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Effect of longitudinal slope of urban underpass tunnels on drivers' heart rate and speed: A study based on a real vehicle experiment

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ABSTRACT

To study changes in physiological and behavioral characteristics in longitudinal segments of urban underpass tunnels, 22 drivers were selected to perform an experiment. An MP150 multi-conductivity physiological recorder and ECU speed acquisition equipment were employed to record and analyze the drivers' heart rate and speed. The index of heart rate growth (HRG) was proposed to analyze the psychological changes, and a scatter chart was used to analyze changes in HRG. Models of the relationships between HRG, speed, and slope were developed to quantify the impact of slope on HRG and speed. The results show that HRG is significantly higher when driving downhill in a tunnel than when driving uphill, indicating that drivers are more nervous when driving downhill. The fluctuation of HRG when driving downhill in a tunnel is significantly greater than when driving uphill, and the peak value is also larger, indicating that the drivers' psychological fluctuations are greater and the degree of psychological tension is higher when driving downhill in a tunnel; thus, drivers should be cautious when driving downhill. The results also show that slope has a major influence on HRG and the speed of the vehicle, and the safe slope and driving speed when driving uphill and downhill in urban underpass tunnels were obtained. Finally, the proposed values of safe slope and safe speed in urban underpass tunnels are given based on the actual safety and control situation.

1. Introduction

The development of underground space has become necessary to resolve the conflict between urban rapid expansion and limited land resources. In recent years, urban underpass tunnels, which have been constructed in large numbers, have played a positive role in reducing urban traffic and the land use and mileage of urban roads, but they have also created new safety problems in that the number of tunnels under cities is gradually increasing, and the consequences of accidents are more serious. Huang (2013) analyzed the spatial distribution characteristics of urban tunnel accidents and found that accidents occur frequently in the uphill sections of tunnel entrances and in downhill exit transition sections. A survey from Italy shows that urban tunnels are riskier than highway tunnels and have higher accident rates and social costs (Caliendo and Guglielmo, 2012). These studies concluded that uphill sections of tunnel entrances and downhill exit transition sections increase the driving risk and create serious security risks. Therefore, safety problems related to the longitudinal segments of urban underpass tunnels warrant substantial attention from urban tunnel managers and users.

The speed limits of urban roads are lower than those of highways, the road alignment is relatively good, and the tunnels are shorter; therefore, managers and users of urban think that urban tunnel will not affect the driver. In fact, previous studies have confirmed that a shorter tunnel does not mean that a driver's behavior will not be affected or that driving is safer. Amundsen and Ranes (2000) show that tunnel length is negatively correlated with the accident rate and explain the higher accident rate near tunnel entrances. The area around the tunnel entrance is a transitional zone between two different driving environments. Linear design, the transition of anti-sliding performance, and the differences in internal and external environments all affect the traffic safety. Especially the change of the import and export illuminance is one of the important causes of traffic accidents (Dai et al., 2010). The tunnel lighting system is designed to deliver the necessary visual information to the driver, improving driving safety and comfort, and preventing traffic accidents due to lack of visual information. Hu et al. (2014) proposed a lighting method for evaluating the safety threshold for lighting or the entrance section of a freeway tunnel based on the driver's visual needs, which provided a reference value for theories, methods, and practices of lighting design and operation management in

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the entrance section of the tunnel. Moretti et al. (2016, 2017) combined lighting and pavement conditions to evaluate tunnel technology, tunnel management and safety. Illumination that is too low or too high at the entrance and exit of the tunnel can adversely affect the driver. In particular, "black hole" and "white hole" effects appearing at the entrance and exit sections of the tunnel will cause visual discomfort for the driver and will affect driving behavior to varying degrees. A similar phenomenon occurs in the lighting system of the longitudinal segment of the urban underpass tunnel and correspondingly, the tunnel wall, which gradually becomes taller, limits sight distance and the "light and dark adaptation" of visual stimulation in the longitudinal segment of an urban underpass tunnel can lead to driver anxiety, uncertainty and other disturbing feelings. Moreover, the special longitudinal slope effect of an urban underpass tunnel will increase the driver's tension. Therefore, drivers usually slow down when driving through these tunnels; at the same time, they increase the horizontal distance from the right wall and take other measures to alleviate this tension. Urban road traffic managers are not concerned about this issue. In China, there is still a lack of design specifications for urban underpass tunnels, although urban tunnel designers often refer to "Highway Tunnel Design Specification JTG D70-2004", "Urban Road Design Specification CJJ37-2012", and "Urban Underground Road Engineering Design Specification" when designing parameters. Furthermore, speed limits and other control measures have rarely been used, and no guidance or reminders are provided to drivers, who mistakenly think that they can drive as they do on other sections of the urban road. However, the visual and psychological characteristics change markedly because of the absence of behavior constraints, making the tunnels prone to traffic accidents. Therefore, urban tunnel managers should impose effective control measures to adapt drivers' physiological and behavioral characteristics based on the changes in the urban underpass tunnel slope, which will reduce the urban tunnel accident rate and improve traffic safety.

Many studies have addressed the physiological and behavioral characteristics of drivers and have involved many aspects of tunnel traffic safety. Narisada and Yoseoikawa (1974) recorded drivers' eye movements near the entrance to the tunnel using a cornea reflex eye movement tracker and confirmed that somewhere near the entrance to the tunnel, the driver's eyes will gaze more and more at the entrance. Zwahlen (1979) also studied the characteristics of the gaze of the driver at the tunnel entrance and analyzed the characteristics of the gaze and scanning of the driver. Du et al. (2007, 2014) mainly studied the pupil area velocity and light and shade visual adaptation based on the light and dark adaptation at the tunnel entrance and focused on the visual oscillation duration as a visual load index that would create a basis for further research on visual and visual load adaptability. He et al. (2017) recorded the eye movement parameters using the non-invasive eye tracking system Smart Eye Pro and used the analysis of the recorded eye motion parameters to study driving safety. Yao et al. (2010) conducted a real vehicle experiment and found that urban tunnels affect both the visual and psychological characteristics of drivers. All of the above research is based on using visual characteristics to explore drivers' physiological characteristics; some scholars also discussed changes in drivers' heart and electrical activity in analyzing the relationship between the traffic safety and physiological characteristics of the driver. Verwey (1995) discussed the influence of the tunnel portals on drivers' physiology and operational behavior by taking heart rate, amount of blinking, galvanic skin response and respiration rate, driving speed and steering wheel reversal as indicators and noted that when approaching the entrance of the tunnel, drivers blinked less. Zhu and Gong (2015) used heart rate changes to analyzed the psychological load characteristics of drivers in tunnels of different lengths, and their results showed that drivers have a large load at the exits of long tunnel. Wu et al. (2016) analyzed the correlation between heart rate, illuminance and speed by conducting a real vehicle experiment, established a multivariate linear model between the entrance center rate and illuminance and speed, and explored the effects of external factors on heart rate. Heart rate growth (HRG) in different tunnel longitudinal segments was quantitatively compared by Zhao et al. (2010), and the results showed that different slopes in highway tunnels significantly influence the driver. In recent years, many researchers have used driving simulators to explore the driving speed, acceleration and transverse position of drivers at tunnel entrances and exits. Manser and Hancock (2007) used a driving simulator to record the speed selection and speed control of the driver in different tunnels and the influence of the visual image and texture of the tunnel on driving behavior (speed perception, selection and speed control). The driving speed, acceleration and transverse position in the access tunnel were explored using the simulator, and the relationship between the accident rate and the tunnel structure was studied (Calvi and Amico, 2013).

These studies show that research on the physiological and behavioral characteristics of drivers in tunnels has focused mainly on visual, ECG and behavioral characteristics of drivers. Although the literature on the physiological and behavioral characteristics of drivers in tunnels is rich, there is still a lack of research on the physiological and behavioral characteristics of drivers in longitudinal segments of urban underpass tunnels. Many studies have overlooked the fact that the slope of a longitudinal segment of an urban underpass tunnel strongly influences the physiological and behavioral characteristics of drivers. Therefore, based on real vehicle experiments, this study analyzed the influence of the longitudinal slope on the driver's heart rate and speed by observation and recording to investigate the following hypotheses:

(1) At a certain speed and a certain slope, when a driver drives from the top of the slope near the tunnel entrance, the driver will feel increasingly nervous due to the narrowing of the tunnel, the more limited view and the more pronounced light and dark adaptation, which will lead to higher HRG when driving downhill in an urban underpass tunnel than when driving uphill.
(2) When the driver drives in a longitudinal segment of an urban underpass tunnel, the slope is positively correlated with HRG. In other words, the greater the slope, the greater the impact on the driver's psychological load and the greater the HRG.
(3) When the driver drives in a downhill section of an urban underpass tunnel, the slope is negatively correlated with speed. In other words, as the slope increases, drivers tend to increase the intensity of brake use and tend to reduce their speed. When the driver drives in an uphill section of an urban underpass tunnel, the slope is positively correlated with speed. In other words, as the slope increases, drivers tend to increase their acceleration and speed.

This paper focuses on the above three assumptions to conduct experiments on the physiological and behavioral characteristics of drivers in a longitudinal segment of an urban underpass tunnel using a quantitative method, which can help explain the relationship among vehicles, the road, the environment and the tunnel users. The findings can provide a reference for traffic safety design and management in longitudinal segments of urban underpass tunnels that will help prevent traffic accidents and ensure the safety of humans in vehicles.

2. Method

2.1. Participants

A total of twenty-two drivers, 19 male and 3 female, were recruited using a snowball method and were included only if they were interested in taking part. The participants had a mean age of 44 years (SD = 8.261) with an age range of 25–56 years. The participants had a mean driving experience of 18 years (SD = 10.157) with an experience range of 4–35 years. Their total mileage was above 50,000 km and their visual acuity was greater than 5.0. This group was selected because the drivers were familiar with the experimental route and drove in the longitudinal segment of the urban underpass tunnel more frequently