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Influence of dynamic highway tunnel lighting environment on driving safety based on eye movement parameters of the driver

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ABSTRACT

In this study, the non-intrusive eye-tracking system Smart Eye Pro was used to record eye movement parameters while drivers were driving through a highway tunnel with two types of lighting environments. The driving safety of the drivers was studied by analyzing the recorded eye movement parameters. The results indicated that the sharp decrease in luminance would result in the change in the position and duration of the fixation point of the driver. The driver performed continuous visual exploration of the unknown highway tunnel lighting environment; this reflects a strong sense of tension. The decreasing luminance, its lower uniformity, and the flicker effect in the tunnel interior zone, resulted in the increase in the pupil diameter of the driver, and the visual load of the driver increased with the change in the rate of increase in the pupil diameter. The eye movement parameters were more stable in a lighting environment with higher luminance on the tunnel sidewall; the optimization of the spatial luminance distribution of the lighting environment and the use of open sun-screens in the entrance portal are recommended for energy saving and traffic safety in highway tunnels.

1. Introduction

Once a traffic accident occurs, the consequences are extremely severe. For example, a traffic accident occurred in the Shanxi Yanhou tunnel in China on Mar 1, 2014, causing the death of 40 people and injuring 12 people. The direct economic loss amounted to US $12 million (State Administration of Work Safety of China, 2014). Another recent traffic accident occurred at the Hachihonmatsu tunnel in Japan on Mar 17, 2016, causing the death of 2 people and the injuring 70 people (Japan Today: Japan News and Discussion, 2016). The studies on road traffic accidents in Singapore expressway tunnels also showed that road tunnel accidents are more likely to occur when entering the tunnel rather than exiting (Jian and Wong, 2013). Meanwhile, lighting must be provided in tunnels 24 h a day. The energy consumption for tunnel lighting should be higher during daytime and lower during nighttime according to tunnel lighting standards (Commission Internationale de l'Éclairage, 2004), owing to the slow visual adaptation of the human eye when transitioning from bright to dark environments. However, the design method "one luminance level throughout the day" is commonly used owing to the excessively high cost of the tunnel lighting control system, particularly in certain short road tunnels of China. The electrical consumption statistics for the Chongqing Highway tunnel show that its average annual cost for electricity is US $62,000 per kilometer; in China, the total annual electrical cost of road tunnels is US $1 billion, of which the lighting accounts for approximately 30% (Liu et al., 2015). As tunnel lighting consumes a notable share of energy, it is necessary and important to research tunnel lighting from the viewpoint of traffic safety and energy conservation.

When a motorist is driving through a road tunnel, his/her visual system must adjust its sensitivity to match the ambient light level. This process is called adaptation. Experiments on adaptation in road tunnels were described by Schreuder (1964), who investigated five topics: the admissible luminance jump, the gradual luminance decrease, the adaptation time, the influence of the pre-adaptation time, and the influence of variations in the pre-adaptation level. Based on the tunnel simulation experiments with observers that were conducted by Schreuder, the luminance transitions were identified based on a probability of observation of 75% by the subjects, while detecting the critical object after entering the tunnel (Schreuder, 1971). Meanwhile, the equivalent veiling luminance of the tunnel entrance was studied by Adrian, based on physiological considerations of the adaptation process (Adrian, 1982). Then, the perceived contrast method was recommended in the CIE 88-2004 guide for the lighting of road tunnels and underpasses

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(Commission Internationale de l'Éclairage, 2004). In highway tunnels, different luminance levels were recommended for the threshold zone, the transition zone, the interior zone and the exit zone, and the luminance evolution method along the tunnel was recommended (Commission Internationale de l'Éclairage, 2004). However, all aforementioned studies were based on the results of visual performance in a specific visual task, instead of the performance mechanism of the driver. Meanwhile, for the application of tunnel lighting standards, the stepdown method is used (The Illuminating Engineering Society of North America, 2011; Ministry of Transport of the People's Republic of China, 2014). Furthermore, luminaries with different powers have been mounted using different layout methods in road tunnels; hence, the black-hole and dark-adaptation effects and the flicker effect were difficult to avoid in real tunnels. Therefore, it is clear that we are aware that these effects may compromise driving safety; however, we have not clarified how these effects influence traffic safety. In a dynamic visual environment, traffic information is obtained via various senses, and approximately 90% of the information is obtained through vision (Sivak, 1996). The quality of the visual environment is closely related to the accessed information quality in terms of its influence on the visual acuity of the driver and his/her perception in the driving process (Jendrusch et al., 1999; Irving, 1965). In the present study, the visual state of the driver in the driving process has been defined as dynamic vision. Dynamic vision will lead to the decrease in the visual sharpness, vision field, visual observation ability, etc. of the observer (Owsley and McGwin, 1999). However, the driving process is closely related to the dynamic vision. The visual search and decision-making process of the driver needs to be performed within a short time in a dynamic visual environment. There is no doubt that different lighting regulations have different effects on the visual performance of the driver; this increases the probability of traffic accidents.

When drivers drive through a tunnel in which the lighting environment alternates between light and dark, owing to the effects of dark-adaptation and flicker, their eye fixation or pupil diameter changes to adapt to the lighting environment. The eye movement and the change in pupil diameter are called eye movement parameters. Several studies have been carried out to discover the relationships between the eye movement parameters and illumination conditions of transportation. For instance, the relationship between speed, lateral placement, and driver eye movement at two-lane rural highways was studied to demonstrate that there are significant differences in driver eye movements under different geometric and illumination conditions (Suh et al., 2006). Meanwhile, the allocation of visual attention can be obtained by measuring the eye position of the driver; the results indicated that the eye movement was a probe of visual attention (Hoang Duc et al., 2008). Moreover, through the information on the fixation duration and the saccades of eye movement, the visual attention and the transition from novice to advanced driver was studied. It was revealed that the experienced drivers would increase the extent of their visual scan and horizontal fixation location as traffic conditions became more complex (Underwood, 2007; Shinoda et al., 2001). It has become obvious that the level of perception of a person of the visual environment can be reflected by the updated eye movement information (Srimal et al., 2008; Suh et al., 2006). However, the influence of the dynamic lighting environment in highway tunnels on the driving safety, based on the eye movement parameters of the driver, has seldom been studied in previous works. Moreover, no similar research has been conducted on how to improve the driving safety based on the eye movement parameters of the driver.

Tunnel walls form part of the background for the detection of obstacles inside the tunnel; they contribute to the adaptation level and the visual guidance. Therefore, the luminance of the tunnel walls is an important component for the quality of tunnel lighting (Commission Internationale de l'Éclairage, 2004; The Illuminating Engineering Society of North America, 2011). Hence, the luminance level and the properties (average luminance, reflection, and color) of the tunnel wall are highly important to driver visual adaptation. The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers was studied through the use of a driving simulator (Kircher and Ahlstrom, 2012). The results showed that tunnel design and illumination have certain influence on the driving behavior, and that light-colored tunnel walls were more important than strong illumination in keeping the visual attention of the driver focused forward. Meanwhile, the luminance of highway tunnels can be improved by employing high-reflection sidewall materials. For instance, the luminance of the road surface improved by 10% and the luminance of sidewall improved by 20% when the reflectance of the sidewall material increased from 0.3 to 0.7 (Pan et al., 2012). Furthermore, the combination of a special asphalt pavement and light-emitting diode (LED) lamps in road tunnel lighting has been studied by Salata et al. (2015), who indicated that the asphalt with a higher reflection coefficient can be used for energy optimization. Moretti compared the life-cycle cost between the concrete pavement and asphalt, and showed that the surface pavement material can contribute to the inter-reflected light and reduce energy consumption (Moretti et al., 2017, 2016). However, no research has been conducted on the effects of spatial luminance distribution in highway tunnels on driver eye movement parameters.

In the present study, a lighting environment of a highway road tunnel with two types of sidewall material was used as the experimental environment. The eye movement parameters were recorded with the non-intrusive eye-tracking system Smart Eye Pro, while drivers drove through a highway tunnel. The eye movement parameters were analyzed and then, the influence of the dynamic lighting environment on the driving safety was evaluated.

2. Materials and methods

A lighting environment with gradual decrease in luminance (from 677.45 cd/m^2 to 4.7 cd/m^2, based on the average road surface luminance in the access zone and the interior zone, respectively) was used. The experiment was conducted as the driver drove through a highway tunnel at a certain speed (50 km/h). The experimental tunnel was located at a curved section (the radius of the curve was 830 m) of the Yunnan Baoteng freeway, as shown in Fig. 1(a) and (b). The tunnel ceiling height was 7.05 m, and the road width was 8.75 m; the left tunnel length was 175 m, and the right tunnel length was 221 m. The left tunnel was used as the experimental tunnel. A 2D plan of the Lushan tunnel is shown in Fig. 2. The compass is northward in the plan, and the driver direction is from east to west.

The road tunnel was divided into the access zone, the threshold zone, the transition zone, the interior zone, and the exit zone according to the corresponding luminance recommended by tunnel lighting standards (Commission Internationale de l'Éclairage, 2004). For the application of road tunnel lighting standards, the lamps with different powers was installed in different kinds of layout to reach the required luminance of each tunnel zones in China (Ministry of Transport of the People's Republic of China, 2014). For instance, in the Lushan tunnel, LED lamps was installed. A combination of basic lamps of 40 W and strengthening lamps of 140 W was installed in the tunnel threshold zone, a combination of basic lamps of 40 W and strengthening lamps of 100 W was installed in the tunnel transition zone, and a combination of basic lamps of 40 W and strengthening lamps of 60 W was installed in the tunnel interior zone. The layout of the lamp placement in the tunnel threshold zone, the transition zone and the interior zone is shown in Fig. 3. The average road surface luminance in the access zone was 677.45 cd/m^2. The luminance parameters at different tunnel zones for the two lighting environment are listed in Table 1 (Ministry of Transport of the People's Republic of China, 2014).

A fireproof coating and an energy-storage and self-luminous coating were selected as the tunnel sidewall materials. The tunnel sidewall plaster height was 3 m. In Table 1, "Fireproof coating" indicates the