Analysis of drivers’ visual characteristics in expressway tunnels with different radii

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Abstract: The aim of this study is to analyse drivers’ visual characteristics in expressway tunnels with different radii by driving simulation experiments. This paper used forum driving simulation device, eye-tracker (SMI ETG™) and UC-win/Road to establish tunnel models with different radii for drivers’ visual characteristics analysis. Critical parameters indicating visual characteristics in the process of driving were sufficiently analysed and discussed. The results showed that there was an indispensable relationship between tunnel radius and eye movement.

1. Introduction
With the increase of construction and usage of expressway in China, many tunnels are used in mountainous areas. Compared with general roads, tunnels are greatly restricted in terms of ventilation, lighting and sight distance. These disadvantages impose an exclusive burden on the drivers psychologically and physiologically. At present, scholars' analysis on tunnel traffic environment mainly focused on the experimental analysis of the visual and driver's psychophysiological characteristics at the tunnel entrances and exits. Meanwhile, the influence of the driving environment on the visual characteristics of the driver has attracted more and more attention. The research on drivers’ visual characteristics has mainly been focused on the comparison of the search strategy of the driver's visual search mode, the influence of the driver's workload and the relationship between driver's fixation area and the traffic facilities (Jimenez et al. 2012).

According to the literature review, most current researches mainly focus on environmental characteristics of the tunnel entrances and exits as well as driver's psychological and physiological changes. To get a better understanding of driver’s visual characteristics in tunnels with different radii, a targeted and in-depth research is necessary. In this study, an eye-tracker (SMI ETG™) and a driving simulation experiment were conducted to obtain the visual characteristics in the curved expressway tunnels with different radii. Critical parameters indicating visual characteristics in the process of driving, such as fixation area, fixation time, saccade angle and speed, eye movement index and variance of pupil diameter, were sufficiently analyzed and discussed. The results indicate that radius of tunnel has a notable effect on visual characteristics of drivers. Thus, some targeted measures should be taken for induction of the sight line to improve tunnel environment. Furthermore, the findings have potential applications for tunnels design of mountainous expressway and safeguard measure of traffic safety.
2. Methods

2.1 Apparatus
Forum driving simulation system, eye-tracker (SMI ETG™) and UC-win/Road simulation from Chang’an University were used to build a platform for drivers’ visual characteristics analysis on road test. Forum driving simulation system, which combines virtual reality technology with cockpit, can simulate the 3D driving process. Cockpit is used to simulate the real driving conditions on the road. An eye-tracker can observe the driver's visual behavior and it can dynamically acquire the driver's visual characteristic parameters during the process of driving. The characteristic parameters include the driver's head saccade angle and speed, gaze direction, pupil diameter, fixation frequency and fixation time, etc. UC-win/Road software can simulate 3D real scenes such as expressway, tunnels and buildings through the computer, and could restore the road environment and driving situations authentically.

2.2 Participants
The experiment is a repeated measures design. Before the experiment, the samples should be determined. In this experiment, bilateral test was used to determine the samples. According to the calculation \(n=18\), at least 18 subjects were needed to meet the standard. At last, 21 participants including 16 males and 5 females completed the study. The ages of participants were between 22 and 55, with an average age of 29.55 and the standard deviation was 6.75. Each participant has a valid driver's license for at least 2 years. The annual average driving mileage was more than 5000 km, and the safe driving mileage was basically more than 20000 km. The condition of participants’ driving skills was relatively coincident with the actual road driving condition.

2.3 Scenario Design and Experimental Procedure
3D tunnel models with different radius were built, and the participants used the cockpit to simulate the driving conditions in tunnel with different radius. We recorded the change of the visual data. Through the analysis of visual parameters, combined with simulation of the vehicle driving conditions, we can analysis the impact on visual and psychological for drivers who drive in small radius tunnel.

The specific experiment process was shown as follows:
(1) UC-win/Road was used to establish 3D tunnel models with different radii and same tunnel cross-section. The radii of tunnel model were 400 m, 600 m, 800 m, 1000 m, 1500 m and 99999 m (linear straight tunnel). The total length of the tunnel was 2 km. The one-way longitudinal gradient was 2% and the cross-section was one-way two lanes with a design speed of 80 km/h whose building boundary was 5 m;
(2) 21 participants were selected and conduct driving simulation in the cockpit according to the established tunnel models. Each participant was assigned to drive three times in each tunnel with different radius during the experiment. And each participant drove for about 15 minutes in each tunnel. To eliminate the effect of time sequence, we randomly arranged the order of tunnel radii.
(3) The visual feature changes of participants were observed wearing the eye-tracker in the process of driving simulation, and the visual characteristics data were recorded. Be-Gaze were used to track the routes of eye fixation points. After dividing reliable viewshed, saccade eye movement, pupil diameter and other parameters were extracted from Be-Gaze.

2.4 Selection and Analysis of Evaluation Indices
Dynamic vision, visual field and light intensity are relatively stable under a certain speed, while the indexes of fixation area, fixation time, pupil diameter and saccade range constantly change in driving process, which can reflect regularity of drivers’ visual characteristics. The fixation area reflects the spatial position that the driver pays attention to in the process of driving, and reflects the driver's visual needs in a comprehensive way. Due to the binocular effect of human eyes, the driver's ability to identify information of different positions in the reliable viewshed is also different.

As is mentioned above, the driver's viewpoint changes during driving. Japanese scholars proposed...
eye movement index which indicated the degree of attention to a certain fixation points during driving process. The index is the product of average fixation time fixation frequency. However, the index only considers the distribution time of eye movement, the effects of distribution areas are not taken into account. This paper establishes a new eye movement index to evaluate the visual recognition ability of the driver in a complex environment. We then segment the driver data into standardized time units to facilitate the analysis of eye movement. A weigh mixture of average fixation time, fixation frequency, saccade angle and saccade speed are considered and the index $\alpha$ is calculated as:

$$\alpha = \frac{1}{n} \sum_{i=1}^{n} q_i k_i T_i = q \sum_{i=1}^{n} k_i T_i = qs$$

$$q_i = T_i N_i / \left[ \left(t_i - t_{i-1} - T_i\right)/2 + \left(t_i - t_i - T_i\right)/2 \right]$$

Where $n$ is the times of fixation; $k_i$ is weight coefficient for distribution of eye movement; $N_i$ is for fixation frequency of $t_i$, which means the average times of fixation during one standardized time unit; $T_i$ is the fixation time of $t_i$; $q_i$ is the rate of fixation time, which indicates important degree about information; $s$ is saccade coefficient, which describes saccade behavior combining saccade time and angle of the equations.

In this study, it is defined as fixation behavior when the time of eye fixation is more than 100ms, otherwise saccade behavior. The angle between the previous and next sight lines is the saccade angle. The faster speed of saccade, the greater degree of tension the drivers get. The bigger saccade angle is, the weaker the ability of the driver has to obtain spatial information and the worse the visual recognition and identification effect are. The weight coefficient for distribution of eye movement $k_i$ is randomly related to the saccade angle and follows normal distribution $(0, \sigma^2)$ as Equations (3). When $d_i = d_{50}$, $k_i = 0.5$.

$$k_i = \frac{1}{\sqrt{2\pi \sigma}} e^{-d_i^2/2\sigma^2}$$

When $d_i = d_{50}$, $k_i = 0.5$.

It is proposed that when with rapid light and shade changes, change rate of pupil diameter increased rapidly. If pupil changes fell to adapt to light and shade changes, it is very difficult to focus for the human eyes, which resulted in instantaneous blind period defined as visual turbulence (Du et al. 2007). In this paper, the change rate of pupil diameter is used as an accurate index to reflect the visual and physiological changes of drivers.

$$\rho = \frac{l_i - l_{i-1}}{l_{i-1}}$$

In which $\rho$ is the change rate of pupil diameter; $l_i$ is the pupil diameter of $t_i$ and $l_{i-1}$ is the pupil diameter of $t_{i-1}$.

3. Results

3.1 Fixation Area

This paper divided the reliable viewshed in the tunnel into five parts: central area, right area, left area, pavement area and top area. Besides the five parts, other areas of the reliable viewshed were also taken into consideration. These areas were marked as AOI 001 to AOI 005 and other areas, respectively, as is shown in Figure 1.
The distribution of fixation time at the reliable viewshed of the 21 participants driving in different tunnels is shown in Figure 2. Figure 2 clearly showed that: (1) In the straight tunnel, the drivers had large visual distances and less operations during driving process. The fixation area is wide and the fixation time distribution in each area is relatively uniform. (2) With decrease of the radius, the driver's fixation point gradually concentrates on the pavement area, and the ratio on other fixation areas decreased sharply.

### 3.2 Fixation Behavior

To describe fixation behavior of drivers, fixation time and frequency were extracted. Fixation time is in proportion to driver’s attention to the tunnel environment. The distribution of fixation frequency of participants driving in different tunnels is shown in Figure 3. The fixation frequency decreased with decrease of tunnel radii from 1500 m. Besides, the fixation frequency of straight tunnel is smaller than the tunnel with the radius of 1500 m.

### 3.3 Saccade Behavior and Pupil Diameter

The normality test and the homogeneous variance test were carried out respectively to estimate the statistics including saccade angle, saccade speed and pupil diameter. The S-W test is also used since the number of samples is less than 2000. The results of the normality test showed that the $P$ value of each group is greater than the significance level of 0.05 (see Table 1). Therefore, the data conformed to the Gaussian distribution. The $P$ values of the saccade angle, saccade speed and pupil diameter were 0.135, 0.546 and 0.165 respectively, which were all greater than the significance level of 0.05. So, all the data met the homogeneity of variance. As shown in table 1, with decrease of tunnel radii, the saccade angle decreased gradually while the saccade speed increased.

| Radius(m) | Saccade angle (°) | Saccade speed (°/s) | Pupil diameter (mm) |
|-----------|------------------|---------------------|--------------------|
|           | average | SD   | P       | average | SD   | P       | average | SD   | P     |
| 99999     | 4.56    | 0.93 | 0.325   | 19.70   | 17.8 | 0.085   | 3.14    | 0.44 | 0.058 |
| 1500      | 3.36    | 2.3  | 0.265   | 24.38   | 15.46| 0.072   | 3.18    | 0.31 | 0.123 |
| 1000      | 1.97    | 2    | 0.227   | 26.06   | 15.37| 0.88    | 3.23    | 0.52 | 0.238 |

Figure 3. Distribution of fixation frequency
5.8 1.29 1.93 0.189 26.84 15.12 0.218 3.44 0.44 0.284
600 1.32 1.68 0.204 30.89 18.68 0.326 3.27 0.43 0.326
400 0.95 0.95 0.117 33.64 14.71 0.13 3.2 0.51 0.134

In addition, pupil diameters of the 21 participants in the tunnel with radius of 400m were shown in Figure 4. The pupil diameter in the tunnel is obviously larger than that at the tunnel entrances and exits.

Figure 4. pupil diameter changes of the 21 participants in the tunnel with radius of 400m in the driving process

3.4 Eye Movement Index

Because the internal environment of the tunnel changes little and the fixation frequency in the tunnel is distributed evenly, fixation time in each unit time is defined as fixation frequency in this study. As is mentioned in Equations (1) and (2), Eye movement index of participants is shown in Table 2.

Table 2: Eye movement index

| Radius (m) | Time (ms) | Number of fixation times | Fixation frequency | Average values of fixation time (ms) | The rate of fixation time /q | Saccade angle/ds (°) | Saccade coefficient /s | Eye movement index /α |
|------------|-----------|--------------------------|--------------------|-------------------------------------|----------------------------|----------------------|----------------------|-----------------------|
| 99999 | 61052 | 92 | 1.507 | 585 | 88.21% | 4.18 | 0.667 | 0.588 |
| 1500 | 60703 | 127 | 2.092 | 397 | 82.99% | 3.21 | 0.725 | 0.602 |
| 1000 | 60719 | 105 | 1.729 | 494 | 85.37% | 1.68 | 0.726 | 0.619 |
| 800 | 31266 | 61 | 1.951 | 439 | 85.64% | 1.21 | 0.736 | 0.630 |
| 600 | 30334 | 58 | 1.912 | 444 | 84.82% | 1.31 | 0.715 | 0.607 |
| 400 | 32598 | 63 | 1.933 | 438 | 84.59% | 1.58 | 0.682 | 0.577 |

Obviously, in the straight tunnel, the fixation time is relatively long and fixation frequency is relatively low. Therefore, the eye movement index is relatively low, as well as the ability of object identification. Meanwhile, with decrease of the tunnel radii from 1500 m to 400 m, the eye movement index increased firstly and then decreased from 800 m. When the radius is 800 m, the maximum value of eye movement index indicated the best ability of object identification.

4. Conclusion

As mentioned above, this paper analyzed the drivers’ fixation behavior, saccade behavior, pupil diameter and eye movement index preliminarily. The pavement markings and signs of curved tunnels were necessary for visual guidance and driving safety. As tunnel radii decreases, the fixation area moves from central area to pavement area, and the rate of pavement area increase constantly. When driving in small radius curved tunnels, the drivers need the objects on the pavement as important references to judge their speed and position. Especially, the inside of curved tunnels is the key for drivers to take measures. Similarly, in a driving simulator study, it is suggested traffic signs and markings with easily identifiable design, such as LED (Wang et al. 2016).
There is a relationship between the driver’s psychological states and fixation frequency and fixation time. The fixation frequency reflects the frequency of drivers changing their fixation points. When drivers feel relaxed, the fixation frequency increases, whereas when drivers are nervous, the fixation frequency decreases. When the radius is very small, the drivers are in a nervous condition. Fixation frequency decreased while fixation time increased. In addition, the faster of saccade speed, the greater degree of tension the drivers get. The bigger saccade angle is, the weaker the ability of the driver to obtain spatial information and the worse the visual recognition and identification effect are. There are several factors that can substantially affect the pupil diameter, such as luminance of environment, the subject distance and activity level of cerebra.

According to the above analysis, the paper suggests the minimum tunnel radius should be 800 m if the design speed is 80 km/h to meet the identification requirements. Besides, in straight tunnel with relatively simple environment, drivers observe the objects more casually. So, the eye movement index of straight tunnel is smaller than the radius of 1500 m. The moderate anxiety, which are common psychological experiences in the process of tunnel driving (Vashitz et al. 2007), is beneficial to driving safety. Therefore, some measures should be taken for safer tunnel driving environment.

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