ZHIGANG DU, Ph.D.
E-mail: zhigangdu21@yahoo.com
HONGLIANG WAN, Graduate student
E-mail: hongliangwan@yahoo.com
School of Transportation
Wuhan University of Technology
1040#, Heping Avenue, Wuhan, 430063, Hubei, P.R.China
CHAOZHONG WU, Ph.D., Professor
E-mail: wucz72@yahoo.com
Intelligent Transport Systems Research Center
Wuhan University of Technology
1040#, Heping Avenue, Wuhan, Hubei, 430063, China
XIAODONG PAN, Ph.D.
E-mail: Panxd3@yahoo.com
Transportation School, Tongji University
4800#, Caoan Road, Shanghai, 201804, China

Human-Transport Interaction
Original Scientific Paper
Submitted: June 19, 2013
Approved: Sep. 23, 2014

SAFETY EVALUATION OF HIGHWAY TUNNEL-ENTRANCE ILLUMINANCE TRANSITION BASED ON EYE-PUPIL CHANGES

ABSTRACT

Utilizing the EMR-8B eye-tracker system, the pupil changes of eight drivers were monitored when they drove through 26 typical highway tunnels. Based on the test results, the driver's pupil areas and pupil illuminance were found to be in a power function relationship at tunnel entrances. Furthermore, a quantitative relationship between the pupil area and its critical velocity was established, and the ratio of pupil area's velocity in relation to its critical velocity was used to evaluate the lighting transitions and to establish the ideal curve of pupil illuminance at tunnel entrances. The results demonstrated that the relationship between the pupil illuminance of the tunnel entrance and the driver's pupil areas conforms to the Stevens law found in experimental psychology; severe pupil illuminance transition within the range of 10 metres of the existing highway tunnel entrances, which results in great visual load, is in urgent need of improvement.

KEY WORDS

Highway tunnel; entrance; illuminance transition; pupil change; visual load;

1. INTRODUCTION

China has the largest number of tunnels in the world. As of 2013, there were 12,132 highway tunnels in that country, with a total length of 9,732,400 metres. Because of highway traffic, tunnels are accident-prone locations, often with heavy casualties. Low visibility and psychological panic in the tunnel make escape or rescue from an accident difficult. Moreover, cars travelling at excessive speed through tunnels are apt to cause secondary accidents.

Research shows that illuminance at a tunnel entrance during the day decreases sharply, from tens of thousands of lux to hundreds of lux. This sharp change in illuminance causes visual adaptation difficulties for drivers, referred to as a visual "black hole effect" which results in bad driving behaviours, and further induces traffic accidents.

While the risk of an accident inside a tunnel is often lower than that in an open-road network, an accident event in a tunnel can be more serious. According to data from the Norway Highway Bureau, 63.7% of tunnel collisions occurred at entrances. Wang (2012) and Dai et al. (2010) analyzed the characteristics of highway-tunnel traffic accidents and found that (a) accidents happen frequently during the day, from 8:00 a.m. to noon; (b) the tunnel accident rate at tunnel entrance sections is higher than within tunnels; and (c) most of the accidents are rear-end collisions, with cars hitting the tunnel wall. These studies concluded that visual adaptation difficulties created by the darker conditions of tunnels were an important factor in tunnel traffic accidents [1-2].

The effect of tunnel-entrance lighting on driving safety has become a key issue in need of immediate attention. In building tunnels, various countries use data on illuminance levels to increase safety and thus prevent collisions. Lighting standards vary in different countries and areas, depending on factors such as density of traffic flow, speed limits, and outdoor conditions. The CIE 088 report (CIE, 2004) is used by most countries in the world. Pachamanov (2008) studied tunnel-lighting settings that meet brightness and glare requirements, considering the transition of lighting as a linear optimization problem between lights and pavement reflection [3]. Then lighting installation and commissioning of the illuminance transition are curve fitting. The calculated results show that this setting is better and more energy-efficient. Kircher (2012) conducted a parametric study of different brightness and colours on sidewalls and suggested that light-coloured sidewalls induce a safer driving environment in the tunnel [4].

Yang (2006) and Dai et al. (2011) studied the speed change at highway tunnel entrances using an accelerometer and observed a significant deceleration at entrances due to dramatic lighting transition [5-6]. Liu et al. (2011) showed that the tunnel lighting has a significant impact on driving behaviour and can effectively relieve fatigue [7].

Brightness reduction is a factor in tunnel lighting in Chinese evaluation criteria, which is mainly based on related Japanese tunnel codes, which are lower than those criteria employed by the United Kingdom, Norway, and the International Association of Lighting for the inlet section of the tunnel. To eliminate the black hole effect, the Chinese industry standard "Highway Tunnel Ventilation and Lighting Design Specifications" (JTJ 026.1-1999) stipulates that "Lighting should be set in tunnels with lengths of 100 metres or more," and the lighting should be enhanced at the tunnel entrance, which results in a huge energy consumption. As of 2012, the annual electricity consumption in Zhejiang Province reached approximately 414 million degrees. In areas with less traffic, especially in the west of China, standard lights are usually equipped but the energy consumption is not affordable. As result, in the process of operation, lights function only partially or even less. This is also considered to be the main reason for traffic accidents during tunnel illuminance transition, according to Dai and Guo (2011) [6].

Tunnel-driving visual load is determined by the visual perceptual load and visual physiological load. The visual perceptual load corresponds to the amount of information involved in the visual perceptual processing of the task stimuli. The visual physiological load is the pupillary physiological function reaction caused by eye movement (2011) [8]. Pupillary response varies according to the size of the pupil, consists of the pupillary light reflex and the task-invoked response. The task-invoked pupillary response is induced by one's mental load. The pupillary light reflex controls the diameter of the pupil in response to the intensity of any light that falls on the retina of the eye, thereby assisting in adapting to various levels of darkness and light (2008) [9]. The task-invoked pupillary response is caused by a person's cognitive load, as a result of the decrease in parasympathetic activity in the peripheral nervous system (1991) [10]. In driving studies, pupil diameter is often employed as a physiological measure of cognitive load. However, the pupil size is primarily influenced by the pupillary light reflex (2012) [11-12]. Cheng (2006) measured the pupil size of various low illuminance levels, ranging from 0.04 lux to 4 lux. Results showed that pupil size is related to the intensity of illumination [13]. Hu (2010) measured the pupil sizes of 13 luminance levels, and evaluated the rational background luminance between 0.7 cd/m^2 and 3.5 cd/m^2 [14].

Drivers' pupil sizes vary in response to environmental transitions in tunnel portals, including tunnel alignment, visual reference objects, and illuminance. The alignment at tunnel portals should maintain a consistent distance greater than 3 seconds, according to the Chinese industry standard "Highway Tunnel Ventilation and Lighting Design Specifications" (JTJ 026.1-1999). At the same time, moderate transitions of visual reference objects cause small pupillary responses at tunnel entrances. Consequently, the drivers' pupillary response is triggered by the sharp illuminance transitions at tunnel entrances.

Generally speaking, the existing Chinese tunnel environment illuminance standards are lower than international standards, and the actual operational standards are even lower than the national standards. A reasonable illuminance transition at tunnel entrances is the key to reducing tunnel vision load and improving tunnel traffic safety in China. This paper (a) develops an evaluation index for illuminance transition at the tunnel entrance, (b) evaluates the current illuminance transition using the developed index, and (c) provides suggestions for the practice. To achieve the objectives of this study, several issues had to be addressed:

- Is there any quantitative relationship between the illuminance at the tunnel entrance and the pupil size of the driver?
- How can the driver's visual ability to adapt be quantitatively evaluated?
- How can the illuminance transition at the tunnel entrance be quantitatively assessed?
- What is the ideal illuminance transition that can be used for most of the tunnels?

2. EXPERIMENT DESIGN AND DATA COLLECTION

2.1 Test tunnels

A total of 26 highway tunnels in Yunnan and Zhejiang provinces were involved in the test. The length of the highway varied between 243 and 3,554 metres, with a speed limit of either 60 km/h or 80 km/h. The selected highway tunnels are bi-directional and dual four-lane motorway with separated sub-grades. The tunnel entrance is not the tunnel exit, and the tunnel experiment was carried out from bi-directions. The width of motorway lane is 3.75 m and the clearing height is 5.0 m in the tunnel. The width of motorway lane is also 3.75 m outside the tunnel.

Table 1 - Selected tunnel profiles

Pavement / Index	Asphalt	Cement	Cement
Speed limit (km/h)	60~80	80	80
Heading	NE-SW	NE-SW	N-S
Entrance type	Sidewall	Sidewall	Sidewall
No. of lanes	2	2	2
Ave. length (m)	1,232	1,033	865
Number of samples (n)	7	4	15

2.2 Test drivers

The selected highway tunnels are located in mountain areas of China with low lighting conditions, the driving is very monotonous and dangerous, so most of long-distance drivers on mountain highways are young males in China. Eight male drivers were selected who were familiar with the local road conditions, professional drivers for at least 3 years, and with fine vision ability. Half of them were between 20 and 30 years of age, and the other half between 30 and 40.

2.3 Test facilities and calibration

To build the connection between illuminance at the tunnel entrance and the pupil size of the driver, both terms were measured as described below. The tests were conducted from 9:00 a.m. to 3:00 p.m. in the middle of May, 2011. Every lane of the motorway was open during the experiment. The traffic volume was low, just about 200-300 veh/h/lane between 9:00 a.m. and 3:00 p.m.

The illuminance levels were measured when the experimental vehicle was located at -20, 0, 5, 10, 20, 30, 50, and 70 metres away from the inside of the tunnel entrance. There are 2 lamps per cross-sections with one-lamp operation, as shown in *Figure 1*. The tunnel lamps are High Pressure Solidums (HPS) golden yellow in colour. The digital luxmeter, Test 545, was vertically attached to the experimental vehicle at the height of 1.3 metres, which is the average height of driver vision, as shown in *Figure 1*. In this way the illuminance at the driver's pupil area was simulated.

The car is the main vehicle type of all traffic vehicles, and accounts for more than 60 percent of all traffic vehicles. The widely-used Volkswagen 2000 with the

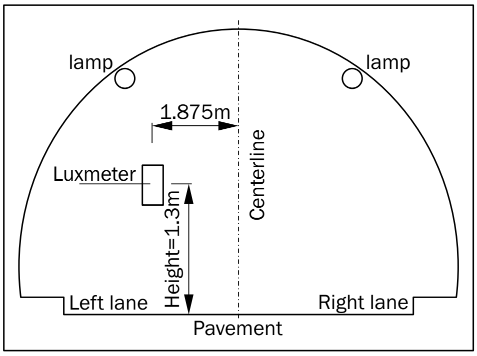
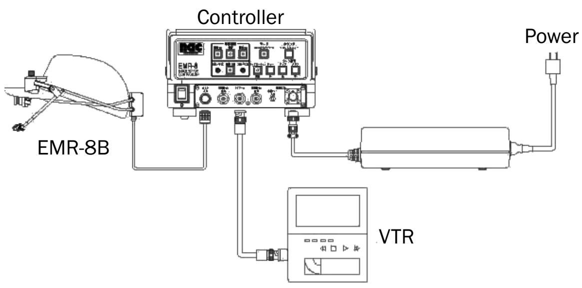


Figure 1 - Sketch map of illuminance instrument



(a) Eye-tracking system

(b) Experiment vehicle

Figure 2 – Pupilsize data acquisition

most popular features was chosen as the experiment vehicle (see *Figure 2*(b)). The size of the eye pupil was the most important consideration in the test, since it is very sensitive and not easy to track. The pupil size of the driver was tracked by EMR-8B, a portable eye-tracking system (ETS) produced by NAC. The ETS was attached to the driver's hat to make sure the pupil size was monitored consistently during the test, as shown in *Figure 2*(a). The data acquisition system, including illuminance measurement and pupil size measurement, was calibrated to ensure the consistency of the timeline of measurements.

2.4 Data collection

Experiments were conducted between 9 a.m. and 3 p.m. to avoid traffic and on sunny days to eliminate weather effects on experimental results. Vehicles drove on side lanes at free speed under the given speed limit. All the experiments were done under similar conditions of weather, time, and tunnel types such that the illuminance and pupil size were obtained with minimal errors. After passing the tunnel entrances, the drivers' comfort degree of visual perceptions were surveyed. The choices in the questionnaire were: extremely uncomfortable, very uncomfortable, uncomfortable and comfortable.

The test instruments, including Test 545 for illuminance and ETS for pupil size, were calibrated before installation. During the test, drivers operated the vehicles according to their customary control without any interference from other personnel. The ETS recorded all pupil-size data, and Test 545 recorded illuminance data at selected measuring points (e.g., -20, 0, 5, 10, 20, 30, 50, and 70 metres away from the inside of the tunnel entrance).

3. EXPERIMENTAL RESULTS

3.1 Relationship between pupil illuminance and pupil size

As shown in *Figure 3*(a), the pupil illuminance, E, in units of lux, is plotted on the X axis, in conjunction with the pupil area, S, in units of mm^2, plotted on the Y axis.

There is no direct quantitative relationship between E and S from *Figure 3*(a), so ES was introduced to further analyze the relationship between E and S. As observed in *Figure 3*(b), $\log_{10}E$ and $\log_{10}(ES)$ are linearly correlated at tunnel entrance. The solid dash line represents the fitting line. The retina's light-adaption mechanism at tunnel entrance is a pupillary light reflex, adjusting the amount of light that reaches the retina. Through linear regression analysis (LRA), the correlation parameters are presented in *Table 2*.

Results indicate that $\log_{10}(E)$ and $\log_{10}(ES)$ correlate very well in a linear relationship, as stated in Equation (1).

$$\log_{10}(ES) = a\log_{10}E + b \quad (1)$$

$$S = 10^{b}E^{a-1} \quad (2)$$

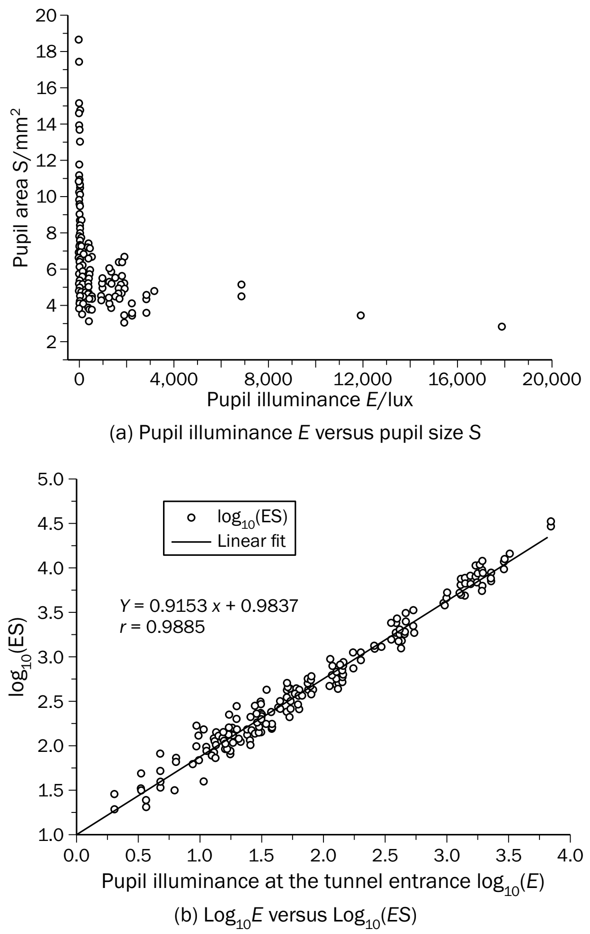


Figure 3 - Relationship between pupil illuminance and pupil size at tunnel entrance

Then the pupil size can be expressed by pupil illuminance in Equation (2). In Equation (2), a and b are constants, and they vary slightly depending on factors of such as pavement properties, tunnel types, and driver habits. According to the linear correlation of $\log_{10}(E)$ and $\log_{10}(ES)$ in *Table 2*, the pupil illuminance E and the pupil size S are in a power function relationship when driving into a tunnel entrance. This is consistent with the Stevens law of experimental psychology, which says that the amount of visual mental physical reactions and the physical stimulus intensity follow a power function relationship.

Table 2 - Inspection table of relationship between $Log_{10}(E)$ and $Log_{10}(ES)$ at tunnel entrance

Parameters / Sample type	Slope a	Intercept b	Correlation Coefficient r	Standard Deviation s	Significance level P	Number of samples n
All samples	0.9153	0.9837	0.9885	0.11448	<0.001	234
Cement pavement	0.8912	0.99902	0.9952	0.11326	<0.001	27
Asphalt pavement	0.9408	0.98298	0.9932	0.04468	<0.001	15
Zhejiang Tunnels	0.92131	0.98252	0.9874	0.11355	<0.001	192
Yunnan Tunnels	0.90579	0.99932	0.9947	0.0632	<0.001	42
Driver age(20 to 30)	0.9081	0.9873	0.9853	0.0923	<0.001	52
Driver age(30 to 40)	0.9244	0.9951	0.9842	0.0743	<0.001	54

3.2 Changing rate of illuminance and pupil area

Test results showed that the drivers' pupil areas changed continuously while vehicles were driving inside the tunnels, indicating rare transient blindness in these driving environments. Transient blindness was generally concentrated in the daytime between 0 to 50 metres away from the inside of the tunnel entrance, where the visual load reached maximum value and hence needed special attention. The monitored short distance around the entrance area takes only 2 or 3 seconds for the test vehicles to drive through. To clarify and simplify the calculation, the driving speed, V (m/s), is considered to be a constant, since the actual acceleration barely varies (<0.5m/s^2) [5]. The velocity of pupil area, V_e, can be expressed as below:

$$V_e = \frac{dS}{dt} = 10^b(a-1)E^{a-2}V\frac{dE}{dx} \tag{3}$$

3.3 Pupil area and its critical velocity

Drivers' pupil is a kind of elastic structure, so the light-adaptation ability is limited. Since the driver has constrained visual adaptation capacity, it is difficult for the lens to accurately focus and make a clear image on the retina when the pupil area changes too rapidly. This often leads to transient blindness, and the transient blindness can lead to unsafe driving behaviours. Our assumption was that safe driving can be ensured when the velocity of pupil area falls in the range of $[V_{ecr}, V_{eci}]$, and that driving is not safe otherwise. The critical velocity of the pupil area is defined as below:

$$V_{ec} = \begin{cases} V_{ecr}(or\ V_{e15}) & V_{ec} < 0 \\ V_{eci}(or\ V_{e85}) & V_{ec} > 0 \end{cases} \tag{4}$$

Wherein, V_{e15} indicates the 15% quantile value of pupil area's velocity, and V_{e85} indicates the 85% quantile value of pupil area's velocity; Vec is the value of pupil area's critical velocity at tunnel portals. We used V_{ecr} (the values can be denoted as V_{e15}) at tunnel exits and V_{eci} (the values can be denoted as V_{e85}) at tunnel entrances.

The roadway of 50 metres away from the inside of the tunnel entrance was divided into 10 sections with 5 metres each. In each section, the 85% quantile values of pupil area's velocity were abstracted to better understand the threshold values of driver's visual characteristics. Based on the statistical analysis, the correlations between pupil area and its velocity at the tunnel entrances are shown in *Figure 4*, Tables 3 and 4.

As summarized from *Table 4*,

$$V_{eci} = fS^2 + gS + h \tag{5}$$

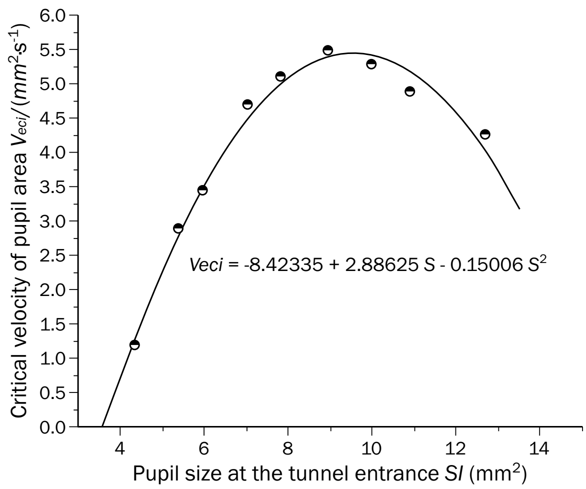


Figure 4 - Correlation between pupil area and its critical velocity at tunnel entrance

where, V_{eci} is the critical velocity of pupil area at tunnel entrance.

From Tables 1, 2 and 4, when the pupil area is very small (<6 mm^2), the critical velocity is small; when the pupil area is between 10 and 14 mm^2, the critical velocity is much larger.

The visual load factor k is based on the critical velocity of the pupil area and was defined as the ratio of

Table 3 - Correlation between pupil area and its changing rate at tunnel entrance

Pupil area S_j (mm^2)	Median pupil area S_{50} (mm^2)	V_{e85} (mm^2/s)	Effective sample size
<4.5	4.374	1.171	8
4.5-5.5	5.391	2.883	10
5.5-6.5	5.983	3.424	18
6.5-7.5	7.069	4.681	26
7.5-8.5	7.843	5.083	30
8.5-9.5	8.973	5.469	20
9.5-10.5	10.010	4.670	18
10.5-11.5	10.920	4.574	18
>11.5	12.702	4.243	10

Note: S_{50} indicates the median of pupil area, and V_{e85} indicates the 85% quantile value of pupil area's velocity.

Table 4 - Relationship between pupil area and its critical velocity

Project condition	Quadratic term coefficient *f*	Coefficient of first degree *g*	Constant *h*	Correlation coefficient *r*	Significance level *P*
V_{eci}	-0.1501	2.8863	-8.4233	0.9463	<0.0001

Note: Quadratic function with 95% confidence level was used for validation.

a pupil area's velocity in relation to its critical velocity at time *t* on certain tunnel roads. For the tunnel road in the daytime, Equation (6) is defined as below:

$$f(t) = k = V_e / V_{ec} = \begin{cases} V_e / V_{eci} & V_e < 0 \\ V_e / V_{ecr} & V_e > 0 \end{cases} \quad (6)$$

Figure 5 shows the visual load is big near tunnel entrances, and *k* is near 1, while *k* is near 0 in the middle of the tunnels. The visual load at the middle tunnel is much lower than the one at tunnel entrances. The visual load at tunnel entrances is near or up to the limit of the driver's capacity to see, so that the velocity of the pupil area may exceed its limit. The value *k* changes significantly at tunnel entrances, which also shows that the visual load of drivers changes significantly during the accommodation process and matches the actual conditions.

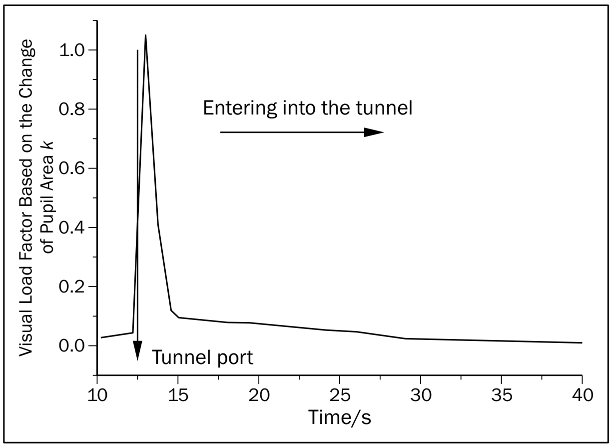


Figure 5 - Visual load factor based on the change of pupil area along tunnel road

4. SAFETY EVALUATION OF THE ILLUMINANCE SETTING

4.1 Safety evaluation of illuminance transition at tunnel entrance

The standard of illuminance transition was established with the survey of the drivers' visual perception as below, based on the visual load factor *k*. When $k > 1$ at the tunnel entrance and the time of operation exceeded the minimum visual simulation time T_m, the conditions were considered to be unsafe (extremely uncomfortable), and the illuminance transition needed to be improved. When $k > 1$ and the operation time was less than T_m but more than 0 second, conditions were considered to be safe, and the illuminance transition needed appropriate improvement. When *k* was between $\bar{k}$ and 1 at tunnel entrances, the conditions were slightly visually uncomfortable. When *k* was less than $\bar{k}$ at tunnel entrances, the conditions were visually comfortable, where $\bar{k}$ was the average visual load factor at tunnel entrances as shown in *Table 5*.

4.2 Ideal setting of illuminance transition at tunnel entrances

At any point *x* away from the inside of the tunnel entrance, if the velocity of the pupil area conformed to Equation (6), which is the average visual load coefficient $\bar{k}$, it was considered to be the most reasonable visual load due to the change of the pupil area, and the illuminance setting was ideal. The ideal velocity of the pupil area was determined as follows:

$$V_e(x) = dS(x)/dt = \bar{k}\, V_{ec}(x)(0 < \bar{k} < 1) \quad (7)$$

Substituting Equation (7) into Equation (5),

$$f\,S^2 + g\,S + h - \frac{VdS}{\bar{k}dx} = 0 \quad (8)$$

Table 5 - Safety evaluation standard of illuminance transition at tunnel entrances

Project conditions	Visual load factor *k*	The minimum visual stimulation time T_m	Corresponding visual perception of drivers' survey	Corresponding illuminance setting
Extremely visually uncomfortable	$k > 1$	$T > T_m$	90% extremely uncomfortable 10% very uncomfortable	Must be improved.
Visually uncomfortable	$k > 1$	$0 < T < T_m$	70% very uncomfortable 30% extremely uncomfortable	Needs improvement.
A little visually uncomfortable	$\bar{k} < k < 1$	-	100% uncomfortable	Needs no improvement.
Comfortable	$\bar{k} < k$	-	-	Needs no improvement.

Note: T_m = 0.2 s for tunnel portals according to the research. T_m has various values from 150 ms to 200 ms, according to the driving experiment [15]. 200 ms is adopted as the value of T_m considering the fixation duration is much longer at tunnel portals than at any other highway section [16].

Solving Equation (8), and Equation (2) substituted, the ideal pupil area at tunnel entrances was obtained as shown in Equation (9).

$$S(x) = \frac{-g + \sqrt{-g^2 + 4fh}\tan\left[\frac{f\sqrt{-g^2+4fh}\,\bar{k}x + VC(1)\sqrt{-g^2+4fh}}{2fV}\right]}{2f} \quad (9)$$

where C(1) was constant, and the ideal pupil illuminance curve was

$$E(x) = \sqrt[(a-1)]{\frac{S(x)}{10^b}} \quad (10)$$

4.3 Case study

For any tunnel on Shangsan Highway in Zhejing, one driver drove 10 times in the daytime. A 50-metre distance from the tunnel entrance was studied: $a = 0.9182$, $b = 0.9833$ at the tunnel entrance. *E*(0) and *E*(50) are known and substituted into Equations (9) and (10), and then $\bar{k}$ and C(1) can be obtained. The current pupil illuminance and ideal pupil illuminance setting are shown in *Figure* 6 and *Table* 6.

Figure 6 and *Table* 6 display these findings:

(1) The current tunnel illuminance level is significantly lower than the CIE088 standards, though they have similar shapes and changing tendencies. The visual load coefficient *k* exceeded 1 from 0 to 10 metres away from the inside of the tunnel entrance, but the duration time was less than 0.2 s, which shows the illuminance setting belonged to the safety range and should be appropriately improved.

(2) The current transition ratio of pupil illuminance was twice the ideal transition ratio of the pupil illuminance and near the driver's adaption limit at 0 to 10 metres away from the inside of the tunnel entrance, which shows that it is necessary to decrease the illuminance transition to reduce visual load at 0 to10 metres away from the inside of the tunnel entrance.

(3) The value of *k* decreased significantly at 30 metres away from the inside of the tunnel entrance, which was all lower than $\bar{k}$ at the tunnel entrance. The pupil illuminance transition was reasonable, and the visual load was not big, which shows that the driver already accommodated the rapid illuminance transition.

(4) The ideal illuminance transition curve did not increase illuminance range a lot (only at 0 to 50 metres away from the inside of the tunnel entrance) and improved the tunnel lighting standard (such as shading setting and solar energy use), which can allay the illuminance transition at tunnel entrance and reduce the visual load significantly at tunnel entrances.

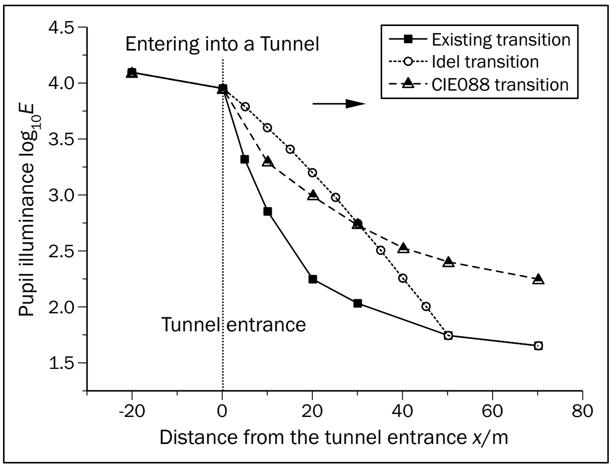


Figure 6 - Pupil illuminance setting at the tunnel entrance

5. CONCLUSION

(1) At 50 metres away from the inside of the tunnel entrances, the relationship between the pupil area and pupil illuminance is a power function, which coincides with the Stevens law from experimental psychology, which states that the amount of visual mental physical reactions and the physical stimulus intensity follow a power function relationship. The relationship also presents that the index of the pupil area is more appropriate than the pupil diameter to analyze the pupillary light reflex and visual load.

(2) The pupil area and the critical velocity of the pupil area are in a quadratic function relationship at tunnel entrances. The ratio of the pupil area's velocity in relation to its critical velocity (denoted as *k*) can be used to evaluate the psychological visual load at tunnel entrances; the visual load at tunnel entrances is larger than the one at the middle tunnel, and the illuminance transition is severe and the visual load is at maximum 0-10 metres from the inside of the tunnel entrances where the improvement is needed.

Table 6 - Current visual load factor k at tunnel entrance

Projects \ X value	0	5	10	20	30	50
Current K	1.143	0.852	0.346	0.165	0.113	0.094
Current pupil illuminance transition D*E*/dx(lx/m)	-1400	-276	-54.4	-6.7	-2.7	-1.0
CIE088 illuminance transition D*E*/dx(lx/m)	-845	-186	-34.4	-3.7	-1.7	-0.7
Ideal pupil illuminance transition D*E*cr/dx(lx/m)	-589.2	-423.1	-244.9	-103.0	-25.2	-2.3
Current/Ideal illuminance transition ratio	2.382	0.651	0.220	0.065	0.102	0.431

Note: all k values are the average of 10 times testing. 8 times are very uncomfortable and 2 times are extremely uncomfortable according to the driver's visual perception survey. The average vehicle speed is 97.77 km/h at the tunnel entrance. $\bar{k} = 0.293$.

(3) Current tunnel entrances usually use sidewall entrances, and the tunnel lighting is set at 10 metres away from the inside of the tunnel entrance. If illuminance is enhanced to allay illuminance transition, the maintenance costs will increase and be difficult to manage. It is suggested that additional shading settings can allay the illuminance transition (such as horn-type entrances, bamboo-truncating entrances and grille entrances) from 0 to 30 metres away from the inside of the tunnel entrances to accommodate the eye movement of the drivers and make it near to an ideal pupil illuminance setting. Buses and trucks should be adopted as vehicle sample in the future.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (No. 51008241) and China Scholarship Council (No.201308420161).

摘要

基于瞳孔变动的公路隧道入口照度过渡安全评价

本文选取26条典型公路隧道及8名驾驶员被试，利用EMR-8B眼动仪系统，测定驾驶员通过隧道入口的瞳孔变动。实验表明，在隧道入口驾驶员瞳孔面积及驾驶员瞳孔照度呈幂函数关系；同时，进一步建立了隧道入口瞳孔面积及面积变动临界速度定量关系，在此基础上利用瞳孔面积速度与瞳孔面积临界速度比值（定义为k）来评价隧道入口视觉负荷及照度过渡，然后构建了基于合理k值的隧道入口照度过渡理想曲线。结果表明隧道入口瞳孔照度与驾驶员瞳孔面积关系符合实验心理学中的史蒂文斯定律；驾驶员瞳孔面积及面积变化临界速度呈二次函数关系；现有公路隧道入口0~10m存在剧烈的照度过渡，视觉负荷极大，且亟需改进。

关键词

公路隧道; 入口; 照度过渡; 瞳孔变动; 视觉负荷

REFERENCES

[1] **Wang BX**. *Analysis of the characteristics of tunnel traffic accidents on Expressway*. Traffic and Transportation. 2012;12(1):22-27.

[2] **Dai YH**, **An CJ**, **Liao ZG**, et al. *Traffic safety features of expressway tunnel section*. High Traffic Information and Safety. 2010;28(2):101-105.

[3] **Pachamanov A**, **Pachamanova D**. *Optimization of the light distribution of luminaries for tunnel and street lighting*. Engineering Optimization. 2008;40(1):47-65.

[4] **Kircher K**, **Ahlstrom C**. *The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers*. Accident Analysis & Prevention. 2012;47:153-161.

[5] **Yang Z**, **Guo ZY**. *Research on Speed Alteration at Entrance and Exit of Tunnel*. Shanghai Highway. 2006;(1):48-51.

[6] **Dai YH**, **Guo ZY**. *Effect of Spatial Visual Pattern on Driving Behaviour in Expressway Tunnel Section*. Journal of Tongji University (Natural Science). 2011;39(9):1307-1312.

[7] **Shi LD**, **Liu HX**, **Zhao WH**. *The Influence of Lighting Zone on Vision Information Capturing for Extra-long Tunnel*. Highway. 2011;(6):213-218.

[8] **Macdonald JSP**, **Lavie N**. *Visual perceptual load induces inattentional deafness*. Attention, Perception, & Psychophysics. 2011;73(6):1780-1789.

[9] **Purves D**. *Neuroscience*. 4th ed. Sinauer Associates; 2008.

[10] **Kramer AF**. *Physiological metrics of mental workload: A review of recent progress*. Multiple-task performance. 1991:279-328.

[11] **Kun AL**, **Palinko O**, **Razumenić I**. *Exploring the effects of size and luminance of visual targets on the pupillary light reflex*. Proceedings of the 4th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. ACM. 2012:183-186.

[12] **Palinko O**, **Kun AL**. *Exploring the effects of visual cognitive load and illumination on pupil diameter in driving simulators*. Proceedings of the Symposium on Eye Tracking Research and Applications. ACM. 2012:413-416.

[13] **Cheng ACK**, **Rao SK**, **Cheng LL**, et al. *Assessment of pupil size under different light intensities using the Procyon pupillometer*. Journal of Cataract & Refractive Surgery. 2006;32(6):1015-1017.

[14] **Ying-kuia HU**, **Jib W**, **Yib LI**, et al. *The change rule of driver's pupil size under road lighting conditions*. Journal of Chongqing University. 2010;8:018.

[15] **Tomoki F**, **Kadoma T**, **Iwasaki M**. *Eye movement and driving behavior in curved section passages of urban motorway* [CD-ROM]. TRB Annual Meeting; 2005.

[16] **Du ZG**, **Jie L**, **Pan XD**. *Driver's minimum fixation duration's ascertain and application in freeway tunnels*. Journal of Highway and Transportation Research and Development. 2010;26(9):118-120.