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Effects of transient adaptation on drivers' visual performance in road tunnel lighting

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ABSTRACT

To improve the safety of traffic in road tunnels, the effects of adaptation on peripheral visual performance were studied by measuring subjects' reaction times and missed target rates. The process of driving through an illuminated road tunnel was simulated in the laboratory by gradually decreasing the luminance of the visual environment. The tests showed that the gradual luminance changes resulted in transient blindness and decreased visual performance. The subjects' acuity and alertness were better for bluish targets than for reddish targets and better for whitish targets than for greenish targets in the tunnel transition and interior zones. The S/P ratio and mesopic luminance in the transition and interior zones, respectively, should be considered when selecting road tunnel luminaires.

1. Introduction

A road tunnel is a tubular, semi-enclosed traffic area. Tunnel lighting is required if it is not possible for approaching motorists to see through the tunnel (International Commission on Illumination, 2004). Road tunnel lighting resembles road lighting but has unique requirements due to the characteristics of the entrances and exits of tunnels in daytime. To ensure that drivers can detect the presence and movement of objects on the road in front of their cars, the current tunnel lighting standards include luminance, luminance uniformity, and threshold increment recommendations for different tunnel zones (International Commission on Illumination, 2004; Ministry of Transport of the People's Republic of China, 2014; The Illuminating Engineering Society of North America, 2011). The details of the layout of the inside of road tunnels for ensuring traffic safety and energy saving of the highway tunnel lighting, which includes the technical and economic evaluation of the road pavement (Moretti et al., 2016, 2017) as well as the effects of sidewall design on drivers while driving (He et al., 2017; Kircher and Ahlstrom, 2012), have been discussed previously. However, some problems related to tunnel lighting remain unsolved.

An overview of traffic safety in the design of road tunnels was conducted by Bassan (2016). He showed that the crash rates in tunnels are lower than those in open roadways but that the crashes are more severe; further, he demonstrated that the numbers of crashes in tunnel zones could be decreased by increasing alertness. Alertness is a state of active attention characterized by high sensory awareness and the abilities to perceive and act quickly. A mathematical model of alertness regulation was studied by Åkerstedt and Connor to predict road crashes. They showed that sleepiness and high alcohol levels result in low alertness and high risk (Åkerstedt et al., 2008). A study of drivers' visual comfort at highway tunnel portals was conducted by Du et al. based on the variations of drivers' pupils (Du et al., 2014). They showed that the lighting in tunnel entrances in daytime was the most uncomfortable for drivers. Consequently, drivers must reduce their speeds when approaching tunnel entrances due to the poor lighting conditions. Road tunnels constitute an important part of the transportation system. However, traffic jams can occur along routes with tunnels when drivers suddenly reduce their speeds upon entering the tunnels. Therefore, it is necessary to research tunnel lighting to decrease the effects of the luminance level changes on drivers' visual tasks and alertness.

Visual performance has been studied since the 1930s to help establish a foundation for illuminance recommendations (Rea, 2012). Two approaches to visual performance research were taken, one by Weston in Great Britain (Boyce, 2013) and the other by Luckiesh in the United States (Luckiesh and Moss, 1937), leading to different illuminance recommendations in the two countries (e.g. 300 lx and 1000 lx for general illumination in Great Britain and the United States, respectively). Because of the energy crisis during the 1970s, visual performance research was applied to identify ways to save energy. The correlation between the models for vision and visual performance was

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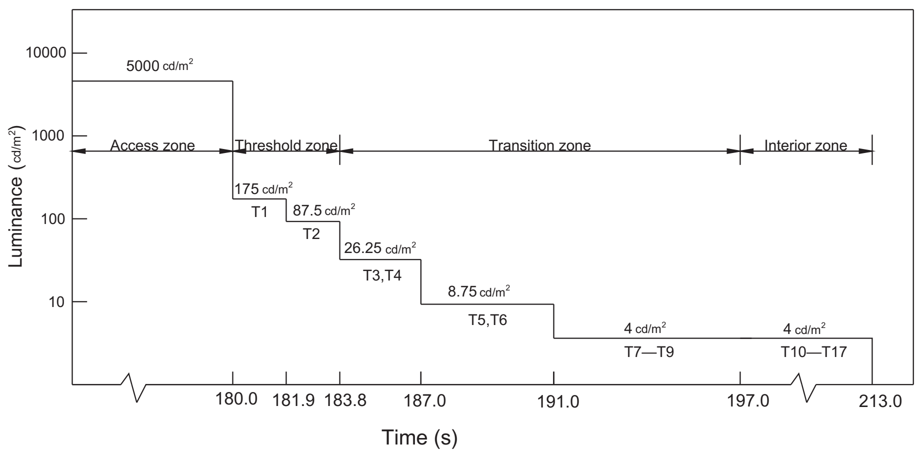

Fig. 1. Stepwise decrease in luminance from 5000 cd/m^2 to 4 cd/m^2 over time. Note: The horizontal axis represents the duration of each luminance step, and the vertical axis represents the luminance. The axes of the figure are not to scale. T1–T17 indicate the targets appearing in each luminance level.

discussed in technical report Commission Internationale de l'Eclairage (CIE) 145-2002 (International Commission on Illumination, 2002). It became evident that a strong relationship exists between visual acuity and performance, which indicates that visual acuity can be evaluated based on visual performance of a visual task. Visual performance means the performance of the visual system as measured, for instance, by the speed and accuracy with which a visual task is performed. Visual performance was also adopted by Eloholma and Halonen to develop the mesopic optimization of visual efficiency (MOVE) model in mesopic photometry (Eloholma and Halonen, 2006). Three visual questions, 'Can an object be seen?', 'How quickly?', and 'What is it?', were addressed in night time driving using the visual performance model. As a result, a system for mesopic photometry based on visual performance was published in technical report CIE 191-2010 (International Commission on Illumination, 2010). The effects of lighting on visual performance in traffic conditions were discussed by Rea (2012) during a Trotter Paterson Lecture in 2012. He stated that visual performance should be a central topic of discussion within the lighting community focusing on outdoor lighting, as drivers' visual performance directly affects traffic safety. Thus, it is important to assess drivers' alertness and visual acuity by studying visual performance.

When a driver is driving through a road tunnel, his or her visual system must adjust its sensitivity to match the ambient light level. This process is called adaptation (Schreuder, 2008). Experiments on adaptation in road tunnels were described by Schreuder (1964), who investigated five topics: the admissible luminance jump, gradual luminance decrease, adaptation time, influence of the pre-adaptation time, and influence of variations in the pre-adaptation level. Based on Schreuder's tunnel simulation experiments with observers, the luminance transitions were identified based on the subject's 75% acceptance of the luminance introduced after entering the tunnel. As a result, luminance recommendations in the threshold and transition zones were published by the CIE. Bourdy et al. showed that the influence of adaptation to the surrounding luminance level was significant at the detection thresholds of objects (Bourdy et al., 1987). The effects of adaptation can be substantial and have led lighting engineers to enhance the luminance levels in the first few hundred meters inside tunnels. However, evaluation of the effects of adaptation on visual performance has mainly been based on target visibility, which address only the question 'Can an object be seen?', while the other two questions, 'How quickly?' and 'What is it?', have rarely been considered. No prior research was found on the effects of adaptation on drivers' visual performance. Therefore, these effects should be evaluated.

Adaptation is defined as a 'process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, SPDs, and angular subtense', where 'SPD' stands for 'spectral power distribution' (International Lighting Vocabulary, 2011). This definition indicates that changes in luminance level, SPD, and angular subtense affect visual adaptation. Visual performance in lighting situations with different SPDs was assessed using measured reaction times by Lewis, who indicated that the luminous flux is not appropriate for characterizing the visual effects of lighting for tasks that are performed in low luminances (Lewis, 1999). Technical report CIE 206-2014 stated that visual brightness, facial recognition, pavement obstacle detection, and preferred lighting appearance are affected by the spectra of luminaires (International Commission on Illumination, 2014). The visual adaptation problem in tunnel transition sections was studied by Yan (2013). He reported that the influences of different luminaires (with different SPDs) on test subject's reaction times were different. When the luminance was decreased from a high level (50 cd/m^2) to a low level (2.4 cd/m^2), the test subjects could adapt faster when a light-emitting diode (LED) source was used than when a metal halide (MH) lamp or high-pressure sodium (HPS) lamp was utilized. However, there is no similar research on how luminance levels and SPDs affect visual performance during adaptation when a driver is driving through a road tunnel.

How do the luminance, adaptation time, and SPD influence drivers' visual performance in conditions with gradually decreasing luminance? Is there any way to improve drivers' visual performance? To answer these questions, the process of driving through an illuminated road tunnel was simulated in the laboratory by gradually decreasing the luminance. The reaction times and missed target rates of the test subjects were measured while the luminance was decreased with different backgrounds, and the results were analysed to assess the influences of the luminance, adaptation time, and SPD on the test subject's visual performance.

2. Methods

2.1. Lighting environment for adaptation

Based on tunnel lighting standard IESNA RP-22-11 (The Illuminating Engineering Society of North America, 2011) and Chinese guidelines (JTG/T D70/2-01-2014) (Ministry of Transport of the People's Republic of China, 2014), the luminance of the uniform background lighting environment used for adaptation was changed from 5000 cd/m^2 to 4 cd/m^2 (shown in Fig. 1). The luminance decrease of the lighting environment was designed to simulate the luminance reduction experienced by a driver while driving through a long tunnel in the northern hemisphere on a highway at 80 km/h. The luminance of 5000 cd/m^2 was used to simulate the adaptation luminance in the tunnel access zone. The reduction factor from the access zone to the threshold zone was 0.035, resulting in a luminance of 175 cd/m^2 in the threshold zone. The luminance in the first half of the threshold zone was 175 cd/m^2, while the luminance in the second half of the threshold zone was 87.5 cd/m^2.