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Speed change behavior on combined horizontal and vertical curves: driving simulator-based analysis

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ABSTRACT

Road alignments that combine horizontal and vertical curves on freeways have effects on drivers' speed changes that can lead to safety problems. This study examines speed changes on four types of combined curves: downslope, upslope, crest and sag. From design blueprints for a mountainous freeway under construction in Hunan Province, a total of 70 combined curves were programmed into the Tongji University driving simulator. Study participants drove through the simulated freeway while vehicle operation data was continuously captured. Speed changes on the combined curves were determined by calculating the differences between minimum and maximum speed values, and were classified into three behaviors: substantial speed decrease, steady speed (minimal change), and substantial speed increase. Multinomial logit models were used and the marginal effects of each variable were calculated in order to examine the effects on speed change behavior of each combined curve type and their adjacent segments. Results show that: 1) the speed change behaviors on the four types of combined curves differ in frequency, 2) the significant effects of geometric design characteristics on speed change differed by type of combined curve, and 3) design characteristics of adjacent segments also have significant and varying effects on speed change. Combined curves should therefore be studied separately, and their adjacent segments should be considered when combined curves are planned.

1. Introduction

China has constructed about 8,000 km of freeways annually since 2009, with the total in 2017 reaching 138,262 km (National Bureau of Statistics of the People's Republic of China, 2017). Much of the new construction is in mountainous areas of western China where the terrain requires engineers to design alignments with combined horizontal and vertical curves, alignments in which vertical curves overlap horizontal curves. It has been shown that poorly designed combined curves can increase driving risk by leading drivers to excessively change speed through the curves (AASHTO, 2011). Currently, however, there are no quantitative guidelines for combined curve design, which can lead engineers to lower design specification standards because of terrain demands and construction costs. If the relationships between the geometric properties of combined curves and speed change behavior could be quantified (Krammes et al., 1995; Hassan et al., 1997; Nicholson, 1998), more objective design guidelines for combined curves could be developed and driving risk could be decreased.

Previous studies have examined the relationship between combined curve design and safety by using computer animated roadway displays (Ministry of Infrastructures and Transports, 2001; Hassan and Easa, 2003; AASHTO, 2011). Such methods, however, do not simulate the dynamic task of driving, and do not collect vehicle operation data. Combined curve designs have also been examined using field studies (Misaghi and Hassan, 2005; McFadden and Elefteriadou, 2000), however, field studies are limited to alignments as they currently exist, so do not enable systematic manipulation of roadways' geometric properties. Field based methods also have difficulties capturing continuous dependent variable data, such as speed, lateral acceleration, and braking force.

While there are some possible disadvantages of driving simulators, including simulator sickness and accurate replication of physical sensations, these disadvantages can be minimized or eliminated by validation testing before being used for research (Bella, 2008). Driving simulators, in contrast to computer animated display and field based research, offer substantial advantages for combined curve analysis of both independent and dependent variables (Bella, 2005a; Yan et al., 2008; Boyle and Lee, 2010). Simulators are capable of systematically varying any geometric property or combination of independent variables desired, enabling the testing of design options for future roadways

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before construction (Lamm et al., 2007). Driving simulators can also continuously capture speed and any other driver-performance dependent variables of interest to the researcher.

The objective of this study is to establish the relationships between speed change behavior and combined curves in order to make possible better geometric design guidelines. A total of 70 combined curves and their adjacent segments were acquired from blueprints of the mountainous Yongji Freeway under construction in Hunan Province. These roadway alignments were programmed into the Tongji University driving simulator, where speed and other performance data were acquired continuously as participating drivers proceeded through the simulated freeway. Speed changes occurring on downslope, upslope, crest, and sag curves were calculated by taking the difference between the maximum and minimum speeds for each driver on each combined curve. Speed changes were classified into three driver behaviors: substantial speed decrease (SSD), steady speed (SS), and substantial speed increase (SSI). The relationships between each of the four types of combined curves and speed change behaviors were examined using multinomial logit models. The marginal effects of each significant variable were calculated to examine the degree to which combined curves and their adjacent segments affect speed change.

2. Literature review

2.1. Combined curves and safety

Most previous studies of roadway alignments have focused on vehicle operation and safety on single, or non-combined curves, although research is increasingly demonstrating that driving risk on combined curves is higher than on separate horizontal and vertical curves (Hassan and Easa, 2003; Bella, 2014b; Hanno, 2004). Therefore, when developing new highways, proper design requires concurrent development of horizontal and vertical curves to allow consideration of their combined effects. Below is a brief summary of combined curve research.

Misaghi and Hassan (2005) discovered that operating speed predictions for non-combined curves are not applicable to combined curves. Fitzpatrick et al. (2000) and Gibreel et al (2001) developed operating speed models for combined curves, which show that the overlapping vertical alignment can influence drivers' choice of speed. Bella (2014a) found that speed differences on sag-curves were greater than on non-combined curves. These studies show that speed behavior on combined curves is different from behavior on non-combined curves, indicating the curves need to be considered separately. Considering combined and non-combined curves separately can lead to more accurately designed combined curves, and thus improve their safety.

Researchers have also compared the effects of various combined curves. Hassan and Easa (2003) compared operating speeds on sag- and crest-curves, and found that drivers decelerated on the approach to crest-curves and accelerated on the approach to sag-curves. Wang et al. (2015) examined the effects of upslope, downslope, crest, and sag curves on lateral acceleration. They found the reciprocal of the horizontal curve radius and the severity of slope affected lateral stability on all four curve types, but that length was positively associated with lateral acceleration only on the crest-curve. These studies point to the varying effects of different combined curves and provide some guidance to improving combined-curve design, but they have not considered in sufficient depth the changes in speed that can reflect unsafe design. Further, it has also been noted that the impact on driving behavior and safety of roadway segments adjacent to combined curves has not yet been clarified.

2.2. Speed change measures

Driver speed change provides a sensitive measure of the acceptability of a proposed design because speed changes are predictive of both operational efficiency and safety (Misaghi and Hassan, 2005; Nie and Hassan, 2007). When geometric design demands speed variability beyond safe limits, drivers may take on inappropriate maneuvers. As speed on highways is comparatively high, inappropriate driving maneuvers may result in crashes of high severity. Some studies, however, have given insufficient attention to increases in speed (Misaghi and Hassan, 2005; Bella, 2007), which tend to pose greater driving risk than do decreases. Thus, substantial speed increase is an important part of this study.

The classical safety criteria I and II proposed by Lamm et al. (1991b) for evaluating design consistency were based on operating speed, but obtaining the speed differential via subtracting operating speeds underestimates the speed reduction taken by individual drivers. Some studies have used 85MSR (Misaghi and Hassan, 2005) and Δ_{85} V (Bella, 2007) to calculate speed change for individual drivers, but data were spot collected at specific locations such as the approach tangent and the center part of the curve, locations which might not be characteristic of the entire curve. The speed changes used in this study were therefore obtained from individual drivers by collecting continuous speed data.

3. Methods

3.1. Equipment

The Tongji University driving simulator (shown in Fig. 1) has been described in previous studies (Wu et al., 2013; Wang et al., 2015), so just a brief description is provided here. The simulator dome houses a fully-instrumented Renault Megane III vehicle cab mounted on an eight-degree-of-freedom motion system with an X–Y motion range of 20×5 m. An immersive five-projector system provides a front image view of $250^\circ \times 40^\circ$ at 1400×1050 resolution refreshed at 60 Hz. LCD monitors provide rear views at the central and side mirror positions. SCANeR™ studio software displays the simulated roadway environment and controls a force feedback system that acquires data from the steering wheel, pedals, and gear shift lever.

Many studies have provided evidence to support the usefulness of driving simulators for solving critical issues in geometric design (Bella, 2005b, 2009; Keith et al., 2005). Driving behavior in simulators is not always identical to on-road driving behavior, so simulators may lack absolute validity; but behavior has been shown to be very similar to actual road behavior, indicating that simulators possess good relative validity (Fisher et al., 2010).

A survey of validation studies found that the greater degree of realism in motion-based driving simulators results in more accurate rendering of real driver behavior than fixed-base simulators (Bella, 2009). Motion-based simulators, such as used in the present study, provide immediate realistic feedback to drivers. By reproducing the experience, e.g., of a driver's sensations of traveling over slopes, bumps and super-elevations on the test roads, the simulator provides an immersion environment. Previous studies have also shown that the level of perceived risk, evaluated by comparison of deceleration and braking behaviors in simulated and test-track environments, is sufficiently similar to support simulator use for research (Wang et al., 2016a, 2016b).

The performance of the Tongji driving simulator was validated by the current researchers in 2011. Simulator sickness, stop distance, and traffic sign size tests were administered to 25 drivers, with a validation level set for all three tests at 75% of drivers passing (Wang et al., 2015; Wang and Xu, 2015). Eighty percent passed the simulator sickness test. The stop distance test required drivers to stop at a maximum distance of two meters from a simulated barrier on the road. Each driver had two trial runs, after which it was necessary to succeed twice in the three next runs; 79% of drivers passed. Traffic sign size was judged as realistic by 75% of drivers. Overall test results showed that the performance of this driving simulator satisfied the three criteria for validation.