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EFFECTS OF GUIDANCE FACILITIES ON DRIVING SAFETY IN ROAD TUNNELS DURING FOGGY WEATHER

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Abstract: The traffic accident rate increases significantly on foggy days. Typically, the light intensity within tunnels is significantly lower than outside, resulting in poorer visibility. The tunnel sidewalls become indistinct, making it challenging to discern the tunnel's alignment. Although the self-luminous visual guidance facilities have been adopted in some tunnels, their effects and setting methods have not been studied in depth. Given this, thirty subjects were invited to conduct a virtual reality driving test to investigate the impact of the location and color of visual guidance facilities on driving safety and comfort. In this process, driving data and physiological data were collected, and subjective evaluation questionnaires were conducted. The results show that the self-luminous visual guidance facilities can make the alignment of tunnel clearer, and can improve the driver's sense of speed in foggy weather. Moreover, the drivers' nervousness is effectively alleviated. The guidance facilities located at the bottom of the sidewall are less disruptive than those located in the middle of the sidewall. Compared with the red guidance facilities, the yellow guidance facilities can relieve the driver's tension more effectively.

Keywords: Road tunnel, Guidance facilities, Foggy weather, Driving safety

1. INTRODUCTION

During foggy weather, the rates of road departure (Das et al, 2019) and rear-end (Li et al, 2023) accidents increase significantly, and the injury and fatality rates of traffic accidents related to fog are notably higher (Sadeghi & Goli, 2024). To enhance traffic safety in foggy conditions, some scholars have conducted research on the light source characteristics of lamps(Jin et al. 2015; Dong et al, 2020). There are also some studies that have explored the role of advanced driver-assistance systems and intelligent transportation facilities in foggy weather (Guan et al. 2022; Zhai et al. 2023).

The semi-enclosed structure of tunnels makes traffic accidents occurring in them often more severe than those on open roads (Liu et al., 2025). Enhancing the brightness inside tunnels and setting up traffic safety facilities are both important measures to improve tunnel traffic safety. Increasing the brightness inside tunnels can improve visibility, but it requires a high cost of electricity (Zhao et al., 2022). In comparison, traffic safety facilities, due to their low cost and high efficiency, are attracting increasing attention from scholars.

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During foggy weather, the tunnel sidewalls become blurred, and the effectiveness of non-self-luminous visual guidance facilities such as reflective rings is weakened (He et al, 2024). It is difficult to identify the tunnel alignment, and accidents involving collisions with the sidewalls are more likely to occur. Although visual guidance facilities have been applied in some tunnels, their effects have not been studied in depth. This paper investigates the impact of visual guidance facilities with different installation heights and colors on driving safety in foggy tunnels through virtual reality driving experiments.

2. MATERIAL AND METHODS

2.1. Subjects

This experiment recruited a total of 30 participants with driving licenses, including 24 males and 6 females, with ages ranging from 19 to 28 years old (mean = 24.5 years, standard deviation = 2.11 years). Their driving experience ranged from 1 to 8 years (mean = 4.2 years, standard deviation = 1.92 years). To avoid the influence of external factors, participants were not allowed to engage in vigorous exercise within 1 hour before the experiment.

2.2. Apparatus and software

The devices utilized in the test are depicted in **Figure 1**, including a head-mounted display, a driving simulator, a computer, and a heart rate armband. The head-mounted display was a Pico 4 Enterprise, which featured a 105° field of view, a 90 Hz refresh rate, and a resolution of 2160×2160 pixels per eye. It was capable of collecting eye movement data, with an acquisition frequency of 100 Hz for eye movement data. The driving simulator employed the “Logitech MOMO Racing Force” steering wheel and pedals, which provided driving data such as speed at a rate of 10 Hz. A CYCPLUS H1 heart rate armband output real-time heart rate at 1 Hz. The VR experimental scene had been modeled using 3ds Max and then imported into the Unity platform for lighting rendering and experimental interaction.

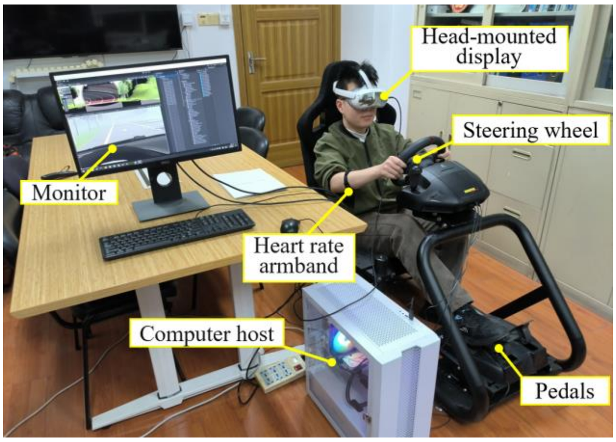


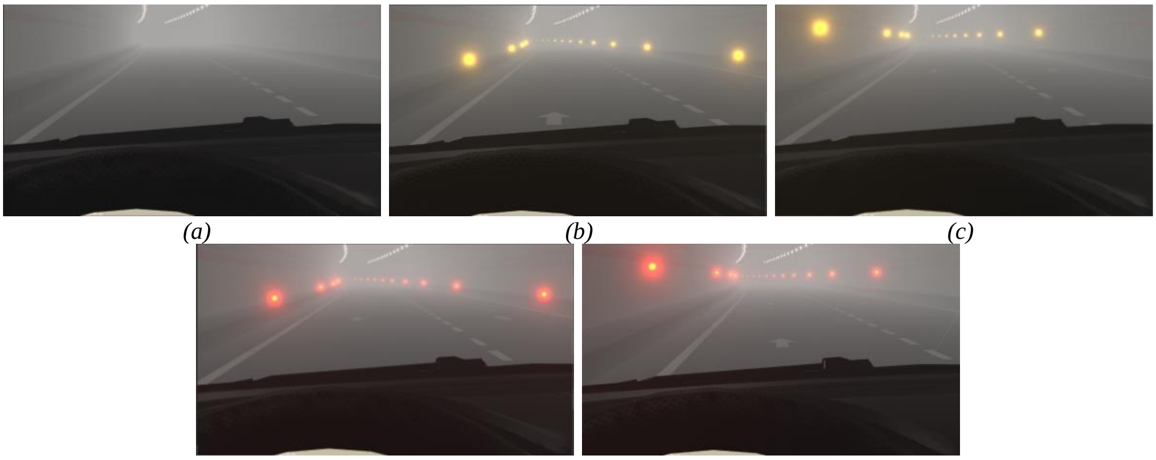
Figure 1. *Test apparatus*

2.3. Scenarios

The test scenarios included a 1200-meter tunnel and 500-meter open road sections before and after it. Both had single-direction dual lanes that were 3.75 meters wide.

The fog concentration inside and outside the tunnel was the same. The fog concentration parameter was determined based on the visibility threshold where participants could barely see the outline of a red vehicle parked 250 meters away outside the tunnel.

The modeling results of the interior zone of the tunnel in each scenario are shown in **Figure 2**. Scenario (a) was the control group without guidance facilities (Abbreviated as CG). Scenarios (b) and (c) featured yellow guidance facilities installed at the bottom and middle of the tunnel sidewalls, respectively (Abbreviated as YB and YM). Scenarios (d) and (e) had red guidance facilities installed at the bottom and middle of the tunnel sidewalls, respectively (Abbreviated as RB and RM).



(a) *(b)* *(c)* *(d)* *(e)*

Figure 2. *The interior zone of the tunnel: (a) Control group (CG); (b) Yellow bottom (YB); (c) Yellow middle (YM); (d) Red bottom (RB) (e) Red middle (RM).*

2.4. Procedures

Before the formal experiment, a brief five-minute training session was arranged for the participants to enable them to get accustomed to the operation of the head-mounted display and the driving simulator. Subsequently, the participants engaged in a ten-minute free driving session as a pre-experiment, which served the dual purpose of allowing them to become familiar with the simulator's operation and verifying the proper functioning of the equipment.

During the formal experiment, participants initiated their driving 500 meters outside the tunnel in each scenario. They then proceeded into a 1200-meter-long tunnel and halted 200 meters after exiting the tunnel to complete a set of experiments. After completing each set of experiments, participants took a five-minute break. They then moved on to the next set of experiments until all five sets were completed. The order of the experimental scenarios was randomized.

After all experiments were completed, each participant needed to complete a questionnaire, which included subjective evaluations of their driving experience, basic information (such as driving experience, age, and gender) and the degree of realism of the virtual environment (including tunnels, fog, and guiding facilities) on a scale from 1 (not realistic) to 10 (very realistic).

The questions related to driving experience in the questionnaire are as follows:

(1) Level of the clarity of tunnel alignment in scenarios (b) (c) (d) and (e). (-1: More blurred than the control group; 0: Similar to the control group; 1 to 4: Higher numbers correspond to greater clarity relative to the control group.)

(2) The effect of alleviating tension in scenarios (b) (c) (d) and (e). (-1: More nervous than the control group; 0: Similar to the control group; 1 to 4: Higher numbers correspond to more relaxed relative to the control group.)

(3) Level of disturbance caused by guiding facilities in scenarios (b) (c) (d) and (e). (0: No interference; 1: Negligible; 2: Minor interference; 3: Major interference; 4: Severe interference; 5: Intolerable).

3. RESULTS AND DISCUSSION

3.1. Lateral deviation

The maximum lateral offset within the central 600 meters of the tunnel is used to reflect the driver's lane-keeping performance inside the tunnel (Wang et al, 2024). The statistical results are shown in **Figure 3.** The average lateral deviations for the 30 participants across the five scenarios are 0.73m, 0.52m, 0.56m, 0.63m and 0.56m, respectively. The results by the ANOVA method show significant differences among the groups ($F = 3.397$, $p = 0.011$). Subsequent pairwise comparisons reveal significant differences between Scenario CG and each of Scenario YB ($p = 0.001$), Scenario YM ($p = 0.008$) and Scenario RM ($p = 0.009$). No significant differences are found among the remaining groups. Although there is no significant difference between Scenario RB and Scenario CG, the average deviation of Scenario RB is also smaller than that of Scenario CG.

Setting up visual guiding facilities can effectively reduce the maximum lateral deviation. By comparing the mean values of the lateral deviation, it can be seen that the yellow guidance facilities located at the bottom of the sidewall (Scenario YB) have a better effect on improving lane-keeping ability.

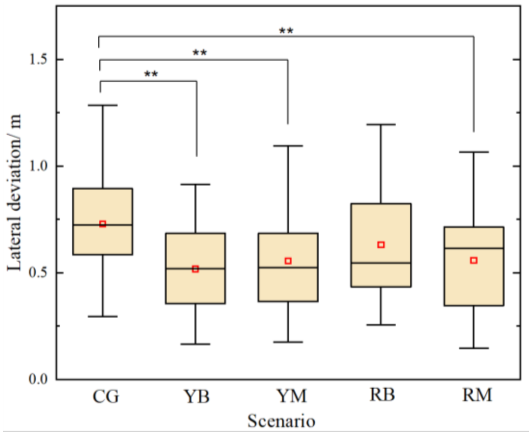


Figure 3. *Maximum lateral deviation inside the tunnel (*: p<0.05; **: p<0.01; ***: p<0.001)*

3.2. Gaze point distribution

The screenshots used to record eye movements are 1500px × 1500px in size, with the origin located at the top-left corner of the screen. The X-axis extends horizontally to the right, and the Y-axis extends vertically downward. The mean values of gaze point distribution characteristics within the middle 600 meters of the tunnel for the 30 participants are shown in **Table 1**, which reflect the spatial allocation of their attention. For the average values of the X-coordinates, the standard deviations of the X-coordinates and the Y-coordinates, there are no significant differences among the five scenarios. But for the average values of the Y-coordinates, the results by the ANOVA show significant differences among the groups (F = 2.443, p = 0.049).

Table 1. *The gaze point distribution characteristics of the experimenters*

Indicator	Scenario	Mean (px)	Significance
Average values of the X-coordinates	Scenario CG	924.5	0.909
	Scenario YB	919.7	
	Scenario YM	913.9	
	Scenario RB	917.5	
	Scenario RM	917.9	
Standard deviations of the X-coordinates	Scenario CG	24.94	0.950
	Scenario YB	24.95	
	Scenario YM	22.34	
	Scenario RB	23.82	
	Scenario RM	24.95	
Average values of the Y-coordinates	Scenario CG	1009.8	0.049*
	Scenario YB	963.3	
	Scenario YM	957.8	
	Scenario RB	971.1	
	Scenario RM	966.3	
Standard deviations of the Y-coordinates	Scenario CG	24.30	0.393
	Scenario YB	22.43	
	Scenario YM	22.27	
	Scenario RB	19.07	
	Scenario RM	21.02	

As shown in **Figure 4**, subsequent pairwise comparisons reveal significant differences between Scenario CG and each of Scenario YB (p = 0.014), Scenario YM (p = 0.006), Scenario RB (p = 0.041) and Scenario RM (p = 0.022). No significant differences are found among the remaining groups. Compared with Scenario CG, the mean

Y-coordinates of the gaze points decrease in the scenarios with guiding facilities. Setting up visual guidance facilities can raise the gaze point positions, making the average gaze points farther away. This might be explained by the fact that the tunnel alignment becomes clearer, reducing driver tension and shifting their focus from the immediate vicinity to a more distant view.

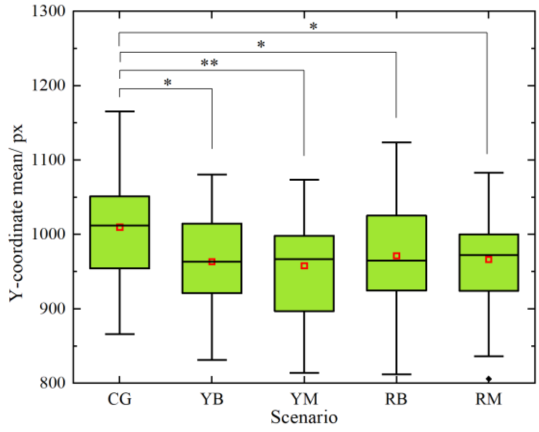


Figure 4. *Y-coordinate mean of the gaze point for the participants (*: p<0.05; **: p<0.01; ***: p<0.001)*

3.3. Heart rate growth

When driving experience increases workload and stress, drivers' heart rate rise significantly (Feng et al, 2018). The average heart rate growth rate (HRG) within the middle 600 meters of the tunnel (i.e., from 300 m to 900 m after entering the tunnel is adopted as a physiological indicator to assess the level of tension inside the tunnel. The results are shown in **Figure 5**. The average HRG for the 30 participants across the five scenarios are 11.7%, 5.7%, 5.6%, 8.5% and 7.9%, respectively. The results by the ANOVA method show significant differences among the groups ($F = 13.515$, $p < 0.001$).

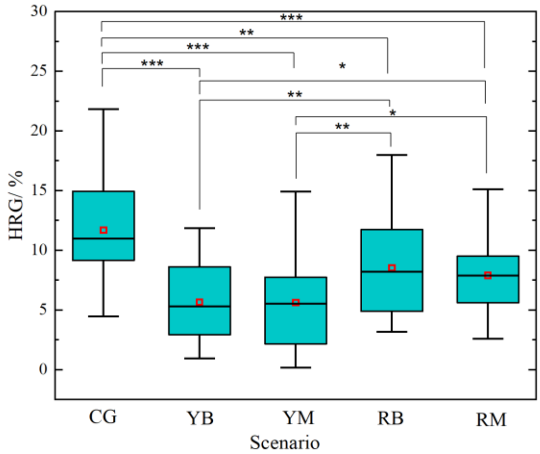


Figure 5. *HRG inside the tunnel (*: p<0.05; **: p<0.01; ***: p<0.001)*

Subsequent pairwise comparisons reveal significant differences between Scenario CG and each of Scenario YB ($p < 0.001$), Scenario YM ($p < 0.001$)， Scenario RB ($p = 0.001$) and Scenario RM ($p < 0.001$). Significant differences are also found between Scenario YB and each of Scenario RB ($p = 0.003$) and Scenario RM ($p = 0.021$) ， as well as between Scenario YM and each of Scenario RB ($p = 0.003$) and Scenario RM ($p = 0.020$). No significant differences are found among the remaining groups. Setting up visual guidance facilities can reduce the drivers' HRG, and the effect of yellow guiding facilities is better than that of red guiding facilities. The location of the guiding facilities has little influence on HRG.

3.4. Subjective feeling

Questionnaires are administered to investigate the impact of setting up guiding facilities on the clarity of tunnel alignment, with the results shown in **Figure 6**. All the test subjects believe that the guiding facilities can improve the clarity of the tunnel alignment. Judging from the average value of subjective evaluation, the effects of the four guiding facilities are not much different. The effect of the red guiding facilities in improving the clarity of the tunnel alignment is slightly better than that of the yellow guiding facilities, and the effect of the guiding facilities located at the bottom of the sidewall is slightly better than that in the middle of the sidewall.

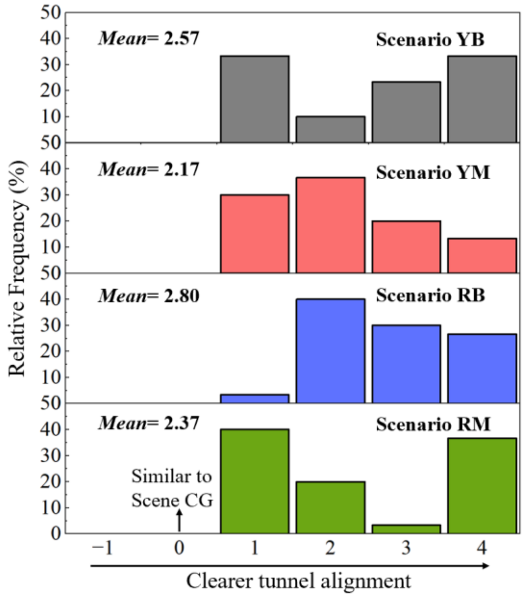


Figure 6. *Subjective evaluation of the clarity of tunnel alignment*

The subjective evaluation of the effect of four guiding facilities in relieving tension is shown in the **Figure 7.** From the average values of subjective evaluation, all four guiding facilities can alleviate the tension of driving in the tunnel on foggy days, but the effects are different. The effect of the yellow guiding facilities in alleviating tension is obviously better than that of the red guiding facilities, with those located at the bottom of the sidewall being the most effective. It is worth noting that some testers believe that the red guiding facilities have intensified the tension because red represents warning and danger.

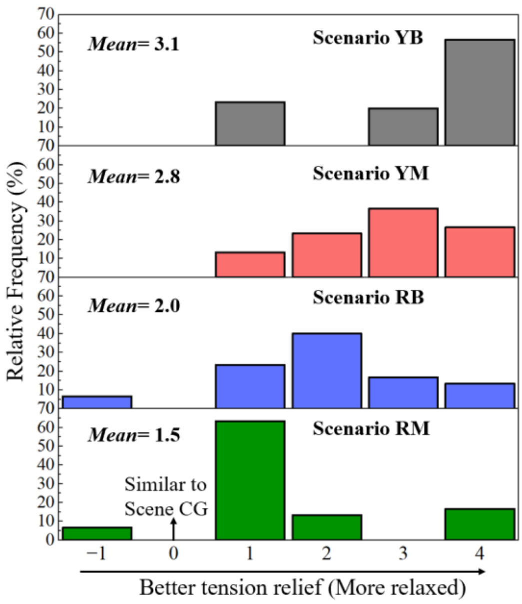


Figure 7. *Subjective evaluation of the effect of alleviating tension*

The subjective evaluation of degree of visual interference of the four guiding facilities is shown in the **Figure 8.** The degree of visual interference in Scenario RM is the highest, while that in Scenario YB is the lowest. The interference degree of the red guiding facilities is higher than that of the yellow ones. The guiding facilities set in the middle of the sidewall cause more severe interference than those at the bottom of the sidewall. This is because the red guiding facilities are too conspicuous to be ignored. The guiding facility located in the middle of the sidewall is basically at the same level as the driver's line of sight. When the driver passes through this facility, the flickering effect is more obvious.

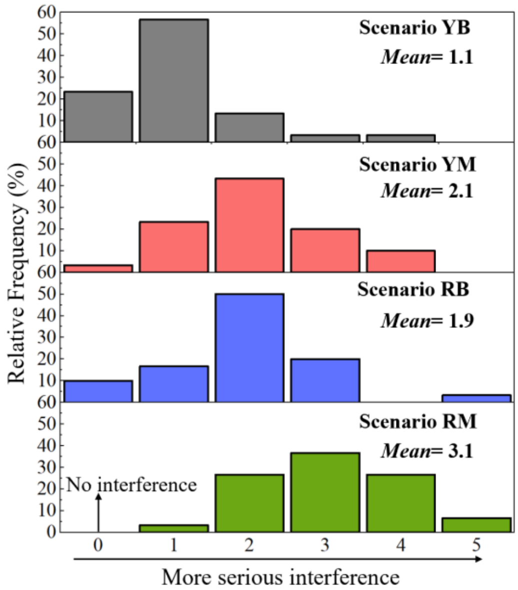


Figure 8. *Subjective evaluation of degree of visual interference*

4. CONCLUSIONS

Setting up visual guiding facilities can effectively enhance the clarity of tunnel alignment and reduce the maximum lateral deviation during vehicle travel. These facilities can also help drivers focus their gaze further ahead, lower the heart rate increase of drivers, and alleviate the tension experienced while driving in tunnels during foggy conditions. Among the four types of guiding facilities tested in this study, the yellow guiding facilities located at the bottom of the sidewall were found to be the most effective in relieving tension and causing the least visual interference.

5. ACKNOWLEDGEMENTS

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