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Reasonable transition form of bridge–tunnel connecting section in mountainous expressway affected by crosswind

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In order to explore a reasonable transition form of mountainous expressway in bridge–tunnel connecting section, driver's dynamic behavioural changes affected by crosswind is analysed through driving simulator. The experimental section is composed of tunnel and bridge, with different width of left shoulder. Driver's dynamic behaviour consists of two main parts: counter steering wheel angle and heart rate. The results show that the influence on driver's dynamic behaviour is greater when the car encountered cross-wind at the exit of the tunnel than the crosswind suddenly disappearing at entry of incoming tunnel. As design speed is 100 kmph, the recommended value of left shoulder width is 1.5 m for tunnel exit, while 1.75 m for entrance. For the facility of design and construction, the theoretical transition form of bridge–tunnel connecting section is simplified.

BRIDGES and tunnels of mountain expressway occupy a large proportion and bridge–tunnel connecting section is prone to cause traffic accidents due to the special interfacing structure. The driver's visual and the state of psychology and physiology directly affect traffic safety; therefore, the analysis of the characteristics of traffic accident and factors affecting driving behaviour on these sections is important. Driving simulating experiment platform was established and the driver's heart rate index was used for safety evaluation of the bridge–tunnel connecting section in different driving speed in foggy weather[1]. The speed is a significant factor for traffic safety. Generally, the more the discrete form of speed distribution, the higher is the accident rate[2]. According to accident data, more than half of the accidents on expressway occurred in bad weather. As for bridge–tunnel connecting section of mountainous area, fog, snow, rain, frost and crosswind were the most influential weather factors[3]. Bridge is often located in deep valley where crosswind blows. If vehicles were blown by strong crosswind while driving, the tyres would deviate transversely and lead to vehicle off-tracking or even sideslipping. The analysis theory of vehicle–bridge coupling vibration with the action of a crosswind load was built[4]. Driving safety problems on a bridge deck in a strong crosswind environment by considering the influence of driver behaviour was also studied[5]. Due to the different size and weight of car and truck, different vehicles affected by bridge deck crosswind have different sensitivity. Two-side clear distance of bridge–tunnel connecting section will cause different psychological reactions from the driver. Reasonable shoulder width could improve the driver's speed and direction control ability, which is an advantage to traffic safety[6]. Bus driver's mental workload in response to the narrow shoulder width and the need to anticipate traffic hazards was a significant concern both for operational and driver safety[7]. The front view is different from general road environment in bridge–tunnel connecting section. There is no study yet on the driver's reaction with different shoulder widths.

In the mountain expressway, the lateral clearance is defined as the clear distance between fence and lane line. The lateral clearance is an important parameter in the design of the expressway. It has important influence on the comfort of the expressway driving safety. The distance

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between the outer edge of the vehicle and the fence is defined as outside clearance. Compared to the lateral clearance, outside clearance can directly reflect the driver's space demand between the vehicle and the fence. Smaller outside clearance will make the driver instinctively counter steer the wheel to close the middle road driving, in a state of high speed, which is not only unfavourable to traffic safety, but also compresses vehicle driving space of the adjacent lane. Therefore, it is necessary to study the reasonable outside clearance. The concept of so-called comfortable outside clearance is proposed. Comfortable outside clearance is a range of values. If it varies within the range, the driver's physiological and psychological indicators are at a normal level. When outside clearance is less than the minimum comfortable outside clearance, driver's physiological and psychological burden will increase and cause the driver to become tense and result in a rise in heart rate, pupil size change, and fixation point, paying close attention to shoulder or fence, which is bad for traffic safety.

Because the left shoulder width is directly related to outside clearance, driver's driving behaviour and characteristics of physiology and psychology under the left shoulder of varying widths will be studied in this communication. The aim is to seek the reasonable transition form and ensure the driving safety in bridge–tunnel connecting section of mountainous expressway.

To study reasonable transition form in bridge–tunnel connecting section of mountainous expressway, it is needed to carry out experiments in such sections. There are three kinds of experiments that could be chosen, i.e. real vehicle experiment, reduced scale experiment and driving simulation. In the method of real vehicle test, there are safety risks during driving and it is difficult to simulate extreme conditions. For reduced scale experiment, there is still sizeable gap between experimental condition and actual environment in experimental vehicles and driving scenes, which results in unsatisfactory effects owing to fuzziness in human/driver behaviour. So driving simulation method is used in this experiment. Driving simulator mainly includes an experimental vehicle and a data acquisition system. Figure 1 shows the driving simulator used in experiment. The vehicle's lateral offset, steering wheel angle could be collected by data acquisition system, while the driver's brain, eye and heart rate data in the driving process could be collected by electroencephalograph, eye tracker and heart rate monitor equipment. So the relationship between vehicle driving characteristics and driver's mental parameters could be obtained.

Since driving speed change by crosswind is hard to treat and frequent change in the speed is also dangerous driving behaviour, an experimental scheme is considered in detail. The driver was asked to run on the experimental expressway with fixed speed. In one-way expressway, the crosswind direction and the dimensions of cross section changed. In order to enhance closeness to the realistic experimental effect, several tunnel–bridge sections were directly connected. The bridge and tunnel appeared alternately. There was no crosswind in tunnels. The vehicle was affected by crosswind from left or right direction on bridge. The speed of crosswind was 60 kmph. The most unfavourable situation of vehicle entering and leaving tunnel was simulated. The experimental scheme of bridge–tunnel connecting section is shown in Figure 2. Each length of bridge and tunnel was 450 m. The width of lane was 3.75 m. The right shoulder width was 2.5 m while left shoulder decreased from 2.5 m to 0.75 m for bridge. The right and left shoulder width were 0.75 m. At the exit and entrance of the tunnel, the left shoulder was needed to widen appropriately to connect shoulder of bridge.

Ten drivers participated in the experiment. The eye tracker equipment required calibration before experiment. The drivers wore the heart rate monitor during the experiment. Drivers were asked to run along the way by the speed of 80 kmph and 100 kmph respectively.

For the driving speed of 80 kmph, the maximum counter steering wheel angle for different left shoulder

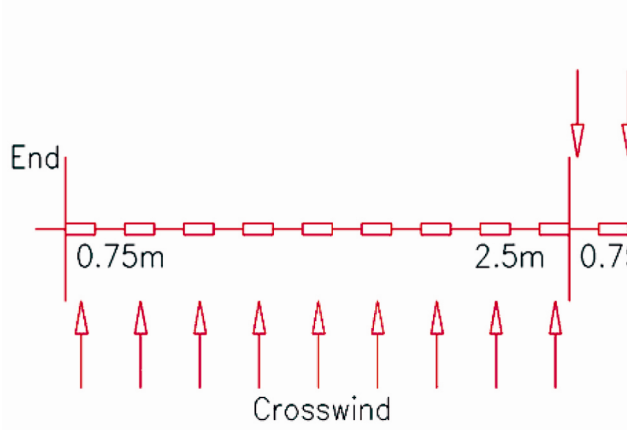**Figure 1.** Driving simulator used in the experiment.

Figure 2. Experimental scheme of bridge–tunnel connecting section.

widths was recorded. The vehicle was affected by crosswind when it was just out of the tunnel. Maximum counter steering wheel angle is shown in Figure 3.

The relationship between maximum counter steering wheel angle corresponding to the left shoulder widths was obtained. Here, a cubic function is used to express this relationship. The equation for driving at 80 kmph speed is

$$y = 3.2x^3 - 11.53x^2 + 11.11x + 10.26, \qquad (1)$$

where y is maximum counter steering wheel angle and x is left shoulder width.

The correlation coefficient R^2 of eq. (1) is 0.704 and residual sum of squares SSE is 5.99. By solving the equation, the minimum value is obtained, which is about 11.54° when the shoulder width is 1.735 m. It can be shown within the limitations of the study that maximum

Figure 3. Box diagram for maximum counter steering wheel angle (80 kmph).

Figure 4. Box diagram for maximum counter steering wheel angle (100 kmph).

counter steering wheel angle reaches minimum value when the left shoulder width is 1.75 m.

Driver's counter steering wheel angles do not increase with decrease of left shoulder widths. When the width of left shoulder takes a larger or smaller value, the counter steering wheel angle reaches a bigger value. When it takes an intermediate value, i.e. 1.75 m, the counter steering wheel angle reaches a minimum. At the exit of tunnel, the vehicle encounters crosswind. Once there is a wider shoulder, namely bigger lateral clearance, the driver will not experience mental tension and make adjustments later. It results in maximum lateral offset value of vehicle being a greater risk to drive out of way. Then the driver modifies the running track by turning the steering wheel. The bigger lateral offset value will lead to a bigger counter steering wheel angle. In such a situation, the threat on traffic safety is relatively small, but should also be avoided. Greater value of left shoulder width is not proposed in highway design.

For the driving speed of 100 kmph, maximum counter steering wheel angle is shown in Figure 4.

The relationship between maximum counter steering wheel angle corresponding to the left shoulder width. The equation for driving speed 100 kmph is

$$y = -3.472x^3 + 22.8x^2 - 43.16x + 35.3. \qquad (2)$$

The correlation coefficient R^2 of eq. (2) was 0.8365, residual sum of squares SSE was 5.805. By solving the equation, a minimum value was obtained, which is about 10° when the shoulder width was 1.384 m. It has been observed in the study that the maximum counter steering wheel angle reached a minimum value when the left shoulder width was 1.5 m.

Bridge–tunnel connecting section is prone to cause traffic accidents resulting from speeding. Based on this consideration, driving speed of 100 kmph should be chosen as aimed speed.

By analysing the driver's rate of heart rate increase at different cross-sections, the most appropriate width of left shoulder could also be reached. Ten drivers' heart rate growth for different left shoulder width was recorded (Figure 5).

From Figure 5 it can be seen when the left shoulder width value of tunnel exit was larger, driver's heart rate change was not obvious regardless of speed. The result was consistent with the analysis of counter steering wheel. For the driving speed of 80 kmph, driver's growth rate of maximum heart rate increased significantly when the left shoulder width was less than 1.5 m. For the driving speed of 100 kmph, it increased significantly when the left shoulder width was less than 1.75 m.

For the driving speed of 80 kmph, the maximum counter steering wheel angle for different left shoulder width was recorded. The vehicle was affected by suddenly disappearing crosswind when just entering the tunnel.
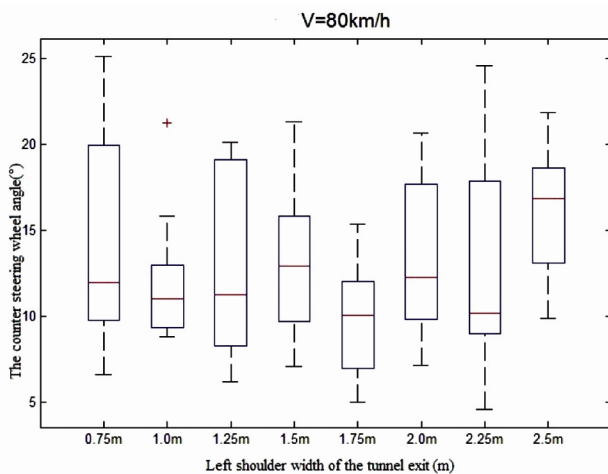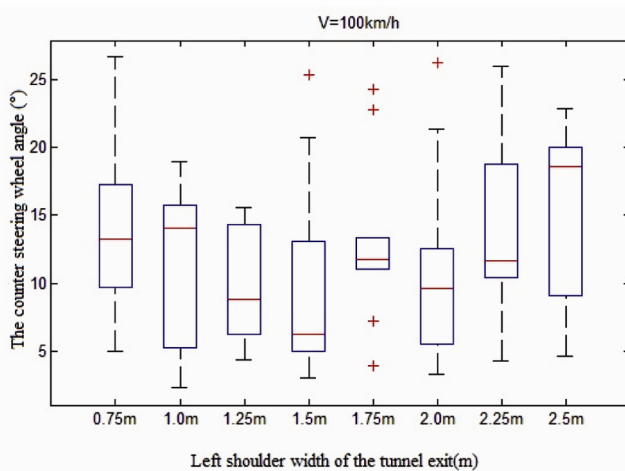
The relationship between maximum counter steering wheel angle corresponding and left shoulder width was obtained. The equation for driving speed of 80 kmph is

$$y = -6.278x^3 + 33.42x^2 - 55.56x + 36.51. \qquad (3)$$

The correlation coefficient R^2 of eq. (3) was 0.7831, residual sum of squares SSE was 3.09. By solving the equation, the minimum value was obtained, which was about 6.96° when the shoulder width was 1.33 m. It was seen that maximum counter steering wheel angle reached minimum value when the left shoulder width was 1.5 m.

For the driving speed of 100 kmph, the equation is

$$y = 0.001152x^3 + 2.527x^2 - 8.918x + 13.51. \qquad (4)$$

The correlation coefficient R^2 of eq. (4) was 0.8409 and residual sum of squares SSE was 1.037. By solving the equation, the minimum value was obtained, which was about 5.65° when the shoulder width was 1.762 m. It was
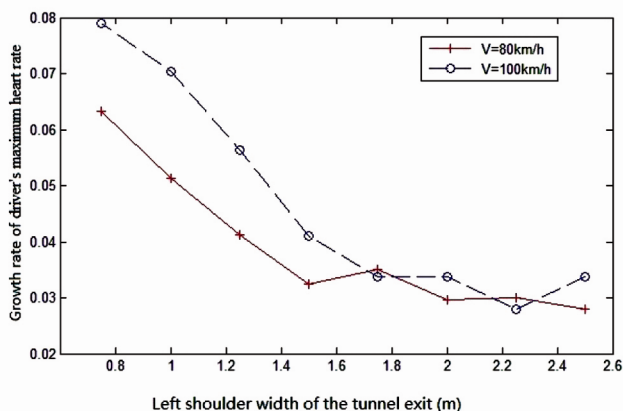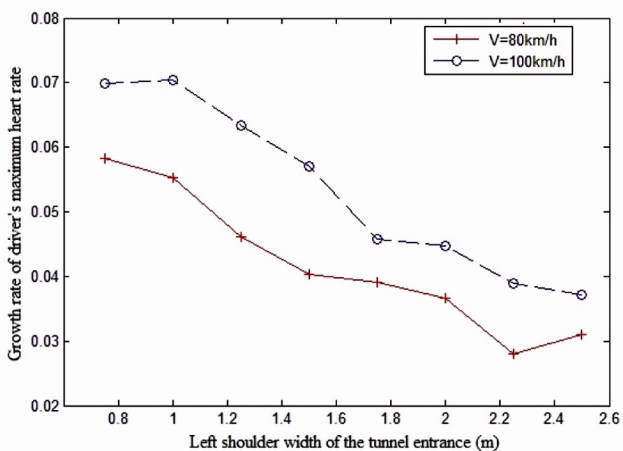
observed that maximum counter steering wheel angle reached a minimum value when the left shoulder width was 1.75 m.

Heart-rate increase for 10 drivers for different left shoulder widths was recorded and shown in Figure 6.

From Figure 6 it can be seen that when the left shoulder width value of tunnel entrance was larger, driver's heart rate remained at 3–4% regardless of driving speed 80 kmph or 100 kmph. For a driving speed of 80 kmph and the width is less than 1.5 m, the growth rate of driver's maximum heart rate increased significantly. For a driving speed of 100 kmph and the width is less than 1.75 m, the growth rate had a significant and sharp increase, reaching up to 7%. It can also be seen that the influence on driver's dynamic behaviour was greater when the car encountered crosswind upon exit of tunnel than the crosswind suddenly disappearing while entering the tunnel. At this time the growth rate was smaller. Therefore, the influence on driver's driving behaviour and characteristics of physiology and psychology was greater when the car encountered crosswind outside the tunnel than when the wind suddenly disappeared on entering the tunnel.

The wind speed was 60 kmph and had a vertical direction to the expressway in analysis. Driver's driving behaviour and characteristics of physiology and psychology were obtained. When design speed was 80 kmph, and the reasonable left shoulder width at tunnel exit was 1.75 m, the counter steering wheel angle reached minimum and driver's maximum heart rate was at critical value. In the same condition, the entrance left shoulder width value of the tunnel was 1.5 m. As design speed was 100 kmph, the reasonable exit left shoulder width was 1.5 m, while the entrance left shoulder width value of the tunnel was 1.75 m. Study on the reasonable transitional form of bridge–tunnel connecting is mainly aimed at the design speed of 80 kmph, which is equivalent to 100 kmph in running speed. At the speed of 100 kmph, the most appropriate left shoulder width value of exit and entrance was 1.5 m and 1.75 m respectively. With respect to the left passing lane being most unfavourable, the right shoulder transition form can be the same as the left shoulder.
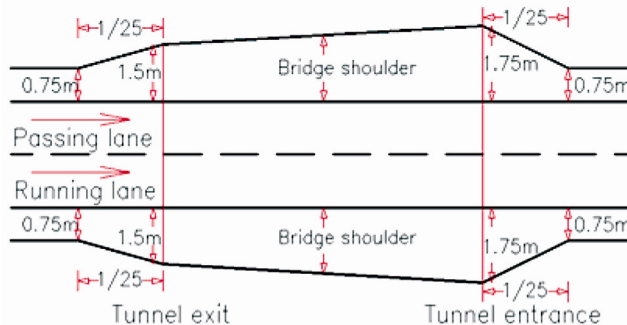

Figure 5. Growth rate of maximum heart rate at tunnel exit.

Figure 6. Variation rate of increase in heart-rate with width of left shoulder at tunnel entrance.

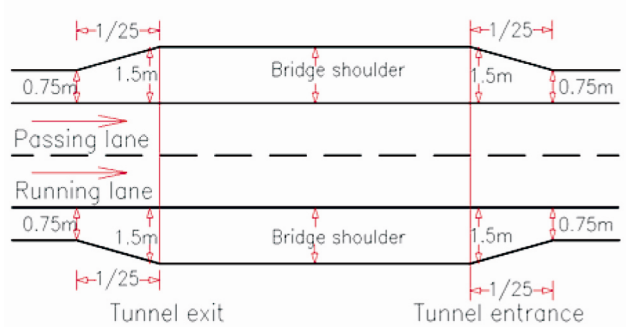**Figure 7.** Theoretical reasonable transition form.

Figure 8. Simplified reasonable transverse section form.

When the speed of crosswind was 60 kmph and had a direction vertical to the expressway, the theoretical reasonable transition form of bridge–tunnel connecting section is as shown in Figure 7.

However, the bridge shoulder form had difficulties to construct from 1.5 m linear transition to 1.75 m. It was necessary to simplify the theoretical transitional forms of bridge–tunnel connecting section. The main simplified content was adopting the unified shoulder width for left and right sides. Just in the tunnel entrance, the cross-section was smoothly transited with 1/25, which required same shoulder width for tunnel exit.

According to calculation of counter steering wheel angle, the angle was smaller when the width was 1.5 m when compared to 1.75 m. Besides, narrow shoulder could result in economical construction, so the shoulder width of the bridge can adopt a unified value of 1.5 m. Simplified reasonable transverse section form of bridge–tunnel connecting section is shown in Figure 8.

From the analysis of driver's mental parameters in bridge–tunnel connecting section of mountainous expressway, some conclusions could be summarized, which may be used as a reference in selection and finalization of reasonable transition form.

The influence on driver's driving behaviour and characteristics of physiology and psychology are greater when the car encountered crosswind when out of the tunnel than the wind suddenly disappearing on entering the tunnel.

As the design speed is 100 kmph, the reasonable left shoulder width should be 1.5 m at tunnel exit and 1.75 m at tunnel entrance. In this case, the counter steering wheel angle reaches minimum and driver's maximum rate of increase of heart rate has a critical value.

From the point of practical application, the theoretical transition form of bridge–tunnel connecting section is simplified. The reasonable bridge shoulder form is varied from 1.5 m linear transition to 1.75 m, which is smoothly transited with 1/25, while the same shoulder width is required for tunnel entrance.

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