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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 studies focused on operating speeds and lateral offsets but paid little attention to vehicle lateral acceleration. The present study focuses on lateral acceleration along different combined alignments with the intent of providing better design guidelines.

3. Methodology

The Tongji University high-fidelity driving simulator was used to model a four-lane (two-way) mountainous freeway that incorporated 71 vertical and horizontal combined alignments. Participating drivers experienced each of these alignments as they drove the simulated mountainous freeway while their lateral acceleration was continuously acquired. Multiple linear regression was used to examine the effects of the combined alignments on lateral acceleration.

3.1. Participants

Eighteen males and four females, ranging in age from 23 to 59 years (mean = 36.5; SD = 10.4) served as participants. To avoid potentially atypical driving performance, the participants were selected from Tongji University students recruited by campus advertisements, who were required to have driven atleast 10,000 total kilometers and to have averaged at least 3000 km annually. One of the participants became sick while driving and was excluded from the study.

3.2. Apparatus

Fig. 1 shows the Tongji University driving simulator used in this study, which is currently the most advanced one in China. Its dome houses a fully-instrumented Renault Megane III vehicle cab and is 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° × 40° at 1000 × 1050 resolution refreshed at 60 Hz. LCD monitors provide rear views at the central and side mirror positions. SCANeR^{TM} 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. A regular privately-owned car was used as the study vehicle during the experiment.

The overall performance of this driving simulator was validated using three tests: simulator sickness, stop distance, and traffic sign size. The overall test results showed that the driving simulator satisfied the three criteria for validation.

Fig. 1. Tongji University driving simulator.

3.3. Simulated road course design

The simulated road course was based on a 24 km long four-lane (two lanes in each direction) section of the Yongji Freeway, a typical mountainous freeway in western Hunan Province, China. The driving scenario reproduced the exact horizontal and vertical alignments and the roadside elements from the freeway design blueprint. Illustrations of the four types of segments with the combined vertical and horizontal alignments investigated are shown in Fig. 2. The geometric features of each combined alignment are shown in Table 1.

3.4. Experimental procedures and design

The experiment was set in daylight with dry pavement conditions. The drivers encountered no other vehicles as traffic effects were not of interest. The experimental sessions consisted of three phases: preparation, warm-up, and test. During preparation, participants completed a questionnaire covering their basic demographic information and driving experience. Then, they were informed of the nature of the simulated driving task, the potential risks, and the purpose of the study, and were familiarized with the vehicle. The warm-up immediately followed, which consisted of each participant driving on a typical freeway for 10 min. Then, the test followed, where each participant drove all 71 of the study segments in the same order. After about 25 min, the driving simulation was completed and the participants received a message to pull over to the shoulder. Participants were paid 100 Yuan per hour for their participation in the experiment.

A post-simulation survey of participants was conducted upon completion of the experiment. The results indicated that none of the drivers felt sick during the experiment and that more than 95% of the drivers said the realism of the simulator system and the road scenarios were good.

3.5. Data collection and measurement

The term centripetal acceleration is often used interchangeably with lateral acceleration when referring to horizontal curve design; however, in this study, we adopted the second term, lateral acceleration, which is used by AASHTO, 2011. The lateral acceleration data that resulted from the driver's operation of the vehicle was measured and recorded at a frequency of 20 Hz. These data were then averaged over five-meter segments and were related to the roadway markers.

The independent variables were as follows: the reciprocal of the curve radius (1/R), the slope grade (G), and the segment length (L). The segment length is the length of the overlapped section of horizontal curve and vertical alignments. The dependent variable was lateral acceleration (LA).

The measured lateral acceleration values averaged over the 21 participants on a single selected segment of each alignment type is illustrated in Fig. 3. The selected segments were similar in length to facilitate comparison among the driving profiles. Each curve type had a distinct LA85 profile, which confirmed the need to examine each alignment type separately.

4. Results–regression models and domain analyses

This section presents the obtained regression models and the results of the domain analyses for the four types of combined alignments. We performed these analyses at the segment level. As stated above, each combined segment was defined as the overlapped section of the horizontal curve and the vertical alignments.

The 85th percentile of the maximum lateral acceleration (LA85) for the 21 participants was computed to represent the vehicle

Fig. 2. Example of combined segments on the simulated freeway.

stability for each segment. A linear regression analysis was performed to estimate the relationship between the LA85 and the geometric variables.

The 95% Bayesian Credible Interval (BCI) was used to evaluate the significance of the variables included in the model. A variable was considered significant if the 95% BCI of the corresponding parameter estimate did not include value 0 (Gelman, 2004; Persaud et al., 2010). The estimated relationships between the LA85 and the significant variables are presented in Fig. 4, Figs. 6, 8, and Fig. 10. The gray area in each of the figures represents the standard deviation; thus a narrower gray area indicates a better fit.

A justification for the use of this surrogate measure is supported by the work of Cafiso and Cava (2009). The results of their work allow us to claim that if a certain driver behavior (e.g., a free-flow speed or its change) is connected with safety, then the 50th and 85th percentiles of the observed behavioral measure can be used as thresholds to predict "FAIR" and "POOR" levels of safety. For the domain analyses, we followed Cafiso and Cava (2009) and took the lateral acceleration of the whole highway section into account. We computed the FAIR threshold at 1.62 m/s^2 and the POOR threshold at 2.34 m/s^2. Using these thresholds, the models allowed for the delimitation of the domains. In Fig. 5, Figs. 7, 9 and Fig. 11 below, the domains are always displayed in the same format. If the predicted value of lateral acceleration under the combined horizontal curvature and grade is considered "GOOD", the lateral acceleration in this segment is expected to be in a safe range. If the predicted value is considered "FAIR", the lateral acceleration in this segment is expected to be in an acceptable range. Otherwise, lateral acceleration is expected to be in an unsafe range.

Table 1
Geometric features of the four types of combined alignments segments.

Section type		Upslope-curve	Downslope-curve	Crest vertical curve-curve	Sag vertical curve-curve
Number		20	25	14	12
Length (m)	Mean	416.75	406.72	417.86	446.25
	S.D.	220.34	221.99	224.82	222.39
Horizontal radius (m)	Mean	899.55	856.67	835.61	828.13
	S.D.	501.34	475.61	485.93	491.39
Maximum grade (%)	Mean	0.0365	0.0334	0.0295	0.0246
	S.D.	0.0188	0.0250	0.0315	0.0366

4.1. Upslope-curve segment analysis

An upslope-curve segment is a combined segment with a vertical upslope and a horizontal curve. There are 20 upslope-curve segments on the Yongji Freeway.

4.1.1. Regression model

The multiple linear regression model is:

$$\begin{aligned} LA85 &= 0.937 + 663.4/R - 3.57G \\ &\quad (0.823,\ 1.051)(545.18,\ 781.42)\,(-7.204,\ -0.004) \end{aligned}$$

where the brackets include the 95% BCIs for all the model parameters.

Both the 1/R and G variables were found to be significant. The results show that for every 1 km^{-1} increase in 1/R, lateral acceleration increased by 0.663 m/s^2; and for every 0.01 increase in G, lateral acceleration decreased by 0.035 m/s^2. The relationship between 1/R and LA85 and between G and LA85 are shown in Fig. 4. The lateral accelerations increased as the horizontal curves became sharper and the vertical grades decreased.

5. Domain analysis

In accordance with the regression model, the ranges for LA85 were calculated under different combinations of R and G, and the results are shown in Fig. 5 below.

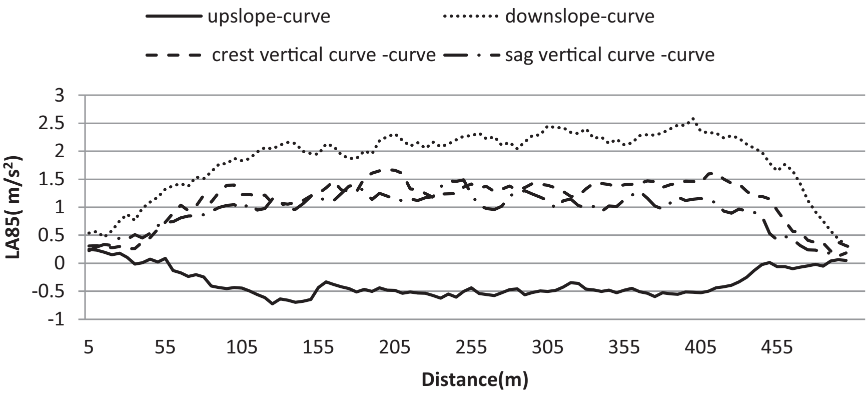

Fig. 3. Lateral accelerations along a typical alignment of each type averaged across all participants.

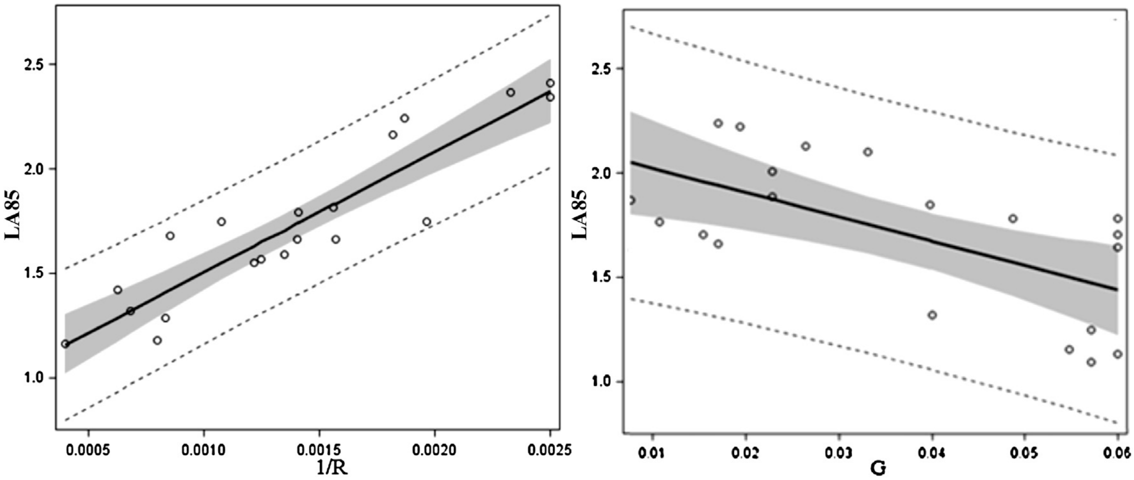

Fig. 4. Relationships of 1/R and G to LA85 of upslope-curve segment.

It can be observed that grade G had little influence on lateral acceleration on the upslope-curve sections while the radius of the horizontal curve substantially influenced lateral acceleration. The estimated thresholds show that for lateral acceleration to remain in the safe range, the radius of the horizontal curve should exceed 1000 m; and once the radius falls below 400 m, lateral acceleration tends to be too high for safe driving.

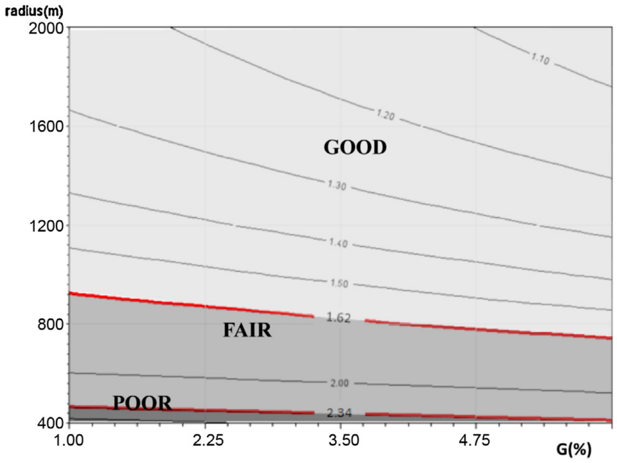

Fig. 5. Predictive value of LA85 and the domain on the upslope-curve segment.

5.1. Downslope-curve segment analysis

A downslope-curve segment is a combined segment with a vertical downslope and a horizontal curve. There are 25 downslope-curve segments on the Yongji Freeway.

5.1.1. Regression model

The regression analysis showed that 1/R and G significantly affected LA85 on the downslope-curve segments. The Bayesian multiple linear regression model is:

$$\mathrm{LA85} = 0.451 + 798.5/R - 12.148G$$

$$(0.301, 0.604)(667.03, 930.77)(-16.385, -7.919)$$

where the brackets include the 95% BCIs for all the model parameters.

The results show that, for every 1 km^{-1} increase in 1/R, lateral acceleration increased by 0.798 m/s^2; and for every 0.01 increase in G, lateral acceleration decreased by 0.121 m/s^2. Fig. 6 shows the increasing lateral accelerations as the horizontal curves became sharper and the vertical grades became steeper.

6. Domain analysis

Fig. 7 shows the ranges of LA85 as calculated under different combinations of R and G using the regression model.

The data show that adequate lateral acceleration for the safety radius depends on the grade. For example, the horizontal curve

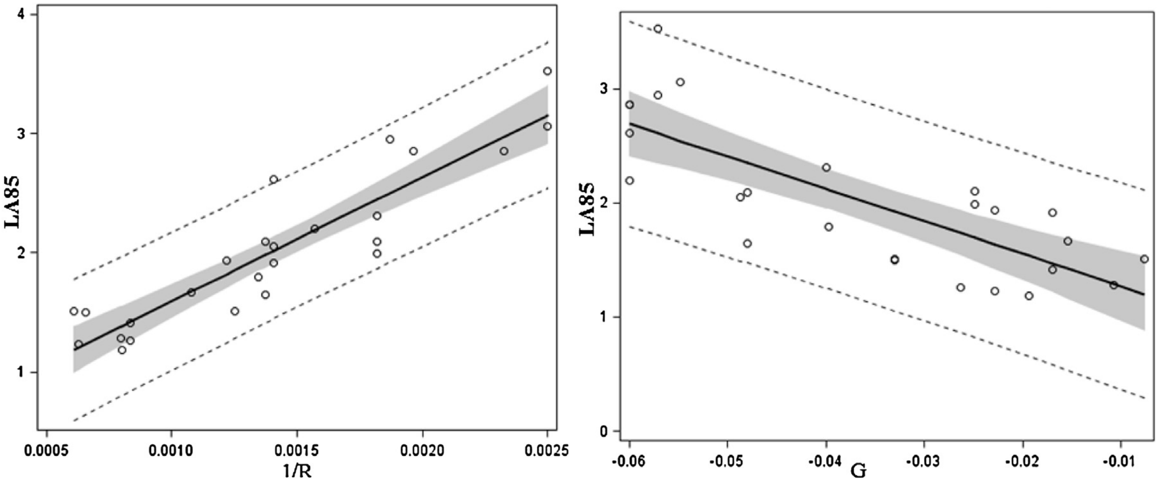

Fig. 6. Relationships of 1/R and G to LA85 of downslope-curve segment.

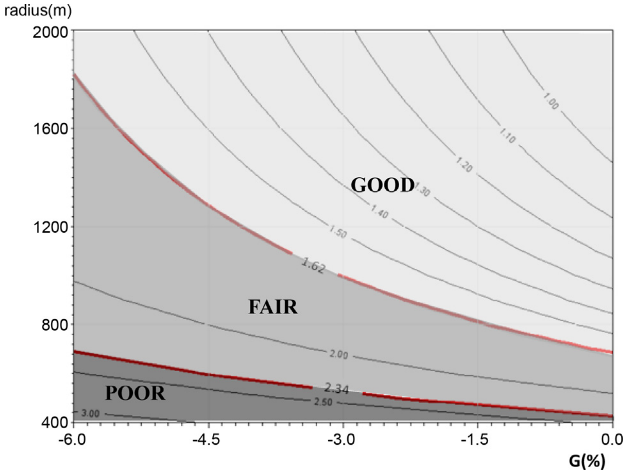

Fig. 7. Predictive value of LA85 and the domain on downslope-curve segment.

radius should exceed 1800 m on the 6% downslope to keep lateral acceleration within the safe limit. Lateral acceleration tends to be unsafely high on the same grade if the radius of the horizontal curve is shorter than 700 m.

6.1. Crest vertical curve-curve segment analysis

Fourteen horizontal curves on the Yongji Freeway are situated on crest vertical curves that connect a longitudinal downslope with another steeper downslope or a longitudinal upslope with a flatter longitudinal upslope (or longitudinal downslope). This combination is called a crest vertical curve-curve in our study.

6.1.1. Regression model

The Bayesian multiple linear regression model is:

$$\mathrm{LA85} = 0.203 + 931.5/\mathrm{R} + 0.0007\mathrm{L}$$

$$(0.055, 0.352)(767.95, 1096.65)(0.00016, 0.00129)$$

where the brackets include the 95% BCIs for all the model parameters.

Both the 1/R and L variables were found to be significant. According to the estimated model, lateral acceleration increased by 0.931 m/s^2 for every 1 km^{-1} increase in 1/R and increased by 0.722 m/s^2 for every 1 km increase in L. Fig. 8 shows the estimated relationships between 1/R and LA85 and between L and LA85. Lateral accelerations increased as the horizontal curves became sharper and the segment lengths became longer.

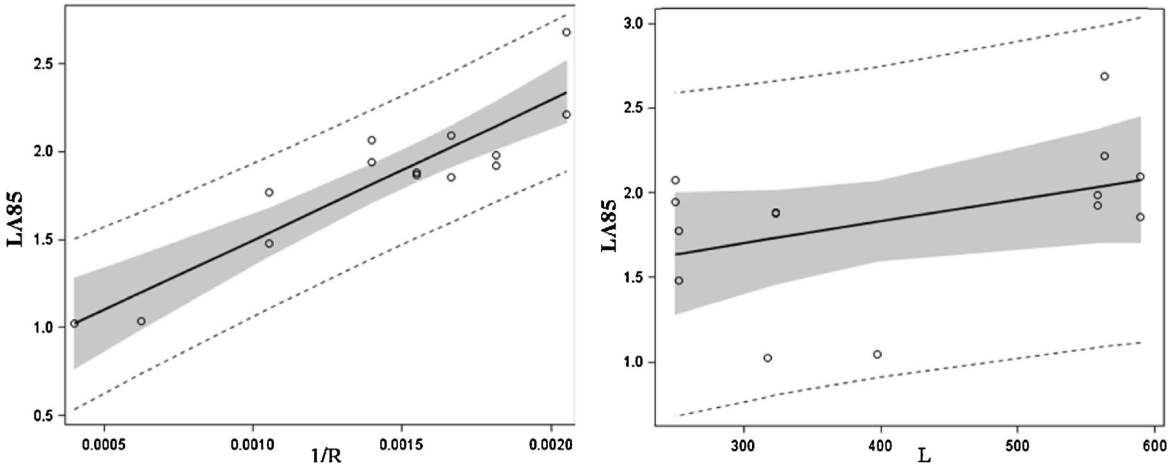

Fig. 8. Relationships of 1/R and L to LA85 of crest vertical curve-curve segment.

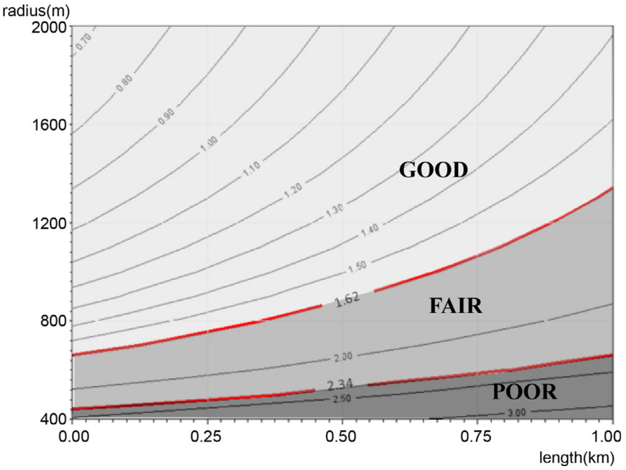

Fig. 9. Predictive value of LA85 and the domain on crest vertical curve-curve segments.

7. Domain analysis

Fig. 9 shows the safety domains between the LA85 thresholds estimated with the regression model under various combinations of R and L.

The results helped to determine the safe radii of horizontal curves given the segment length. Larger curve radii would be required for longer crest combined alignments. For example, a 500 m crest combined alignment requires the curve radius to be larger than 860 m to keep lateral acceleration at a safe level, while a 1000 m crest combined alignment would require the radius to be 1300 m.

7.1. Sag vertical curve-curve segment analysis

There are 12 horizontal curves on the sag vertical curves on the Yongji Freeway. A crest curve connects a longitudinal upslope with a steeper longitudinal upslope, or a longitudinal downslope with the next flatter longitudinal downslope (or longitudinal upslope). Such a curve is called a sag vertical curve-curve in this study.

7.1.1. Regression model

The Bayesian multiple linear regression model is:

$$LA85 = 1.383 + 539.1/R(0.932, 1.832)(351.52, 762.78)$$

where the brackets include the 95% BCIs for all the model parameters.

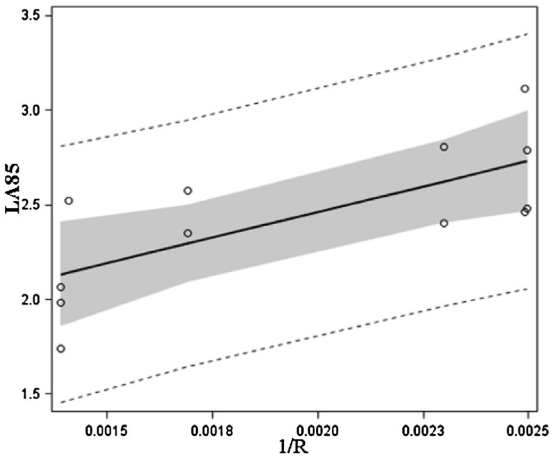

Fig. 10. Relationship of 1/R to LA8 of sag vertical curve-curve segment.

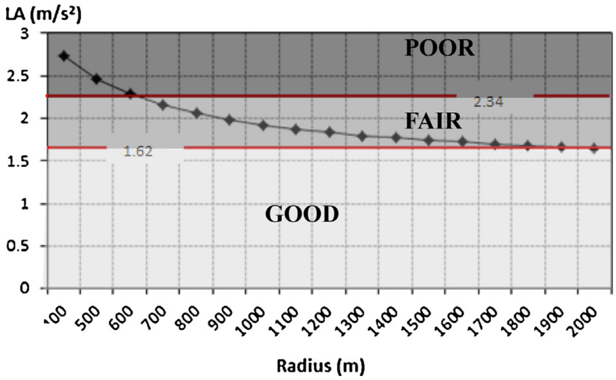

Fig. 11. Predictive value of LA85 and the domain on sag vertical curve-curve.

The only significant variable in the sag vertical curve-curve was 1/R. According to the obtained model, for each 1 km^{-1} increase in 1/R, the lateral acceleration increased by 0.539 m/s^2. Fig. 10 shows the relationship between 1/R and LA85. The lateral accelerations increased as the horizontal curves became sharper.

8. Domain analysis

Fig. 11 shows the safety domains between the thresholds values of LA85 calculated with the regression model for various values of R.

Unlike the other alignment types, 1/R was the only significant variable on the sag vertical curve-curve segment. Thus, the shapes of the corresponding safety domains differ from the domains obtained for other types. The results show that the lateral acceleration of the sag vertical curve-curve section was in the safe range as long as the horizontal curve radius exceeded 1800 m and in the unsafe range if the radius fell below 600 m.

9. Summary

Designing safe mountainous freeways presents a special challenge to the engineer because the terrain often does not allow the preferred solutions. The objective of this study was to determine the domains for combined horizontal and vertical alignments on mountainous freeways by examining the effects of these alignments on the lateral acceleration–a surrogate measure of safety. This study employed a driving simulator to recreate a mountainous freeway in Hunan Province using four types of combined horizontal and vertical alignments. The performance of drivers as they drove along these simulated alignments produced lateral acceleration data that was used to develop design limits for each type of combined alignment.

The combined alignments were classified into four types based on geometric properties. Regression models were developed to analyze the differences in the lateral acceleration profiles among the four distinct alignment types. The 1/R variable was the only variable that had a significant influence on lateral acceleration for all four alignment types. The significance of variables G and L depended on the alignment type. The G was found to be significant on slope-curve combined alignments while L was found to be significant on the crest curve-curve alignments.

A design domain analysis was conducted to determine the preferred minimum radii of horizontal curves combined with different vertical alignments. The suggested minimum horizontal curve radius was 400 m for upslope curves, 660 m for horizontal curves combined with sag curves, 700 m for downslope curves if its grade was 6%, and 640 m for horizontal curves combined with crest curves if the overlapped segment length was at 1000 m.

10. Discussion

The advantages of using a surrogate measure of safety as a means to improve design guidelines was demonstrated in this study. The surrogate measure used, lateral acceleration, has been shown in previous research to be predictive of skid and rollover crashes (NHTSA, 2006; AASHTO, 2011).

The research findings show that each of the four types of combined curves examined influence lateral acceleration differently. These differences have usually been ignored in current design practice, and instead a single model is applied to a horizontal curve without consideration of the vertical alignment. The reciprocal of the radius (1/R) significantly affected lateral acceleration for each type of curve studied. This result supports the AASHTO rationale for horizontal curve design (AASHTO, 2011). However, it shows further the necessity of considering vertical alignment on such curves. This finding of our study is in accordance with the conclusion drawn by the Transportation Research Board (TRB, 1994) that longitudinal grade is an important variable to consider when designing horizontal curves. The study presented here show that grade has opposite effects depending on whether the segment with the horizontal curve is an upslope or a downslope. This is because lateral acceleration is affected by the horizontal curve radius and the operating speed, and the operating speed depends to a large extent on the grade level and direction. This result confirms the AASHTO design principle for horizontal curves (AASHTO, 2011).

The relationship of longitudinal grade and operating speed, which in turn affects lateral acceleration if a horizontal curve is present, indicated that the speed reductions attributable to differing up-slopes and speed increases attributable to differing downslopes make clear the need to consider these longitudinal effects on speeds when designing curves for mountainous freeways.

Another finding of potential use to engineers was that the length of horizontal and crest curve overlap had a significant effect on lateral acceleration. In addition, we found a larger curve radius was required for the sag vertical curve-curve segments than for the crest curve-curve segments tested in this study. This finding may be explained by the more distorted view of a horizontal curve seen by drivers approaching sag curves than when approaching crest curves. The result is consistent with the findings of a previous study by Bella (2005).

The current Chinese highway standards were therefore determined to be insufficient for designing mountainous freeways. The Chinese standards, as well as many similar standards in other countries, recommend minimum horizontal curve radii without consideration of vertical alignment. The only stated Chinese minimum standard for a radius of horizontal curvature is 400 m (Ministry of Transport of the P.R.C., 2004). Our study shows that this requirement is sufficient only for upslope horizontal curves and for horizontal curves placed on sag vertical curves. Even stricter standards are needed for downslope horizontal curves and for horizontal curves placed on crest vertical curves to avoid excessive lateral acceleration rates.

In this paper, we followed Cafiso and Cava (2009) and used the 50th and 85th percentile critical values as thresholds for determining the design domains. Although lateral acceleration is attributed to skids and rollovers (Furtado et al., 2002), further research is needed to verify the proposed thresholds through an estimation of the likelihood of skidding or rolling over under various road geometric conditions. A naturalistic driving experiment is planned to be carried out after the Yongji Freeway is opened to traffic to confirm and possibly expand the findings from this paper. Further research on lateral stability in driving simulators is needed to estimate the proximity of the observed situation to the actual sliding or rolling over of a vehicle on a combined alignment. Such research would better define the margin of safety and the risk of crash under various road geometric conditions.

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