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Experimental research on safety impacts of the inside shoulder based on driving simulation

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ABSTRACT

Statistical data shows that single-vehicle crashes account for half of all traffic crashes on expressways in China, and previous research has indicated that main contributing factors were related to whether and how the inside shoulder was paved. The inside shoulder provides space for drivers to make evasive maneuvers and accommodate driver errors. However, lower-cost construction solutions in China have resulted in the design of numerous urban expressway segments that lack inside shoulders.

This paper has two objectives. The first is to reveal the safety impacts of inside shoulders on urban expressways by driving simulator experiment. The second objective is to propose optimal range and recommended value of inside shoulder width for designing inside shoulders of urban expressways. The empirical data, including subjects' eye movement data, heart rate (HR) and the lateral position of vehicles, were collected in a driving simulator. The data were analyzed to evaluate the safety impacts of the inside shoulder. The results have revealed that the inside shoulder has an impact on drivers' visual perception, behaviors, and psychology; in particular, it has a significant effect on vehicle operations. In addition, this paper recommends the desired and optimal inside shoulder widths for eight-lane, two-way divided expressways.

1. Introduction

Statistical data has consistently shown that single-vehicle crashes account for 50 percent of all traffic crashes on China's urban expressways, and the three major contributing factors for single-vehicle expressway crashes are tire blowouts, speeding, and driver error. Furthermore, previous research has indicated that these factors are directly or indirectly related to inside shoulders (Zhong et al., 2011). For example, if the tire blowout suddenly occurred on a vehicle in the innermost lane and there is no inside shoulder served as a temporary parking area, the vehicle is likely to stop or move laterally at relatively low speed, which can lead to dangerous and severe rear-end or lateral-collision crashes.

Two types of shoulders exist—inside and outside shoulders (namely left and right shoulders)—whose functions are not completely identical. The inside shoulder (or left shoulder for divided right-hand traffic) is regarded as an effective countermeasure providing space for emergency storage of disabled vehicles, and offering a lateral clearance for drivers to maneuver to avoid crashes. However, there are no inside shoulders among all four-lane and six-lane bi-directional expressways in China. According to the Chinese Design Specification for Highway Alignment (JTG D20-2006), eight-lane expressways should be paved with an inside shoulder of 2.5 m (Design Specification for Highway Alignment (JTG D20-2006), 2006); however, most of the new or rebuilt eight-lane and even ten-lane two-way expressways do not have paved inside shoulders.

Little research has been conducted to analyze the safety impacts of inside shoulders in China. Due to the lack of knowledge about inside shoulders, transportation agencies have considered only the economic benefits of shoulder paving, which undoubtedly compromises the safe operation of expressways in the future. In addition, as China increases its capital investment for transportation infrastructure, providing guidelines for how best to design inside shoulders of expressways becomes an increasingly urgent concern. Thus, this research took an eight-lane bi-directional expressway as an example, revealing the safety impacts of different inside shoulder widths. Based on the analysis, an optimal range and a recommended value of the width of inside shoulders were provided for the effective construction and operation of expressways.

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The paper is organized as follows: Section 2 reviews previous research studies related to the impact of inside shoulders on traffic safety and relevant methodologies; Section 3 discusses the experimental design of the driving simulation used in the analysis; Section 4 gives the empirical results and their interpretation in terms of traffic safety; Section 5 provides a discussion and interpretation of results, limitations and future work; and Section 6 reaches to the conclusion about this study.

2. Literature review

The criteria for shoulder paving are clearly stated in the specifications and standards for roadway design in many countries. In the United States, roadway design policy specifies that expressways must have both inside and outside paved shoulders, and the minimum width of the outside shoulder is 10 ft (3.05 m). For four-lane expressways, the inside paved shoulder is usually 4–8 ft (1.22 m–2.44 m) wide. For six-lane and other multilane expressways, the inside shoulder width should not be less than 10 ft (3.05 m). The inside shoulder width should be 12 ft (3.66 m) when truck volume exceeds 250 vehicles per hour (A policy on Geometric Design of Highways and Strrets, 2001).

Apart from guidelines and standards for shoulder paving, numerous research studies have investigated the impacts of shoulders on traffic safety and operations. However, these findings have been mainly focused on outside shoulders, while the effects of the inside shoulder on driving safety remained unclear.

Urbanik and Bonilla studied the safety impacts of increasing the number of travel lanes by decreasing the shoulder width on urban expressways (Urbanik and Bonilla, 1987). Data in Texas failed to demonstrate increased crash rates after removing the inside shoulder. After decreasing the inside shoulder width of 12 road sections in California from 8–12 ft (2.44m–3.66 m) to 1–3 ft (0.31m–0.91 m), 10 of the 12 segments showed that the crash rate decreased.

Hadi et al. studied the impacts of shoulders on traffic crashes on rural multilane highways (Hadi et al., 1995). This study found that increasing the unpaved outside shoulder width was estimated to decrease crash rates on four-lane rural highways. Furthermore, the use of a 4–6 ft paved outside shoulder (1.22 m–1.83 m) was found to be the most effective in decreasing crashes on rural freeways. Besides, Hadi's research also stated that widening lanes, median, and inside and outside shoulders could contribute to decreasing traffic crashes.

Based on the data of road safety information system in Illinois, Noland and Oh analyzed the relationship between roadway geometry, roadbed construction and traffic safety (Noland and Oh, 2004). They concluded that fatal crash rates increased with the widening of lanes, but the number of crashes decreased when the outside shoulders were widened. However, the safety impacts of the median and inside shoulder width were not statistically significant. In addition, Bamzai et al. established the relationship between shoulder-related crashes and shoulder widths using Illinois highway crash data from 2000 to 2006 (Bamzai et al., 2011). This study stated that the number and severity of shoulder-related crashes increased significantly when the outside shoulders were more than 8 ft (2.44 m) wide.

All studies above were based on historical data of traffic crashes in real road and traffic environments; thus the impact of confounding factors on research findings could hardly be eliminated completely. In recent years, relatively more research has been conducted based on driving simulation, which provides a practical method for the current study. Ben-Bassat and Shinar analyzed the effects of shoulder width, guardrails and roadway geometry on driver perception and behavior using a driving simulator (Ben-Bassat and Shinar, 2011). The results showed that shoulder width had a significant effect on actual speed, lane position, and perceived safe driving speed, but only when a guardrail was present. The results also demonstrated that narrow shoulders could reduce driving speeds, having a positive effect on maintaining a stable lane position, but at the same time they may increase the probability of crashes. van der Horst and de Ridder analyzed the influence of roadside infrastructure (including emergency vehicle lanes, guardrails, and so on) on drivers' speed choice and the lateral position of their vehicles by using a driving simulator (van der Horst and de Ridder, 2007). One of the important findings is that the emergency vehicle lane affects driver behavior in the tangent section of an expressway. Bella studied effects of three road configurations (no guardrail, standard guardrail and red-and-white guardrail) on vehicle's speed and lateral position on a two-lane rural road, depending on different cross-sections (with or without shoulder) as well as geometric elements (Bella, 2013). Analytical results revealed that driver behavior is only influenced by cross-sections and geometric elements, but not by road configurations.

Research in China has also mainly focused on outside shoulders; some researchers demonstrated the necessity of paving inside shoulders on eight-lane expressways (Zhong et al., 2011). For outside shoulders, previous research has concentrated on studying the optimal widths of shoulders by comprehensively analyzing the main factors affecting shoulder paving.

Wu et al. recommended the width of the paved outside shoulder to be 3.5 m or 3.0 m with an unpaved outside shoulder that was 1.0 m in width (Wu et al., 1996). Their studies mainly considered safety implications, economic benefits and time savings of paved shoulders. Tang and Xu analyzed the shoulder's suitability combined with the alignment and driving characteristics in mountainous terrain as well as the economic benefits of shoulders (Tang and Xu, 2010). In this study, researchers stated that the main factor in determining a reasonable shoulder width was the shoulders' functions of providing lateral clearance; they recommended emergency pull-off areas in the case of a temporary closure of outside shoulders; they suggested that the minimum width of the outside shoulder should be at least 3 ft (1 m).

With the application of psychology to traffic safety research, some researchers in China have begun to study optimal roadway design from the perspective of drivers' psychological reactions. Guo chose heart rate (HR), speed of eyeball movements and area of gazing point to reflect the change in drivers' physiological and psychological status; a relationship was then established between drivers' stress and vehicle's speed and lateral clearance (Guo, 2005). Guo also recommended the width of outside shoulders for expressways in mountainous terrain, based in part on the relationship between driver fatigue and safety.

In summary, most research has focused on outside shoulders. On the basis of historical data of traffic crashes, some researchers analyzed the safety impacts of different shoulder widths, establishing a relationship between the crash rate and widths of shoulders; others determined the optimal shoulder width by investigating and analyzing the traffic functions of shoulders and the factors affecting shoulder paving, such as economic benefits and time cost. Although the research based on historical traffic crashes records and data can help to judge the effectiveness of inside shoulder, it can just provide limited support to the research focusing on the safety impacts of inside shoulder on vehicle operation and driver behavior. Actually, the driving safety was the combined product of drivers, vehicles and roadway conditions, with the driver being the most important factor among them. In addition, to eliminate the negative effects of confounding factors on experimental data and to ensure drivers' safety, driving simulation has been used in related research (Ben-Bassat and Shinar, 2011; van der Horst and de Ridder, 2007). Therefore, this