



Effects of Tunnel Environment on Speed Cognitive Skills in Drivers

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ABSTRACT

Complex traffic situations and low driver perception are the leading contributing factors to traffic crashes. This paper explores speed cognitive skills of drivers on the effect of two types of expressway traffic environment, including a straight and flat filling section (Tianqiao section of G5 Expressway) and a tunnel section with the similar geometric parameters (Qinling mountain NO.1 tunnel of G5 Expressway). 8 participants were recruited to conduct a speed cognition experiment under the same controlled conditions, 246 groups of data were observed. The experiment results indicated that driver's perception is different at different speeds, speed cognitive ability inside tunnel is better than that of outside tunnels under the condition with a great number of tunnel lamps to provide light sources. When accelerating dramatically after a long-time low-speed driving, the speed cognitive value gradually decreased along common section while increased inside tunnel. The research results can be used to analyze traffic safety in highway tunnel environments and assist engineers with safety facility allocation so as to improve speed cognitive ability of drivers to decrease accidents.

Key Words: Human Factor, Speed Cognition, Expressway Tunnel, Driving Environment, Driving Behavior

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Introduction

When the car is driving, the driver and the vehicle are in a time-varying and dynamic road traffic environment. Different external environment has different influence on the drivers, which is mainly reflected in the change of driving behavior (Kaber *et al.*, 2012). Generally speaking, driver's driving behavior can be divided into three stages: perception, decision-making and practical operation. The impact of external environment on driver's cognition stage is particularly prominent. In the perception stage, the driver's vision, hearing, touch and smell are mainly used to complete the cognition of the surrounding environment (Chiang *et al.*, 2004), and get information including driving vehicle condition, road condition, weather and so on. Among them, the cognitive of vehicle driving state is mainly perceived as the perception information of

vehicle speed. The speed cognition ability of drivers is the foundation to ensure their driving safety. The wrong speed perception will bring problems such as brakes not urgent, improper operation, vehicle instability and other problems (Peng *et al.*, 2013; Stanton and Salmon, 2009; Tornros and Bolling, 2006), which will lead to traffic accidents (Tseng *et al.*, 2005).

The highway tunnel has the characteristics of airtight space; poor light, noise pollution and so on (Amundsen and Ranes, 2000). These complex driving environments have an impact on the cognitive skills of the drivers in the tunnel (Amundsen, 1994; Muhrer and Vollrath, 2011; Cao *et al.*, 2015), resulting in a change of perception that is different from the common road. By comparing the cognition difference between drivers and drivers in tunnel section and common section, we can find out the law

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of change of speed perception ability and provide theoretical basis for improving tunnel traffic safety.

In order to understand the driver's cognitive behavior, some research on driver's cognitive mechanism, cognitive load and cognitive distraction are carried out (Patten, 2006; Cafiso and Cava, 2009). Marcin Biernacki investigated the driving behavior of 160 drivers using the modified Eysenck personality questionnaire, and studied the evaluation method of cognitive ability degradation based on multiple level regression analysis (Marcin and Adam, 2011). Li studied driving behavior caused by visual and cognitive factors, analyzed the multi model features used to distinguish visual dispersion factors and cognitive dispersion factors, and proposed a method of driving behavior definition based on visual cognition dispersion space (Li and Busso, 2015). Pavlidis through the simulation experiment of the 59 pilots, studied the effect of cognitive level, emotional factors, sensorimotor ability and stress of different factors on the driver's arousal level, compared with the standard of performance, and obtained a solution of cognitive errors or emotional factors, coping mechanism of compensation (Pavlidis *et al.*, 2016). Pasquale Sena developed an experimental framework for braking response time for different levels of excitation based on the DRIVE IN2 project, and studied the cognitive decentralization that led to it (Pasquale *et al.*, 2016). Nengchao analyzed the driving behavior and driving performance of drivers under different cognitive loads when driving in complex terrain area, and evaluated the corresponding traffic safety level, so as to provide guidance for highway safety evaluation (Nengchao, 2017).

The driving safety of tunnel sections has been attracting more and more attention, including the setting up of traffic safety facilities in tunnels, and the observation and analysis of psycho-physiological indicators of drivers in tunnels (Lidström, 1998; Manser and Hancock, 2007). Drivers' psycho-physiological data such as the eye movement, heart rate, body-skin temperature, myoelectricity, respiration depth and frequency are collected through a variety of observation tests (Bella, 2008; Ronchi, D *et al.*, 2016; Domenichini *et al.*, 2017). On the basis of these data analysis, the driving behavior of the driver in the tunnel is studied, such as distance cognition and acceleration of driver. Moreover, more and more studies have focused on the

impact of tunnel safety facilities on driver behavior. Some researchers considered that the driving performance was affected by flashing light (also known as strobe light), information board, pavement marking, speed bump, cable broadcast, delineator and so on. Further analysis shows that the impact of safety facilities on driving behavior was achieved by influencing the driver's perception (Zeitlin, 1983; Stutts and Hunter, 2003; Reimer, 2009).

Previous research has shown that driving environment significantly influence driver's perception and concentration (Ou and Liu, 2012; Jia *et al.*, 2016), but few of the studies explore the cognitive skills difference between tunnel section and common section, especially the drivers' speed cognition in tunnel (Manser and Hancock, 2007; Wan, 2015). The tunnel security facilities cannot be set up in combination with the actual perception of the driver, and the safety efficiency of the facility is reduced. Thus, this paper aims to investigate the influence of different driving environment on driver's perception and behavior, especially speed cognition, to assist engineers in tunnel safety facilities design and arrangement to reduce traffic accidents. The data were collected by field experiments at Tianqiao section and Qinling mountain NO.1 tunnel on G5 Expressway, Shaanxi Province, China.

Methods

Description of the experiments

Participants

Eight drivers participated in the experiment, each groups contained participants of different genders and ages as shown in Table 1. Participants in this study were 2 females and 6 males between 23 and 42 years of age (mean=29.38, standard deviation=7.25) recruited through mailing lists and social media. All of them had a driver license. Their average driving experience was 5.38 years (standard deviation=2.68) and average annual mean driving distance was 20,125 kilometers. There were 1 (12.5%) civil servants, 3 (37.5%) business and service individuals, 3 (37.5%) students and 1 (12.5%) transport workers.

Driving Environment

In order to compare the speed perceptive differences between the tunnel section and the common section, a straight and flat filling section (Tianqiao section of G5 Expressway) and a tunnel section with the similar geometric parameters (Qinling mountain NO.1 tunnel of G5 Expressway)

were selected as the test section. G5 Expressway, located between Xi'an and Hanzhong, is a one-tube double-lines expressway as shown in Figure 1. The test vehicle was Volkswagen Lavida as shown in Figure 2.

Table 1. Experiment participant number

	Age	Driving year	Driving mileage (km)	Occupation	Gender
Driver 1	25	5	15000	Student	Male
Driver 2	24	4	10000	Student	Female
Driver 3	24	3.5	6000	Student	Male
Driver 4	23	2.5	5000	Business	Male
Driver 5	42	8	40000	Business	Male
Driver 6	34	10	50000	Civil servants	Male
Driver 7	26	3	5000	Individuals	Female
Driver 8	37	7	30000	Transport workers	Male



Figure 1. Test section



Figure 2. Test vehicle

In the test, there were only two people in the car who are tested and observer. The participants were asked to drive along the right lane towards only one direction. Lane-changing was not permitted. Participants were required to drive the experimental vehicle between the Huxian toll station and the Qinling Mountains service area, the observer asked the questions and recorded the data in the vice pilot.

In addition, the requirements of the test environment included the following points:

a. There is a wide field of vision on both sides of the fill section.

b. The experiment selects the stable section of the lighting change which is influenced by the safety facilities such as no sign, non-variable information board and red-blue flash.

c. Select free flow state as much as possible during the inquiry process.

d. If the surrounding vehicles have an impact on the vehicle being tested, such as overtaking, lane changing, acceleration and deceleration, it is necessary to record in the remark.

Experiment Design

Each test should be carried out strictly in accordance with the requirements and steps of the test. The main steps are as follows.

a. Record driver information: age, gender, age and occupation (or occupation driver);

b. Cover the vehicle dashboard, the front cover, vice driving can observe the speed of the gap in the side;

c. After entering the tunnel, listen to the password of the observer, let the vehicle speed up or decelerate to the designated speed range. When the speed is steady, ask the driver's current speed as a perception speed, and record the actual vehicle speed at the same time. The driver is required to speed up or slow down to the other specified speed range and repeat the test process. The experimental process of repeated tunnel section in the common section.

d. The 10km/h range is a speed range, and the speed is divided into 8 speed intervals: 45-55km/h, 55-65km/h, 65-75km/h, 75-85km/h, 85-95km/h, 95-105km/h, 105-115km/h and 115-125km/h. When the real speed is selected in the experiment, the intermediate values of three speed intervals (50km/h, 60km/h, 70km/h, 80km/h, 90km/h, 100km/h, 110km/h, 120km/h) are selected as much as possible.

Data extraction

Through the experiment, 246 groups of data were observed. After data effectiveness analysis and data de-noising, 231 groups of effective analysis data were obtained. In order to compare the difference of speed perception in different driving environment between tunnel section and general road section, and compare driver's perception of speed difference under the same road condition and different vehicle speed. The *D*-value between the perceptual speed and the real speed is chosen

as the evaluation indicator. The D-value can be defines as:

$$D = |S_c - S_r| \quad (S_c > 0, S_r > 0) \quad (1)$$

Where, D is the difference value (km/h), S_c is the cognitive speed (km/h), S_r is the real speed (km/h). The more the D is, the stronger the perception is, and vice versa.

The drivers' speed cognition can be defines as:

$$d = \frac{|S_c - S_r|}{S_r} \quad (S_c > 0, S_r > 0) \quad (2)$$

Where, d is the drivers' speed cognition. The less the d is, the stronger the perception is, and vice versa.

Results

Analysis of speed cognition along common section

Figure 3 shows the speed cognitive skills of the samples at different speed section along open roads. Speed cognitive skills at speed section [55, 65) and [75, 85) were worst. It probably because that most drivers felt no pressure at low level of driving speed and less concentrated on road environment to estimate speed. Speed cognitive skills improved greatly from speed section [75, 85) to [85, 95) and achieved best condition at [95, 105). Participants stated that they could exactly feel the high moving speed and accelerate when driving more than 85 km/h, and they were more cautious and concentrative. When the driving speed is larger than 105 km/h, the speed cognitive ability gradually decreased again.

It can be found from Figure 1 that the dispersion degree of speed cognition of drivers at speed section [55, 65) and [85, 95) was low and others were very high. Although some media values are low, it should be noticed that there exist high values, for example, the media value at [105, 115) is 1 km/h while the highest value is 10.5 km/h. Some devices or operations, such as variable message board and special road landscape design, are suggested to use at these speed section roads to improve speed cognition skills of drivers.

There is no relationship between gender, age and skills of speed cognition along open road at every speed section by independent sample test ($p > 0.05$). However, there is a significant relationship between driving experience and speed cognition skills of drivers. The speed

cognitive skills of drivers with more than 8-year driving experience is noticeably better than others at speed section [75, 85) ($F=0.196$, $\text{Sig.}=0.647$, $p=0.004 < 0.005$) and [95,105) ($F=1.145$, $\text{Sig.}=0.301$, $p=0.000 < 0.005$). These very experienced drivers were good at speed estimation whether at low speed of high speed. Participants worked in transportation area performed insignificant in speed estimation than others, and it is likely that transport personnel recruited in this study had driven less than 4 years. And it can be inferred that for some people with same driving-age, these worked in transportation area are more experienced and can judge driving speed more exactly than others.

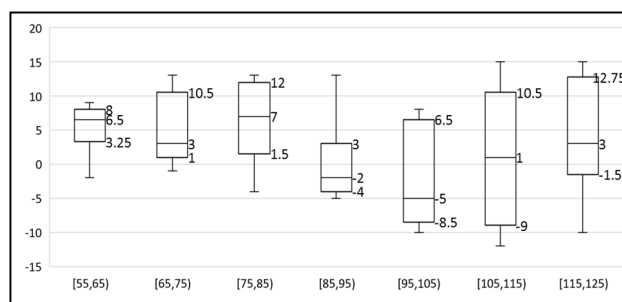


Figure 3. Speed cognition of drivers along common section

Analysis of speed cognition inside tunnel

Figure 4 presents speed cognition ability of drivers at different speed section inside tunnel. The media values of speed cognition [45,85) were all negative and gradually increased from -7.5 to -2 while the media values of [105,125) were positive and reached to 7.5. Compared with speed cognitive ability along the road, it acted better inside tunnels. The data concluded that speed cognitive ability of drivers inside tunnel was worse than that of outside tunnels; they explained that tunnel environment is semi-closed and dark so that visual sense of drivers is relatively poor and narrow when passing through tunnels. On the contrary, it seems that speed cognitive ability inside tunnel is better in this research. Except for some short tunnels, most tunnels are equipped with a great number of tunnel lamps to provide light sources. When travelling through tunnels, the scene of tunnel lamps is dynamic and changes with vehicle speed, on other words, the visual difference of tunnel lamps of drivers reflects the driving speed at the same time. Therefore, drivers could estimate their vehicle speed easily on the reference of tunnel lamps scenes. What's more, it was a stressful task to travel tunnels, so drivers



were very cautious and nervous and trended to overestimate their speed. Two things are considered in this study when conducting experiments. First, arrangement distance of tunnel lamps would influence visual sense of drivers greatly so that the design of tunnel lamps kept the same in all tunnels in our experiment. Then, the reference effect of tunnel lamps might weaken when the tunnel is too long and drivers become fatigue, so extra-long tunnels were excluded from this study.

It should be noticed that 95 km/h was a dividing speed of drivers to estimate speed; it was very dangerous to drive over 95 km/h because many drivers would consider their speed as a lower level. Also, some facilities and operations should be adapted to decrease dispersion degree of values at [55, 75) and [95, 105) to improve tunnel safety. In China, the speed limit of most highway tunnels is between 40km/h and 80 km/h, which is reasonable and generally safe for tunnel travelling from the view of speed cognitive skill of drivers in this study, and it can appropriately increase to 95km/h if the tunnel environment is in good condition.

The relationship between age, career and speed cognitive skills inside tunnel at each speed section is insignificant by independent sample test ($p > 0.05$). There is a big difference of speed cognitive ability between male drivers and female drivers at speed section [65, 75) ($F = 2.356$, $\text{Sig.} = 0.441$, $p = 0.002 < 0.005$). The median value of female drivers at [65, 75) was -6 while that of male drivers was 0.5. It is perhaps because those females were more anxious and nervous than males inside tunnels when judging speed. The higher speed value drivers estimate, the more likely they slow down and keep distance from forward vehicles. Therefore, male drivers, considered as confident and aggressive individuals, should be often reminded to keep alert and slow down when travelling through tunnels.

There is a noticeable relationship between driving-age and speed cognitive skills. Drivers with more than 12-year driving experience could estimate speed more exactly inside tunnels than that of less than 12 years at every speed section ($p < 0.005$). And as we discussed before, it can be speculated that for people with same driving-age, transport personnel are more likely to estimate driving speed exactly than others.

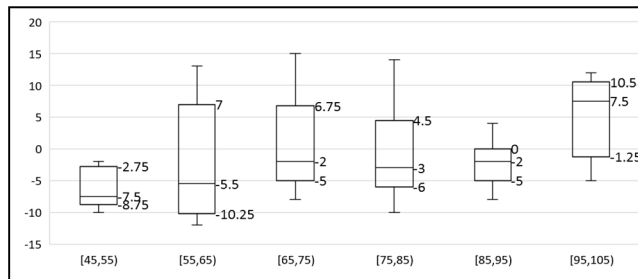


Figure 4. Speed cognition of drivers inside tunnel

Analysis of speed cognitive variation

As demonstrated in Figure 5, when dramatically accelerating vehicles after a long-time low-speed driving along common section, the speed cognition value changes from positive value 7.5 km/h to negative value -12.5 km/h. It means that the estimated speed was generally closer and even larger to the real speed, and it is beneficial in this way for the point of road safety. The distribution of speed cognition of drivers for accelerating procedure can be fitted as a straight line:

$$y_1 = -0.2825x + 22.329, R^2 = 0.9407 \quad (3)$$

The speed cognitive value equaled 0 when the travelling speed was 79.0 km/h. Thus, when driving at a low speed for a long time and sharply speed up more than 79.0 km/h, drivers probably estimate speed lower than the real one, and it indicates that it is on safe level on the speed cognition level.

When dramatically decelerating vehicles after a long-time; high-speed driving along the open road, the speed cognitive value slightly decreased and convergent. Compared with speed cognition distribution in Figure 1, the speed cognition values were positive and larger than that of in Figure 1 at speed section [85, 105). It means when the vehicle sharply slowing down to [85, 105) after fast driving for a long time, the speed cognition skill of drivers was poor than usual cases. There seems almost no connection between reduced speed and speed cognition values since R^2 was only 0.0368. It also demonstrated that drivers were more sensitive to acceleration than deceleration when driving along common section.



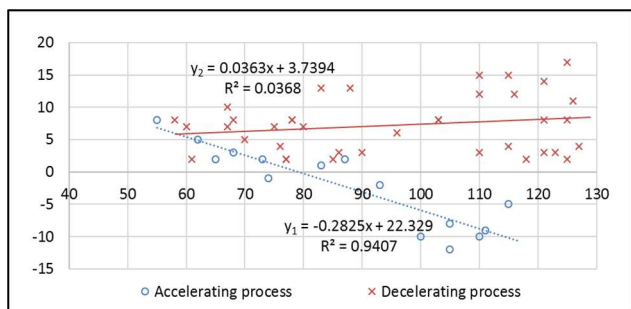


Figure 5. Speed cognitive of drivers along common section

Figure 6 presents the results of dramatically acceleration or deceleration inside tunnels. It seems that there is a linear relationship between increased speed and speed cognitive value while there is no significant relationship between decreased speed and speed cognitive value. During the accelerating process inside tunnels, the speed cognitive value varied from negative value -12.5 km/h to positive value 10 km/h little by little. This principle can be fitted as a straight line:

$$y_1 = -0.2998x - 26.22, R^2 = 0.9103 \quad (4)$$

The speed cognitive value equaled 0 when the travelling speed was 87.5 km/h. Thus, when driving at a low speed for a long time and sharply speed up more than 87.5 km/h, drivers probably estimate speed higher than the real one, which is under potential rear-end or rollover risks considering the speed cognition skills of drivers.

Compared with Figure 5, the trend of speed cognitive value during accelerating process in Figure 6 is completely opposite to that in Figure 3. Tunnel environment is usually depressive and dull, when drivers speed up sharply inside tunnels, they are more terrified and nervous than travelling along open roads. And the highest limit speed inside tunnel is supposed to be 85km/h in this case.

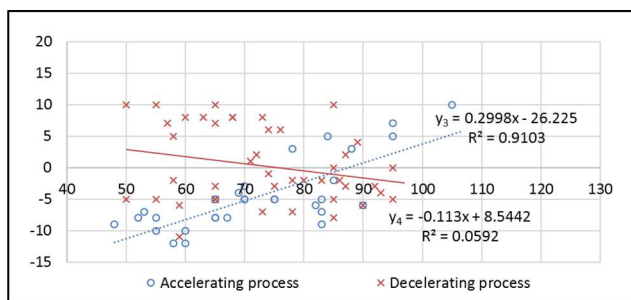


Figure 6. Speed cognitive of drivers inside tunnel

Conclusions

This paper researched the speed cognitive skills of drivers at different speed range in tunnel environment, and studied the variation trend of speed cognitive values during accelerating process and decelerating process. 8 drivers participated in all the experiment at Xihan Highway and valid data collected from experiment were enough to analysis.

Under conditions of this study, the major findings of this paper include: (1) Speed cognition skills of drivers are better when travelling through tunnel than travelling along open road; (2) Very experienced drivers could estimate moving speed more exactly than less experienced drivers; (3) Special devices and operations should be used at low speed section [55,85) and high speed section [105,125) along open road and at speed section [95,105) inside tunnels; (4) When accelerating dramatically after a long-time low-speed driving, the speed cognitive value gradually decreased along open road while increased inside tunnel. It means it is safe to speed up along open road but positively dangerous inside tunnel; (5) the driving speed inside tunnels should be limited less than 85 km/h to the safe concern on the speed cognition level.

A total of 8 drivers were collected in this study, with fewer female drivers and older drivers, and these numbers of experiments needed to be increased in the rear. Future works will focus on the effect of tunnel devices on speed cognition ability for both passenger car drivers and truck drivers. In summary, the findings of this paper can be applied to recognize and evaluate the speed cognition value of drivers inside and outside tunnels, and provide bases for safety measures.

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