Vault design of highway tunnels based on the driver’s physiological characteristics

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ABSTRACT
Most studies about tunnel environments focus on the adjustment of brightness in tunnels and pay little attention to the decoration of the walls. This study is based on a highway tunnel in Jilin province, China. Five design schemes (white, gray, dark-blue, light-yellow, and blue sky with white clouds) were selected for the tunnel vaults. The experiment was conducted on a self-developed driving simulation platform. Pupil diameter and heart rate growth (HRG) were proposed to analyze the driving comfort. A SMI eye tracker and a Polar heart-rate belt were employed to record the pupil diameter and heart rate, respectively. The results indicate that the color of the tunnel vault considerably influences the pupil diameter and HRG of a driver. The degrees of emotional fluctuation and psychological tension are higher for drivers in dark-color environments than in light-color environments. Therefore, light colors must be prioritized when designing tunnel vaults. The results also indicate that a tunnel vault in blue sky with white clouds is the most comfortable for drivers. This experiment provides a reference for the tunnel design.

1. Introduction
The rapid rise in the social economy has resulted in the need for constant improvement in the road traffic infrastructure. By the end of 2018, there were 17,738 highway tunnels in China, including long and extra-long tunnels accounting for more than 30% (MTPRC 2019). Although tunnels improve traffic convenience, they give rise to challenges involving the driving environment. For example, owing to the particularity of the tunnel structure, a driver would be nervous and afraid when the line of sight disappears, thereby increasing the rate of accidents (Leitner 2001; Kirkland 2002; Carvel and Marlair 2005).

Domestic and foreign scholars have conducted many studies on the safety of tunnel environments. According to the tunnel structure, the research objects were divided into the external environment, transition environment, and internal environment. The external environment was primarily based on the tunnel landscape. Ye et al. (2012) analyzed the design scheme of the mountain highway tunnel to reduce visual fatigue and
proposed a principle of landscape design. The transition environment was dominated by the change of illumination at the entrance and exit of the tunnel. Improper illumination inside and outside the tunnel would lead to visual problems faced by the driver such as the black-hole and white-hole effects. Onaygil, Güler, and Erkin (2003) proposed that certain structural measures must be taken in the access and the entrance zones of the tunnel to reduce the lighting level of the access zone and improve the safety and comfort of driving. The internal environment included tunnel lighting and color. Based on the different positions, tunnel design could be divided into the sidewall and vault. In the study of the safety of the tunnel sidewall color, Manser and Hancock (2007) believed that the tunnel sidewall pattern considerably influenced a driver’s perception of speed and control force. Kircher and Ahlstrom (2012) considered that the accident rate was lower in the case of light-colored sidewalls than in the case of dark-colored sidewalls. Moreover, Norway, Sweden, and other countries have proposed white-colored sidewalls within a certain height.

Many studies on tunnel traffic safety involved the drivers’ visual and psychological characteristics. The visual perception was an important information source to judge safety while driving (Duncan and Humphreys 1989; Sivak 1996). Most of the external information was directly received by the eyes and then sent to the brain. Wierwille (1999) first proposed the concept of percentage of eye closure (PERCLOS) that was used to judge the degree of fatigue of the driver when driving. Sodhi and Reimer (2002) pointed out that the duration of distracted driving, looking away from the front area, directly determined driving safety. In other words, the longer the distraction duration was, the more likely the vehicle was to deviate from its lane or collide with nearby vehicles. By recording the drivers’ eye movement data and selecting six eye movement indices that include fixation time and pupil diameter, Liang, Lee, and Reyes (2007) developed a relationship model between a driver’s behavior and distraction. In the aspect of a driver’s psychological characteristics, scholars discussed the relationship between heart rate and driving behavior. Miller and Boyle (2015) analyzed driver stress under complex traffic environments through heart rate and standard deviation of interbeat intervals, they discovered that drivers were uncomfortable with the tunnel segments. Feng et al. (2018) established a relationship between HRG, speed, and urban tunnel pavement slope and analyzed the safe slope and speed control value.

In conclusion, scholars have implemented studies on tunnel safety and achieved some findings, but there are few studies on the effect of the decoration of the tunnel vault on driving behavior. In investigating a large number of operational tunnels, it was found that the vault color was mainly white, yellow, blue, and gray. Some tunnels adopted blue sky and white clouds, stars, and other patterns. When driving in the tunnel, the tunnel vault occupied a large proportion of the drivers’ visual range. Different decoration colors affected drivers’ visual perception and driving psychology, which impacted the comfort and safety of driving. Based on a highway tunnel in Jilin Province, China, this study recorded the drivers’ pupil diameter and heart rate while driving with different vault colors. The results were analyzed to determine the influence on driving comfort, in order to recommend colors that would improve driving safety in the

Figure 1. Research results in China.
Figure 2. Statistical chart of solid color of tunnel vault.

(a) White
(b) Gray
(c) Light yellow
(d) Dark blue
(e) Blue sky with white clouds

Figure 3. Test schemes.
tunnel. This study also provided a reference for the design of tunnel decoration in the future.

2. Test scheme of tunnel vault color

2.1. Project overview

The parameters of the test model were based on a highway tunnel in Jilin province, China. The tunnel was 610 m long, and it had two lanes in each direction; the speed limit was 80 km/h. According to the structure of the tunnel, the decoration design could be divided into sidewall and vault. The sidewall was decorated mainly with white tiles.

2.2. Test scheme design

Through the investigation of existing tunnels in China, covering Shaanxi, Shanxi, Liaoning, and other provinces, nearly 300 cases of domestic tunnel decoration were categorized as shown in Figure 1, indicating that the color of vault decoration was mainly gray, blue, white, and yellow. Figure 2 indicates that 270 cases had solid color for tunnel vaults, accounting for 90%. Among them, the vault was mainly decorated in gray, with little difference in proportion between blue, white, and yellow. Interestingly, color usage has a definite relationship with the design age. In earlier constructions, tunnels were generally in gray, whereas light yellow and light blue have been gradually applied in recent years. Patterns such as a blue sky with white clouds and stars were introduced with the construction of long and extra-long tunnels.

To analyze the influence of the color of the tunnel vault on driving comfort, this experiment chose five decoration schemes: white, gray, light yellow, dark blue, and blue sky with white clouds (later referred to as clouds) as shown in Figure 3(a–e). To minimize the influence of white- and black-hole effects on driving behavior, the illumination at the tunnel’s entrance zone was consistent with the tunnel’s access zone.

3. Driving simulation experiment

3.1. Principle

Existing research (Farah et al. 2012; Manseer and Riener 2014) has investigated tunnel drivers’ physiological characteristics, mainly focusing on visual and electrocardiogram attributes. Based on the driving simulation platform, this study analyzed the influence of vault color on driving comfort by observing drivers’ pupil diameter and heart rate. Specific parameters were selected as follows:

3.1.1. Pupil data

A total of 80% of the information was obtained by the driver’s vision while driving, which shows that vision is the sense of receiving the most information (Anshel 2007). Besides, people’s processing of information appears to be physiological characteristics, including pupil size, heart rate, respiration, etc. Therefore, pupil size can be used as a sensitive index of physiological characteristics. Because pupil size is different in different individuals, it is meaningless to study the relationship between pupil size in different people. Therefore, to compare and analyze, this paper takes the percentage change in pupil size as an alternative. According to existing research (Zhao and Hu 2007), the threshold value of the percentage change in pupil area (U) in the driving process is defined as (1) comfortable if U < 20%, (2) more nervous if 20% ≤ U ≤ 40%, and (3) very nervous if U > 40%.

Percentage change in pupil area is represented by:

\[
U = \frac{\text{Pupil area under driving} - \text{Pupil area without driving}}{\text{Pupil area without driving}} \times 100\% 
\]  

(1)

The pupil diameter data were gauged directly by the eye tracker, considering that the shape of the pupil was approximately circular. This study used the percentage change in pupil diameter instead of the percentage change in pupil area for performing driving comfort analysis, and the formula was as follows:

\[
E_i = \frac{(e_i - e)}{e} \times 100\% 
\]  

(2)

Where \(E_i\) = percentage change in pupil diameter when driving in the tunnel in the moment \(i\) (%); \(e_i\) = pupil diameter when driving in the tunnel in the moment \(i\) (mm); \(e\) = pupil diameter without driving in the tunnel in the moment \(i\) (mm).

As a result, the threshold value of driving comfort was adjusted to (1) comfortable if \(E_i < 10\%\), (2) more nervous if 10% ≤ \(E_i\) ≤ 18%, and (3) very nervous if \(E_i > 18\%\).

3.1.2. Heart rate

Heart rate can reflect the driver’s nervous and irritable mental state to some extent. Because of an individual’s physical condition, the driver’s heart rate has differences in the same situation, Therefore, a simple comparison of heart rate changes cannot reflect the impact

Figure 4. Driving simulator.
3.2. Driving experimental simulation and could form characteristics.

Figure 5. Eye tracker.

Figure 6. Heart rate belt and dressing effect.

- of the road environment on a driver’s physiological characteristics. Consequently, this test proposed HRG as the evaluation index and analyzed the driving comfort from this perspective. This was calculated as

\[ N_i = \frac{(n_i - \bar{n})}{\sigma} \times 100\% \]  

Where \( N_i \) = HRG when driving in the tunnel in the moment \( i \) (%); \( n_i \) = heart rate when driving in the tunnel in the moment \( i \) (bpm); \( \bar{n} \) = heart rate without driving in the tunnel in the moment \( i \) (bpm).

3.2. Experimental equipment

3.2.1. Driving simulator

This test adopted a self-developed driving simulation system. The main components of the driving platform were a computer simulation system and a driving simulator. The computer simulation system used the game software Euro Truck Simulator 2 as the test platform and Blender and Photoshop CS6 as the modeling and rendering tools. This software was compatible with the code to facilitate building a realistic tunnel driving simulation scene. The self-developed driving simulation platform is shown in Figure 4.

The biggest advantage of this platform was that it could generate traffic flow, and simulate different times and weather conditions. Thanks to the high picture quality of the simulation scene, realistic lighting, and texture, the driving simulator could create a close-to-real driving environment. Besides, the ambient and car sounds in the driving simulator were all from the real environment, so that the driver was immersed in the virtual scene.

3.2.2. Eye tracker

The eye data acquisition equipment is an eye tracker produced by a German SMI company (Figure 5). The eye tracker is a portable, eye-glass eye tracker, comfortable to wear, without any restrictions on the use of the environment. Device data, sampled at a frequency of 120 Hz, can automatically compensate for deviations to ensure reliable data collection.

3.2.3. Heart rate belt

The driver’s heart rate was recorded using a Polar heart rate band (Figure 6), which worked with the micro-voltage signal generated by the heartbeat, the same principle as the medical electrocardiogram. Heart rate data were transmitted in real time via Bluetooth, without interference with the driver.

3.3. Experimental process

Too few participants will reduce the reliability of the results, while too many will result in a waste of time and resources. The selection of sample size in this paper is based on expected variance, target confidence, and error margin to calculate the required sample size. The calculation formula is:

\[ n = \frac{Z_{\alpha/2}^2 \sigma^2}{E^2} \]  

(4)
Where \( n \) is the sample size; \( Z \) is the standard normal distribution statistic; \( \sigma \) is the standard deviation; \( E \) is the maximum error.

In this paper, the significance level of 20% is chosen to reflect the 80% confidence level of unknown parameters. When the confidence level is 80%, \( Z_{0.25} = 1.282 \sigma \) value is 0.25 ~ 0.5 (Chow et al. 2008), due to the driving simulation test limit, the value of \( \sigma \) is 0.25; \( E = 10\% \). Therefore, the minimum sample size required for calculation is 11 people. A total of 13 licensed drivers were recruited as the participants, including 9 males and 4 females, aged 21 to 48 years (based on the gender and age ratio of Chinese drivers). All participants must have at least two years of driving experience and have driving experience in tunnels. Also, participants must not be color blind or chromaticity, with normal naked vision or corrected vision. To avoid the influence of external factors, the subjects did not exercise vigorously 1 hour before the experiment, did not drink alcohol or caffeine within 12 hours before the experiment, and ensured adequate sleep. Besides, the purpose, location, and sequence of the tests were not informed in advance. To avoid interference of other electrical signals with the acquisition instrument, all unrelated electronic devices were turned off during the test process.

\[ \text{Figure 7. Familiarize training.} \]

\[ \text{Figure 8. Eye tracker calibration.} \]

\[ \text{Figure 9. The test process.} \]

\subsection{3.3.1. Measuring static heart rate}

Before the test, each participant wore the heart rate band to measure the heart rate in a calm state. The data acquisition process was carried out in strict accordance with the requirements of equipment operation to ensure the continuity and effectiveness of the data.

\subsection{3.3.2. Familiarization training}

The test participants were informed how to operate the driving simulator, then they were required to complete the simulation scene familiarization training, as shown in Figure 7. Participants are required to drive in the specified simulated road environment for at least 20 minutes without additional driving tasks, only adapt to the simulated driving environment, and obey traffic rules during the driving process.

\subsection{3.3.3. Eye tracker calibration}

After training, the participants wore the eye tracker to correct the error between the eye and the device by calibration. The calibration adopted the 3-point method, and the 4th point was used for verification. At the same time, the current pupil diameter was collected. Only when the calibration results met the test requirements could the formal test be started. If the standard was not achieved, the calibration was adjusted repeatedly until the requirements were attained. The calibration process is shown in Figure 8.

\subsection{3.3.4. Formal test}

To avoid excessive testing requirements disturbing the drivers, participants drove freely according to personal habits, passing through five tunnel models in turn. During the experiment, the recorder always paid attention to the working conditions of the instruments. If the equipment failed midway, the data were considered invalid and the test was restarted after adjustment. After passing through each tunnel, the driver took a 10-minute break to re-establish the initial psychophysical conditions and recalibrate the settings until all simulation tests were completed, as shown in Figure 9.
4.1.1. Eye movement data

The main factors that affect the size of the pupil are light intensity, color, and mood (Watson and Yellott 2012). The driver remained in a calm state before each test. Since the pupil size is greatly affected by the illumination intensity, we strictly controlled the illumination before the test to make the change of pupil size more closely related to the tunnel vault color as far as possible. From modeling to driving simulation, brightness control is divided into four aspects: 1. The brightness of the color itself in the modeling; 2. Brightness, reflectivity, and other parameters in material adjustment; 3. The brightness of the screen; 4. Laboratory environment brightness. In this model, we strictly controlled the brightness from 2 to 4 aspects to ensure that the difference of brightness in driving in the tunnel was only related to the color of the tunnel vault.

4.1.1. Pupil diameter

The experiment was conducted under 5 color factors (white, gray, light yellow, dark blue, and clouds). Figure 10 (a) and (b) show the pupil diameter results of participants 4 and 9 when driving in the tunnel, where 1 represents the moment when the vehicle enters the tunnel portal, and 24 represents the moment of departure from the tunnel. Table 1 shows the mean pupil diameter of all participants.

From the results of the two sets of experiments, it can be seen that drivers’ pupil diameter changed greatly in the enter and exit zones. The pupil diameter increased significantly when entering the tunnel, and the pupil diameter decreased significantly when driving out of the tunnel. This phenomenon was mainly attributed to the difference in brightness between the inside and outside of the tunnel. When driving from the open environment into the closed environment, the driver would have a sense of tension and the pupil diameter would increase to a certain extent.

During the tunnel driving, there was visual disturbance caused by the change of illumination. Relevant tests show that visual disturbance rarely appears in the middle of the tunnel. Therefore, visual disturbance testing generally focuses on the distance between 5 ~ 50 m.
from the entrance of the tunnel in the daytime, indicating that the tunnel entrance and exit zone visual disturbance is the most obvious (Qin et al. 2018). This study mainly focused on the impact of vault color on comfort when driving in the tunnel. To reduce the impact of visual disturbance two data points before and after the test were removed. Specifically, twenty experimental data points from the middle section were selected. Table 1 is the mean of the pupil diameter of all drivers after processing.

From the test results, it can be seen that drivers’ pupil diameters were significantly larger while driving in the gray and dark blue environments when compared to the white, light yellow, and clouds environments, indicating that the deep color gave drivers a higher sense of tension. Out of the five groups of vault color, the clouds resulted in a generally small pupil diameter, and the fluctuation was not obvious. The clouds belonged to the light color system decoration that created a more open driving environment, reduced closed and depressed feelings, and improved driving comfort to some extent. The order of influence of decoration on driving is deep pure color > light pure color > clouds.

4.1.2. Percentage change in pupil diameter
4.1.2.1. Significance test of difference. In order to further study the influence of vault color on driving behavior, a significant difference analysis of color decoration was carried out using the Statistical Package for the Social Sciences (SPSS). According to mathematics statistics (Shi and Li 2005), the measured the percentage change in pupil diameter was checked by nonparametric tests, and the results are shown in Table 2. The Statistical Analysis System (SAS) states that when the sample size \( n \leq 2000 \), the result is based on the Shapiro-Wilk (W-test), and when the sample size \( n > 2000 \), the result is based on the Kolmogorov-Smirnov (D-Test). As the degrees of freedom (DF) of this experiment was 20, the significance result \( P > 0.05 \) was calculated by the W-Test. Combined with the normal Q-Q graph (Figure 11), data points aligned with the normal distribution, indicating that the collected data could be used to test the significant influence of 5 levels on the percentage change in pupil diameter.

In this study, the differential test of each driver’s pupil diameter data were carried out by one-way analysis of variance. If \( F \geq F_{\alpha} \), it was considered that this factor had a significant effect on the test results. The differential test results of some subjects are shown in Table 3.

The value of \( F \) was larger than \( F_{\alpha} = 2.4567 \), which indicated that the percentage change in pupil diameter under five kinds of tunnel decoration schemes had significant differences. Therefore, the effect of different vault colors on the driver was obvious.

4.1.2.2. Results analysis. The box-plot, which visually reflects the distribution of individual data, was used to analyze the driver’s percentage change in pupil diameter under the five color schemes. It can be seen from Figure 12 that no “very nervous” tension points appeared (\( E > 18\% \)), indicating that drivers in five color schemes were “comfortable” or “more nervous”. The effect of dark color on the driver was significantly higher than light color, and the drivers were in a state of tension during most of the driving process under dark blue and gray. The interquartile range of the dark color was larger than that of the light color, indicating that the pupil state of the driver in the dark color was unstable, and the driver in the light color could adapt to the environment quickly.

Table 3. Variance analysis of the pupil diameter.

| Experimenter | Sum of Squares | DF | Mean Square | F Value |
|--------------|----------------|----|-------------|---------|
| 001          | SS4 5.5453     | 4  | 1.3863      | 60.5915 |
|              | SSE 2.6312     | 115| 0.0029      |         |
|              | SST 8.1764     | 119|             |         |
| 002          | SS4 9.5997     | 4  | 2.3999      | 88.1657 |
|              | SSE 3.1304     | 115| 0.0072      |         |
|              | SST 12.7200    | 119|             |         |

Figure 12. Box-plot of percentage change in pupil diameter.

Figure 13. Heart rate growth.
Based on the percentage change in pupil diameter in different environments, it can be concluded that dark blue has the greatest influence on the driver, followed by gray, resulting in decreased driving comfort. Light color has little influence on driving comfort and little interference to drivers.

According to the results of pupil diameter and the percentage change in pupil diameter, the effect of the color in the tunnel vault on the pupil of the driver was sorted as dark blue > gray > white > light yellow > clouds.

4.2. Heart rate growth

The heart rate growth rate of each driver was processed to obtain the mean heart rate growth of the test subjects at five levels, as shown in Figure 13.

It can be seen that the HRGs of drivers under the dark colors were higher than 6% on the whole, thereby indicating a higher degree of psychological tension. In the gray decoration, the HRG of the driver gradually increased, which was consistent with the interquartile range under the gray in Figure 13. Under vaults of light colors, the driver’s HRG was relatively small, between 3% and 6%, and the psychological state was fairly stable during driving. In the dark colors, dark blue had a greater effect on the driver than gray. In the light colors, white had a slightly greater effect on the driver than light yellow and clouds.

HRG results correspond to the results reflected by the change rate of the pupil diameter, which shows that the effect of vault color on drivers was consistent from a physiological and psychological perspective. The effect of the color in the tunnel vault on driving was sorted by large to small as dark blue > gray > white > light yellow > clouds.

5. Conclusion and prospects

1. Based on the self-developed driving simulation platform, a method was proposed to evaluate the decorative design of the tunnel inner-wall by analyzing the driver’s pupil diameter and heart rate.

2. Compared with the light color, under the dark color of tunnel inner-walls, the driver’s feeling fluctuation is greater and more nervous, which indicates that driving comfort is higher when light color is adopted in tunnel top inner-walls. Therefore, from the point of view of driving comfort, it is recommended to give priority to light color when selecting colors for tunnel vaults.

3. Among the five schemes, the decorative scheme of blue sky and white clouds decoration scheme be chosen when the economic situation permits.

In the design of tunnel vaults, aside from considering the impact of vault color on driving, the auxiliary role of tunnel lighting should also be considered in future research. With the increase of long tunnel construction, the visual fatigue of drivers should be considered in the design of tunnel vault.

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