Effects of Combined Horizontal and Downgrade Alignments on Speed Consistency

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Word count: 4920 words test + 5 tables/ 3 figures × 250 words (each) = 6920 words

Submission Date July 29, 2015

ABSTRACT

Combined horizontal and vertical alignment designs on highways have been shown to have impacts on operational and safety problems. Previous studies have evaluated vehicle operations on combined alignments but have not been focused on horizontal curve components. A horizontal curve may be conveniently separated into three successive components: approach transition, circular, and departure transition curves. Vehicle operations on these three components have not examined before. Such a study is needed because speed consistency, defined as changes in speed that occur as a driver drives through the three components, can affect safety. Previous studies focused on characteristics such as radius, and length and grade of horizontal curves, while changes in design characteristics such as length differences, and grade changes between successive components were neglected. The objective of this study is to identify the influence of geometric design on horizontal curve of combined alignment. In this study, the relationship between geometric design characteristics of horizontal curves combined with downgrade alignments, and speed consistency was investigated. To analyze drivers' speed choices, speed consistency across these components was categorized into positive and negative speed differences, and was separately examined using Tobit models. Results showed grade changes, component length differences, and component turning directions of influenced speed consistency. Performance differences among test drivers were accounted using Random Effects Tobit models. The results showed that there is no heterogeneity among different drivers.

Keywords: Combined horizontal and downgrade alignments, Transition curves, Circular, curves, Speed consistency, Tobit models, Random effects

1. INTRODUCTION

In China, about 8,000 kilometers of freeways have been constructed annually since 2009, and by 2014, reached 104,400 km (*1*). Much of the new construction is in mountainous areas of western China that requires engineers to design alignments in which horizontal curves and vertical ascents or descents are combined. These combined alignments have led to vehicle operational and safety problems (*2; 3*). Previous studies analyzed the effect of combined horizontal and vertical alignments on vehicle operations and showed that horizontal curve design was significantly associated with crash frequency increases [you need a citation here]. Several researchers attempted to address these safety problems by evaluating combined alignment designs based on driver's sight distance (*2; 4; 5*), however; these studies have not been able to offer engineers much more than subjective recommendations.

Speed consistency is defined as changes in speed as the driver moves through changes in alignment configurations (*4; 6)*. Geometric designs that lead to unnecessary and excessive changes in speed increase driving crash risks (*6; 7*). If such risks could be systematically linked to roadway geometric properties, the relationship between the geometric properties of combined alignments and speed consistency could be quantified (*4; 6; 7*), and objective guidelines for the design of combined alignments could then be developed.

A horizontal curve may be separated into three successive components: approach transition, circular and departure transition curves. Previous studied have shown that horizontal curve design is significantly associated with crash frequency (*8*), and a few studies found that transition curves (*9*) and circular curves (*10*) are key factors in horizontal curve geometric design. However, previous studies did not examine speed consistency on these components of horizontal curve.

This study investigated speed consistencies of individual vehicles as they travel across combined horizontal and downgrade alignments. The data were collected using Tongji University's eight-degree-of-freedom driving simulator. The speed consistency data of each driver were classified into positive and negative speed difference values. The data was then analyzed using a model suitable for situations where a dependent variable (speed consistency) is associated with independent variables (geometric design characteristics) (*11*). Random Effects Tobit Models were used to determine the extent to which performance differences among drivers were associated with their speed consistency.

2. LITERATURE REVIEW

Effect of Combined Alignments on Vehicle Operation

A few prior studies looked at combined alignments and vehicle operations on highways. Wang et al. (*12*) analyzed effects of upgrade-curve, downgrade-curve, crest vertical curve-curve, and sag vertical curve-curve combined alignments on lateral acceleration, and found the reciprocal of the curve radius and the severity of the grade affected lateral stability on all four alignment types, while length was significant only the crest curve-curve alignments. Kontaratos et al. (*13; 14*) investigated the relationships between combined horizontal and grade alignments and found horizontal curve radius and grade direction (down or up) were associated with vehicle friction. Gibreel et al. (*15; 16*) evaluated alignment design effects on vehicle operation at sag and crest combined alignments, and found vertical curve length, and grade and deflection angle of horizontal curves were associated with vehicle operating speed. These studies focused on the design characteristics such as radius, length and grade on operating speed, but design characteristics such as length differences and grade changes between successive components were neglected.

Speed Consistency Measurement

Speed consistency measurements have frequently been used to evaluate geometric designs (*17*). Inconsistent alignments bring about unnecessary speed changes that may lead to crashes. Two types of speed consistency measurement methods have been proposed. The first type takes the difference of mean operating speeds of a group of vehicles as it passes through sequential locations of a combined alignment's tangents and horizontal curves (*17; 18; 19; 20*). A second method calculates speed consistency by measuring each individual driver's change in speed as he passes through the tangents and curves. A shortcoming of the first method is that it assumes the speed distributions on adjacent configurations are the same, and this is not necessarily the case (*20*). Another shortcoming of the first method is that speed consistency occurs at the individual vehicle level, and therefore it must be acquired at the individual vehicle level, and not at an aggregated level (*21*).

The second type of speed consistency measurement was derived from the application of the methodology proposed by Hirsh (*20*) who suggested the distribution of speed changes of each driver should be examined to calculate the speed differential value. A measurement, 85MSR is determined as the 85th percentile of the distribution of maximum speed reduction experienced by each driver *(19; 21; 22)*. Misaghi and Hassan (*23*) developed the $\Delta_{85}V$ measurement which is defined as the differential speed not exceeded by 85% of the drivers traveling under free-flow condition. The measurements reflected vehicle operation at those locations but cannot reflect vehicle operation at overall configuration (*21; 24*). The 85MSR and $\Delta_{85}V$ cannot reflect individual drivers speed choice (increase or decrease speed).

In this study, driver speeds on the alignment components will be examined using the mean speed difference by obtaining positive and negative speed differences of individual drivers on adjacent components.

Tobit models

Speed consistency data are censored data because the data have been classified into positive and negative speed differences. A Tobit model also called a censored regression model, is designed to estimate linear relationships between variables when there is either left- or right-censoring in the dependent variable. Censoring from above takes place when cases with a value at or above some threshold, all take on the value of that threshold, so that the true value might be equal to the threshold, but it might also be higher. In the case of censoring from below, values those that fall at or below some threshold are censored. Talley (*25*) used a Tobit model to predict the determinants of accident damage cost because the distribution of damage cost per gross ton data are above zero that censored data. The Tobit model is designed to explicitly account for a censored dependent variable. If the relationship is estimated by linear regressing model, the resulting ordinary least squares regression estimator is inconsistent, and will yield a downwards-biased estimate of the slope coefficient and an upward-biased estimate of the intercept. One example is the Farah et al. (*26*) study that used a Tobit model to explain minimum time to collision because they found that ordinary least square regression was not suitable to model the minimum time to collision given that the minimum time to collision only takes on positive values.

3. DATA PREPARATION

Geometric Design Data

A total of 22 combined horizontal and downgrade alignments on a 24km mountainous west to east freeway section located in western China was simulated for testing using the Tongji Highway Driving Simulator. Specifications for the simulation, including the grade of vertical curves, length of horizontal curves, super-elevation, curvature, circular radius, and milepost were obtained from Computer Aided Design drawings provided by Hunan government.

To identify the relationship between the geometric characteristics and speed consistency, the geometric design statistics were separated into two categories: the actual design characteristics, and the differences in the design characteristics among the three components (approach transition, circular and departure transition curves). Descriptive statistics for interval and nominal data elements used in this study are shown below in Table 1and Table 2.

TABLE 1 Descriptive Statistics for Geometric Design Characteristic

Variable	Description	Mean	S.D	Min	Max
Geometric Design Characteristics					
L_{AT}	approach transition curve length (m)	102.28	19.78	75	155
L_{C}	circular curve length (m)	199.78	127.21	40	440
L_{DT}	departure transition curve length (m)	103.23	19.25	75	155
L_{HC}	horizontal curve length (m)	406.92	221.99	220	670
G_{AT}	mean grade of approach transition curve (%)	0.68	0.021	0.01	2.9
G_{C}	mean grade of circular curve (%)	0.74	0.034	0.01	4
G_{DT}	mean grade of departure transition curve (%)	0.69	0.023	0.01	3.31
G_{HC}	mean grade of horizontal curve (%)	0.72	0.025	0.01	3.32
R	radius of horizontal curve (m)	856.67	475.61	400	1600
Difference in Geometric Design Characteristics					
ΔL_{AT-HC}	absolute value of length difference between approach transition and horizontal curve (m)	304.68	125.12	130	550
ΔL_{C-HC}	absolute value of length difference between circular and horizontal curve (m)	208.39	35.41	70	310

TABLE 2 Descriptive Statistics for Geometric Design Categorical Data

Variable	Description	Group	Value	Count
$Ldir_{C-AT}$	length between circular and approach transition curve	circular curve longer	1	13
		circular curve shorter	-1	9
$Ldir_{DT-C}$	length between departure transition and circular curve	Same	0	1
		departure transition curve length is longer	1	10
		departure transition curve length is shorter	-1	11
$Gdir_{C-AT}$	grade change between circular and approach transition curve	same grade	0	4
		circular curve steeper	1	10
		circular curve gentler	-1	8
$Gdir_{C-HC}$	grade change between circular and horizontal curve	same grade	0	4
		circular curve steeper	1	8
		circular curve gentler	-1	10
$Gdir_{DT-C}$	grade change between departure transition and circular curve	same grade	0	10
		departure transition curve steeper	1	7
		departure transition curve gentler	-1	5
$Gdir_{DT-HC}$	grade change between departure transition and horizontal curve	same grade	0	4
		departure transition curve steeper	1	9
		departure transition curve gentler	-1	9
$CVdir_{AT}$	approach transition curve direction	left turn	0	12
		right turn	1	10
$CVdir_{C}$	circular curve direction	left turn	0	12
		right turn	1	10

Equipment

The Tongji Driving Simulator used in this study (shown in Figure 1). This simulator incorporates a fully instrumented Renault Megane III vehicle cab housed in a dome. It mounted on an eight degree-of-freedom motion system with an X-Y range of 20 × 5 meters. 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 presented the simulated roadway and controlled a force feedback system that acquired data from the steering wheel, pedals and gear shift lever.

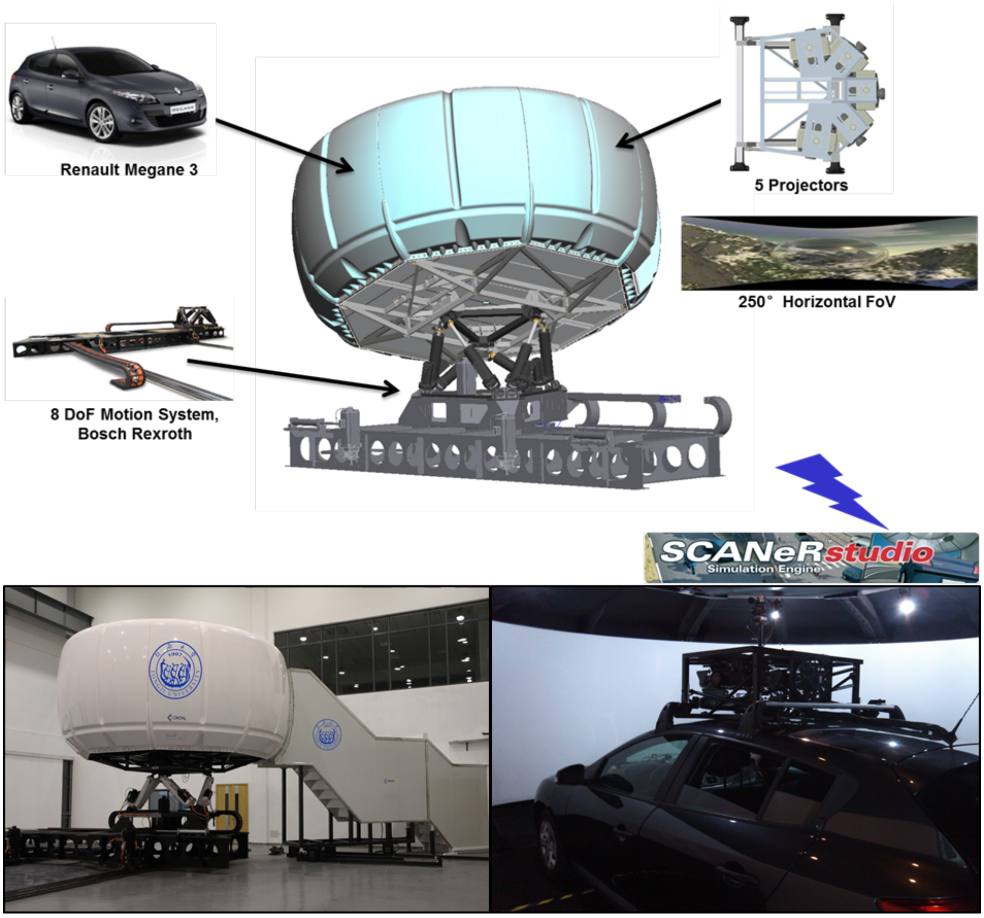

FIGURE 1 Tongji university driving simulator.

Participants

Eighteen males and four females, ranging in age from 23 to 59 years, who held valid driver licenses with previous total driving distance no less than 10,000 km and an average annual driving distance at least 3,000 km, served.

Procedure

Upon arrival at the driving simulator facility, participants were asked to complete a questionnaire covering demographics, driving history, and several simulator sickness items such as giddiness, headache, etc. They were then briefed on simulator vehicle operation, and given a 10-minute practice drive. Following these preliminary procedures, participants drove in an easterly direction along the simulated mountainous road course during daylight conditions with no other vehicles. After a five-minute break, they were asked to drive the same course in a westerly direction.

Figure 2 shows a visual image as seen by a participant when driving in the simulator. The driving scene was reproduced in virtual reality by recreating the exact horizontal alignments, the cross-section and roadside elements from the design blueprint.

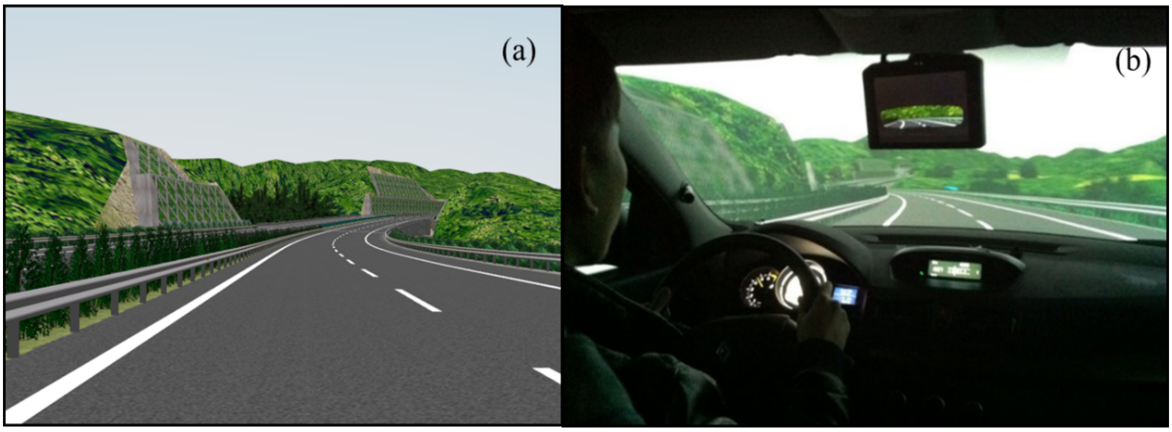

FIGURE 2 (a) Example of combined horizontal and downgrade alignment; (b) Video monitor.

Speed Consistency Data

The driving simulator recording system acquired travel time and vehicle real-time speed and travel distance data at a frequency of 20Hz. The mean speeds of each driver were calculated for the 22 combined horizontal and downgrade alignments, and the mean speeds during the approach transition, circular, and departure transition sections were calculated separately, and denoted as V_{AT}, V_C and V_{DT} respectively. Table 3 below shows data summary statistics of the speed consistency measurements.

TABLE 3 Data Summary Statistics for the Speed Consistency Measurements

Variable	Description	Mean	S.D.	Min	Max
Average Speed Parameters					
V_{AT}	mean speed at approach transition curve (km/h)	96.71	12.36	35.44	133.94
V_C	mean speed at circular curve (km/h)	98.08	10.51	48.78	135.68
V_{DT}	mean speed at departure transition curve (km/h)	99.14	9.81	61.59	137.52
Speed Consistency Parameters					
$\Delta VI_{C\text{-}AT}$	V_C-V_{AT} >0 (km/h) (count: 263)	4.62	4.77	0.013	32.76
$\Delta VD_{C\text{-}AT}$	V_C-V_{AT} <0 (km/h) (count: 199)	-2.89	3.65	-24.17	-0.014
$\Delta VI_{DT\text{-}C}$	V_{DT}-V_C >0 (km/h) (count: 274)	3.98	4.15	0.001	21.99
$\Delta VD_{DT\text{-}C}$	V_{DT}-V_C <0 (km/h) (count: 188)	-3.21	3.47	-20.05	-0.05

4. METHODOLOGY

The speed differences were categorized into positive and negative to analyze individual drivers' speed choices. However，(as mentioned above) the influence of geometric design characteristics on speed choice cannot be reflected by linear regression model because of the characteristics of the distributions. If negative speed differences have a positive relationship with a geometric design characteristic. The negative speed differences will be up to zero, and continue to ascend to become positive value (Figure 3 (a)). Positive speed differences have a negative relation with a geometric design characteristic. The positive value will be drop to zero, and continue to decline to become negative value (Figure 3 (b)).

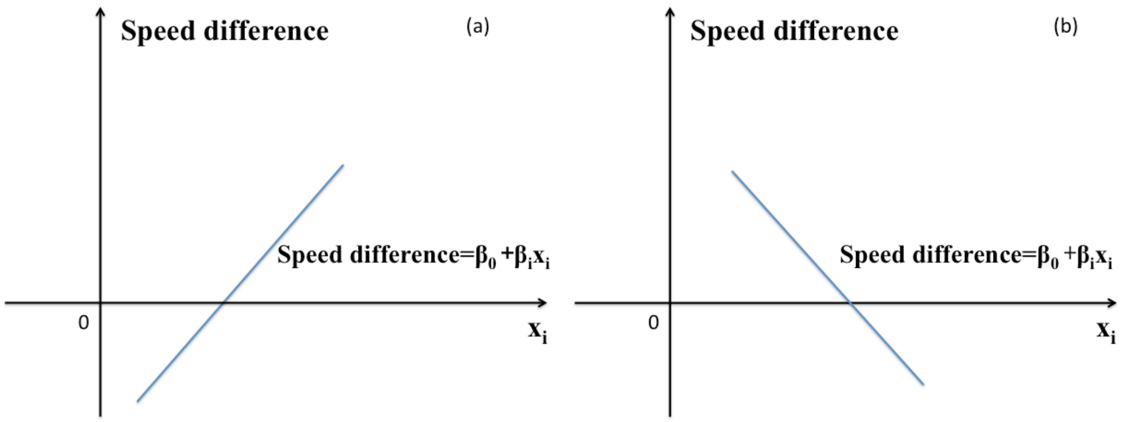

FIGURE 3 (a) Speed difference will ascend with geometric design characteristics (x_i); (b) Speed difference will decline with geometric design characteristics (x_i).

Tobit Model

A Tobit model supposes that there is a latent (i.e., unobservable) variable y_{it}. This paper let y_{it} represent individual driver speed consistency. Geometric design characteristics and differences in the design characteristics among the three alignment components are defined by x_{it}. The relationship between y_{it} and x_{it} is determined via a vector of parameter β. In addition, there is a normally distributed error term u_i to capture random influences on this relationship. The speed consistency is defined to be equal to y_{it}^* whenever the latent variable is above zero and under zero. The speed consistency is defined to be a positive speed difference when it is above zero, and defined to be a negative speed difference when it is under zero.

$$y_{it} = \begin{cases} \text{positive speed difference}, & if \ \ y_{it}^* \quad > 0 \\ \text{negative speed difference}, & if \ \ y_{it}^* \quad \leq 0 \end{cases} \quad (1)$$

$$y_{it}^* = X_{it}\beta + \varepsilon_{it}, i = 1, 2, \ldots, N, t = 1, 2, \ldots, T_i \quad (2)$$

The Tobit model is formed by decomposing the error term ε_{it} into two parts:

$$\varepsilon_{it} = \mu_i + v_{it} \quad (3)$$

where μ_i is the random effect that follows a normal distribution with its mean equal to zero and its variance equal to σ_μ^2. The v_{it} is the remaining disturbance term that follows normal distribution with zero means and variance σ_v^2. The model is a standard Tobit model when v_{it} is zero, and becomes a Random Effect Tobit model when v_{it} is not zero. The θ^2 is a parameter estimated for ε_{it}. AIC is a parameter to evaluate the fit of the Tobit and Random Effects Tobit models to the data.

The formulas of right and left censored with random effects as followed:

Right censored with random effects

$$L(\theta)f(x) = \begin{cases} \left(\frac{1}{\sigma\sqrt{2\pi}}\right) e^{\frac{-(y_{rit}-\mu_{it})^2}{2\sigma^2}} & if\ \ y_{it}^* < 0 \\ 1 - \phi(\frac{y_{rit}-\mu_{it}}{\sigma}) & if\ \ y_{it}^* \geq 0 \end{cases} \quad (4)$$

Left censored with random effects

$$L(\theta)f(x) = \begin{cases} \left(\frac{1}{\sigma\sqrt{2\pi}}\right) e^{\frac{-(y_{lit}-\mu_{it})^2}{2\sigma^2}} & if\ \ y_{it}^* < 0 \\ \phi(\frac{y_{lit}-\mu_{it}}{\sigma}) & if\ \ y_{it}^* \geq 0 \end{cases} \quad (5)$$

For the model estimation, PROC QLIM procedure in SAS 9.2 software was used to estimate the standard Tobit models, while the Random Effects Tobit models were developed using PROC NLMIXED procedure (*27*).

5. MODELING RESULTS

Four models were developed in this study. Two models for speed increase and decrease between approach transition and circular curves, and two similar models for the speed consistency between circular and departure transition curves.

Speed consistency between approach transition and circular curves

Table 4 shows the modeling results for speed consistency between approach transition and circular curves.

TABLE 4 Speed Consistency between Approach Transition and Circular Curves

Model	Parameter	Tobit Model		Random Effect Tobit Model		Sample size
		Coefficient	*p* Value	Coefficient	*p* Value	
$\Delta VI_{C\text{-}AT}$	Intercept	-6.592	<0.0001	-9.0359	<0.0001	263
	L_{AT}	0.1308	<0.0001	0.1308	<0.0001	
	ΔL_{AT-HC}	-0.0055	0.0041	-0.00558	0.0044	
	$Gdir_{C-AT}$					
	0	-2.788	0.0018	-2.7883	<0.0001	
	1	1.956	<0.0001	1.9565	0.002	
	-1					
	$CVdir_{AT}$					
	0	-2.44	<0.0001	-2.4434	<0.0001	
	1					
	γ	3.304	<0.0001	10.858	<0.0001	
	θ^2	-	-	0.0603	0.8993	
	AIC	1389		1391		
$\Delta VD_{C\text{-}AT}$	Intercept	-3.1214	<0.0001	-3.7844	<0.0001	199
	$Gdir_{C-HC}$					
	0	2.004	0.0006	2.0082	0.0008	
	1	1.2309	0.0444	1.2948	0.0219	
	-1					
	$Ldir_{C-AT}$					
	1	-1.2072	0.0201	-0.5929	<0.0095	
	-1					
	γ	3.453	<0.0001	10.7387	<0.0001	
	θ^2	-	-	1.2435	0.1355	
	AIC	1068		1065		

Both the $\Delta VI_{C\text{-}AT}$ and the $\Delta VD_{C\text{-}AC}$ model results showed that the variances of random effects term (θ^2) are not significant, which means there are no random effects on the drivers. AIC values of the Tobit and Random Effects Tobit models are almost the same, which revealed the two models are not substantially different in terms of how well they fit the data.

The $\Delta VI_{C\text{-}AT}$ model showed the lengths of approach transition curves (L_{AT}) have a positive coefficient indicating that as the L_{AT} increase the speed consistency will drop (*3*). The length differences between approach transition and horizontal curves (ΔL_{AT-HC}) have negative coefficients indicting that as the ΔL_{AT-HC} increase, speed consistency will improve. This suggests that drivers will maintain steady speeds across properly proportioned component lengths, thereby have good speed consistency. The grade change between approach transition and circular curves ($Gdir_{C-AT}$) are significant: unchanging grade between these components would aid to maintain speed consistency. The circular curves with steeper grade are more likely to reduce the speed consistency because drivers will increase their speed across steeper components. The finding agrees with previous results by Abdul-Mawjoud (*28*). Another finding is that the directions of approach transition curves ($CVdir_{AT}$) influence on speed consistency. Compared to approach transition curves to the right, those to the left is more likely to help maintain speed consistency.

From the $\Delta VD_{C\text{-}AT}$ model, the estimated coefficient of changes in grade between circular and horizontal curves ($Gdir_{C-HC}$) is significant: that is, the same grade between these two components will improve speed consistency. Similarly, the speed consistency will be improved when circular curves get steeper than horizontal curves. It shows that the speed decreasing is different showed that a gentle grade change will help drivers maintain constant vehicle speed. The length differences between approach transition and circular curves（$Ldir_{C-AT}$）are significant: longer circular curves will reduce speed consistency. This result implies that drivers are unable to maintain speed if circular curves were longer than approach transition curves.

Speed consistency between circular and departure transition curves

Table 5 shows the estimates for speed consistency between circular and departure transition curves.

TABLE 5 Speed Consistency between Circular and Departure Transition Curves

Model	Parameter	Tobit Model		Random Effect Tobit Model		Sample size
		Coefficient	*p* Value	Coefficient	*p* Value	
$\Delta VI_{DT\text{-}C}$	Intercept	-1.0321	0.4712	-1.2419	0.0078	274
	L_C	0.008	<0.0001	0.009	0.0001	
	ΔL_{C-HC}	0.0265	<0.0001	0.02257	<0.0001	
	$Gdir_{DT-C}$					
	0	-1.3475	0.0231	-1.557	0.0238	
	1	-0.1001	0.8632	-0.1004	0.8629	
	-1					
	$CVdir_C$					
	0	-2.635	<0.0001	-2.6356	<0.0001	
	1					
	γ	3.635	<0.0001	13.16	<0.0001	
	θ^2	-	-	0.05	0.9208	
	AIC	1499		1500		
$\Delta VD_{DT\text{-}C}$	Intercept	-5.54	<0.0001	-5.54	0.0002	188
	$Gdir_{DT-HC}$					
	0	2.09	<0.0003	2.09	<0.0001	
	1	1.44	0.0146	1.44	0.1544	
	-1					
	$Ldir_{DT-C}$					
	0	3.835	<0.0002	3.835	<0.0001	
	1	2.8689	<0.0001	2.8689		
	-1					
	γ	3.107	<0.0001	9.4976	0.9999	
	θ^2	-	-	0.1604	0.9999	
	AIC	971		973		

Both the $\Delta VI_{DT\text{-}C}$ and $\Delta VD_{DT\text{-}C}$ model results showed that there are no substantial differences among the drivers. AIC values of the Tobit and Random Effects Tobit models revealed that two models have close model fit.

The $\Delta VI_{DT\text{-}C}$ model results showed that circular curve lengths (L_C) have significant effects on speed consistency between circular and departure transition curves; longer circular curves will lead to more speed inconsistency. It can be understood as that drivers will increase vehicle speed when they enter departure transition curves if they have enough length to stabilize vehicle speed on circular curves (*3*). Speed consistency is negatively associated with length differences between circular and horizontal curves (ΔL_{C-HC}). This is because drivers can maintain steady speeds across properly proportioned components lengths. The grade change between circular and departure transition curves ($Gdir_{DT-C}$) effect on speed consistency significantly. Same grades between these two components and steeper departure transition curves will improve speed consistency (*29*). The directions of circular curves ($CVdir_C$) have influence on the speed consistency. Compared to circular curves turn right, turn left is more likely to improve speed consistency. This finding is consistent with the $\Delta VI_{C\text{-}AT}$ model.

The $\Delta VD_{DT\text{-}C}$ model results showed that changes in grade between departure transition and horizontal curves ($Gdir_{DT-HC}$) significantly affect speed consistency: same grades will improve speed consistency. Similarly, speed consistency will be improved when departure transition curves are steeper than horizontal curves. The length differences between departure transition and circular curves ($Ldir_{DT-C}$) are significant: compared to shorter departure transition curve, the same length between these two components, and longer departure transition curves will improve speed consistency. It suggests that valid proportion of circular and departure transition curve length will improve speed consistency. Furthermore, drivers were proved to have no substantial influence on speed consistency.

The modeling results showed that the geometric characteristics that influence speed choice are different. The L_{AT}, ΔL_{AT-HC}, $Gdir_{C-AT}$, $CVdir_{AT}$ will influence on speed increase between approach transition and circular curves. The $Gdir_{C-HC}$ and $Ldir_{C-AT}$ will effect on speed decrease between approach transition and circular curves. The L_C, ΔL_{C-HC}, $Gdir_{DT-C}$, $CVdir_C$ will influence speed increase between circular and departure transition curves. The $Gdir_{DT-HC}$ and $Ldir_{DT-C}$ will influence on speed decrease between circular and departure transition curves.

6. SUMMARY AND DISCUSSION

This study investigated the relationship between geometric design characteristics and speed consistency of combined horizontal and downgrade alignments a highway. The objective was to identify significant geometric design and changes in geometric design characteristics to support the development of evaluation standards and quantitative design guidelines for combined alignments. Speed consistency data were collected using the Tongji University Driving Simulator.

The mean speed of drivers was calculated as they drove over a simulated mountainous freeway that presented 22 combined horizontal and downgrade alignments. Speed consistency between the approach transition and circular curve, and between the circular and departure transition curve were analyzed separately. Tobit models were used to identify geometric characteristics that affected speed consistency and the extent to which driver differences affected speed consistency.

The advantage of maintaining speed consistency of individual drivers have been shown in previous studies, however, the measurement method in this study differs in that it reflects the speed choices of each driver. These data allowed the models to show that the length of approach transition and circular curve, length difference between these two components and horizontal curves, grade changes between transition (approach and departure) and circular curve, and curve direction will only influence speed increase. On the contrary, grade changes between circular and, horizontal curves, grade changes between departure transition and horizontal curves and length difference between transition (approach and departure) and circular curves will affect speed decreases only. These findings indicted that it is necessary to separate the speed change into speed increase and speed decrease groups.

Another finding is that the geometric characteristics that influence speed consistency between approach transition and circular curves differ from those between circular and departure transition curves. These differences have usually been omitted in current studies. Based on the findings from this study, preliminary guidelines to engineers are (a) that approach transition curve and circular curve components should be short, and length differences between these two components and horizontal curves should be minimized; (b) grade differences should be eliminated where possible; c) if grade differences cannot be eliminated because of terrain, steep circular and departure transition curves should be used; d) warning signs should be installed when approach transition or circular curves are to the right.

In future studies, acceptable ranges of speed consistency should be defined to evaluate combined alignment designs, and other combined alignments such as sag and crest should be investigated and the effects on different types of vehicles (such as trucks and coaches) should be also be investigated.

ACKNOWLEDGEMENT

This study was jointly sponsored by the Science and Technology Commission of Shanghai Municipality (15DZ1204800), Chinese National Science Foundation (51138003), and the Fundamental Research Funds for the Central Universities. The authors would like to thank Hunan Communications Bureau for offering the detailed road design blueprint of the freeway.

REFERENCE

1. National Statistical Yearbooks of 2014. National Bureau of Statistics of the People’s Republic of China, 2014.

2. Hassan Y., Easa S.M. and Abd El Halim A.O. State-of-the-art of Three-dimensional Highway Geometric Design. *Canadian Journal of Civil Engineering*, Vol. 25, NO. 3, 1998, pp. 500-511.
3. Hanno D. Effect of the Combination of Horizontal and Vertical Alignments on Road Safety. Doctoral dissertation, University of British Columbia. 2004.
4. Hassan Y., Easa S.M. and Abd El Halim A.O. Design Considerations for Combined Highway Alignments. *Journal of Transportation Engineering*, Vol. 123, NO. 1, 1997, pp. 60–68.
5. Al-Masaeid H.R., Hamed M., Aboul-Ela M. and Ghannam A.G. Consistency of Horizontal Alignment for Different Vehicle Classes. *Transportation Research Record*，NO. 1500, 1995, pp. 178-183.
6. Krammes R.A., Rao K.S. and Oh H. Highway Geometric Design Consistency Evaluation Software. In *Transportation Research Record: Journal of the Transportation Research Board, NO. 1500,* Transportation Research Board of the National Academies, Washington, D.C., 1995, pp. 19-24.
7. Nicholson A. Super-elevation, Side Friction, and Roadway Consistency. *Journal of Transportation Engineering*, Vol. 124, NO. 5, 1998, pp. 411-418.
8. Park, Fitzpatrick K. and Lord D. Evaluating the Effects of Freeway Design Elements on Safety. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2195, 2010, pp. 58-69.
9. Cafiso S., Di Graziano A. and La Cava G. Actual Driving Data Analysis for Design Consistency Evaluation. In *Transportation Research Record: Journal of the Transportation Research Board*, *Vol. 1912, NO. 1*, 2005, pp. 19-30.
10. Easa S.M. and Dabbour E. Design radius requirements for simple horizontal curves on three-dimensional alignments. *Canadian Journal of Civil Engineering*, Vol. 30, NO. 6, 2003, pp. 1022-1033.
11. Tobin J. Estimation of Relationships for Limited Dependent Variables. *Econometrica: Journal of the Econometric Society*, 1958, pp. 24-36.
12. Wang X., Wang T., Tarko A., and Tremont P.J. The Influence of Combined Alignments on Lateral Acceleration on Mountainous Freeways: A Driving Simulator Study. *Accident Analysis & Prevention*, Vol. 76, 2015, pp.110-117.
13. Kontaratos M., Psarianos B. and Yotis A. Minimum Horizontal Curve Radius as Function of Grade Incurred by Vehicle Motion in Driving Mode. *Transportation Research Record*，NO. 1445*,* 1994.
14. Psarianos B., Kontaratos M. and Katsios D. Influence of Vehicle Parameters on Horizontal Curve Design of Rural Highways. *Transportation Research Board, International Symposium on Highway Geometric Design*, 1995.
15. Gibreel G.M., Easa S.M. and El-Dimeery I.A. Prediction of Operating Speed on 3d Highway Alignments with Sag Vertical Curves. In *Proceedings of the Transportation Speciality Conference*, *Design and Management.* Canadian Society for Civil Engineering, Montreal, Quebec, Canada. 1998, pp. 373-384.
16. Gibreel G.M., Easa S.M. and El-Dimeery I.A. Prediction of Operating Speed on Three-dimensional Highway Alignments. *Journal of Transportation Engineering*, Vol. 127, NO. 1, 2001, pp. 21-30.

17. Lamm R., Psarianos B. and Mailaender T. Highway Design and Traffic Safety Engineering Handbook. 1999.
18. Gibreel G.M., Easa S.M., Hassan Y. and El-Dimeery I. A. State of the Art of Highway Geometric Design Consistency. *Journal of Transportation Engineering*, Vol. 125, NO. 4, 1999, pp. 305-313.
19. Jacob A., Dhanya R. and Anjaneyulu M. Geometric Design Consistency of Multiple Horizontal Curves on Two-lane Rural Highways. *Procedia-Social and Behavioral Sciences*, Vol. 104, 2013, pp. 1068-1077.
20. Hirsh M. Probabilistic approach to consistency in geometric design. Journal of Transportation Engineering, Vol. 113, NO. 3, 1987, pp. 268-276.
21. Bella F. Parameters for Evaluation of Speed Differential: Contribution Using Driving Simulator. In *Transportation Research Record: Journal of the Transportation Research Board*, *Vol. 2023, NO. 1*, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 37-43.
22. McFadden J. and Elefteriadou L. Evaluating Horizontal Alignment Design Consistency of Two-lane Rural Highways: Development of New Procedure. In *Transportation Research Record: Journal of the Transportation Research Board*, *Vol. 1737, NO. 1,* Transportation Research Board of the National Academies, Washington, D.C., 2000, pp. 9-17.
23. Misaghi P. and Hassan Y. Modeling Operating Speed and Speed Differential on Two-lane Rural Roads. *Journal of Transportation Engineering*, Vol. 131, NO. 6, 2005, pp. 408-418.
24. Hassan Y., Gibreel G. and Easa S.M. Evaluation of Highway Consistency and Safety: Practical Application. *Journal of Transportation Engineering*, Vol. 126, NO. 3, 2000, pp. 193-201.
25. Talley W.K. Safety Investments and Operating Conditions: Determinants of Accident Passenger-vessel Damage Cost. *Southern Economic Journal*, 1995, pp. 819-829.
26. Farah H., Bekhor S. and Polus A. Risk Evaluation by Modeling of Passing Behavior on Two-lane Rural Highways. *Accident Analysis & Prevention*, Vol. 41, NO. 4, 2009, pp. 887-894.
27. SAS OnlineDoc® 9.2 SAS Institute Inc., Cary, N.C., 2004.
28. Abdul-Mawjoud A.A. and Sofia G.G. Development of Models for Predicting Speed on Horizontal Curves for Two-lane Rural Highways. *Arabian Journal for Science and Engineering*, Vol. 33, NO. 2, 2008.
29. Hasan M., Sayed T. and Hassan Y. Influence of Vertical Alignment on Horizontal Curve Perception: Effect of Spirals and Position of Vertical Curve. *Canadian Journal of Civil Engineering*, Vol. 32, NO. 1, 2005, pp. 204-212.