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Driver's Shy Away Effect in Urban Extra-Long Underwater Tunnel

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ABSTRACT

For urban extra-long underwater tunnels, the obstacle space formed by the tunnel walls on both sides has an impact on the driver's driving. The aim of this study is to investigate the shy away characteristics of drivers in urban extra-long underwater tunnels. Using trajectory offset and speed data obtained from real vehicle tests, the driving behaviour at different lanes of an urban extra-long underwater tunnel was investigated, and a theory of shy away effects and indicators of sidewall shy away deviation for quantitative analysis were proposed. The results show that the left-hand lane has the largest offset and driving speed from the sidewall compared to the other two lanes. In the centre lane there is a large fluctuation in the amount of deflection per 50 seconds of driving, increasing the risk of two-lane collisions. When the lateral clearances are increased from 0.5 m to 2.19 m on the left and 1.29 m on the right, the safety needs of drivers can be better met. The results of this study have implications for improving traffic safety in urban extra-long underwater tunnels and for the improvement of tunnel traffic safety facilities.

KEYWORDS

traffic safety; urban extra-long underwater tunnel; shy away effect; driving behaviour; driving characteristics.

1. INTRODUCTION

Underwater tunnels are built to cross rivers, lakes and seas, reducing travel times and improving accessibility for residents. In recent years, urban extra-long underwater tunnels have been widely used in cities like Wuhan, Hangzhou, Qingdao and Xiamen in China [1]. However, with the increase of applications, corresponding traffic crashes have also followed. A study on tunnel crashes found that the crash rate in tunnels is higher than in open sections [2]. Narrower tunnels are generally considered less safe than wider tunnels, while longer tunnels are often considered more dangerous than shorter tunnels [3]. Analysis of existing long tunnels shows that, due to geographical constraints, urban long tunnels have continuous downhill entrances and uphill exits, with many curves and slope changes inside the tunnel, and long and relatively enclosed spaces in the middle, making it difficult to rescue people after crash and increasing the probability of mass fatalities and injuries. Crash fatality rate inside the tunnel is twice as high as outside [4].

The environmental influences on drivers in tunnel intervals should not be neglected. Due to the confined and narrow environment in tunnels, drivers feel nervous and their instinctive safety reactions greatly increase the distance between the vehicle and the tunnel wall [5]. Drivers usually adjust their lateral position and speed to avoid getting too close to the tunnel wall [3]. At this point, it can be determined that the tunnel sidewalls are exerting an inhibiting influence on the driver. There are sidewall effects in tunnels, as Ye and Su [6], Song et al. [7] noted. The so-called 'sidewall effect' is the psychological impact of the tunnel wall on the driver, who fears colliding with it, making the driver nervous and therefore sluggish, even making it difficult to drive the car steadily and precisely. For this reason, the focus of this research is on the shy away behaviour of drivers in tunnels and the distinct personality characteristics they display.

The amount of lateral offset in the driving trajectory is the most direct indicator of driver performance when influenced by the environment. Hu et al. [8] suggest that driving risk can be assessed based on the amount of lateral offset of the driver. Shangguan et al. [9], Anik et al. [10] suggest that driving intentions can be predicted by driving offsets. Therefore, quantifying the steering risk of vehicles through the study of their lateral movement characteristics and the steering shy away behaviour of drivers is an objective that needs to be considered for future research. However, it is difficult to obtain driving data in tunnels, so most quantitative studies of trajectories have focused on tunnel entrances and exits. For example, Chen and Liu [11] described three ways to calculate the trajectory offset of the tunnel cavity and proposed a criterion for judging that the road alignment of the tunnel cavity is consistent with the driving trajectory. Ouyang et al. [12] through the study of driving track, the driving conflict in weaving section in front of two short tunnels is predicted. The study of the interior trajectory of the tunnel is more qualitative, with more subjective descriptions of patterns and fewer quantitative descriptions. Qin et al. [13] used simulation tests to investigate the effect of the amount of colour information in a tunnel on the driver's driving offset and showed that the driving offset decreased as the amount of colour information on the tunnel sidewalls increased.

The principle of the driver's shy away effect can provide ideas for improving safety in tunnels. Zhao et al. [14] suggest that various combinations of tunnel sidewall patterns can improve the stability and speed control of drivers driving longitudinally in tunnels to a certain extent and improve driving safety. Shah and Lee [15] analysed the relationship between avoidance behaviour and crash risk and suggested that avoidance behaviour could be used to develop driver warning messages to reduce driver avoidance action variability and speed variation between drivers to reduce crash risk. Or assess the reasonableness of the lane width design by considering driving offset and speed fluctuations due to inhibiting influences. Or by increasing lateral clearances to reduce the impact of sidewall inhibition on drivers. The shy away effect of drivers can also be used reasonably to reduce the risk of collision by installing facilities in crash-prone areas. Therefore, the primary objective of the study is to investigate the driver characteristics of urban extra-long underwater tunnels, to explore the shy away effect of tunnel sidewalls on drivers and provide theoretical support for the design and improvement of tunnel traffic safety.

In summary, this paper focuses on answering the following questions:

Firstly, what is the shy away effect?

Secondly, what is the influence of the shy away effect on drivers?

Thirdly, what ideas to improve tunnel safety can be given by the shy away effect on drivers?

Table 1 – Summary of relevant research analyses

Research directions	Examples of research literature	Main conclusions	Shortcomings of the research
Tunnel crash statistics and cause analysis	Wang et al., 2018; Caliendo et al., 2013; Bassan, 2016.	1) The crash rate in tunnels is greater than in open roads. 2) The narrower and longer the tunnel, the greater the probability of a crash.	Fewer studies have been carried out on the causes of crashes in urban extra-long underwater tunnels.
Correlation of tunnel driving behaviour with the environment	Calvi et al., 2012; Caliendo et al., 2013; Ye et al., 2003; Song et al., 2010.	1) The closed environment of a tunnel can create tension for the driver, which can cause changes in the control of the vehicle. 2) The tunnel environment, especially the tunnel sidewalls, has a strong influence on drivers and can alter their judgement of speed and trajectory.	The quantitative analysis of tunnel interiors has been less studied and is mostly described subjectively.
The effect of tunnel sidewalls on drivers	Hu et al., 2021; Shangguan, et al., 2022; Anik Das, et al., 2019; Chen et al., 2017; Ouyang, et al., 2022; Qin et al., 2020; Zhao et al., 2022; Shah et al., 2021.	1) The amount of lateral offset can represent the driver's intention and estimate the driving risk. 2) Trajectory offsets at tunnel entrances and exits increase traffic conflicts. 3) The effect of tunnel sidewalls on driver trajectory offset and speed can be mitigated by the installation of different guidance facilities on the tunnel sidewalls.	It is difficult to obtain driving data inside tunnels and most studies focus on tunnel entrance and exit trajectory offsets. The impact analysis of the sidewalls is usually carried out with simulation tests and lacks the support of real vehicle test data.

2. THEORY OF SHY AWAY EFFECT

Lateral clearance is an absolute distance that drivers need to consider for safety reasons. When the lateral clearance is too small, the driver's psychological pressure will increase and the driver will seek a certain safe distance and produce a deviation of the trajectory [16]. Too much lateral clearance will result in the lane width being compressed, causing the nominal right of way to be incompatible with the actual right of way, resulting in a waste of road resources and increasing the irregularity of driving behaviour [17]. Therefore, the driver's instinct to move away from an obstacle to avoid colliding with it during the driving process is called the shy away effect.

The shy away effect is more significant in road environments such as tunnels [5], highway roadside [18], ramp entrances and exits [19], and the specific performance in the traffic environment is shown in *Figure 1*. When the vehicle is driving in the innermost or outermost lane, if there is an obstacle within the lateral clearance of the road, the driving trajectory will be shifted towards the side away from the obstacle. In the case of vehicles driving in the same direction in two adjacent lanes, the larger the vehicle type in the adjacent lane, the greater the effect on the lateral offset of the smaller vehicle type on the side next to it. (For example, in *Figure 1a* and *Figure 1b* when there is an obstacle on the left side of the vehicle, $A_L > B_L$, and in *Figure 1c* and *Figure 1d* when there is a truck in the left lane of the vehicle, $C_R > D_R$, where A_L, B_L, C_R and D_R are the distance between the centre of the vehicle and the lane edge respectively).

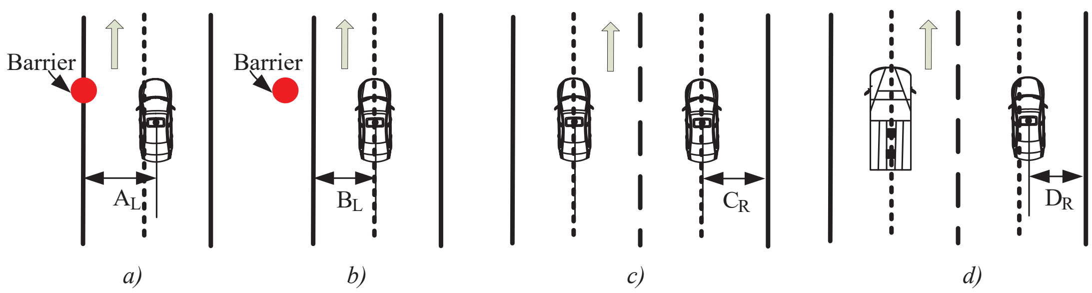


Figure 1 – Schematic representation of the shy away effect

The shy away effect usually causes the driver to move away from the obstacle intermittently or continuously, resulting in erratic driver directional control and snaking characteristics of the vehicle, as well as discontinuities and inconsistencies in the guidance facility. Understanding the specific effects of the shy away effect on the driver and seeking reasonable lateral clearance is the key to reducing the excessive shy away effect and ensuring safe driving.

3. TEST SCHEME AND METHOD

3.1 Test road

The Wuhan Rail-cum-Road Yangtze River Cross Tunnel was selected for the test, with a total length of 4660 m and an underwater section of 2590 m. Two lanes at the entrance and exit, three lanes in the middle section, speed limit 60 km/h in the main section of the tunnel, maximum vertical slope 5%. *Figure 2* shows the tunnel cross-section with the actual road, where *W* is the width of each lane, 3.5 m. *C* is the residual width,

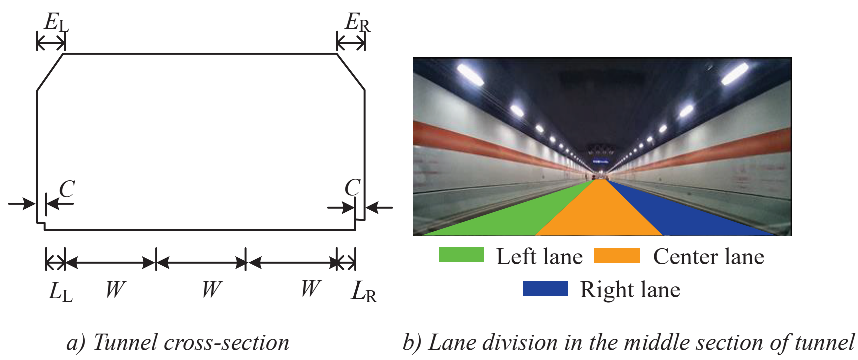
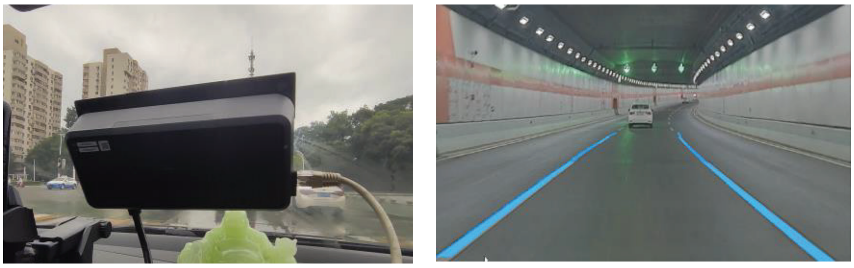


Figure 2 – Test road

0.25 m. L_L is the left side width, 0.5 m. L_R is the right side width, 0.5 m. E_L is the left top corner width of the building boundaries and E_R is the right top corner width of the building boundaries. As the three-lane section of the tunnel has no pavements or maintaining roadway, the lateral offsets are taken to be the minimum value of 0.5 m specified in the code [20].

3.2 Test instruments and subjects

Lee et al. [21] propose that vehicle lane keeping can be studied inexpensively with dual cameras and within 0.17 m of recognition error. In this way, for the strong signal interference in the tunnel, the test uses the SmarterEye S1CG V0.0.2 to collect the distance between the vehicle driving position and the lane edge in real time, as shown in *Figure 3.* The vehicle's real-time operating speed and other information is collected via OBD, and to prevent signal interference in the tunnel, a small dashboard recorder is added to capture the speed of the dashboard. The car recorder captures the driving process. The test vehicle was a small 5-seat Volkswagen, approximately 180 mm wide and 4570 mm long.



a) Equipment *b) Instrument identification interface*

Figure 3 – SmarterEye S1CG V0.0.2.

Several studies have shown that the effect of random error can be excluded when the sample size of the test is greater than 20 [22–24]. Based on this, the test recruited 21 drivers in the community, 13 of whom were male, with an age distribution of 24–40 years (*M*=28, *SD*=4.76) and a driving experience distribution of 2–20 years (*M*=8.6, *SD*=4.60). Eight females were distributed between 23–31 years of age (*M*=26.1, *SD*=2.37) and 1–11 years of driving experience (*M*=5.5, *SD*=3.12). All drivers had good vision and no biopsychological disorders.

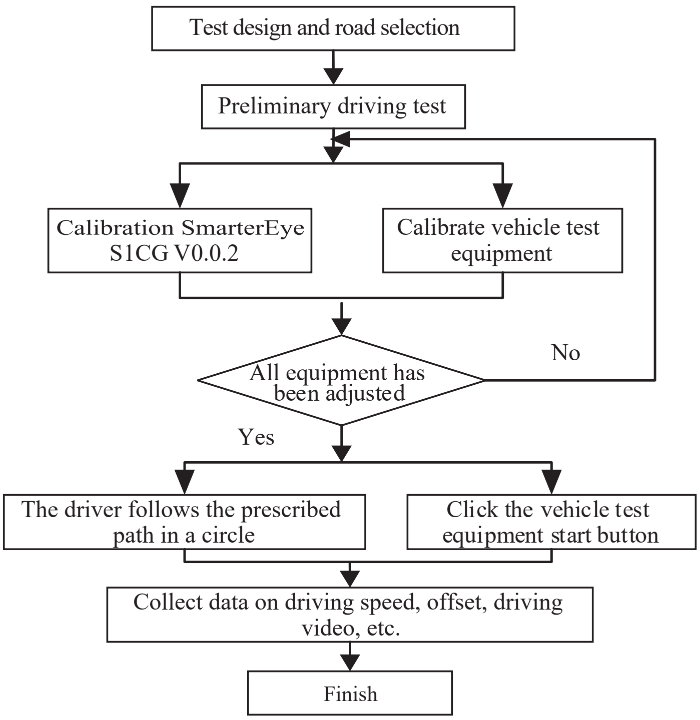


Figure 4 – Test flow

3.3 Test programme and procedure

The tests were concentrated between 14:00 and 17:00, and 20:00–22:00 to minimise morning and evening rush hours affecting test results. Each driver stops after one driving cycle and the attendant records the start time, the time of entry into three lanes, the time of exiting the three lanes and the end time, saves the driving data and then follows the next driver. A driving cycle means that the driver starts from the starting point and follows the prescribed route: left lane entry – left lane return – centre lane entry – centre lane return – right lane entry – right lane return. The SmarterEye S1CG V0.0.2 was collected at a frequency of 10 Hz. The test flow is shown in *Figure 4*.

3.4 Data analysis

Examine the car recorder and take out any road situations, including overtaking and following, which can affect the test results. Intercepted travel speed and trajectory offset data at three lanes. Vehicle offset collected by the instrument is the distance from the vehicle centre point to the lane markings on both sides of the lane, i.e. *DL* vs *DR* in *Figure 5*. *DL* is the distance in metres between the centre of the vehicle and the left-hand marking when driving in this lane. *DR* is the distance in meters between the centre of the vehicle and the right-hand marking when driving in this lane.

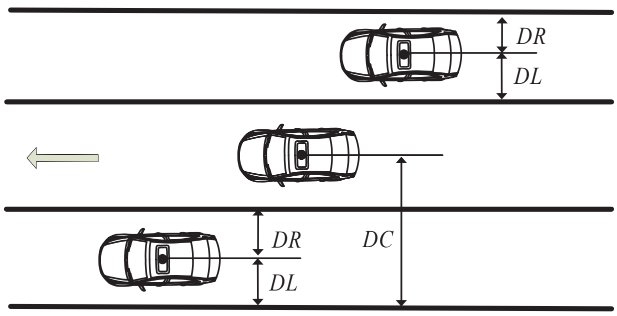


Figure 5 – Three-lane offset distance

In the analysis that follows, for sidewall shy away distances, *DL* is chosen for the left lane as the shy away distance for the left wall and *DR* is chosen for the right lane as the shy away distance for the right wall. *DC* is the distance of the vehicle centre point from the left tunnel wall when driving in the middle lane, in metres, as the distance by which the middle lane is offset by the left wall.

The concept of sidewall shy away deviation (*SSAD*) was introduced for a more intuitive comparison of the left and right sidewall suppression strengths. Calculated as shown in *Equation 1*, when *SSAD* is greater than 0, it means that the driver is significantly influenced by the left-hand wall during driving, creating a driving characteristic of avoidance to the right. When the *SSAD* is equal to 0, it indicates that the driver maintains the centre of the lane and the side wall has a weak influence on them. When the *SSAD* is less than 0, the driver is significantly influenced by the right-hand wall and develops a left-avoidance driving characteristic.

$$SSAD = |DL| - |DR| \tag{1}$$

4. SIDEWALL SHY AWAY ANALYSIS

4.1 Overall sidewall distance

Figures 6 and 7 show the frequency distribution of sidewall distances to and from the three lanes in both directions. There is no significant difference in sidewall distances in different directions for the same lane, with the maximum frequency distribution intervals (1.7575 m, 1.7675 m), (5.2525 m, 5.2625 m), (1.7325 m, 1.7425 m) for the left, centre and right lanes, respectively, with an average of 46.82%, 43.63% and 48.24%. That is, in most states of driving at urban extra-long underwater tunnels, the driving trajectory is offset to the left, but the overall offset is small and drivers show a more conservative driving style.

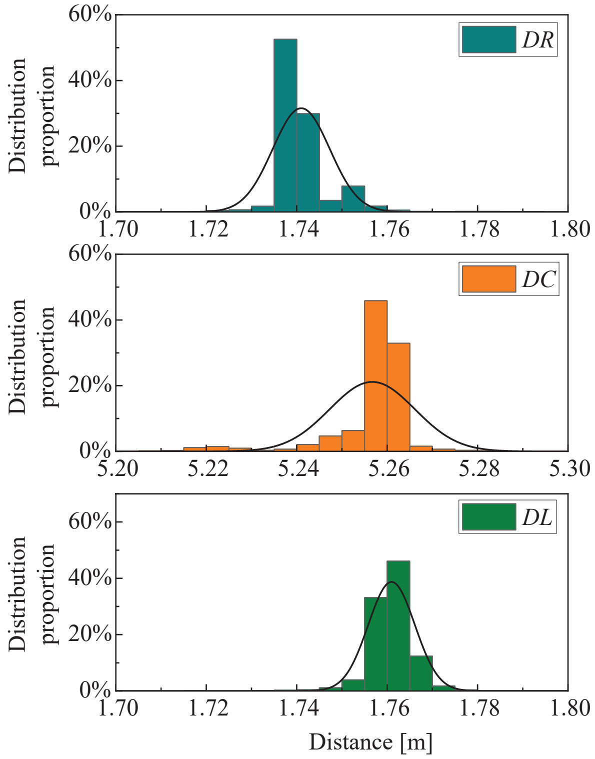


Figure 6 – Frequency distribution of sidewall distances for Hankou-Wuchang

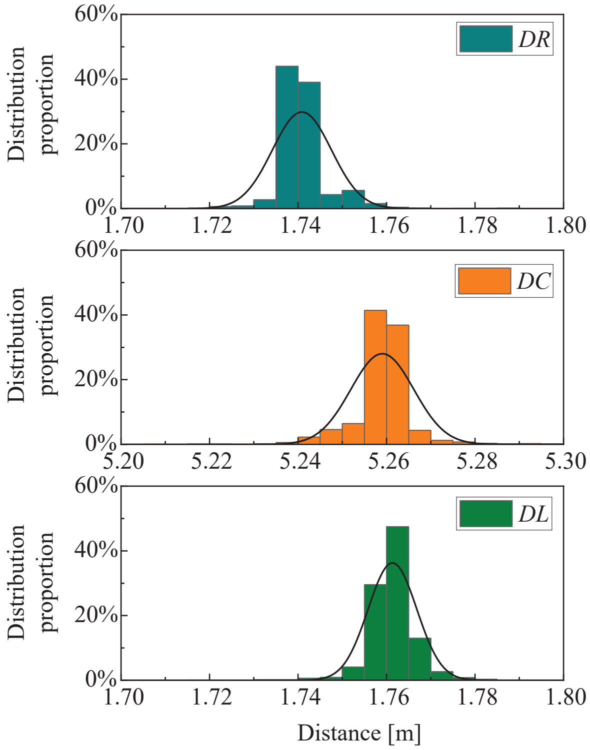


Figure 7 – Frequency distribution of sidewall distances for Wuchang – Hankou

As can be seen from the maximum sidewall distance analysis *Table 2*, the maximum sidewall distance in the left lane is 1.8567 m, which is offset to the right by 0.107 m relative to the middle of the left lane (1.75 m).The maximum sidewall distance in the right lane is 1.8107 m, with an offset of 0.061 m to the left in relation to the middle of the right lane (1.75 m). The maximum offset in the centre lane has a wider distribution of offsets compared to the maximum offset in the left and right lanes. The offset is between 0.06 m and 0.13 m, based on the left-hand wall, and the ratio of left to right offset is 1:9, using the middle of the centre lane as the boundary (5.25 m).

Table 2 – Eigenvalues of sidewall distances

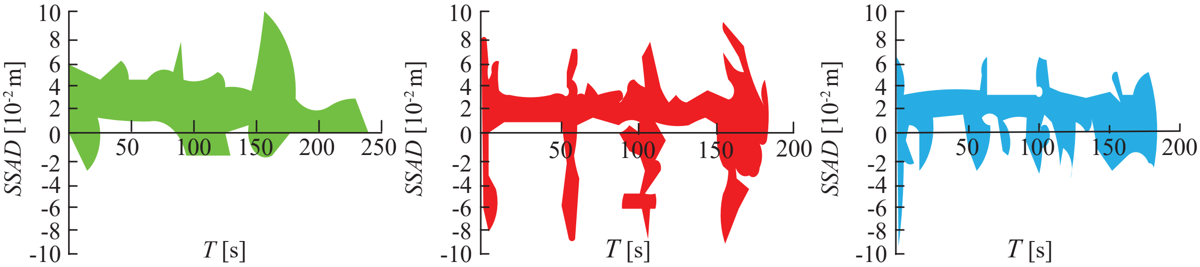
	Hankou - Wuchang			Wuchang - Hankou		
	Left	Centre	Right	Left	Centre	Right
Median of the maximum frequency distribution interval [m]	1.7625	5.2575	1.7375	1.7625	5.2575	1.7375
Frequency [%]	46.15	45.85	52.51	47.48	41.41	43.97
Maximum sidewall distance [m]	1.8567	5.3062	1.8000	1.8013	5.3754	1.8107
Minimum sidewall distance [m]	1.7073	5.1931	1.6979	1.6914	5.2017	1.6199

In summary, the driver's trajectory fluctuates from left to right when driving on different lanes of the urban extra-long underwater tunnel. The maximum offset shows that the left lane is offset to the right by the left wall, the right lane is offset to the left by the right wall and the overall offset of the centre lane is more influenced by the left wall.

4.2 Sidewall shy away deviation

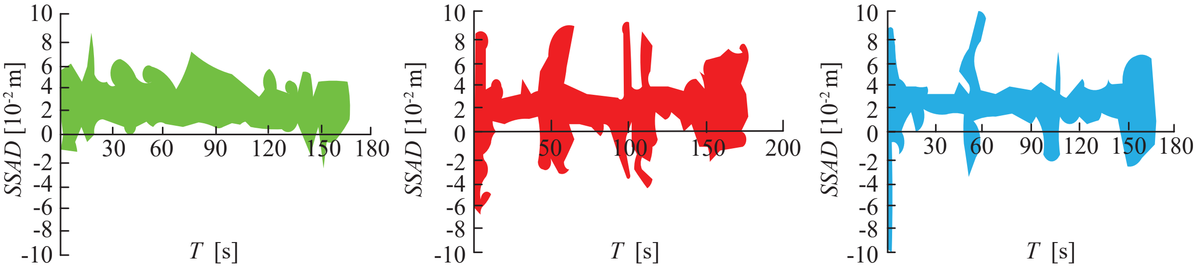
Sidewall shy away deviation (*SSAD*) is the difference between the distance of the vehicle from the left marker and the distance from the right marker. The calculation of the difference between the two allows a more visual observation of the direction of the driver's instantaneous offset. D_S refers to the distance of the driver from the side wall, in metres. The D_S is taken as 1.3 m for the left lane, 2.2 m for the right lane and 4.8 m for the centre lane when the vehicle is driving in the centre of the respective lane.

The envelope area of the left-centre-right lane sidewall shy away deviation can be seen in *Figures 8 and 9*. The sidewall shy away deviation in the left lane is the least volatile, being more evenly distributed between 0 and 0.06 m. The centre lane is even more discrete and shows larger fluctuations every 50 seconds. The vehicle veers left and then quickly right before reverting to the regular 0.02–0.04 m. That is, when driving in the centre lane, the driver is far away from the left and right sidewalls, and after a certain distance, a transient relaxation behaviour occurs. Pervez et al. [25] calculated for crashes in different areas of the tunnel that single vehicle crashes are more likely to occur in the middle of long tunnels due to driver fatigue, which is consistent with the results calculated in this paper. The volatility of the sidewall shy away deviation in the right lane lies between the centre and left lane, with a small difference between the left and right distances, mainly distributed between 0.02 and 0.03 m.



a) Left lane *b) Centre lane* *c) Right lane*

Figure 8 – SSAD envelope area for Hankou-Wuchang



a) Left lane *b) Centre lane* *c) Right lane*

Figure 9 – SSAD envelope area for Wuchang – Hankou

According to the overall *SSAD* statistics as a percentage, in *Table 3*, the left side of the vehicle offset is greater than the right side of the vehicle offset at more than 84% of the moments when driving in urban extra-long underwater tunnels. *SSAD* is greater than 0 and is more significantly influenced by the left-hand wall. The largest proportion of right-hand offset (*SSAD*>0) occurred when driving in the left lane, 97.529% and 97.138% respectively. The highest percentage of driving in the middle of the current lane (*SSAD*=0) occurred when driving in the centre lane, with 3.739% and 1.373% respectively. The percentage of left offset (*SSAD*<0) is such that the middle lane is greater than the right lane than the left lane.

Table 3 – Percentage of overall SSAD statistics [%]

Direction	Hankou-Wuchang			Wuchang – Hankou		
Lane	Left	Centre	Right	Left	Centre	Right
Less than 0 [%]	2.001	11.902	8.878	1.938	7.994	6.872
Equal to 0 [%]	0.470	3.739	2.127	0.925	1.373	1.244
Larger than 0 [%]	97.529	84.359	88.995	97.138	90.632	91.884

Table 4 – Average values of SSAD for different lanes [10^{-2} m]

Lane (D_s)	Hankou-Wuchang	Wuchang – Hankou
Left (1.3 m)	2.24	2.28
Right (2.2 m)	1.79	1.81
Centre (4.8 m)	1.34	1.78

As seen in *Figure 10*, the sidewall distance is negatively related to the sidewall shy away deviation. The further the driver is from the sidewall, the less the left-right fluctuation and the steadier the driver's driving. Hu et al. [26] point out that during driving, the driver, vehicle and environment form a closed-loop system in which the driver integrates the road environment with the vehicle's driving status to produce the appropriate driving behaviour. When driving in the tunnel, the inhibiting influence of the sidewalls causes the driver to be more nervous and create a driving offset, but as the driver's distance from the sidewalls increases, the degree of sidewall shy away gradually decreases and the driver gradually follows the prescribed driving behaviour.

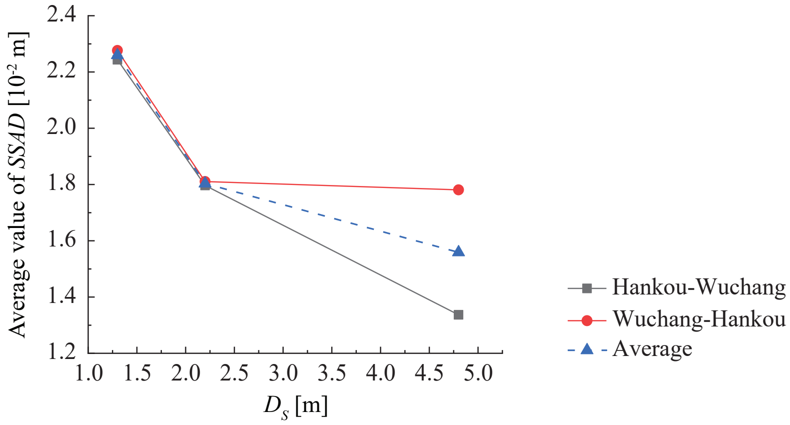


Figure 10 – SSAD average versus D_S

5. DISCUSSION

5.1 Influence of curve

Interception of a straight section and a curved section in the tunnel. Enter straight ahead section ① first in the direction of Hankou-Wuchang, then enter the right-turn road section ②. The Wuchang-Hankou direction enters the left-turn road section ③ first and then enters the straight ahead area ④. As shown in *Figure 11*.

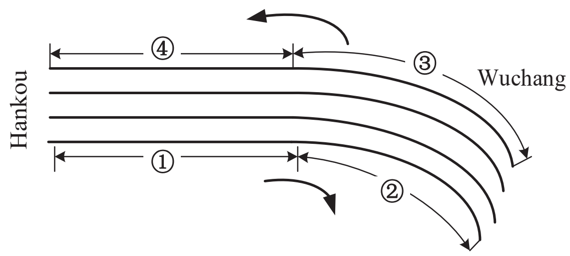
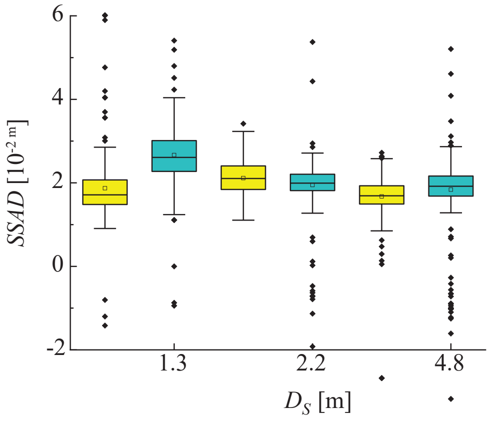


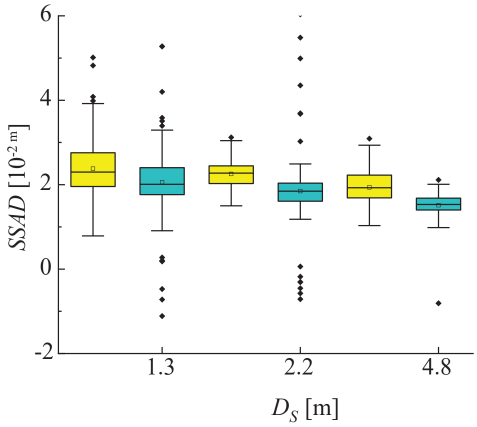
Figure 11 – Position and orientation of curved and straight sections.

Figure 12a shows that when entering the left turn lane, driving in the left lane (1.3 m corresponding area), the *SSAD* is maximum and the tendency to sidewall shy away is more pronounced. The *SSAD* gradually decreases as the driver's distance from the tunnel boundary increases. The average *SSAD* for the curved section of the left lane is $2.67 \cdot 10^{-2}$ m, significantly greater than the average *SSAD* for the straight section of $1.87 \cdot 10^{-2}$ m. Jiao et al. [1] studied the sight distance and area of vision of drivers in urban extra-long underwater tunnels under different radii and turning conditions, and concluded that the area and distribution of the drivers' field of vision became wider with increasing radius. At the same radius, the average sighting time was longer for left turns than for right turns. This paper demonstrates that when driving on a left turn lane, the closer the driver is to the sidewall, the more pronounced the sidewall shy away effect is, as the driver's field of vision is influenced by the left-hand wall. The average *SSAD* values for the left, right and centre lanes were $2.67 \cdot 10^{-2}$ m, $1.95 \cdot 10^{-2}$ m and $1.84 \cdot 10^{-2}$ m respectively, i.e. the *SSAD* gradually decreased by 27% and 31% as the driver's distance from the road boundary increased.

Wang et al. [27] analysed the visual characteristics of drivers in small radius tunnels and concluded that the smaller the radius, the greater the driver's psychological stress. In the right-turn section, *Figure 12b*, the driver shy away effect is not as high as in the left-turn, and it even appears that the overall *SSAD* distribution is smal-



a) Wuchang Hankou (left turn and straight section)



b) Hankou Wuchang (right turn and straight section)

Figure 12 – SSAD of different road sections

ler than for the straight section. The average *SSAD* values for the curved left, right and centre lane sections of the right turn are $2.06 \cdot 10^{-2}$ m, $1.85 \cdot 10^{-2}$ m and $1.51 \cdot 10^{-2}$ m respectively, which are smaller than the average *SSAD* values for the straight section left, right and centre lanes, which are $2.38 \cdot 10^{-2}$ m, $2.25 \cdot 10^{-2}$ m and $1.94 \cdot 10^{-2}$ m respectively. The paper further compares and differentiates between left and right turns on curved sections, and concludes that the driver's sidewall offset when turning left in the left lane is greater than on straight sections than on right turns, when the psychological pressure is greatest. Based on this, it is understood that left turns are the most dangerous in curved sections of urban extra-long underwater tunnels, i.e. subsequent safety improvements could focus on left turns in curved sections by using high frequency, continuous single linear guidance signs on the left and low frequency combined linear guidance signs on the right (Du et al. [28] showed that visual guidance facilities can effectively improve the light environment inside the tunnel and enhance drivers' sense of speed and direction). Furthermore, additional reflective rings to anticipate the presence of curves and enhance visual recognition of the tunnel boundary in the curved section (Du et al. [29] have shown that the combined use of different numbers of reflective rings can effectively improve the driver's ability to perceive the curvature of a curve and reduce the reaction time).

5.2 Influence of speed

Driving speed, as the most intuitive change in the driver's driving process, reflects the judgement made by the driver regarding the current driving environment and has become a major parameter in the study of driving characteristics. Li [30] points out that when driving inside of the tunnel, drivers will drive at a lower speed than outside of the tunnel in order to avoid the psychological pressure of the 'sidewall effect' of driving too fast and hitting the tunnel walls on both sides. In *Figure 13* the speed distribution in the left lane is 20–85 km/h with an average speed of 62.69 km/h. The speed distribution in the right lane is 40–80 km·h^{-1} with an average speed of 60 km·h^{-1}. The speed distribution in the centre lane is 30–80 km/h with an average speed of 59.88 km/h. The specific parameters are shown in *Table 5*.

Table 5 – Average values for each parameter

D_S [m]	Average speed [km/h]	Average *SSAD* [10^{-2} m]
1.3	62.69	2.26
2.2	60.00	1.80
4.5	59.88	1.56

Ma et al. [31] analysed and calculated the average and dispersion of drivers' driving speeds at extra-long tunnels and concluded that the differences in driving speeds between lanes were small. The differences in average values of speeds calculated for each lane in this paper ranged 0.12–2.69 km/h, similar to its results. In *Figure 14*, the average sidewall shy away deviation decreases as the driver moves further away from the sidewall

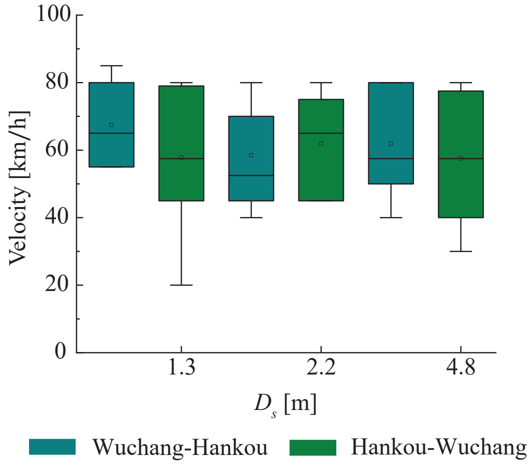


Figure 13 – Velocity versus Ds in different directions

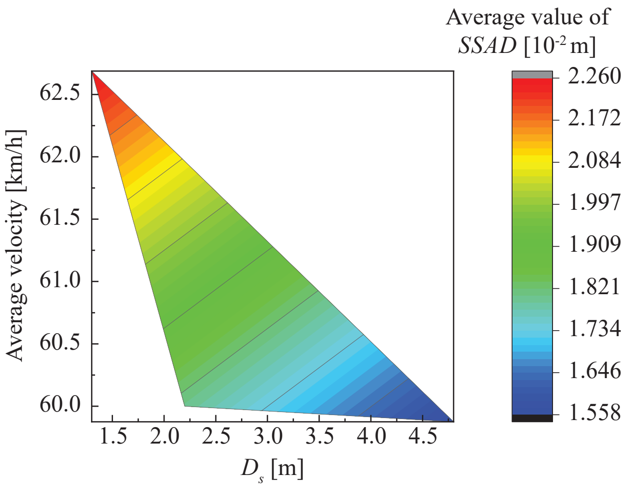


Figure 14 – Relationship between average velocity, SSAD and Ds

and drives at a lower speed. The average speed decreased by 4.5% and the average sidewall shy away deviation decreased by $0.7 \cdot 10^{-2}$ m. As the speed limit in the tunnel is 60 km/h, the distribution of the box plots shows that in most cases drivers will exceed the speed limit. The results of this paper show that in tunnels, drivers prefer to deviate from the direction of the tunnel sidewalls at a greater speed in order to gain a sense of safety in their own driving. In this state, however, the actual danger is increased. In particular, drivers driving in the centre lane will become relaxed after a certain distance due to the relative stability of the environment, and their trajectory fluctuates sharply (50 s in the analysis above). At this point, the left and right lanes encroach on the centre lane at a greater speed and lateral offset, increasing the likelihood of collisions between vehicles. Therefore, with this as a reference, in the subsequent safety improvement, it is necessary to strengthen the control of speed and the management of lane keeping, e.g. by adding LED speed limit signs at 500 m intervals (Eigentler [32] proposed an effective application of LEDs in tunnels) and by adding a variety of landscape lighting in the middle of the tunnel (Patten et al. [33] found that appropriate landscaping in extra-long tunnels can give drivers appropriate visual stimulation and contribute to driving safety).

5.3 Influence of lateral offset

Lateral offset is the vertical distance from the road building limit to the edge of the road margin. That is, *Figure 2a* in the L_L, L_R, 0.50 m. Relevant studies and norms show [34–36] that the regulations for lateral offset of tunnels differ significantly between China and other countries, as shown in *Table 6*. In the existing Chinese road tunnel design code, the lateral offset between the left and right side is only 0.50 m. The left side is 1/5–1/3 of the lateral offset in the relevant Japanese and American regulations, and the right side is 1/6–1/2 of the lateral offset in the relevant American and Japanese regulations. As can be seen from the current situation of traffic crashes in China's tunnels, it is worth thinking about what lateral offset values can be adopted in tunnels, where conditions permit, to improve traffic safety. In this paper, the optimum driver distance from the tunnel building limit is found by establishing a fitted equation between the sidewall shy away deviation and the distance of the driver from the tunnel building limit.

Table 6 – Comparison of lateral offset by country

Country	Lateral offset to the left [m]	Lateral offset to the right [m]
United States (Schroer et al, 2018)	1.50	3.00
Japan (Yamada et al, 1999)	2.50	1.00
China (Yu et al, 2015)	0.50	0.50
This paper recommends	2.19	1.29

The *SSAD* averages for the different lanes in both directions of travel were fitted to the width of the driver's distance from the road boundary taking into account the lateral offset. The fitted curve is shown in *Equation 2*, where x is the distance of the driver from the tunnel building limit (m), y is the sidewall shy away deviation (m). The fitted equation R^2 is 0.836. The valley of the fitted curve is (4.399 m, $1.463 \cdot 10^{-2}$ m). This means that when the distance between the driver and the tunnel wall is 4.399 m, the left-right deviation is minimal and driving is safest at this point. However, the existing road lateral offset allows a distance of only 1.80 m between the driver in the left lane and the sidewall, and only 2.70 m between the driver in the right lane and the sidewall, which differs significantly from the best distance fitted. The existing lane margins are close to the sidewalls and the lateral offset are inadequate, causing drivers to offset while driving and increasing the risk of driving. Therefore, in the subsequent design of the lane widths in the tunnel, the lane widths should be compressed and the lateral offset increased.

$$y = 0.118x^2 - 1.0381x + 3.7462 \quad (2)$$

Related studies [37, 38] indicate that a 0.25 m increase in the lateral width of the road has a small effect on the scale of the project. According to fitting *Equation 2*, the trajectory is corrected by 5.8% for every 0.25 m increase in lateral width before fitting the curve valley. In *Figure 15*, the fitted curves are partitioned to give the distance of the existing driver from the tunnel sidewall with the corresponding sidewall shy away deviation (grey area) and the distance of the optimised driver from the tunnel sidewall with the corresponding sidewall shy away deviation (green area). When the distance of the driver from the tunnel side wall is 3.49 m, the original area intersects the optimised area and this point is defined as the optimum distance (yellow star). Based on the existing distance of the driver from the tunnel sidewall, a lateral offset of 1.69 m is added to the left side and 0.79 m to the right side in order to reduce driving offsets caused by the influence of the sidewall on the driver. The final recommendation is a lateral offset of 2.19 m on the left and 1.29 m on the right.

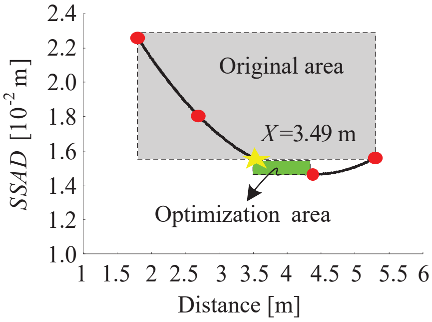


Figure 15 – Fitting curve

5.4 Psychological impact of drivers

The driver's internal judgement of safety and danger may influence the actions taken during driving. Meanwhile, the discrepancy between what is expected and what is shown during actual driving may also reflect the influence that the internal environment has on the driver under real driving conditions. Therefore, a corresponding questionnaire was administered to the drivers after they had completed the real vehicle test. Based on the questionnaire methodology mentioned in Jiao et al. [39], the survey was conducted in three main areas.

The first aspect is to find out how nervous the driver is when driving. A scale is used to assess the sensations associated with driving through the tunnel, with five levels of sensation: 0–20 'very weak', 20–40 'weak', 40–60 'general', 60–80 'high' and 80–100 'very high'. The corresponding four scoring projects are, 'Tension level when entering the tunnel', 'Tension of driving to the middle section of the tunnel', 'Tension of leaving the tunnel', 'Pressure brought by the sidewall of the tunnel when driving'.

As shown in *Figure 16*, more than 76% of drivers who scored more than 60 points considered themselves very nervous when entering the tunnel. The majority of drivers (43%) were less nervous (40–60 points) when they were driving in the middle of the tunnel. The tension level increases to a higher level when they are about to leave the tunnel, with 52% of drivers completing a score of 60–80. That is, most drivers perceive themselves as going through a psychological change process of tension – relaxation - tension when driving in an urban extra-long underwater tunnel. On the other hand, there were differences in the assessment of the sensation of pressure from the side walls of the tunnels, but the results were mainly concentrated in the interval of >40 points, i.e. overall the sensation of pressure from the side walls was different for different people, but they all had some impact.

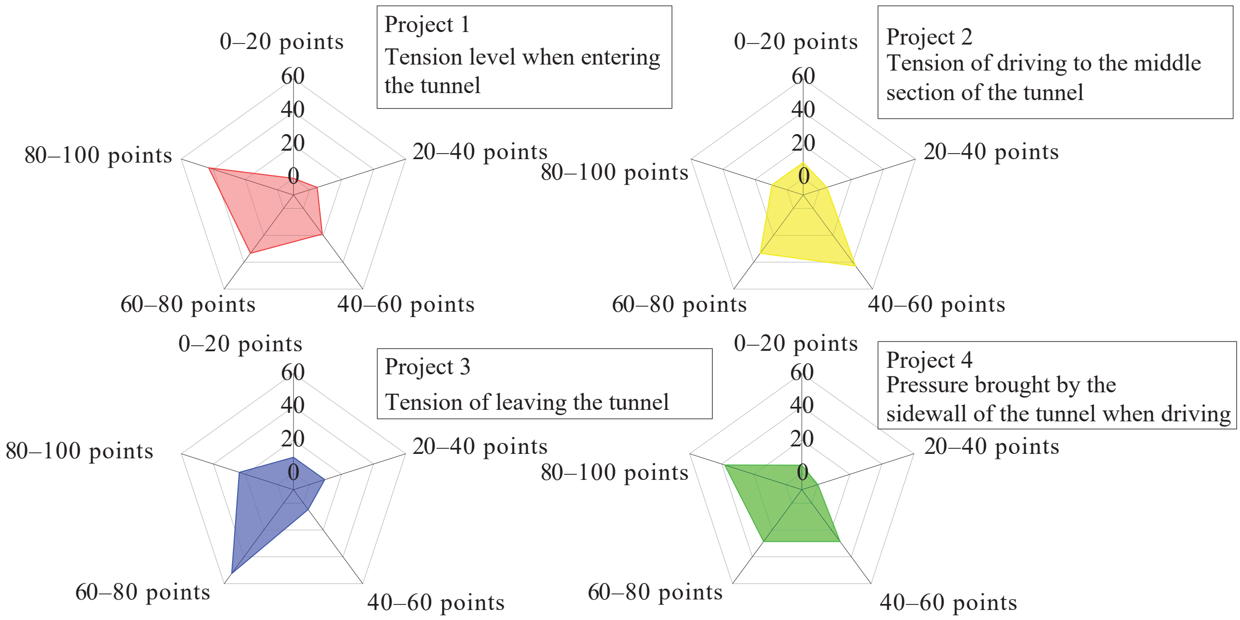


Figure 16 – Proportion of participants in each scoring range of different projects

The second aspect is to find out the driving pressure of the driver at different lane positions in the three-lane tunnel. This was also done by means of a rating scale, which was the same as the previous tension survey. The corresponding 3 scoring projects are, 'psychological stress when driving in the left lane', 'psychological stress when driving in the middle lane' and 'psychological stress when driving in the right lane'.

Averaging the scores of all drivers in the three projects gave a high level of psychological stress of 72.86 points when driving on the left side. Psychological stress when driving on the right side was 59.05 points and psychological stress when driving in the middle was 56.45 points, which is a general degree. As can be seen in *Figure 17*, the psychological stress of the driver when driving on the left and right sides is greater than when driving in the centre. Combined with the degree of trajectory offset in the centre lane analysed in the previous section, it can be further confirmed that even driving in the centre lane, where psychological pressure is minimal, can be affected by sidewall effects.

The third aspect is to find out the driver's awareness of driving safety and the level of driving standards. Driver selects 'yes', 'no' and 'uncertain' around four questions – Question 1: Do you think it is more dangerous to drive in urban extra-long underwater tunnels than on normal roads? Question 2: Do you choose to drive off the sidewall of the tunnel because of the oppressive feeling it brings? Question 3: Do you choose to slow down because of changes in alignment and environment when entering or leaving a tunnel? Question 4: Do you drive strictly according to the regulated speed limit on roads where there are no illegal photographs?

In *Figure 18*, the majority (81%) of drivers judged the safety of driving in urban extra-long underwater tunnels to be more dangerous in this scenario. It is also subject to sidewall deflection (71%) and slows down due to changes in alignment (86%). However, in terms of the level of driving compliance, although most people consider driving in urban extra-long underwater tunnels to be dangerous, they do not strictly reduce their speed to below the speed limit (67%).

The results of the questionnaire show that firstly the majority of drivers (81%) believe that they would go to change the lateral position of their driving trajectory to achieve a safe lateral distance from the tunnel sidewall because of the influence of the tunnel sidewall. Secondly, drivers perceive themselves to be under a high level of psychological stress when driving in the left-hand lane (mean score of 72.86). This is consistent with the results obtained from the real vehicle test, where drivers experienced the greatest lateral offset in the left-hand lane.

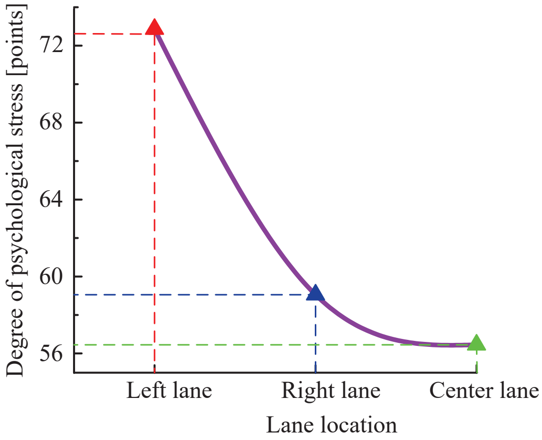


Figure 17 – Psychological stress levels for driving at different lanes

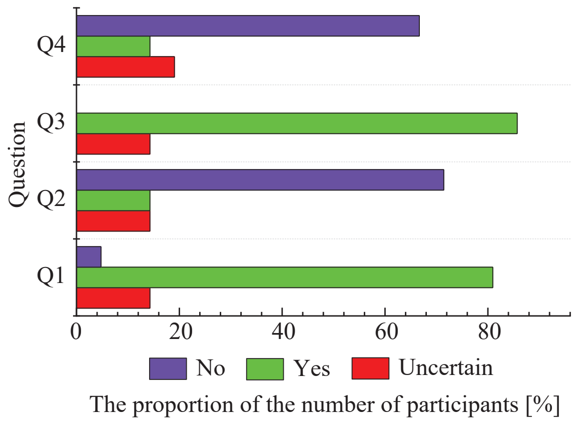


Figure 18 – Proportion of participants on different question

Then, drivers perceive an ordinary level of driving tension in the middle section of the tunnel (40–60 points), with the least psychological stress at the centre lane (56.45 points). This is consistent with the results of the real vehicle tests, where drivers driving in the centre lane had the least amount of offset, but driving a certain distance produced sharp fluctuations.

And in the following survey on speed limit, 67% of drivers said they would not follow the speed limit if the tunnel was not illegally photographed. This is also consistent with the findings from the real vehicle tests, where the speed distribution area exceeds the restricted speed of 60 km/h more often and the average speed across the lanes is greater than or equal to 60 km/h.

6. CONCLUSIONS AND IMPLICATIONS

The aim of this study is to investigate the shy away characteristics of drivers in urban extra-long underwater tunnels. Taking into account the different lane distances from the sidewalls, the effects of sidewalls on drivers were analysed by lane area. Using the trajectory offset and speed data obtained from real vehicle tests, the sidewall shy away deviations at different lanes were compared, and the effects of different factors on the amount of offset were discussed and compared with the results of the drivers' subjective judgement to summarise the driver shy away effect concept.

The results show that drivers in the left and right lanes are influenced by and drift away from the sidewalls, and that the amount of offset is influenced by road alignment, speed, lateral clearance and the driver's psychological reaction. The left lane is most affected by the sidewalls, which correlates with the drivers in China being on the left side of the vehicle. The offset of the driving trajectory at the centre lane fluctuates repeatedly within a small range, but every 50 seconds the offset produces a sharp fluctuation.

Based on these driving characteristics, this study reveals the effect of lateral clearance on driver behaviour. Firstly, it was found that the shy away effect produced by the left lane is greater, mainly due to the fact that the tunnel sidewall acts as a traffic barrier, causing drivers to avoid hitting the sidewall and creating lateral offset. Therefore, a safer lateral clearance distance was calculated and it was recommended compress the lane width and increase the lateral clearance distance from 0.5 m to 2.19 m on the left side and 1.29 m on the right side of the tunnel, which is sufficient lateral space for the driver when driving in the tunnel.

Secondly, a vehicle driving in the left lane is more likely to occupy a portion of the centre lane at higher speed to avoid the left wall, which is then more likely to cause a collision if drivers in the centre lane are in the fluctuating phase of the driving trajectory. Therefore, additional fatigue wake-up devices are needed in the middle of urban underwater tunnels, such as coloured linear induction patterns on the tunnel walls [39] and colourful lighting on the roof [33].

Meanwhile, the results of the driver's subjective survey show that the tension caused by the sidewalls when driving in urban extra-long underwater tunnels is significant (over 71%), but there is a difference between subjective judgement and actual performance in terms of judgement of their own driving speed, which can lead to increased uncertainty when driving in tunnels. Therefore, it is necessary to focus on speed limit management and lane keeping in tunnels. Facilities such as lane indicators, exit signs and road markings can be installed inside the tunnel to help drivers control traffic direction and improve safety and efficiency [28].

In the future, a more rigorous approach should be used to exclude possible effects of environmental factors, such as lights and other vehicles, on drivers' eventual behavioural performance. This paper only investigates the shy away effect for drivers in urban extra-long underwater tunnels, but there are in fact many other scenarios, such as highway tunnels and the presence or absence of barriers at urban intersections, which could be investigated for validation and then further evidence of the prevalence of the shy away effect.

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城市水下特长隧道驾驶人规避效应研究

摘要：对于城市水下特长隧道，两侧的隧道壁形成的障碍空间给驾驶人的行驶带来了影响。本研究的目的在于探讨城市水下特长隧道驾驶人的规避特性。利用实车试验获取的轨迹偏移、速度数据，研究城市水下特长隧道不同车道处的驾驶行为，提出规避效应理论以及定量分析的侧壁规避偏差指标。结果表明，与其他两车道相比，左侧车道受到侧壁的影响产生的偏移量与行驶速度均为最大。中间车道处每行驶50 s偏移量会产生较大的波动，增加了两车道碰撞风险。当隧道侧向净距由0.5 m增加到左侧2.19 m，右侧1.29 m，可以更好的满足驾驶人的安全需求。本研究结果对提高城市水下隧道交通安全、隧道交安设施的改善等方面有一定的启示。

关键词：交通安全；城市水下特长隧道；规避效应；驾驶行为；驾驶特性