel, an ultralong tunnel, in Yunnan Province, whose length is 11430 m. It can be seen that driving in the monotonous environment in the Laoying ultralong tunnel for a long time is likely to cause driving fatigue and increase the hidden danger of accidents. Therefore, it is necessary to set up a fatigue relief zone to optimize the environment inside the tunnel and to create a safe driving environment. The design of such a fatigue relief zone for this tunnel is a major engineering difficulty.

4.2 Setup process
To study the setting of the fatigue relief zone, the factors that affect driving fatigue were first determined. In this study, two factors, i.e., the color temperature of the light source and the type of decoration, were considered. Accordingly, tunnel models under different color temperatures and different decoration types were created. Then, these models were imported into the fatigue detection system, and simulation tests were conducted by the participants. Finally, the test data were analyzed, and the degrees of driving fatigue of the test personnel under different schemes were compared to obtain the best setting form of the fatigue relief zone. The overall process is shown in Fig.4.
4.3 Tunnel modeling
The model of Laoying tunnel was established according to the investigation data (including 2D drawings of tunnel plan and vertical section provided by the tunnel design institute) and remote sensing data of the site (downloaded online), which mainly included tunnel portal modeling and interior section modeling.

(1) Tunnel portal modeling
The portal model had three main parts: the portal infrastructure, lighting environment at the portal, and landscape around the portal. As this study mainly studied the fatigue relief zone set in the middle of the tunnel, the shading shed, portal signal lights, reflective ring, and other visual induction facilities were not modeled at the portal. The established portal model is shown in Fig. 5.

(2) Interior section modeling
The model of the interior section mainly included the road facilities, marking system, and lighting environment. Road facilities included the pavement, pavement steps, and side stone lights. The marking system included the lane markings, pavement markings, and waistlines. The lighting environment comprised primarily of parallel light strips and point light sources. The final model of the interior is shown in Fig. 6.

4.4 Experimental setup
To study the effect of decoration types on driving fatigue, a decorative pattern of blue sky and white clouds, as shown in Fig. 7, was used in the middle of the tunnel by referring to existing similar projects (e.g., Qinling-Zhongnanshan Tunnel). Two sets of comparative experiments were conducted: one with blue sky and white clouds and one without the sky and clouds. In addition, the tunnel models with different color temperatures were also established. A tunnel model under warm light is shown in Fig. 8.
During the experiment, the fatigue characteristics of the participants under warm, normal, and cold lights (set in Unity) were compared to explore the best color temperature to relieve driving fatigue.

Twenty subjects were recruited for the experiment. The subjects were healthy, without any visual impairment, and had experience of driving in ultralong tunnels. Each participant was asked to sit quietly for 2 min before the test and then performed the simulation test.

4.5 Results

While analyzing the test data, a relative growth rate of the collected attention value was adopted by subtracting the attention value in the calm state from the test data to reduce individual differences. The analysis results are listed in Table 2.

|                      | Mean  | SD    |
|----------------------|-------|-------|
| With “blue sky, white cloud” | 7.79% | 25.60%|
| Without “blue sky, white cloud” | -1.12% | 23.44%|
| Warm light           | -0.32% | 46.23%|
| Cold light           | 3.29%  | 25.60%|

As seen from the data in Table 2, the “blue sky and white clouds” pattern in the middle of the tunnel could clearly relieve driving fatigue. Compared with the undecorated section in the middle of the tunnel, the attention increased by 8.91% in the decorated section. Moreover, the drivers’ attention was better under cold light than under warm light, and thus, the use of a cold light can help avoid the traffic accidents caused by driving fatigue to some extent. Therefore, the fatigue relief zone setting can be a combination of a “blue sky and white cloud” pattern and a high-color-temperature light source in the middle.

5 Conclusion

A study on the fatigue relief zone in an ultralong tunnel was performed based on VR. The main conclusions are as follows:

(1) The environmental factors affecting driving fatigue in the ultralong tunnel, including the lighting and decoration environments, are summarized.

(2) A driving fatigue detection system that incorporates integrated VR equipment, analog driving equipment, and attention collection equipment was developed.

(3) The preferred setting of the fatigue relief zone was found to be a combination of a “blue sky and white cloud” pattern and a high-color-temperature light source in the middle.

Note that this study only explored the setting of the fatigue relief zone from the perspective of the type of decoration and the color temperature of the light source. Other factors such as the brightness of the light source and the length of the fatigue relief zone can be investigated in the future.

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