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Analysis and Adjustment of Vehicle Trajectories in the Entrance Area of Freeway Tunnels: from the Perspective of Visual Guiding System

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ABSTRACT

This study aims to quantitatively assess the adjustment effects of various visual guiding schemes on the abrupt change of vehicle trajectory. A driving simulation experiment was conducted using five simulated scenes: (1) baseline (actual situation), (2) pavement (road studs), (3) low position (flexible guideposts), (4) high position (warning alignment signs and retroreflective arches) and (5) multilayer (combination of all devices). Raw data, including vehicle positions, steering wheel angles and lateral offset, were collected. Based on these data, the gradual change degree of vehicle trajectory (G) and average steering wheel angle (SWAav) were computed to quantitatively evaluate the extent of vehicle trajectory deviation and the stability of steering wheel operations respectively. These two evaluation indicators were then translated into trajectory gradualness (TG) and operation stability (OS), respectively, to assess the adjustment effects of different visual guiding schemes. The study results demonstrate that road studs perform a certain degree of enhancement on operation stability (OS). Flexible guideposts exhibit the best effects on operation stability (OS). Additionally, the combination of warning alignment signs and retroreflective arches demonstrate the best regulation of trajectory gradualness (TG). Multilayer visual guiding system achieves the optimal trajectory gradualness (TG) and operation stability (OS).

KEYWORDS

tunnel entrance zone; traffic safety; visual guiding; driving behaviour; vehicle trajectory.

1. INTRODUCTION

The scale of highway tunnels in China is among the highest worldwide, and this number continues to increase annually. By the end of 2021, China possessed 23,268 road tunnels with a total length of 24,698,900 linear meters, indicating a growth of 1,952 tunnels and 2,699,600 linear meters compared to the previous year [1]. However, it is important to note that the spatial distribution of traffic accidents within these tunnels is not uniform. Despite the lower mileage of the tunnel entrance/exit zone, the percentage of traffic accidents occurring in this zone is significantly higher and more severe than in other sections of the tunnel [2]. When drivers entering a tunnel, their driving behaviour undergo significant changes, which is the most direct factor contributing to the high frequency of traffic accidents [3, 4].

In the tunnel entrance zone, a significant portion of the abrupt change in driving behaviour can be attributed to the drastic alterations in the light environment [5]. The light environment encompasses the illumination levels and the human eye's perception of the visual reference system within a given space. When driving into a tunnel, the visual impact of the substantial change in illumination level, combined with the discontinuous visual reference system in the tunnel entrance zone, leads to sudden changes in driving behaviour within this zone [6–8]. Moreover, other factors such as a sudden decrease in the speed limit at the tunnel entrance [9] and a sudden increase in the amount of information [10] can also contribute to abrupt changes in driving behaviour.

Wan et al. [7] propose that during the process of vehicle entering a tunnel, there will be changes in lateral clearance, which can cause a driver to experience psychological stress and deviate from the centre of the lane, thereby creating a security risk. Wang et al. [11] divided the tunnel entrance area into the approaching zone (250–150 m before tunnel entrance), the transition zone (150 m before tunnel entrance to 150 m inside the tunnel) and the inside zone (150–250 m inside the tunnel). Their study found that novice drivers tend to stay away from the tunnel side walls in the inside zone, exhibit larger lateral deviation in the transition zone compared to the inside zone, and this difference is further amplified during night-time. The research findings of Calvi et al. [12] demonstrate that not only novice drivers, but all drivers tend to stay away from the tunnel side walls when entering a tunnel. Liu et al. [13] conducted a simulated driving experiment to study the impact of different lanes (left, middle, right), lane width, and shoulder width on lane deviation in urban tunnels. The research found that drivers in all lanes tend to stay away from the side walls, with varying degrees of deviation. In the left and right lanes, the wider the lane and shoulder width, the smaller the mean lane deviation but with a larger standard deviation. Xu et al. [14] investigated the correlation between physiological indicators such as heart rate fluctuation and pupil diameter with lateral deviation. The study found that from 250 meters before entering the tunnel, a driver's heart rate fluctuates significantly and the pupil diameter gradually increases, indicating a state of tension. At the same time, drivers in the right lane tend to shift the vehicle to the left. This involuntary movement can cause drivers to intrude into adjacent lanes, leading to lateral interference with vehicles in those lanes. This presents a potential hazard in tunnel entrance zones. However, there is a lack of effective measures to regulate sudden changes in travel trajectories in the tunnel entrance zone.

The application of visual guiding technology involves installing diverse visual guiding devices with varied colours and shapes to enhance local brightness and contrast of peripheral visual information. This stimulates and directs the gaze of drivers, facilitates attention allocation and augments perceptual abilities [15, 16]. Within a tunnel, the employment of a visual guiding system can effectively regulate optical illusions, fulfil drivers' security requirements, reduce instances of poor driving behaviour and mitigate traffic accidents [17]. Hence, there exists the potential to mitigate the sudden alteration of the vehicle's trajectory via the implementation of visual guidance technologies in a reasonable manner.

In summary, the occurrence of abrupt changes in driving trajectories within the tunnel entrance zone poses significant safety risks. And these risks may be mitigated through reasonable visual guidance technologies. Therefore, the objective of this study is to address the following inquiries:

1) How can we quantitatively assess the abrupt change of vehicle trajectory within the tunnel entrance zone?
2) What are the distinct effects of various visual guiding techniques on the modulation of the abrupt change of vehicle trajectory?
3) In order to regulate the abrupt change of vehicle trajectory, how can visual guidance technologies be applied in engineering practice?

2. VISUAL GUIDING TECHNOLOGIES

2.1 Application of visual guiding technologies

In China, visual guiding devices such as road studs, chevron alignment signs and retroreflective arches have emerged as essential measures for enhancing safety within tunnels. Zhao et al. conducted driving simulation tests to examine the safety implications of road studs in freeway tunnels. The findings indicated that road studs effectively alleviate drivers' anxiety, boredom and fatigue associated with the dark and monotonous tunnel environment, while enhancing alertness and speed perception [18]. Furthermore, Jiao et al. analysed the alignment guidance provided by chevron alignment signs and retroreflective arches in curved tunnel sections. Results demonstrated that both devices significantly improve alignment guidance along horizontal curves, and retroreflective arches exhibit superior performance to chevron alignment signs [19]. However, the spacing of retroreflective arches remains a subject of debate. Du et al. suggested that the inclusion of three visible retroreflective arches within the sight distance enhances the driver's ability to perceive curvature and ensures an appropriate reaction time [20]. While Zhao et al. proposed a spacing of 300 metres for retroreflective arches in curved sections and 400 metres in straight sections within the central tunnel zone [21]. In addition, the combination of different visual guiding facilities can integrate their respective advantages, provide multi-level alignment and contour guidance, improved clarity of spatial right-of-way and improve the self-explanatory performance, thereby enhancing the traffic safety level inside the tunnel more effectively [22, 23].

Several scholars have also investigated the impact of visual guiding devices on lateral driving behaviour, but these devices are not installed in the tunnel entrance area. These studies on lateral driving behaviour encompass lateral position and steering wheel angle. Lateral position refers to the distance between the centre of the driver's vehicle and the nearest side-line to the left tunnel wall. Pike et al.'s research [24] indicates that lateral position reflects the extent of the driver's control over the vehicle's lateral position and their perception of driving risk. Chen et al. [25] examined the impact of tunnel-decorated interior walls on lateral control stability. They used the mean and maximum values of lateral position to measure lateral control stability, and found that the lateral control stability of tunnel-decorated interior walls with longitudinal strips was superior to that of conventional tunnel walls in both straight and curved sections. This may be attributed to the ability of these interior walls to guide drivers in perceiving slight changes in geometric alignment, thus enhancing the lateral stability of vehicle operation [26]. Zhao et al. [27] investigated the impact of raised pavement markers on lateral position and found that the deployment of raised pavement markers alters lateral position and is influenced by the length of the tunnel. In order to provide drivers with timely exit information and ensure safe freeway exits, Yang et al. [28] propose the installation of a guardrail painted with yellow colour before the exit. They suggest that a smaller maximum steering wheel angle indicates the driver's increased vigilance in steering wheel operation. Additionally, the study indicates that the maximum steering wheel angle of participants in the yellow colour guardrail scenario was significantly smaller than that in the baseline scenario.

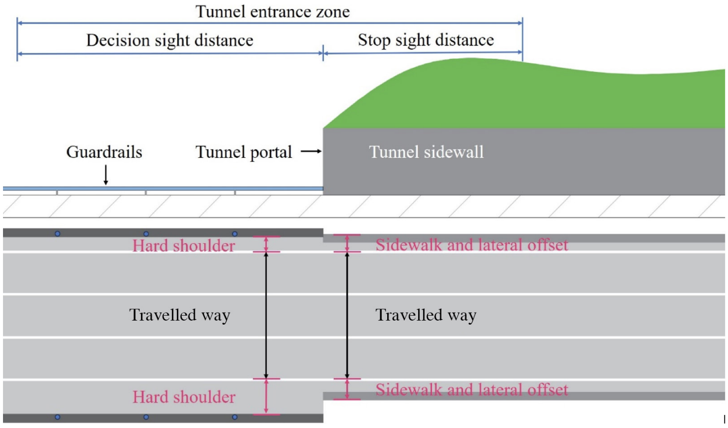
2.2 How to apply it to the tunnel entrance zone

Characterisation of tunnel entrance zone

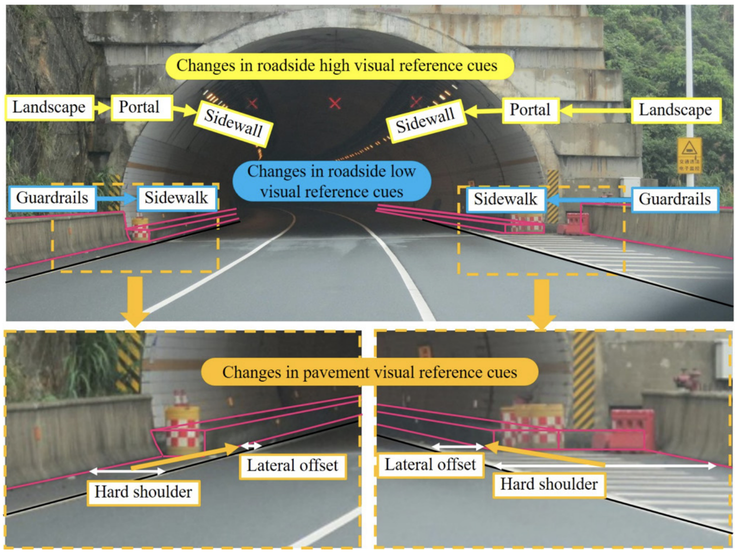
Prior to entering the tunnel, vehicles are required to decelerate, maintain their lane and appropriate distance. Once inside the tunnel, it is only necessary to ensure the maintenance of lane and distance between vehicles. Consequently, the tunnel entrance zone is defined as the distance from one decision sight distance (Condition D) prior to the tunnel portal to one stopping sight distance beyond the portal, as depicted in *Figure 1a*. The decision sight distance (Condition D) guarantees that drivers can make informed choices regarding speed, trajectory and direction. On the other hand, the stopping sight distance ensures that drivers are able to safely come to a halt upon sighting an obstacle ahead [29]. Notably, the visual reference cues within the tunnel entrance zone experience discontinuity in terms of their presence on the pavement, low roadside position and high roadside position, as illustrated in *Figure 1*.

The visual guiding system matching tunnel entrance zone

We have developed a multilayer visual guiding system specifically designed for the tunnel entrance zone, incorporating the principles of continuity and consistency. The setup parameters for this system are depicted in *Figure 2* and *Table 1*, in accordance with the relevant Chinese standards. *Table 2* outlines the functions of visual guiding devices at different vertical positions. It is important to note that these values serve as references only and the optimal setup parameters for the specific visual guiding devices should be determined through testing and evaluation.



(a) Tunnel entrance zone and the visual reference cues therein



(b) Changes in pavement, roadside low and roadside high visual reference cues

Figure 1 – Discontinuity of visual reference system in the tunnel entrance zone

Continuity entails the uninterrupted installation of visual guiding devices at pavement, low and high positions. Consistency encompasses three key aspects: firstly, the utilisation of identical or similar visual guiding devices at corresponding vertical positions (pavement, low position and high positions); secondly, maintaining consistent spacing of visual guiding devices both inside and outside the tunnel at the same vertical position; and lastly, ensuring a proportional and aligned spacing of visual guiding devices between the pavement, low level and high level.

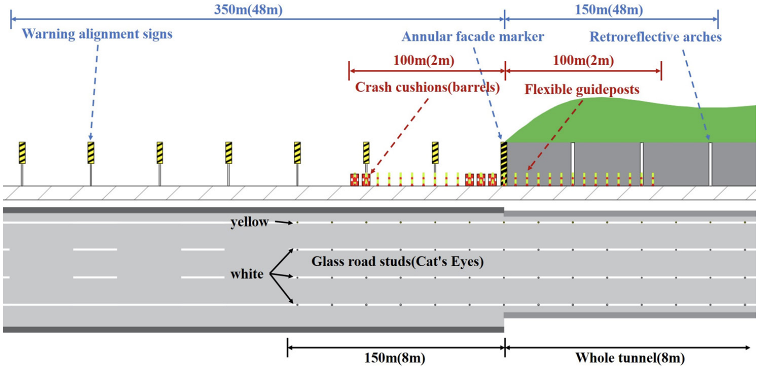


Figure 2 – Longitudinal installation range and spacing of devices in the multilayer visual guiding system at the entrance zone of freeway tunnels

Table 1 – Horizontal position of different visual guiding devices at the entrance zone of freeway tunnels

Devices	Horizontal position
Road studs	Edge of travelled way and lane line
Flexible guideposts	Close to the sidewalk
Crash cushions	Outside the flexible guideposts and inside the guardrails
Retroreflective arches	According to the inner outline of tunnel
Annular facade marker	According to the outline of tunnel portal
Warning alignment signs	20cm outside the guardrails

Table 2 – Functions of visual guiding devices at different vertical position

Vertical position	Devices	Functions
Pavement	Road studs	Improve the continuity of pavement visual reference cues; Alert vehicles that are crossing the lane line.
Low (≤1.2m)	Flexible guideposts	Improve the continuity of visual reference cues on the pavement and roadside low; Prevent vehicles from mistakenly entering the hard shoulder and reduce the severity of accidental crashes into hole gates.
	Crash cushions	
High (≥1.2m)	Retroreflective arches	Outlining the tunnel contour, portal contour, while compressing the sight zone outside the tunnel, thus improving the continuity of roadside high visual reference cues; Increasing the viewing distance.
	Annular facade marker	
	Warning alignment signs	

The rationales behind selecting these parameters are as follows:

1) To assist drivers in accurately judging the distance between vehicles, roadside high visual guiding devices are positioned at a spacing of 48 meters.
2) According to the requirements outlined in China's industry standard JTG D70/2-2014, the continuity of horizontal and profile alignment should be maintained within the 3-second travel zone both before and after the tunnel entrance. Following this standard, the installation range of roadside low visual guiding devices in the tunnel entrance zone should exceed the 3-second travel zone inside and outside the tunnel entrance section.
3) Flexible guideposts cling to the sidewalk to minimise driver evasion. They are positioned at a 2-meter spacing to prevent vehicles from crossing the gap.
4) At the beginning of the flexible guidepost installation, 2 crash cushions are installed to prevent vehicles from accidentally entering the hard shoulder. Additionally, 3 crash cushions are placed in front of the tunnel portal to minimise damage to vehicles in the event of an impact.
5) Considering that the spacing of Chinese freeway guardrail posts is 2 meters or 4 meters, the spacing of these devices is a multiple of 2 meters to ensure that the devices and guardrail posts in different vertical positions can be set up in alignment.

3. METHODOLOGY

3.1 Test apparatus

The experiments were carried out using the simulated driving platform developed by the Intelligent Transportation Systems Research Centre (ITSC) at Wuhan University of Technology, in conjunction with the DG3 (Dikablis Glasses 3) eye-tracking device from ERGONEERS, Germany, as shown in *Figure 3*. The driving simulation platform comprises a cockpit and a curved screen that offers a wide field of view spanning 180 degrees. The cockpit, adapted from the Volkswagen Polo, incorporates realistic force feedback mechanisms in its throttle, brake, clutch and steering wheel. Actual driving experiences, such as vibration and sound, are provided by supplementary equipment within the cockpit. The arc screen, consisting of five projections, enables the creation of immersive simulation scenes. Extensive studies have demonstrated the effectiveness of this driving simulator [30, 31], and it has been validated for use in various environments, including urban roads, urban expressways and freeways [32].

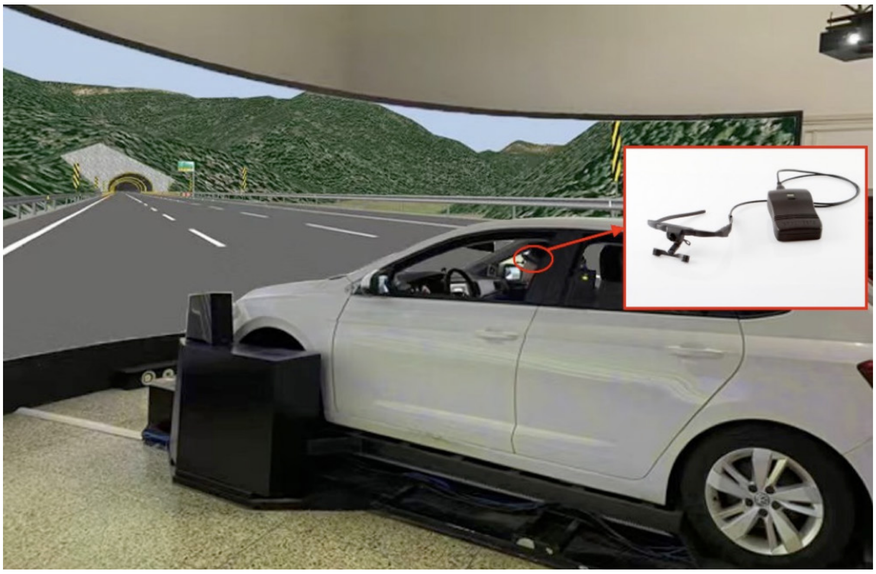


Figure 3 – Simulated driving platform and DG3 (Dikablis Glasses 3) eye-tracking device

3.2 Simulated road scenario

China’s freeways typically enforce the following speed limits: 80 km/h for large vehicles and 100 km/h for small vehicles within tunnels, while the speed limit outside tunnels is set at 120 km/h. Simulated road scenarios adhere to these speed limits, employing a straight and level alignment. Given the independent traffic flows in opposing directions, only one direction is modelled in the simulation, spanning from 2 kilometres prior to the tunnel entrance to 2 kilometres inside. The travelled way inside and outside the tunnel seamlessly connect, yielding a total width of 11.25 meters with three equally-sized lanes. It is worth noting that in certain tunnels in China, both the cross-sections and guardrails lack transitional sections, which poses the highest risk. Consequently, these conditions are included in the simulated road scenario.

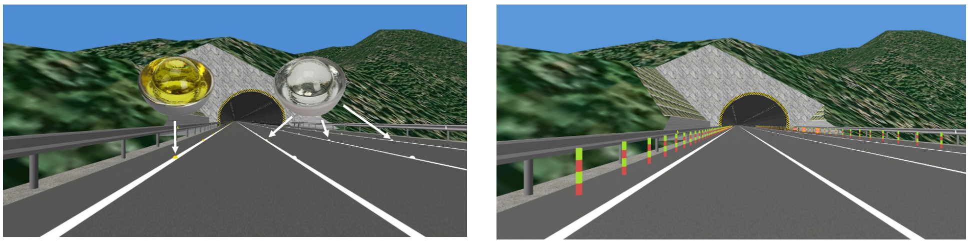
3.3 Visual guiding scenes

The 3D visualisation software, 3ds max, was employed to reconstruct the visual guiding devices incorporated into the simulator scene. Five scenes were included in the experiment, as depicted in *Figure 3*. The distinguishing factor among the tests was the variation in visual guiding devices within each scene. *Figure 4a* illustrates the visual recognition effect at a distance of 220 metres from the tunnel portal, while *Figure 4b, 4c, 4d and 4e* depict the visual recognition effect at 65 metres preceding the tunnel portal. Scene1 (baseline) was established to replicate the current conditions of Wang Bei Au tunnel, encompassing portal annular facade markers, tunnel light signs, vehicle type-specific speed limit signs, lane line markings (solid lines inside the tunnel and 150 metres ahead of the tunnel), delineators (on guardrails, sidewalk and sidewall) and LED tunnel lights. Scenes 2, 3, 4 and 5 introduce additional visual guiding devices to scene 1, as outlined in *Table 3*.

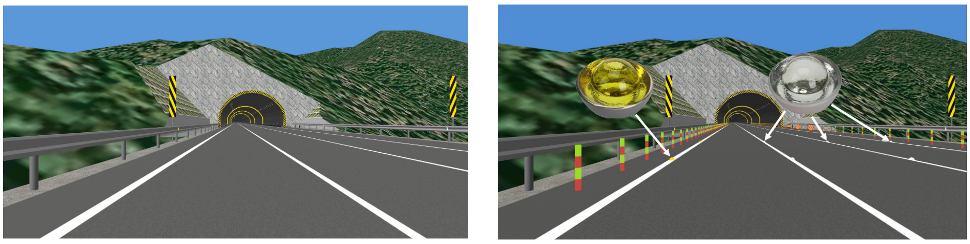
Table 3 – Visual guiding scenes and type of devices they contain

Scene		Type of devices	Abbreviation
1	Baseline	According to actual situation	Actual situation
2	Pavement	+ Glass road studs (Cat’s Eyes)	Road studs
3	Low position	+ Flexible guideposts and crash cushions (barrels)	Flexible guideposts
4	High position	+ Warning alignment signs and retroreflective arches	WAS&RA
5	Multilayer	+ All visual guiding devices above	Multiple devices

(a) Scene 1: Baseline, actual situation



(b) Scene 2: Pavement, road studs *(c) Scene 3: Low position, flexible guideposts*



(d) Scene 4: High position, WAS&RA *(e) Scene 5: Multilayer, multiple devices*

Figure 4 – The visual guiding scenes tested in driving simulations

3.4 Participants

The selection of subjects took into account the sample size and subject composition, ensuring that the sample size met the necessary requirement and the subject composition reflected the gender and age structure of Chinese drivers. The formula to calculate the minimum sample size is represented by *Equation 1*:

$$N = Z^2 \sigma^2 / E^2 \tag{1}$$

where N represents the sample size, Z is the standard normal distribution statistic, σ is the standard deviation and E is the maximum error. A significance level of 10% is typically chosen to denote a 90% confidence level for unknown parameters. With a confidence level of 90%, Z is equal to 1.25 and σ ranges from 0.25 to 0.5. Considering the limitations of the driving simulation test population, σ is set as 0.40 and E as 10%. Consequently, the calculated minimum sample size required is 25. To ensure increased accuracy while meeting the minimum sample size requirement, this study utilises a sample size of 30.

In China, the male-to-female driver ratio in 2021 was 1.97:1, with 70.71% of drivers falling within the 26–50 age group and 14.48% within the 51–60 age group [33]. To account for cases where some samples may not meet the requirements, 37 drivers were recruited from Wuhan University of Technology and the local community, ensuring a 23% redundancy in this test. During the final data analysis, valid data from 30 subjects were selected, aligning with the gender and age structure of Chinese drivers in 2021. Among the 30 subjects, 20 were male drivers and 10 were female drivers, resulting in a male-to-female ratio of 2:1. Their ages ranged from 22 to 54 years old, with 21 drivers falling within the 26–50 age group (70%) and 4 drivers within the 51–60 age group (13.33%). All drivers had good visual and hearing abilities and had driven more than 10,000 km on freeways.

3.5 Procedure

The experimental procedure in this study involved an adaptive exercise, an exam and a formal test, as depicted in *Figure 5*. Both the adaptive exercise and the exam took place in the same open-road scenario, featuring a road cross-section that mirrored the out-of-tunnel section in the formal test. Prior to beginning the adaptive exercise, drivers were informed that they could only progress to the formal test upon passing the exam, and they would receive compensation upon completing the formal test, ensuring that participants approached the practice seriously.

To pass the exam drivers were required to meet three conditions: (1) following instructed acceleration and deceleration to specific speeds, (2) maintaining their lane, and (3) abiding by traffic laws. Throughout the exam, the examiner recorded whether drivers followed instructed speed changes and adhered to traffic laws, and at the conclusion of the exam, the lateral deviation data was reviewed to determine if drivers maintained their lane. The adaptive exercise and exam were solely employed to ensure that participants had adapted to the simulated driving environment before the formal test, and the data collected from these activities will not be utilised in subsequent research.

Prior to the formal test, drivers were instructed to maintain their position in the leftmost lane, where the speed limit ranged 110–120 km/h, surpassing the maximum speed limit of 100 km/h in the tunnel. It should be noted that the study did not involve a following situation, thus there were no other vehicles in the simulation scenario. During the formal test, drivers completed testing for 5 different scenarios in a randomised order, as indicated in *Figure 5*. Upon completion of the trial, each participant received 200 RMB, which exceeded the average daily wage level at the trial site. Although we allotted 220 minutes for each participant to complete the entire procedure, many participants finished the entire process within 160 minutes due to the low incidence of errors during the formal test.

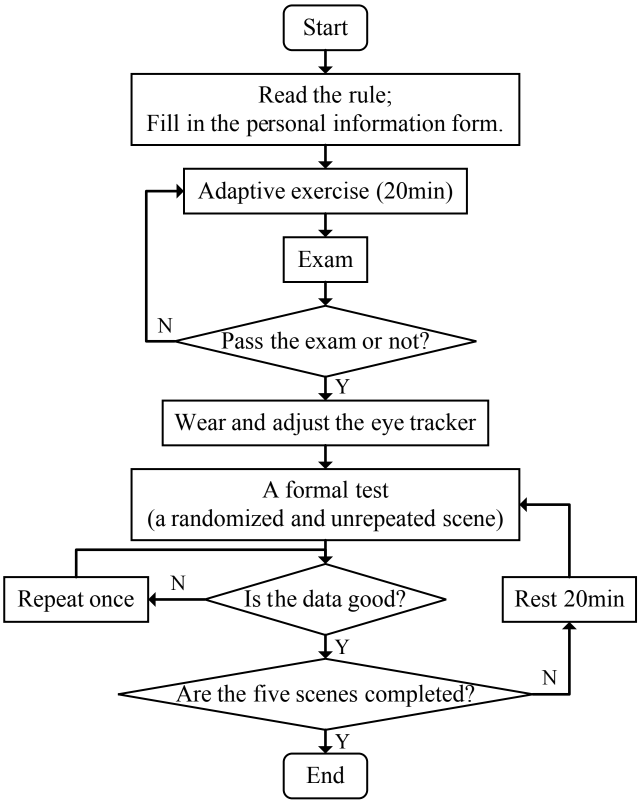
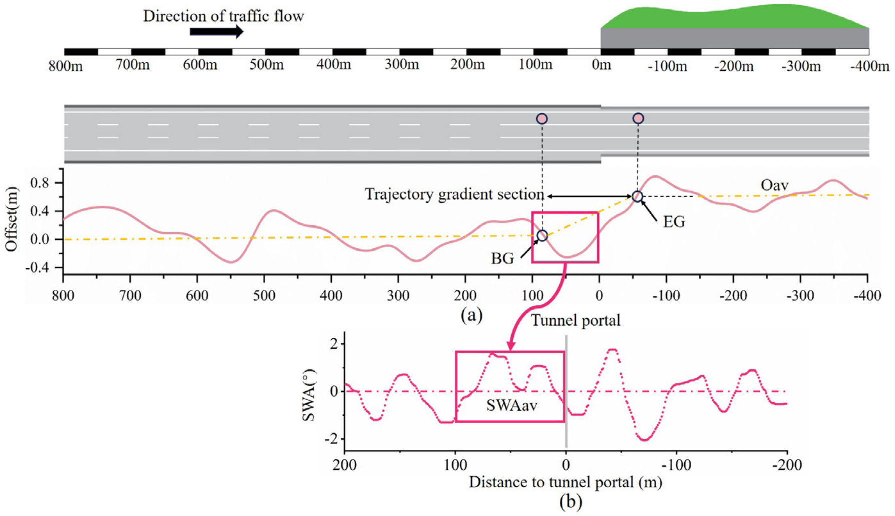


Figure 5 – Experimental procedure

The simulated driving platform captures several data after each test, including time, distance along the road, steering wheel angle, offset from lane centre.

3.6 Data collection

Based on the data collected by the driving simulation platform, we constructed a series of original indicators, which are shown in *Figure 6* and *Table 4*. Next, we further constructed evaluation indicators using these original indicators to assess the degree of abrupt changes in vehicle trajectory in the tunnel entrance zone, and the relevant data have been organised in *Table 5*.



(a)

(b)

Figure 6 – Schematic diagram of original indicators

Table 4 – The meaning of original indicators

Original indicators	Meaning
Oav/cm	Average offset at -400~-150m, where the trajectory is stable
BG/m	Beginning of trajectory gradient section
EG/m	Ending of trajectory gradient section
SWAav/°	Average of steering wheel angle at 0~100m

Table 5 – The meaning of evaluation indicators

Evaluation indicators	Meaning
G	The gradual change degree of the vehicle trajectory in the tunnel entrance zone
SWAav/°	The degree to which the driver evades the tunnel portal

Some of the details of constructing these indicators are explained next:

1) In all visual guiding scenes, the vehicle trajectories displayed stability up until entering the tunnel entrance zone, remaining near the lane centreline, and exhibiting relative stability within the range of -400m to -150m. Hence, this study employed the average offset from -400m to -150m (Oav) to reflect drivers' trajectory selection preferences during this segment.
2) To eliminate the influence of periodic trajectory fluctuations, this study selected the point corresponding to the lane centreline as the beginning of the trajectory gradient section (BG), and the point corresponding to the Oav as the ending of the trajectory gradient section (EG).
3) The gradual change degree of the vehicle trajectory (G) is calculated using *Equation 2*:

$$G = (BG - EG)/Oav \tag{2}$$

By dividing the distance by the offset, the magnitude of G can indicate the smoothness of the trajectory change. Larger G suggest smoother trajectory changes.

4. RESULTS

This section presents the results of the data analysis focusing on the impact of different visual guiding scenes on driving behaviour. We employed the Kolmogorov-Smirnov and Shapiro-Wilk tests, along with analysing skewness and kurtosis, to assess the normality of the distributions. Additionally, Levene's test was utilised to evaluate variance homogeneity. The results demonstrated that all indexes satisfied the assumptions of normality and variance homogeneity, enabling the application of one-way ANOVA for significance testing. We selected these methods based on their well-established principles and widespread use in statistical analysis. The analysis focused on five groups, which corresponded to five different visual guiding scenes. The results, summarised in *Table 6*, included statistical descriptions such as the mean and standard deviation (in parentheses). One-way ANOVA revealed significant effects of visual guiding scenes on G and SWAav.

Table 6 – Influence of visual guiding scenes on driving behaviour

Variable	**Visual guiding scenes**					**Statistical test results**	
	1	**2**	**3**	**4**	**5**	**F**	**P**
G	2.93 (0.30)	3.23 (0.33)	5.25 (0.50)	10.84 (0.74)	11.32 (0.87)	1433.85	0.000
SWAav/°	0.661 (0.090)	0.332 (0.076)	0.121 (0.041)	0.193 (0.055)	0.114 (0.038)	385.90	0.000

To investigate significant differences between means among the groups, we employed LSD post-hoc tests. The symbols used to represent significant differences are as follows: ns, *, **, *** and **** denote p-values ≥0.05, ≤0.05, ≤0.01, ≤0.001 and ≤0.0001, respectively. Below are the results obtained from the LSD post-hoc test.

4.1 Gradual change degree of vehicle trajectory (G)

The LSD post-hoc test results, as depicted in *Figure 7*. The result indicates that the addition of road studs has no impact on the gradual change degree of the vehicle trajectory (G). However, incorporating flexible guideposts, WAS & RA, and multiple devices all increase G. Flexible guideposts lead to a 79.18% increase, WAS & RA result in a significant 269.97% increase and multiple devices show the highest increase at 286.34%. This suggests that both flexible guideposts and WAS & RA contribute to the smooth transition, WAS & RA proves particularly effective, and there is a synergistic effect when both methods are applied to regulate the trajectory.

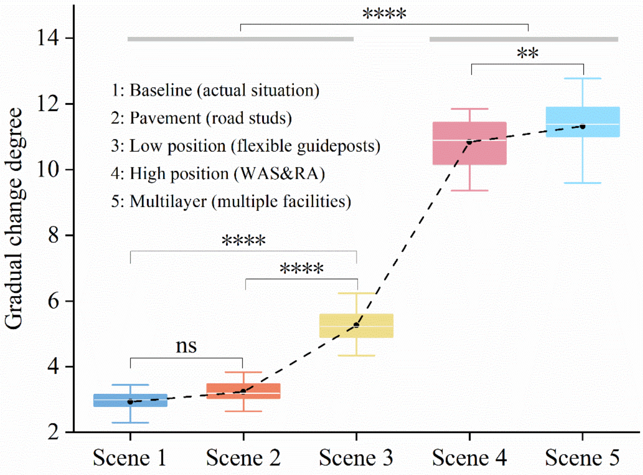


Figure 7 – LSD post-hoc tests results of gradual change degree of the vehicle trajectory (G)

4.2 Average steering wheel angle (SWA_{av})

The LSD post-hoc test results for the average steering wheel angle (SWAav) are presented in *Figure 8*. It is observed that the addition of road studs, flexible guideposts, WAS & RA, and multiple devices significantly reduce

SWAav. Notably, no significant difference is found between the effect of flexible guideposts in Scene 3 and multiple devices in Scene 5. Specifically, road studs lead to a 50% reduction in SWAav, flexible guideposts result in an 81.82% reduction and WAS & RA contribute to a 71.21% reduction. Importantly, implementing multiple devices does not further enhance the reduction in SWAav. These findings indicate that road studs, flexible guideposts and WAS & RA effectively mitigate drivers' evasive manoeuvres in front of the tunnel portal. Among them, flexible guideposts demonstrate the most favourable effect and do not exhibit a synergistic effect with the other two devices.

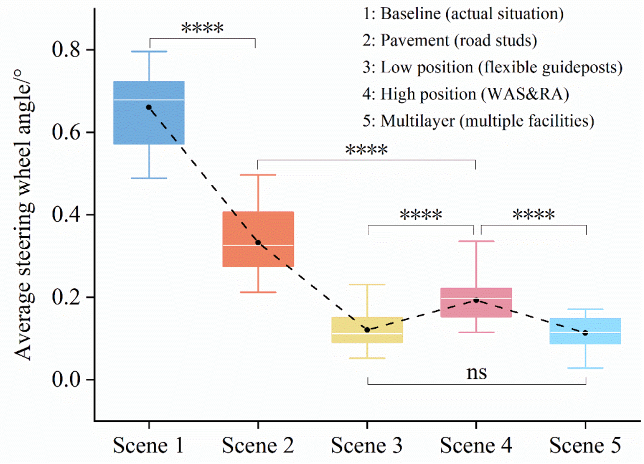


Figure 8 – LSD Post-hoc test results of average steering wheel angle (SWAav)

4.3 Trajectory gradualness (TG) and operational stability (OS)

Without the addition of visual guiding facilities, the vehicle's trajectory undergoes a sudden change in the tunnel entrance zone. Additionally, drivers make sudden steering wheel adjustments to evade the tunnel portal. To quantitatively assess the adjustment effects of different visual guiding scenes on these phenomena, the formula *Equation 3-4* is used to convert the gradual change degree of vehicle trajectory (G) and average steering wheel angle (SWAav) into trajectory gradualness (TG) and operational stability (OS). TG and OS are dimensionless parameters ranging from 0 to 10, with higher values indicating better adjustment effects. The TG and OS values for different visual guiding scenes are shown in *Table 7*.

$$TG = G/1.3 \tag{3}$$

$$OS = 1^{\circ}/SWAav \tag{4}$$

Table 7 – Regulating effect of different scenes on the abrupt change of vehicle trajectory

Visual guiding scenes	TG	OS
Scene 1: actual situation	2.28	1.51
Scene 2: road studs	2.52	3.01
Scene 3: flexible guideposts	4.11	8.28
Scene 4: WAS&RA	8.42	5.19
Scene 5: multiple devices	8.76	8.79

As depicted in *Figure 9* and *Table 7*, the pavement visual guiding devices only marginally enhance operation stability (OS) by 99%, falling short of the capabilities of the roadside high-position and low-position visual guiding devices. The roadside low-position visual guiding devices exhibit an improvement of 80% in trajectory gradualness (TG) and an astonishing 448% in operation stability (OS), primarily intended to enhance the latter. On the other hand, the roadside high-position visual guiding devices demonstrate a significant boost of 269% in trajectory gradualness (TG) and 244% in operation stability (OS), primarily intended to enhance the former. Optimal for regulating the abrupt change of vehicle trajectory, the multilayer visual guiding system surpasses the others, achieving a remarkable enhancement of 284% in trajectory gradualness (TG) and 482% in operation stability (OS).

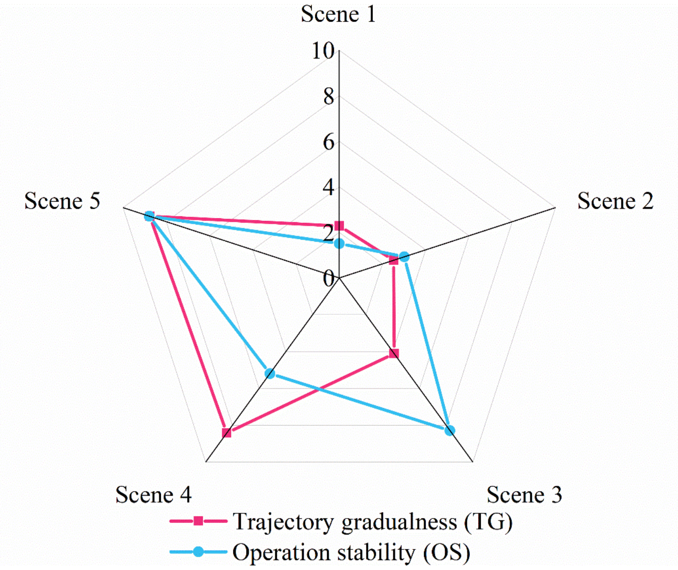


Figure 9 – Trajectory gradualness (TG) and operational stability (OS) of different visual guiding scenes

5. DISCUSSION

Scholars generally agree that vehicle trajectory in the entrance zone of a freeway tunnel tends to deviate away from the side walls [11–14], which is also reflected in the performance of indicators G and SWAav in this study. Wang et al. [12] quantitatively evaluated the extent to which vehicles evade tunnel sidewalls using lateral deviation and the standard deviation of steering wheel angle. The lateral deviation in the inside zone (-250~-150m) remained below 0.2 metres during both day and night, while in the transition zone (-150~150m), it was below 0.3 metres during the day and had a mean value of 0.45 metres for novice drivers at night. These values indicate that drivers exhibit a higher degree of evasion in the transition zone compared to the inside zone. However, they failed to recognise that evasion in the transition zone (-150~150m) is a dynamic process, with lateral deviation gradually increasing. The average value of lateral deviation in the -150~150m zone weakens the actual degree of evasion. Similar issues exist in the studies conducted by Calvi et al. [13] and Xu et al. [15]. Additionally, evasion is not only related to the magnitude of lateral deviation but also to the length of the section in which the deviation occurs. For example, a 50 cm lateral deviation after traveling 50 m exhibits more pronounced avoidance compared to a 50 cm deviation after traveling 100 m. The G indicator used in this study takes these factors into account effectively.

Wan et al. [11] and Wang et al. [12] encountered challenges in effectively evaluating trajectory changes using steering wheel angle data due to their simplistic approach of averaging data over long roadway segments, which failed to capture relevant behaviour. In contrast, our study meticulously analysed the steering wheel angle over a short (100 m) roadway segment prior to entering the tunnel, as actual data indicated that drivers avoid the tunnel's side walls in this interval. The advancements of the G and SWAav (0~100 m) indicators in this study are pioneering and specifically developed to provide a more precise assessment of trajectory changes in the tunnel entrance zone. The combined application of these indicators results in a more accurate evaluation of the regulatory effects of various traffic safety measures, in addition to the manifestation of trajectory changes.

Some scholars have demonstrated the effectiveness of visual guidance facilities in tunnels, such as road studs [18], chevron alignment signs and retroreflective arches [19], as well as a combination of different visual guiding facilities [22, 23]. However, no previous studies have investigated the regulatory effects of these visual guidance facilities on trajectory changes in the entrance zone of tunnels. This study fills this research gap. WAS&RA, which comprises retroreflective arches at the tunnel entrance and warning alignment signs in front of the tunnel portal, is proposed as a solution. The retroreflective arches provide a clear outline of the tunnel, assisting drivers in positioning themselves and reducing offset when entering. The warning alignment sign narrows the driver's field of view, facilitating adaptation and earlier transition of trajectory. As a result, WAS&RA significantly enhances trajectory gradualness (TG). Additionally, flexible guideposts are strategically placed on the inside of guardrails, tunnel portals and sidewalks to divert driver attention from these structures. These guideposts are continuously positioned along the tunnel entrance zone, ensuring good operational stability (OS) in front of the tunnel portal.

6. CONCLUSION

In this study, a simulated driving test was conducted to investigate the adjustment effects of visual guiding devices at different vertical positions, as well as a multilayer visual guiding system, on the abrupt change of vehicle trajectory in this zone. The main conclusions are as follows:

1) In the absence of visual guiding technologies, the trajectory of vehicles in the entrance zone of a freeway tunnel will undergo abrupt changes, posing a safety risk. To quantitatively evaluate the degree to which the trajectory deviates from the centre of the lane and the stability of steering wheel operation by the driver, two parameters, namely the gradual change degree of vehicle trajectory (G) and the average steering wheel angle (SWAav), can be employed.
2) The reasonable application of visual guide technologies can effectively regulate the sudden changes in vehicle trajectory. Specifically, pavement visual guiding devices offer a certain enhancement effect on operation stability (OS), resulting in a 99% improvement. The roadside low-position visual guiding devices demonstrate optimal effects on operation stability (OS), with an improvement of 448%. Furthermore, the roadside high-position visual guiding devices are most effective in regulating trajectory gradualness (TG), with an improvement of 269%. These visual guiding devices exhibit synergetic effects, and integrating them into a multilayer visual guiding system yields optimal results in mitigating abrupt changes in vehicle trajectory, enhancing trajectory gradualness (TG) and operation stability (OS) by 284% and 482%, respectively.
3) It is recommended to implement a multilayer visual guiding system in the tunnel entrance zone to enhance the continuity of visual references, thereby improving trajectory gradualness (TG) and operation stability (OS). However, in tunnels equipped with guardrail transition sections, it may be permissible to omit the roadside low-position visual guiding devices if there are limitations on lateral clearance.

This study provides a reference for the installation of visual guiding devices at the entrance zone of freeway tunnels and the improvement of tunnel traffic safety. Although the effect of the visual guiding system on driving behaviour at the tunnel entrance zone was initially investigated, further research is still needed on the traffic conditions of large trucks and following vehicles. Additionally, the simulated driving test and the natural driving test complement each other, and further natural driving tests are needed to supplement the findings of the simulated driving test.

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高速公路隧道入口区域车辆运行轨迹分析与调节：从视线诱导系统的角度

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摘要

本研究旨在定量评价各种视线诱导方案对隧道入口区域车辆运行轨迹突变的调节效果。设计了5种模拟场景进行驾驶模拟实验：（1）对照组（实际情况）、（2）路面（突起路标）、（3）低位（弹性交通柱）、（4）高位（警示型线形诱导标和反光环）、（5）多层（所有这些设施的组合）。收集了包括车辆位置、方向盘角度和横向偏移在内的原始数据。基于这些数据，计算车辆运行轨迹渐变度（G）和平均方向盘角度（SWAav），分别用于定量评价车辆运行轨迹偏离车道中心的程度和驾驶人对方向盘操作的稳定性。将这两个评价指标分别转化为轨迹渐变性（TG）和操作稳定性（OS），定量评价不同视线诱导方案的调节效果。研究结果表明：突起路标对操作稳定性（OS）有一定程度的提高；弹性交通柱对操作稳定性（OS）的提高效果最好；警示型线形诱导标与反光环的组合对轨迹渐变性（TG）的提高效果最好；多层视线诱导系统实现了最优的轨迹渐变性（TG）和操作稳定性（OS）。

关键词

隧道入口区域；交通安全；视线诱导；驾驶行为；车辆运行轨迹。