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Dark Adaptation Time Study on Road Tunnel Daytime Lighting Based on Visual Performance Method

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Visual adaptation in road tunnel daytime driving is very important to driving safety and should be paid full attention. Visual adaptation consists of light-adaptation and dark-adaptation, daytime threshold zone dark-adaptation problem when driving from outside into the tunnel is more important in tunnel lighting, current studies have described significantly distinct in the length of adaptation time. This study simulates the daytime lighting environment in the road tunnel threshold zone and records the reaction time and pupil change to many test subjects according to visual performance method in the condition of the luminance from light condition (ambient exterior luminance 4000 $cd \cdot m^{-2}$) and to dark condition (interior zone luminance 2$cd \cdot m^{-2}$), through the data analysis the length of dark adaptation time is obtained (19.8s). Study on length of effective dark adaptation time can provide length basis for road tunnel threshold zone daytime lighting design.

1. Introduction

Visual adaptation in road tunnel daytime driving is very important to driving safety and the accidents happened in tunnels emerge in endlessly (Yeung and Wong, 2014; Kircher and Ahlstrom, 2012), so it should be paid full attention. The visual adaptation consists of light-adaptation and dark-adaptation, driving outside the tunnel in the daytime corresponds to light-adaptation and the time is relatively short while driving into the tunnel in the daytime corresponds to dark-adaptation and the time is relatively long. The degree of adaptation is closely related to driving safety. The main objective of road tunnel lighting with many changes in light and dark is to diminish dark AT (adaptation time) and through installing transitional lighting to meet the demand of the visual adaptation (Zhou et al., 2016).

The length of light and dark AT is related to the ratio of luminance change, absolute value (Blaser and Dudli, 1993) and individual physiological factors. Generally speaking, the light-adaptation time is about several seconds to several minutes while the dark AT is more than ten seconds or half an hour. Kabayama (1967) proposed that one needs about ten seconds to restore eyesight in dark-adaptation but about 1 second in light-adaptation. Zhang and Zhang (1994) did the investigation on vehicle drivers' dark-adaptation, concluded the overall mean dark AT is 34.17±14.25 seconds. Xie Xiuying believed that one can restore ordinary visual work in about 1 minute when entering the light environment from the dark. Only after 3~5 minutes the outline of the surroundings can be differentiated when entering the dark from the light. Du and Huang, (2013) evaluated the visual burden of road tunnel through pupil size changing speed, pointed out that in the middle and long tunnels, the dark AT is less than 23 seconds and the light-adaptation time is less than 13 seconds. A. Pena-Gacia (2012) pointed out that one needs at least 8 minutes to adapt to the dark environment from the light. Huang Yan believed that one needs about 30 to 40 minutes to gain the complete dark-adaptation. This time is a bit too long and is meaningless to tunnel lighting design. The stipulations above have great differences, the reasons are on one side the adaptation region is different (different luminance change), on the other side the research method is also different. Different industries have studied the AT aimed at their specialty, but lack of the pertinence of road tunnel lighting. The thesis defines the dark adaptation of achieving road tunnel driving visual acknowledgement and ensure driving safety as road tunnel effective dark-adaptation, the dark AT under this condition has more research and applicable value to road tunnel driving safety.

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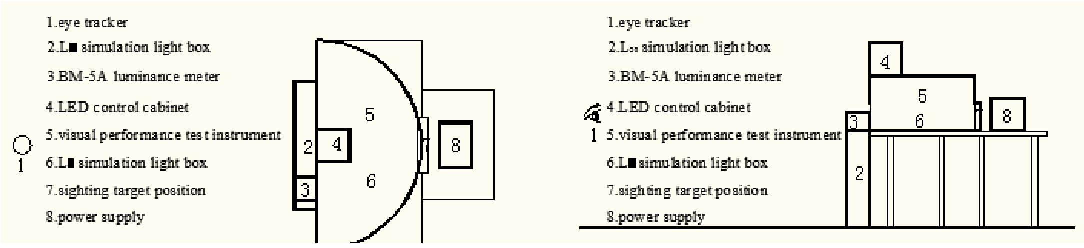
Visual performance method have been applied in road tunnel lighting research. Nakamichi and Narisada, (1967), and Kabayama (1967) proposed visual performance method, whose experimental contents are just measuring the RT (reaction time) data of visual performance. Zhang and Hu, (2017) analyzed the comprehensive efficiency of road tunnel lighting based on visual performance method. Zhang and Yang, (2009), Zhang and Li, (2013), and Li (2009) studied the influence to road lighting in virtue of RT. Du et al., (2007), and Hu et al., (2016) studied the road tunnel lighting in the means of pupil change.

2. Research method

The thesis adopts visual performance method, simulates and reappears road tunnel driving optical circumstance in the lab, finishes the experiment on pupil change and RT. The pupil change is related with safety and comfort while the RT is coherent to driving safety. The test are aimed at 13 test subjects, seven males (occupy 54%) and six females (occupy 46%), aged between 20 and 30. The naked eye vision are meanly above 0.7 (the decimal eye chart), all without color blindness and weakness.

2.1 Experiments on pupil change

(1) Experimental instruments: Road tunnel visual performance test instrument, road tunnel ambient exterior luminance (L_{20}) simulation light box, interior zone luminance (L_{in}) simulation light box, LED light controlling box, BM-5A luminance meter, iView-X eye tracker, CS-2000 spectral radiation luminance meter etc. The plan and elevation of the experiment are shown in Figure 1 and the experimental instruments in Figure 2.



(a) Plan (b) Elevation

Figure 1: Plan and elevation of the road tunnel visual performance experimental instrument (pupil change)

Figure 2: Experimental instruments

(2) Experimental parameters

The luminance of each lighting zone are based on CIE88-2004, the luminance between ambient exterior and interior zone is smoothly changed. The value of L_{20} is typical value of 4000 cd·m^{-2}, and the L_{in} is 2 cd·m^{-2}. The final purpose is to find how long the time will be to adapt from the L_{20} to L_{in}. The time difference is just the time utilized in the strengthened entrance lighting zone. The study adopts same light source, which is LED that with high luminous efficiency, good light color and good adjustability, The CCT (abbr. for correlated color temperature) of the LED lights is 5000K and the CRI (abbr. for color rendering index) is 75.3. The SPD (abbr. for spectral power distribution) of the light is shown in Figure 3.

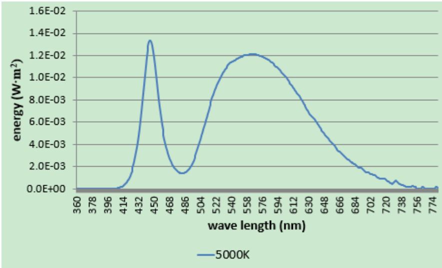


Figure 3: SPD of the experimental LED lights

(3) Experimental procedure

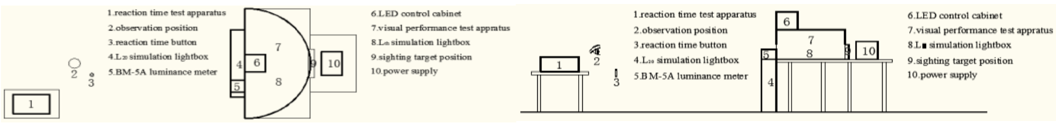
The test subjects take part in the experiment in good manner. Firstly, the test subject concentrates on the exterior environment, after full adaptation the subject watched the L_{20} simulation light box (with the luminance of 4000 cd·m^{-2}); Secondly, after full adaptation, shut off the L_{20} simulation light box and at the same time turn on the L_{in} simulation light box, the sighting target (with the size 0.01m×0.01m) will appear in three different position (-10°, 0°, 10°) randomly meanwhile. The test subject searches and verifies the sighting target in the L_{in}. Finally, the eye tracker records the data of pupil change and scenario change.

2.2 Experiments on RT

(1) The test subjects are the same to the experiment of pupil change. The experimental instruments are also similar to last experiment, but without eye tracker. The plan and elevation of the experimental instruments are shown in Figure 4.

(2) Experimental procedure

The test subjects take part in the experiment in good manner. The first procedure is just like the last experiment; Secondly, after full adaptation, turn on the L_{in} simulation light box and the subject waits for different AT (5s, 10s, 15s, 20s, 25s, 30s, 35s, 40s, 45s, 50s), then the sighting target (with the size as above) will appear in three different position (the angle as above) randomly meanwhile the RT instrument begins to count the time. The test subject searches and verifies the sighting target in the L_{in}. When the subject finds the sighting target, the RT button will be pressed. Finally, the RT instruments record the RT (between releasing the sighting target and pressing the button).



(a) Plan (b) Elevation

Figure 4: Plan and elevation of the road tunnel visual performance experimental instrument (RT)

3. Research result

The road tunnel effective dark AT are verified by synthesizing the data of pupil change and RT. The distinguish basis for pupil change is the trend of pupil size. When the trend is stable which means adaptive. The distinguish basis for RT is the principle of shorter RT reflects more adaptive.

The experiments are tested to 13 test subjects. Finally, the results are as follows.

3.1 Data of pupil change

There are many data through iView-X eye tracker. A frame occupy 50ms and there are 20 frames in one second. The typical data are shown in Figure 5~7.

In Figure 5, the horizontal axis means time with the unit frame, while vertical axis means the diameter of pupil with the unit mm (millimeter), the blue data stand for X-directional pupil size and the red data stand for the Y-directional pupil size. The law of the two are quite similar. For analyzing the data more conveniently, smoothing the data of Y-directional pupil size, the results are shown in Figure 6.

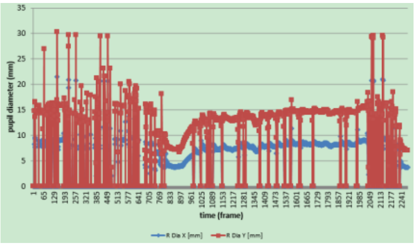


Figure 5: Pupil change data of a test subject

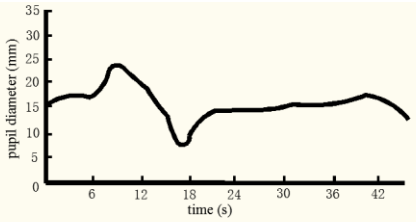


Figure 6: Pupil change data of a test subject after smoothing

From Figure 5~6, the pupil size is changing rapidly with the different adaptation. When human eyes adapt to some extent, that is, when the lights become weak that leads to the pupil size increasing to some extent, the data shows some law. When the luminance from 4000 cd·m^{-2} to 2 cd·m^{-2}, the pupil size gradually enlarged from 801 frames (with the Y-directional diameter 3.2726mm) to 1201 frame (with the Y-directional diameter 5.8609mm). It can be seen that the total time is 400 frames (20.0 seconds) to the overall adaptation procedure and accomplished the adaptation task. In order to see the procedure more clearly part of the data is enlarged to Figure 6.

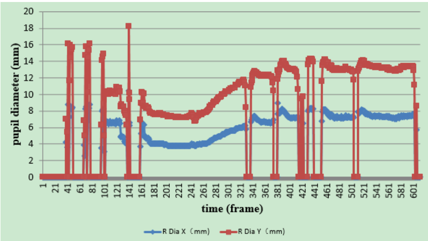


Figure 7: Pupil change data of a test subject after cutting out

From Figure 7 the procedure can be seen more clearly. From 4000 cd·m^{-2} to 2 cd·m^{-2}, the pupil size gradually enlarged from 159 frame (with the Y-directional diameter 3.2726mm) to 559 frame (with the Y-directional diameter 5.8609mm). The total adaptation procedure cost 20.0 seconds.

In the same way 8 groups of effective data are achieved through trimming. The other data lack of some useful data or the instruments meet some problems. The useful data are shown in table 1.

Table 1: Dark AT of the test subjects from the pupil change

Test subjects	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
gender	male	male	female	female	female	female	male	male
age (a)	24	21	21	30	26	30	22	26
Dark AT (s)	19.9	20.2	22.1	19.2	18.7	18.8	19.1	18.8

The statistical results to the data of effective AT are shown in table 2.

Table 2: Effective dark AT statistics

Mean value (s)	Standard deviation (s)	Observation data	Confidence coefficient (95%)
19.6	1.16	8	0.97

The statistics shows that the length of effective mean dark AT is 19.6 seconds.

3.2 RT data

The shorter RT means safer driving behavior and the suitable AT is corresponding to this shortest RT. So the shortest RT is the basis here.
Select the data of a test subject and listed in table 3. Here the data of RT and AT are fitted and the result shows with the increase of AT the RT firstly decrease and then increase. The fitting result shows they conforms best to quadratic, the R^2 (multiple correlative coefficient) is 0.7067. Shown in Figure 8.

Table 3: The AT and RT of a test subject

AT (s)	5	10	15	20	25	30	40
RT (ms)	458	443	432	302	347	364	457

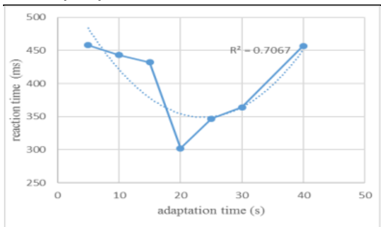


Figure 8: The relationship between RT and AT of the subject

From Figure 8, the shortest RT of this subject is 302ms, and the corresponding AT is 20s. Eleven groups of data among thirteen subjects are effective. After analyzing the data, the results are shown in table 4.

Table 4: The effective dark AT data corresponding to the RT of all subjects

Test subjects	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Shortest RT(ms)	384	410	293	275	416	361	309	286	302	375	481
Effective dark AT(s)	25	10	25	15	30	35	25	30	20	40	15

Through the analysis, the effective dark-adaptation (some of the data in table 4 are the same) time and shortest RT data are shown in table 5.

Table 5: The data of effective dark AT and shortest RT of all subjects

Effective dark AT(s)	10	15	20	25	30	35	40
Shortest RT(ms)	420	386	295	310	350	360	375

Fit the relationship of dark AT and shortest RT, the relationship conforms to quadratic the best, the R^2 is 0.7601. Shown in Figure 9. When the shortest RT is 20s the effective AT is 20.0s.

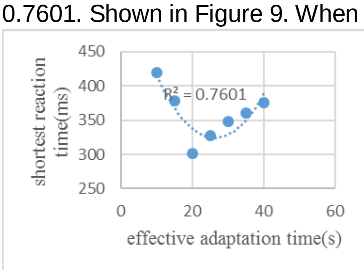


Figure 9: Relationship between effective AT and shortest RT

4. Conclusion

The thesis introduced visual performance method, utilized the parameters of pupil change and RT, and finished the experiment on dark AT. Synthesize the two results, the conclusions are drawn.
(1) Although complete adaptation is important, for the road tunnel driving, the AT in complete adaptation is too long and lack of actual meaning. Through the current studies, human eyes can even accomplish visual work

while driving into the tunnel without complete adaptation. This thesis defines this time as effective dark AT, which is the start point of this study.

(2) The study adopted visual performance, the parameters are respectively pupil change and RT. Through the two parameters the mean effective dark AT is 19.8s when the luminance is typically from (L_{20}) 4000 cd·m^{-2} to (L_{in}) 2 cd·m^{-2}.

(3) According to the principle of effective dark AT corresponds to tunnel travel length, the length of the strengthened entrance lighting zone is 440m. Through the analysis to CIE and the specifications of many countries, the conclusion is that in order to achieve driving safety utmost, the length of CIE and the stipulations of other countries should be prolonged.

(4) The constitution of eyes and visual fatigue caused the great difference to the current study and the commonly thinking.

(5) This study aimed at the luminance change from ambient exterior to interior zone, the luminance values are typical 4000 cd·m^{-2} to 2 cd·m^{-2} and the travel speed is 80km·h^{-1}. The future study will aim at more luminance change and travel speed, to perfect and replenish the effective dark AT research.

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