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The impact of rhythm-based visual reference system in long highway tunnels

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ABSTRACT

As typical weak visual reference systems, highway tunnels have low illumination, monotonous environment and few references, which may reduce drivers' speed perception ability and thus easily cause overspeeding and rear-end collision accidents. This study performed psychophysical experiments to assess the effect of interior visual environment on the driving safety of drivers by using the 3ds Max software, driving simulator, and E-prime software. A rhythm-based marking system was proposed to improve the visual environment of tunnels by arranging rhythm curves on side walls and note symbols on pavements, as well as multi-frequency markings (high, medium and low frequency). The accuracy rate of speed judgment and reaction time of drivers were analyzed by statistical methods and the logistics curve fitting method. The results showed that: (a) single-color rhythm markings enhanced the accuracy ratio of speed judgment by 3.33–11.66%, while multi-color rhythm markings increase this parameter by 3.33–25%. The accuracy ratio was increased by 18.33% for the second change of color in multi-color rhythm markings ($t = 72$ s); (b) for common highway tunnels, the reaction time of drivers showed a significant association with the driving duration in the tunnel. For tunnels with improved visual environment by rhythm markings, no significant relationship between the reaction time and driving time was noted, with drivers' fatigue effectively released; and (c) the driver reaction time depended on both the visual environment and driving duration. Rhythm markings in tunnels could effectively reduce driver reaction time. Multi-color markings had better effects than monochrome ones.

1. Introduction

A driver obtains traffic information from vision, by which he or she judges, decides and operates. The low illumination, monotonous environment and semi-closed characteristics of highway tunnels are prone to weaken the drivers' speed sensing and thus easily cause over-speeding and rear-end collisions. In addition, a driver may feel fatigue when driving in highway tunnels with monotonous and semi-closed environment for a long time. This fatigue effect is defined as the state in which one is reluctant to continue the current task or hopes to engage in a new task. This state depends on task feature, frequency and environment (Akerstedt, 1995; Brown, 1994; Howard and Joint, 1994) (see Tables 1 and 2).

China has the largest number of highway tunnels in the world. As of 2015, there were 14,006 highway tunnels in this country, with a total length of 12,683,900 m. Surveys from China Highway Traffic Police Department reveal that 38% of traffic accidents are closely related to the drivers' illusion of their driving speed (Zhang et al., 2014). A reduction in speed illusion of drivers can therefore significantly reduce the speeding behavior and enhance road traffic safety. Currently, reasonable arrangements of tunnel lighting and traffic engineering facilities are the two main methods used to improve the tunnel environment and enhance the drivers' perception of speed.

This study assessed the effect of long-term driving in tunnels on the reaction time and speed sensing of drivers. The visual environment was improved by arranging traffic facilities and establishing rhythm-based marking systems. The improved visual environment could release the fatigue driving due to long-term driving in tunnels, enhance speed sensing, and thus improve driving safety in tunnels.

2. Literature review

Driver fatigue can be divided into two categories (Saxby, 2007). These include passive fatigue related to underload, or mental

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Table 1
Validation of model accuracy.

Test	Term						
	Speed (km/h)	Error (%)	Single sample statistic		Single sample T-test (α = 0.05)		
			Sample (N)	Standard deviation	Sig (double side)	95%confidence intervals	
						Lower limit	Upper limit
Field test	74	1.52	20	2.748	0.083	73.839	76.411
Simulator test	75.13						

Table 2
Design of multi-frequency marking systems in the middle of tunnels.

Location	Term			
	Facilities	Length × width (m)	Type of reflective material	Note
Road side	Bridge-type outline	0.154 × 0.040	Diamond grade reflective film(white in the right, yellow in the left)	Medium frequency of 0.8 Hz, attached on the side wall in heights of1.2 m and 1.6 m
	Vertical marking	5.0 × 0.5	High strength grade reflective film	Medium frequency of 0.8 Hz, extended to the top of tunnel
	Distance warning marking(arrow)	3 × 0.4	High strength grade reflective film	Low frequency of 0.2 Hz, 4 groups of vertical markings
	Side-wall elevation marking	3.0 × 0.6	All-weather reflective marking	High frequency of 7.4 Hz, red and white, height of 0.6 m, spacing of 3.0 m
Pavement	Pavement visual illusion marking	8.0 × 0.5	All-weather reflective marking	Low frequency of 0.2 Hz, transverse spacing of 0.5 m
	Distance keeping marking(arrow)	3 × 0.4	High strength grade reflective film	Low frequency of 0.2 Hz, 4 groups of transverse markings
	Passage roadway marking	3.0 × 0.75	All-weather reflective marking	High frequency of 7.4 Hz, red and white, spacing of 3.0 m
	Pavement raising marking	0.15 × 0.75	High strength grade reflective film(white in the right, yellow in the left)	High frequency of 4 Hz, arranged at lane lines
	Pavement note symbol	3 × 1.5	High strength grade reflective film	Low frequency of 0.2 Hz, 2 groups of transverse markings
Side wall	Rhythm marking(blue)	100 × 4 (height)	Reflective marking	Low frequency of 0.2 Hz, period of 100 m
	Rhythm marking (yellow)	50 × 1.5 (height)	Reflective marking	Low frequency of 0.2 Hz, period of 50 m

Note: Rhythm marking is the sine curve.

fatigue; the major symptom of mental fatigue is a general sensation of weariness, feelings of inhibition, and impaired activity. The other type is active fatigue, which is related to overload, namely physical fatigue and caused by circadian disruption and sleep deprivation (Lal and Craig, 2001). In this study, driver fatigue mainly refers to mental fatigue. Thiffault and Bergeron (2003) proposed that driver fatigue may be caused by the lack of environmental stimuli such as noises and vibrations, as well as open environment. They used cockpit simulators to evaluate the formation of driver fatigue in monotonous environments. The results showed that the magnitude and frequency of steering wheel movement in a monotonous environment depend on the driving duration. This indicated a reduction in the operation capacity of driving. Dinges (1995) found that the fatigue effect may affect a driver's short-term memory and increase reaction time, causing accidents when driving in a high speed. Liu and Wu (2009) found that the driving behavior and performance of fatigued drivers are more affected by changes in road environment than the length of driving time. Indeed, the switch from complex to monotonous road environments has a negative impact on both visual and numerical calculation capabilities, namely distance overestimation and increased reaction time. Zhao and Rong (2013) found that stimulation in a monotonous environment has a significant influence on preventing driver fatigue, and proposed the optimal stimulation interval in the road environment to be no more than 8 min.

For the setting of tunnel lighting to improve the environment and driving safety, Thompson (1981) assessed the effect of contrast ratio on the judgment of speed. It was found that reduction in contrast ratio leads to an underestimation of driving speed. The threshold of speed underestimation depends on the spatial frequency of visual information. Buchner et al. (2006) and Zhao et al. (2013) investigated the effect of illumination on the judgment of distance between vehicles. The results showed that reduced illumination in tunnels leads to increased perceived distance of drivers. Reports by Kircher and Lundkvist (2011) and Katja and Christer (2012) showed that a driver's focus may move away from the road in a tunnel. The dark tunnel wall could lead to a reduction of drivers' concentration. Therefore, the luminance of side walls is more important for the safety and comfort of driving than illumination. A side wall in a light color is safer. There are multiple codes in China for the illumination and ventilation of highway tunnels (JTG/T D70/2-01-2014, 2014; JTG/T D71-2004, 2004). Due to the natural and economic conditions in Midwest China, which comprise mountainous and underdeveloped areas with less traffic volume and governmental finance as well as low incomes, tunnel lighting is unaffordable for operators, especially since it is very expensive. It is common to only use part of the illumination or even none in highway tunnels (Zheng and Wang, 2007). The practical illumination in operation is thus significantly lower than design specifications, which has adverse effects on driving safety.

For the visual speed control by traffic facilities, Denton (1980) proposed that transverse markings with reduced spacing may cause drivers' overestimation of speed and thus reduce speed. According to statistical data, the average driving speed was reduced by 23% and speed difference decreased by 37%. Manser