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The influence of combined alignments on lateral acceleration on mountainous freeways: a driving simulator study

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ABSTRACT

Combined horizontal and vertical alignments are frequently used in mountainous freeways in China; however, design guidelines that consider the safety impact of combined alignments are not currently available. Past field studies have provided some data on the relationship between road alignment and safety, but the effects of differing combined alignments on either lateral acceleration or safety have not systematically examined. The primary reason for this void in past research is that most of the prior studies used observational methods that did not permit control of the key variables. A controlled parametric study is needed that examines lateral acceleration as drivers adjust their speeds across a range of combined horizontal and vertical alignments. Such a study was conducted in Tongji University's eight-degree-of-freedom driving simulator by replicating the full range of combined alignments used on a mountainous freeway in China. Multiple linear regression models were developed to estimate the effects of the combined alignments on lateral acceleration. Based on these models, domains were calculated to illustrate the results and to assist engineers to design safer mountainous freeways.

1. Introduction

China's highway system has grown by about 5700 km annually since 1997 and by 2013, it reached 98,000 km in length (China Freeway News, 2014). Much of the new construction has been occurring in the mountainous areas of western China. In Hunan, by 2011 there were 4046 km of freeways and plans call for 8720 km of freeways by 2030 (Hunan Province Department of Transportation, 2010). These mountainous freeways require numerous combined horizontal and vertical alignments. Designing such alignments at acceptable costs is difficult because of the challenging terrain, and therefore engineers frequently lower the design standard of horizontal curves and combine them with short vertical curves and steep grades. However, such solutions may reduce safety because there are no quantitative guidelines for combined alignments to guide designers.

The design of horizontal curve alignments plays an important role in freeway safety. As Lamm et al. (1991a) pointed out, more than half of the fatalities on rural two-lane highways in the U.S. occur on curved roadway sections. This safety problem particularly arises on sharp horizontal curves where considerable lateral acceleration increases the difficulty of controlling the vehicle (Peter and Iagnemma, 2009). The lateral acceleration experienced by the driver when traversing a curve is a primary design parameter of horizontal curves. A too large lateral acceleration causes discomfort for drivers as they brake on curves and increases the risk of running off the road or colliding with other vehicles. Once lateral acceleration reaches a critical level, the vehicle becomes at risk of a skid or rollover (Furtado et al., 2002). Lateral acceleration is determined by both the horizontal curve radius and the vehicle speed. Speed, while controlled by the driver, is significantly influenced by vertical alignment. Therefore, vertical alignment needs to be considered when determining an acceptable horizontal radius for combined horizontal and vertical alignments.

Prior field studies (Wilson, 1968; Pei and Ma, 2003; Abdel-Aty et al., 2006; Park et al., 2010; Hanno, 2004) have examined the relationships between the alignment elements and crash data, but they have not considered the specific impacts of differing combined alignments on freeway safety. Other field studies (Said et al., 2007; Cafiso and Cava, 2009) used driving performance measures, such as operating speed, lateral offset, and lateral acceleration as safety surrogates to study the relationships between combined alignments and safety. Such studies, however, have not generated sufficient data to quantify the role of these

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variables. Also, because these studies were observational, they did not systematically manipulate the key variables as would be possible in an experimental setting. In contrast, driving simulator-based experiments provide the opportunity to fully control the variables expected to affect lateral acceleration. Previous driving simulator-based studies (Yang et al., 2011; Bella, 2005; Easa and Ganguly, 2005) have focused on relationships between road alignment and operating speed and between road alignment and lateral offset. However, these studies did not consider the effects of different combined horizontal and vertical alignment types on lateral acceleration.

The current study measured the effects of combined alignments on speed selection and ultimately on lateral acceleration. A mountainous freeway in Hunan Province with 71 combined horizontal and vertical alignments was modeled using Tongji University's Driving Simulator. Four combined alignment types were separately examined: upslope-curve, downslope-curve, crest vertical curve-curve, and sag vertical curve-curve. Vehicle motion data including speed, lateral offset to the central axis of the road, vertical loads on tires, and steering angle were collected. Lateral acceleration was calculated for each combined alignment type for further analysis. Multiple linear regression analyses were used to estimate the effects of alignment on lateral acceleration, and domain analyses were performed to quantify acceptable ranges of lateral acceleration for each alignment type studied.

2. Literature review

2.1. Freeway road alignment and its effects on safety

Roadway alignment has been shown to influence freeway safety (Lamm et al., 1991b). Wilson (1968) found that the crash rates on curves with radii less than 200 m were about four to five times greater than on curves with radii greater than 900 m. In China, a similar study was conducted by Pei and Ma (2003), who concluded the existence of a power relationship between the reciprocal of the curve radius and the crash rate.

Statistical models have also been developed to quantify the relationship between the curve radius and the crash rates. Abdel-Aty et al. (2006) obtained multiple binary classifications of crashes to identify their associated variables using freeway geometric characteristics and microscopic traffic variables. They found that road curvature and the presence of on or off-ramps strongly influenced crash rates. Park et al. (2010) investigated the safety effects of the ramp density and the horizontal curve radius using negative binomial regression models and found the effect of horizontal curve radius on freeway crashes to be significant.

The above studies showed how horizontal curvature is related to the crash rate, but they did not consider the influence of combined horizontal and vertical alignments on crashes. It has been shown, however, that poorly designed combinations of horizontal and vertical alignments can cause problems (AASHTO, 2011). Hanno (2004) developed a generalized linear regression model to investigate vertical and horizontal curve relationships. The traffic flow, horizontal curve length, horizontal curve radius, vertical gradient, percentage of vertical and horizontal curve overlap, and ratio between the horizontal and vertical curve radii were found to affect the crash rates. However, while his study included a wide range of variables, it was limited to crash rates.

2.2. Surrogate measures and driving performance

Surrogate measures of safety are used if crash data are not available or insufficient. Good surrogate measures are directly linked to crash occurrence and are affected by variables known to affect safety. In well-designed experiments, surrogate measures vary in response to fully-controlled conditions that provide a convenient opportunity to investigate the safety effects of these conditions and the corresponding variables. The surrogate measure used in this study, lateral acceleration, is mainly affected by the horizontal curve radius and vehicle speed. As such, it is a good predictor of skids and rollover crashes in mountainous freeway settings, which is the focus of this study.

Cafiso and Cava (2009) carried out a naturalistic driving experiment and found that the differences between maximum speeds and minimum speeds (ΔVmax and ΔVmean) along a certain road are good indicators of design inconsistency associated with crashes. They were seeking a means to establish a criterion for what they called design consistency. They proposed threshold ΔVmax and ΔVmean values as the 50th and the 85th speed percentiles to determine GOOD, FAIR, and POOR domains of design consistency. It was also found that the calculated threshold values supported the general hypothesis that speed differences from a mean of over 10 km/h and over 20 km/h can be used as consistency evaluation references for FAIR and POOR design, respectively.

Various aspects of driving performance have been used as surrogate safety measures (Wu et al., 2013; Said et al., 2007; Cafiso et al., 2005). The vehicle path and the position of a test vehicle were used by Said et al. (2007) in a study of driver performance on curves. They found that the steering paths adopted by drivers were not consistent with the actual curve length. Cafiso et al. (2005) looked at speed and longitudinal and lateral acceleration (in addition to vehicle path), in an attempt to establish threshold values of various performance indicators for different road designs. Despite the utility of real-world experimental data, the small sample size and the lack of control over the driving environment limited the generality of their findings.

Computer simulations have been used to evaluate the safety effects of combined alignments. Furtado et al. (2002) simulated vehicle dynamics to compare a vehicle's stability on a minimum flat horizontal curve determined in a traditional way with the minimum 3D curve determined by vehicle dynamics. They concluded that the minimum radius recommended by the current North American geometric design guides should be increased by 3–16%. Using computer simulation, Easa and Dabbour (2003) evaluated the effects of vertical alignment on the minimum radius requirements for trucks and determined that the curve radius needed to change when changes were made in the combined alignments. A similar study was conducted by Dabbour et al. (2004), who investigated the required minimum radius for reverse curves on freeway mainlines based on vehicle stability. The authors found that an increase in the minimum radius requirements of horizontal reverse curves is required in order to maintain an acceptable driver comfort level. These studies, while helpful, did not systematically compare lateral acceleration on different combined alignments and further research on this subject is therefore needed.

Driving simulators can solve some of the mentioned methodological problems by making the acquisition of all driving performance data possible while offering full control of the driving environment. High-fidelity simulators can realistically replicate studied scenarios at much lower risk to the participating subjects and at higher efficiency levels than real-world studies (Yang et al., 2011). A few driving simulator studies have investigated relationships between road alignment and driver behavior (Godley et al., 2002; Bella, 2005; Tarko, 2011; Easa and Ganguly, 2005; Furtado et al., 2002). Godley et al. (2002) found a close correlation between driving speeds in an advanced simulator and on roads. Bella (2005) compared operating speeds on horizontal curves combined with sag and crest vertical curves in a driving simulator and found that the existing roadway design guidelines for combined alignments were acceptable. These