Impact of Combined Alignments on Lane Departure: A Simulator Study for Mountainous Freeways

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ABSTRACT

Lane departures are responsible for many side-swipe, rear-end and single-vehicle run-off-road crashes. There is a dearth of research, however, on how lane departures are impacted by roadway alignments. The objective of this paper is to examine which geometric design characteristics, including road alignment at the current segment and the adjacent segments, have significant influence on lane departure. Lane departure data from a total 30 drivers were collected from a driving simulator study of a four-lane (two lanes in each direction) divided mountainous freeway. Lane departures were classified into *lane keeping*, *lane departure to the left* and *lane departure to the right* for all-alignments (Dataset I), and *lane keeping, lane departure to the inside* and *lane departure to the outside* for curves-only (Dataset II). A mixed multinomial logit model for each dataset was employed to examine the contributory factors. This approach allows for the possibility that the estimated model parameters can vary randomly to account for unobserved effects potentially relating to heterogeneous driver behaviors. Fixed parameters that had a significant increase on lane departure were horizontal curvature at the current segment, and the difference (max-min) in horizontal curvature within the 300-m adjacent upstream alignment. Downward slope and upward slope with fixed parameters significantly decreased lane departure. Estimated parameters related to the direction of the curve, driving lane (bordering median or hard shoulder) and driving speed had found to have randomly distributed over the drivers. This indicates that driver behavior is not consistent in the effect of these three variables on lane departure. These results can assist engineers in designing safer mountainous freeways.

Keywords: Mountainous Freeways, Combined Alignments, Lane Departure, Mixed Multinomial Logit Model, Driving Simulator.

INTRODUCTION

Lane departure is a critical safety event that occurs when a vehicle unintentionally moves out of its current lane. It is considered to be the primary precursor of roadway departures and single-vehicle run-off-road (ROR) crashes (Transportation Research Board, 2011). An analysis of 2007 to 2013 crash data from the Fatality Analysis Reporting System (FARS) database reveals that an average of 59% of annual motor vehicle traffic fatalities in the United States occurred due to roadway departure (NHTSA, 2016). Lane departure can also lead to rear-end and side-swipe crashes in the case of divided roadways, and to head-on crashes on undivided roadways. In China, the proportion of traffic crashes associated with lane departure is about 42% in 2007 (Zhou, 2010).

Research on lane departure has mainly focused on the design and development of warning systems that are capable of detecting whether lane departure is imminent, and then inform the driver using visual, vibration and sound warnings. There is a dearth of research, however, on how lane departures are influenced by roadway geometry. Some studies have shown that certain road alignments increase the likelihood of roadway departure crashes (e.g. Eustace et al., 2014; Lord et al., 2011; Liu and Subramanian, 2009); and Torbic et al. (2004) have indicated that approximately 76% of curve-related fatal crashes are single-vehicle ROR crashes. It can be assumed, then, that some geometric alignments may be correlated with lane departure. If the combinations of horizontal and vertical alignments at the current segment (road alignment at the current position of a vehicle) are improperly designed, e.g. a sharp horizontal curvature with an upward slope, the alignments could lead to unnecessary and excessive lane departures. In addition to the current segment, the roadway alignments at both upstream (i.e. road just passed) and downstream (i.e. road ahead) adjacent segments (termed as ‘*adjacent alignments*’ henceforth) may affect lane departure. For example, when two curves with small radii are adjacent or a long downhill alignment is followed by a small radius curve, a vehicle may easily deviate from its lane, especially at a high speed. The combined horizontal and vertical alignments at the current segment and the adjacent alignments are here referred to as ‘*combined alignments*’.

Safety assessment of road alignments design has mainly focused on determining of the threshold values for single horizontal alignments and single vertical alignments independently. For example, the criteria of the minimum radius and the maximum grade for appropriate combinations of design speed and terrain type have well established (e.g. AASHTO, 2010; MOT, 2015). In response to studies that have shown that horizontal and vertical alignments should be considered together, several qualitative design guidelines for combined alignments are presented in Design Specification for Highway Alignment (AASHTO, 2011; MOT, 2006). Safety criteria for combined alignments are, however, not systematic in current guidelines, and safety criteria for adjacent alignments are not currently available at all (AASHTO, 2010; MOT, 2015).

The objective of this research, therefore, is to examine how the combined alignments affect the probability of lane departure while controlling for other factors. Since real-world data on the corresponding occurrences of lane departure with combined alignments are not readily available, a driving simulator study was conducted. Lane departure events, lane keeping states and other operational data (e.g. speed) were continuously captured by the simulator software during a varied road alignment scenario of a mountainous freeway. Factors such as road environment and traffic conditions were kept consistent in the simulation so as to reduce extraneous impact on lane departure. The mixed multinomial logit model was employed, which accounts for the possibility that the estimated model parameters can vary randomly in response to unobserved effects relating to drivers' behaviors.

LITERATURE REVIEW

Due to the lack of research on the effects of combined alignments on lane departure, this section will review and synthesize existing related studies. They include road alignments' effects on safety and the means of evaluating those effects, and factors that specifically influence lane departure, particularly vertical and horizontal alignments.

Effects of road alignments on safety

Horizontal curvature and vertical grade have been found to be correlated with crash occurrence in a number of studies. Torbic et al. (2004) reported that the crash rate of horizontal curves is approximately three times that of tangent sections. A review of crash data in Iowa between 2001 and 2005 indicated that 12% of all fatal crashes and 15% of all major injury crashes occurred on curves (Transportation Research Board, 2011). A study by Miaou and Lum (1993) revealed that as vertical grade increases, accidents involving trucks also increase. Wang et al. (2015) developed multiple linear regression models to estimate the effects of combinations of horizontal and vertical alignments on lateral acceleration.

Traffic crashes, however, result from the interaction of a complex range of factors such as driver, roadway, vehicle and weather. The intrinsic complexity of these factors combined with the often poor quality of traffic crash data results in an insufficient supply of information about crash causation (Tarko, 2012). Because the shortcomings of this information can make it difficult to evaluate the impact of single factors such as road alignment on safety, crash surrogates are therefore commonly used. Good surrogate measures are directly linked to crash occurrences and are affected by variables known to also affect safety (Wang et al., 2015).

Speed consistency is a commonly and widely used surrogate. For instance, on the basis of the 50% (median) and the 85% critical values of the sample distribution of $\Delta Vmax$ and of $\Delta Vmean$ as thresholds ($\Delta Vmax$ is the difference between the minimum speed on a curve and the maximum speed on a tangent; $\Delta Vmean$ is the difference between the minimum speed on a circular curve and the mean speed for the entire test course), Cafiso et al. (2009) used a naturalistic driving experiment to determine good, fair, and poor domains of design consistency. Similar evaluation criteria were also recommended by *Specifications for Highway Safety Audit* of China, which used speed consistency to evaluate the coordination between adjacent road segments. Evaluation criteria were divided into three levels: i) good, $|\Delta V85|<10$km/h; ii) fair, 10km/h<= $|\Delta V85|<=20$km/h; and iii) poor, $|\Delta V85|>20$km/h, in which

$\Delta V85$ represents the 85th percentile of the distribution of maximum vehicle speed on the adjacent road alignment segments (MOT, 2015).

Alignments and other factors influencing lane departure

One way to detect lane departure is to use lateral offset, which is defined as the distance between the lane’s center-line and the vehicle’s center-line (Jung and Kelber, 2005). Once lateral offset reaches the threshold that a vehicle moves out of its current lane, it is termed as a lane departure behavior, which is identified as a risky lateral offset (NHTSA, 2011).

Research on the influence of road alignments on lane departure has mostly focused on horizontal geometrical parameters, e.g. curve radius, curvature (reciprocal of the radius, unit: 1/km), and curve direction (i.e. left-turn or right-turn). For instance, Jalayer and Zhou (2017) found that horizontal curvature was one of the most significant variables for ROR crash frequency. Lin et al. (2011) concluded that a small curve radius led to a large lateral offset. Wu et al. (2013) constructed a prediction model for the standard deviation of lateral offset using the multivariate linear regression model and showed that the length of the tangent alignment, the length of the circular curve, and the curvature change rate were all significant independent variables. Spacek (2005) showed that drivers maintained a clearly larger distance from the road edge than to the center line both in left-turn curves and in right-turn curves, but nearer to the center line on left-turn curves than right-turn curves. Spacek (2005) then concluded that the variation in lateral offset may be caused by curves, centrifugal acceleration and speed. Yet none of these previous studies considered the possible impact of vertical alignments.

Adjacent alignments have been found to be related to speed change, and speed change has been shown to contribute to lane departure. When, for example, the length needed for deceleration to curve n+1 from curve n is less than the available length, some speed changes from the previous curve will occur (Fitzpatrick and Collins, 2000). Xu et al. (2013) demonstrated a correlation between speed change and trajectory. Therefore, it can be assumed that speed change can lead to lane departure. Yu et al. (2012) found that when a vehicle enters a curve, its path has a tendency to shift inward, but that its path tends to shift outward as it exits the curve. The influence on lane departure of upstream and downstream adjacent alignments, however, needs a systematic analysis.

Other factors extraneous to alignment also affect lane departure and should be considered. With a driving simulator study, Horst and Ridder (2007) showed that when roadside trees were introduced in combination with a guardrail, drivers tended to choose a position away from the guardrail and trees. When trees were introduced solely, without the guardrail, no effects on lateral position were found. Using video-image detection on a straight segment, Wang et al. (2016) found a considerable difference in lateral offset depending on lane: vehicles in the lane closest to the median tend shift to the other side of the lane (to the right, in China, where driving is on the right side of the road), apparently to keep a safe distance from the median.

In summary, it can be concluded that although research has been conducted on the influence of single current horizontal and adjacent alignments to lane and/or road departure, there is a lack of research on the joint influence of combined alignments. Horizontal and vertical alignments complement each other, and poorly designed combinations can be unsafe and aggravate the deficiencies of each (AASHTO, 2011). For curve with frequent direction changes or large difference between maximum and minimum curvature on adjacent horizontal alignments, the scale of lane departure may be severe. Therefore, this study aims to examine the influence of these combined alignments on lane departure. Due to the limited availability of real-world data connecting lane departures to combined alignments, this study used the Tongji University driving simulator.

DATA PREPARATION

Driving Simulator

With technological developments, innovative technologies for advanced representation of motion and visual cues, cabin and control equipment, vehicle motion and environmental factors were adapted for driving simulators (Bhatti et al., 2015). Driving simulators have increasingly been used to study driving behaviors, road safety and design features (Eryilmaz et al., 2014). This study has also employed an advanced driving simulator for the purpose of data collection.

Figure 1 shows the Tongji University driving simulator used in this study. This simulator, currently the most advanced in China, incorporates a fully instrumented Renault Megane III vehicle cab in a dome mounted on an 8 degree-of-freedom motion system with an X-Y range of 20×5 m. An immersive 5-projector system provides a front image view of 250°×40° at 1000×1050 resolution refreshed at 60 Hz. SCANeR^{TM} studio software (OKTAL) is used to display the simulated roadway environment and controls a force feedback system that acquires data from the parameters of road alignment, vehicle speed and vehicle position on the road. The overall performance of the Tongji University driving simulator has been validated by the manufacturer in three separate tests: simulator sickness, stop distance, and traffic sign size. Test results showed that the driving simulator satisfied the three criteria: 80% of drivers reported no sickness; 79% stopped within 2 meters of a designated stop line, exceeding a frequently used 75% criterion; and 75% of drivers judged traffic sign size as realistic (Wang et al., 2016).

Insert Fig. 1 about here

Participants

Drivers were chosen randomly through an open invitation (via posters and internet) where a cash reward of $20 per hour was offered to any participant accepted for the study. It was made clear in the invitation that participants must meet certain criteria in order to qualify for the experiment. Because driver factors such as age and accumulated driving years may decrease or increase lane departure behavior, drivers younger than 20 and older than 60 were excluded. They were required to be in possession of a valid driver’s license; had a cumulative driving distance of at least 10,000 km and an average annual driving distance of at least 3,000 km; had no criminal record, nor any record of mental illness or drug use; and had no physical conditions such as heart disease or frequent headaches. During the experiment’s pre-briefing session, participants were informed of the purpose of the study and their option to end the experiment if they felt sick when driving.

A total of 30 drivers were employed in the analysis, a sample similar to that of most simulator studies, which had employed fewer than 30 drivers (Richard, 2007; Yu, 2012; Tarko, 2012). Their ages ranged from 24 to 58 years (with a mean age of 36.3 years and a standard deviation of 8.7 years), and 3 were female and 27 were male. Wary of the gender imbalance, we estimated two models: (1) all participants (n=30) and (2) male participants (n=27). As no difference was found in the results, we retained the n=30 model.

Experimental procedure

The experimental sessions consisted of three phases: preparation, warm-up, and test. During the preparation phase, participants were informed of the experiment’s content, and they completed a questionnaire covering their basic demographic information and driving experience. The warm-up phase entailed a 10-minute dry-run drive to ensure that participants familiarized themselves with the simulator. The final test phase consisted of two driving tasks: one for the northbound (outbound) direction of the freeway segment and the other for the southbound (inbound). In both directions, dry pavement conditions in daylight were ensured with a free-flow traffic condition. The average duration of the test driving for each driver in the simulator was 35 minutes. Participants were asked to drive as naturally as possible. After the experiment, all drivers were asked to complete a second short questionnaire about their experience during the experiment. Over 85% of the drivers reported that the driving conditions and road scenarios were realistic.

Geometric Design

The simulated road was a 24-km four-lane divided mountainous freeway in the southwest of China. The road was designed under China’s 2006 MOT specifications for highway alignment, with a design speed of 100 km/h. The simulated stretch of the freeway consisted of horizontal curves with small radii and long downslopes, for a total of 71 vertical and horizontal combined alignments. The longitudinal grades of these alignments ranged from – 6.0% to +4.0% in the outbound direction (i.e. -4% to 6% inbound) and the values of the horizontal curvatures ranged from 0 to 2.5 km^{-1}. The cross-section was 24.5 meters wide with a lane width of 3.75 meters and shoulder width of 2.5 meters. These measurements are schematically shown in Figure 2.

Insert Fig. 2 about here

To gather all relevant data, the road line was divided into 5-m spatial segments according to the length of the vehicle. Horizontal and vertical geometrical parameters, as well as vehicle speed, were acquired for every 5-m segment. To determine the relationship between lane departure event (in every 5-m segment) and the geometric characteristics of the adjacent alignments, both upstream and downstream adjacent alignments were divided into 50-m, 100-m, 150-m, 200-m, 300-m and 400-m segments as shown in Figure 2. Variables with different lengths on the upstream or downstream alignments were also acquired, e.g. difference in curvature within 300-m upstream alignment. A total of 143 independent variables were explored to determine their relationships with lane departure. Descriptive statistics for data elements used in this study are shown below in Table 1.

Insert Table 1 about here

Lane Departure

Lane offset is defined as the distance between the lane center line and the vehicle center line. The width of the vehicle used in the simulator is 220 cm and the lane width is 375 cm. The offset threshold for lane departure is therefore 77.5 cm, which is shown in Figure 3.

Insert Fig. 3 about here

We considered that there might be two perspectives for analysis. Categories for all-alignments (straight alignments and curves, termed as Dataset I) are *lane departure to the left*, *lane departure to the right* and *lane keeping*. For subset of curves-only (termed as Dataset II), they are *lane departure to the inside, lane departure to the outside* and *lane keeping*. In some cases the inside of a curve is on the left, but in other cases it’s on the right. Each data set was used to build a separate model. We suspected that combined the results of the models of two data sets, the impact of alignments on lane departure could accurately be revealed.

The categories of lane departure are shown in Figure 4. The percentage values for all-alignments behaviors are lane keeping, 90.4%; lane departure to the left, 4.1%; and lane departure to the right, 5.5%. For curves-only, the values are lane keeping, 87.9%; lane departure to the inside, 10.1%; and lane departure to the outside, 2.0%.

Insert Fig. 4 about here
Insert Table 2 about here

There were 697 lane departure behaviors to the left with an average length of 65.5 meters and 750 departure behaviors to the right with an average length of 82.0 meters in Dataset I (Table 2). A single lane departure behavior was acquired at every 5-m segment (one event). Therefore, only one lane departure event from a single lane departure behavior was considered in the development of the model so as to avoid the inherent correlation. Lane departure events were randomly selected by the software, along with a similar proportion (i.e. 6.87%[1]) of lane keeping for the all-alignments model (Dataset I). For the curves-only model (Dataset II), 943 lane departure events to the inside and 217 departure events to the outside were randomly selected, with a similar proportion (i.e. 7.39%[2]) of lane keeping.

MODELLING METHODOLOGY

Since the dependent variable, *occurrence of lane departure,* is a nominal categorical variable, the most appropriate statistical method is a multinomial logit model (Horowitz, 1980). This is the most practical discrete choice model in which we assume a sample of *N* drivers with the choice of *J* alternatives on *T* choice occasions or making their choices at *T* time periods. The utility that a decision maker *n* choosing alternative *i* on a choice occasion *t* has two parts: (i) representative or observed utility ($i.e. V_{nit}$) and (ii) a random component (i.e. ε_{nit}) denoted as:

$$U_{nit} = V_{nit} + \varepsilon_{nit} \tag{1}$$

In which the random component captures the unobserved factors that are not included in the observed utility. The multinomial logit (MNL) model is therefore derived by assuming that each ε_{nit} is independently and identically distributed (IID) extreme value known as Gumbel and type I extreme value distribution (Train, 2003). The probability that a decision maker *n* chooses alternative *i* on a choice occasion *t* can be expressed as:

$$P_{nit} = Prob\left(U_{nit} > U_{njt}\right) \qquad \forall j \neq i \tag{2}$$

The logit choice probabilities are obtained by the following formula:

$$P_{nit} = \frac{\exp(V_{nit})}{\sum_{j=1}^{J} \exp(V_{njt})} = \frac{\exp(\beta X_{nit})}{\sum_{j=1}^{J} \exp(\beta X_{njt})} \qquad j = 1, 2, 3, .., J \tag{3}$$

As multiple lane departures (i.e. choice occasions *T*) were performed by each of the drivers participating in the simulation experiment (average 48 per driver), unobserved individual-level correlated effects and heterogeneity (i.e. taste variations) should be taken into account. However, the MNL model assumes that the random components of the utilities of different choice alternatives are IID and does not allow taste variations. The mixed multinomial logit (MMNL) model offers significant advantages over the MNL model (e.g. McFadden and Train, 2000) by allowing for random taste variation across drivers in their sensitivities to contributory factors such as combined alignments and speed on lane departures.

The random-parameters formulations of the MMNL model employs integration of the standard MNL choice probabilities over the assumed distribution of the random taste coefficients in that the probability of *n* driver choosing alternative *i* on a choice occasion *t* is given by:

$$\mathrm{P}(y_{nt} = i) = \int \frac{\exp(\beta_n X_{nit})}{\sum_{j=1}^{J} \exp(\beta_n X_{njt})} f(\beta|\theta) d\beta \tag{4}$$

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[1] $6.87\% = \left(\frac{5}{65.5} + \frac{5}{82.0}\right)/2$; Length of each segment = 5m; see Table 2 for other values

[2] $7.39\% = \left(\frac{5}{72.8} + \frac{5}{63.2}\right)/2$; Length of each segment = 5m; see Table 2 for other values

where $f(\beta|\theta)$ is a density function where θ is the vector of parameters to be estimated that represents, for instance, the mean and standard deviation of a contributory factor.

The primary drawback of the MMNL model relates to the fact that the integrals representing the choice probabilities as shown in Equation (4) do not have a closed-form expression and need to be approximated through simulation. One of the efficient simulation techniques is the Halton sequence (Bhat, 2003; Halton, 1960). This is a relatively straightforward type of a quasi-Monte Carlo approach and has the advantage of cost saving over the use of pseudo-random draws. Therefore the Halton sequence was employed in estimating the parameters of the MMNL model.

Both MNL and MMNL models were initially estimated with statistical package STATA. As discussed, the dependent variable in both models has three nominal categories for each of the two data sets in which Dataset I represents all-alignments lane departures and Dataset II represents the sub-set data related to lane departures at curves only. Although the set of statistically significant variables was found to be almost the same in both models for the two data sets, the various goodness of fit statistics (log-likelihood ratio index, log-likelihood at convergence, and the accuracy of predicted probabilities) suggested that the MMNL model performs better than the standard MNL model for both data sets. This implies the existence of a significant level of heterogeneity in tastes, especially with respect to speed at the upstream and curve direction (i.e. left or right), characterized by fixed (deterministic) and random driver-level variation. Therefore, model interpretation and further discussion are based on the findings from the MMNL model.

MODELING RESULTS

In Dataset I (all-alignments), choice alternatives or lane departure categories are *lane keeping* (i.e. Y_{nt}=1), *lane departure to the left* (i.e. Y_{nt}=2) and *lane departure to the right* (i.e. Y_{nt}=3); In Dataset II (curves-only), the categories are *lane keeping* (i.e. Y_{nt}=1), *lane departure to the inside* (i.e. Y_{nt}=2) and *lane departure to the outside* (i.e. Y_{nt}=3). *Lane keeping* is the reference category for both data sets.

A total of 143 explanatory variables, as discussed in the data preparation section, were examined. In selecting the final set of variables, many were found to be statistically insignificant at the 95% confidence interval, then the insignificant variables were taken out from the final model (a variable was removed if its p-value was more than 0.05). With the aid of the correlation coefficient matrix, many variables were found to be correlated with each other (e.g. difference in curvature within 200-m upstream and 300-m upstream, shown in Table 2). For these correlated variables, we employed the variables one by one respectively and many models were separately estimated. With the examination of their levels of statistical significance through the p-values and the models' goodness of fit (i.e. the log likelihood function at convergence, a larger value of log likelihood indicates a better model), the final set of explanatory variables was attained. We done this process manually rather than using a computer program. To ascertain whether the coefficient of an independent variable was randomly distributed over the observations, a normal distribution was assumed. If the mean and the standard deviation of a coefficient were statistically significant, the variable was considered to follow a random distribution.

Dataset I (all-alignments) results for lane departures to the left and right

Six variables in the all-alignments dataset were found to be statistically significant at the 95% confidence interval. These consisted of three categorical variables and three continuous variables. The three categorical variables were: 1) curve direction at the current segment (left vs straight; right vs straight); 2) driving lane (Lane 1 borders the median and Lane 2 borders the hard shoulder); and 3) slope type (upward ≥+2% vs flat; downward ≤–2% vs flat). The three continuous variables were: 1) horizontal curvature at the current segment; 2) difference in horizontal curvature (max-min) within the 300-m upstream adjacent alignment; and 3) the average speed within the 300-m upstream adjacent alignment. The 300-m adjacent segment had the best level of significance as compared to the other segment lengths, based on p-values and the models' goodness of fit. The results are presented in Table 3 below.

Insert Table 3 about here

For both left and right lane departures, estimated parameters for curve direction at the current segment and average speed within 300-m upstream segment were found to be randomly distributed by driver. This indicated that driver behavior was not consistent for the effect of curve direction and average speed on lane departure to the left or the right.

More specifically, in the *lane departure to the left* category, the mean parameter of the left-turn curve variable was found to be +2.463 with a standard deviation of 1.625, indicating that the impact of the left-turn curve variable on the probability of lane departure to the left might have a mixed effect. Since the standard deviation of the coefficient is quite large relative to the mean value of the coefficient, there is a high possibility that some of the coefficients would be negative. Since the coefficient was assumed to follow a normal distribution, the Z-statistic was obtained to calculate the area under the normal curve between the mean (i.e. 2.463) and 0 as follows:

$$Z = \frac{0-2.4635}{1.625} = -1.52 \tag{5}$$

Z=1.52 represents 43.57% of the area under the normal curve. This means that 43.6% + 50% = 93.6%, of drivers show a positive sign, indicating that left-turn curves have positive influence on probability of lane departure to the left for the 93.6% of drivers whereas 6.4% of drivers on the left-turn curves exhibit a negative sign, implying that left-turn curves are negatively associated with the probability of lane departure to the left. Therefore, it can be said that driver behavior with respect to driving on a left-turn curve is not consistent.

Variables with fixed parameters show only positive or negative probability for all drivers (e.g., driving on a right-turn curve, all drivers showed a negative sign for departing to left, at the 95% confidence interval).

Interpretation of the variables included in the model for Dataset I

As compared to driving on a straight segment, driving on a right-turn curve was found to be with a fixed parameter that had a significant positive impact on *lane departure to the right* and a negative impact on *lane departure to the left*. The distributed parameter of left-turn curve had a mean of 2.463 and standard deviation of 1.625 for *lane departure to the left*, and a mean of -1.047 and standard deviation 0.794 for *lane departure to the right*. According to the same approach (Equation 5), this implied that driving on a left-turn curve increased *lane departure to the left* for 93.6% of the drivers, with 6.4% exhibiting the opposite behavior, i.e., a decrease in *lane departure to the left*. For 90.6% of the drivers, driving on a left-turn curve decreased the likelihood of *lane departure to the right,* while it was increased for 9.4%.

The parameters of vertical slope were fixed, and negatively associated with lane departure. Downward slope less than -2% (vs flat segment) had a significant negative impact on *lane departure to the left*. Upward slope, as compared to flat segment, was found to decrease the risk for *lane departure to the right*. This suggested that drivers were more cautious when driving on downslope and upslope.

The simulated road was a four-lane (two lanes in each direction) divided mountainous freeway on which Lane 1 borders the median on the left, and Lane 2 borders the hard shoulder on the right. Its estimated parameter was fixed across drivers. The risk of *lane departure to the left* on Lane 2 (bordering the shoulder) was higher than that of Lane 1, while Lane 1's risk for *lane departure to the right* was greater. This finding was expected, as drivers might reasonably avoid fixed impediments such as shoulders and medians.

Curvature is normally a scalar quantity that takes into account the bending of horizontal curve. Horizontal curve that bend more sharply has higher curvature. Driver behavior was consistent for the effect of horizontal curvature at the current segment, i.e. the probability of both *lane departures to the right* and *to the left* were found to be positively influenced by the horizontal curvature.

The difference between maximum and minimum horizontal curvature (1/km) within the 300-m upstream adjacent alignment was also found to be with a fixed parameter. As with horizontal curvature at the current segment, a large curvature difference significantly increased the likelihood of both *lane departure to the right* and *lane departure to the left.*

Average vehicle speed within the 300-m upstream adjacent alignment (*AvgspeedU300*) was a significant variable for lane departure. Considering the random parameter, it was found that a greater average vehicle speed had a positive effect on *lane departure to the left* for 98.1% of the drivers, while for 1.9% it decreased the probability. Average vehicle speed within the 300-m upstream adjacent alignment had a negative effect on *lane departure to the right* for 91.6% of the drivers, but increased the probability for 8.4%. Since cliffs often appear to the right of the hard shoulder on mountainous freeways in China (where vehicle traffic keeps to the right side of the road), drivers are more likely to depart to the left from their lanes so as to avoid running off the road.

Dataset II (curves-only) results for lane departures to the inside and outside

For lane departures to the inside and outside of a curve, five variables were found to be statistically significant at the 95% confidence interval. The two categorical variables were: 1) driving lane, (Lane 1 borders the median and Lane 2 borders the hard shoulder), and 2) slope type (upward ≥+2% vs flat; downward ≤–2% vs flat). The three continuous variables were: 1) horizontal curvature at the current segment; 2) the difference in horizontal curvature (max-min) within the 300-m upstream adjacent alignment; 3) speed at the current segment. The results are presented in Table 4.

The parameters found to be random were driving lane and vehicle speed at the current segment. This indicated that the effects of these two variables on drivers' lane departures to the inside and outside of the curve were not consistent.

Insert Table 4 about here

Interpretation of the variables included in the model for Dataset II

Vertical slope was found to be with a fixed parameter that significantly decreased the likelihood of *lane departure to the inside*. Both downward slope of less than -2% (vs flat segment) and upward slope of more than 2% (vs flat segment) had negative impact on *lane departure to the inside.*

The Lane 1 parameter (bordering the median, vs Lane 2) was distributed with a mean of -0.335 and standard deviation of 0.527 for *lane departure to the inside,* and a mean of -1.152 and standard deviation of 0.637 for *lane departure to the outside*. This implied that on curves, driver behavior was not consistent with respect to the effect of driving lane.

The parameters of both horizontal curvature at the current segment and the difference in curvature within the 300-m upstream adjacent segment were found to be fixed. Both variables (parameters) had a positive impact on *lane departure to the inside.*

The parameter of speed at the current segment was distributed with a mean of 0.226 and standard deviation of 0.014, i.e. greater speed at the current segment significantly increased *lane departure to the outside* for 96.9% drivers. High traveling speed on the curve would seem to make it easy for a driver to slip to the outside.

DISCUSSION

When the results of the models of two data sets are combined, the impact of alignments on lane departure can be revealed accurately. In results of two models, horizontal curvature at the current segment, difference in horizontal curvature in adjacent segments, and downward and upward slope were all found to be with fixed parameters, indicating that driver behavior was consistent for the effect of these variables on lane departure. *Curve_Direction* (left-turn curve or right-turn curve) had significant effect on lane departure to the left and the right (model results of Dataset I), but had no significant effects on lane departure to the inside or outside (model results of Dataset II). Moreover, the proportion of inside lane departures is 81.3%, much larger than departures to the outside (18.7%) and the average speed is the lowest during inside departures (Table 5). These results suggest that drivers tend to avoid the possibility of running off the curve by decelerating (Yu, et al., 2012).

Insert Table 5 about here

The difference between maximum and minimum horizontal curvature within 50-m, 100-m, 150-m, 200-m, 300-m and 400-m segments of both upstream and downstream adjacent alignments were correlated with each other, and had similar positive effects on lane departure. Thus, twelve models for each data set, based on the 6 different adjacent segment lengths, were separately estimated while other variables in the model were held constant. With examination of their levels of statistical significance through p-value (should be less than 0.05) and models' goodness of fit (i.e. the log likelihood function at convergence, in which a larger log likelihood value indicates a better model fit), the optimum length of the immediate upstream segment was found to be 300 meters, while the difference in horizontal curvature on the downstream alignment was not statistically significant.

Using the same p-value and goodness of fit approach, when vertical grades of upward slope and downward slope were defined by ± 2%, the influence of downward slope and upward slope decreased the probability of lane departure significantly. The 2015 Chinese *Specification for Highway Safety Audit* (MOT 2015) recommends using only two categories of vertical grade, namely an 'upward' grade (≥3%) and 'not upward' grade (<3%). However, as in both of this study's models, the 2% upward slope and the -2% downward slope were found to be statistically significant at the 95% confidence interval, suggesting the MOT specifications should be adjusted.

Previous studies on the relationship between vehicle speed and roadway geometry have mainly focused on the characteristics of horizontal alignments, e.g. length of tangent, length of tangent following the curve, horizontal curvature (Fitzpatrick and Collins, 2000; Figueroa and Tarko, 2007). However, downgrade was usually associated with higher speed and upgrade with lower speed (Montella et al., 2014). Our results found that there was no significant difference for speed on downward slope, upward slope and flat grades (Table 6). The lower than expected speed on downward slopes may be a result of the horizontal alignments.

Insert Table 6 about here

The coefficients presented in Tables 3 and 4 above have been employed to estimate how the probabilities of lane departure change with variation in the corresponding key explanatory variables, and thus can assist in formulating recommendations for designing the combined alignments common on mountainous freeways. Using the findings in Table 3, the probability of *lane departure to the left* can be predicted, for example, for downward slope along left-turn curve in lane closest to the median. Figure 5 below shows 2-D probability plots indicating how *lane departure to the left* varies by horizontal curvature at the current segment (*Curvature_C*) and the difference in curvature within the 300-m upstream adjacent segment (*DiffC_U300*). Either *Curvature_C* or *DiffC_U300* increases, the probability of *lane* *departure to the left* increases. It is notable that lane departures to the left are more frequent when increasing the vehicle's average speed within the 300-m upstream adjacent segment (*AvgSpeedU300*) for the same *Curvature_C* and *DiffC_U300*. This relationship implies that if there is a need to increase speed limit or design speed, a design guideline that minimizes the curvature or the difference in horizontal curvature within the 300-m upstream adjacent segment should be recommended.

Insert Fig. 5 about here

CONCLUSIONS

There has been a dearth of research on how potentially dangerous lane departures are impacted by horizontal and vertical combined roadway alignments at adjacent as well as at the current segments. The objective of this study was to facilitate the design of safer combined alignments on mountainous freeways by examining the effects of these alignments on lane departure. Employing a driving simulator to create a typical four-lane mountainous freeway in China, this study selected a range of geometric characteristics associated with horizontal and vertical alignments on current, upstream and downstream segments to build a mixed multinomial logit model. Two data sets were used to build individual models: all-alignments data and the subset data of curves-only, which was able to provide a much better understanding of the effect of combined alignments on lane departure.

According to the results of the two data set models, the main influencing factors are horizontal curvature at the current segment, the difference in horizontal curvature within the 300-m adjacent upstream alignment, and downward and upward slope. These variables have found to have a fixed effect, indicating that driver behavior is consistent in these conditions. Specifically, lane departures increase with these horizontal alignments, but decrease with downward and upward slopes. Additionally, driving in the lane closest to the hard shoulder increases the probability of lane departure. A left-turn curve has a significant positive impact on lane departure to the left, and a right-turn curve is likely to cause lane departure to the right, as drivers commonly tend to depart their lanes toward the inside of a curve.

The upstream adjacent segment should be considered interdependently in order to reduce potentially dangerous lane departure. The optimum length is found to be 300 meters on the immediate upstream segment. An additional finding that would assist engineers during the design stage of mountainous freeways is that when the vertical grade is divided by ± 2%, the influence of slope on lane departure is significant. The effects of these factors should be given top priority in designing safer mountainous freeways with respect to lane departure.

This research began the study of combined and adjacent alignments on lane departure by addressing normal conditions, i.e. dry pavement conditions in daylight with a free-flow traffic condition. Future work shall investigate the problem with different conditions, including how adverse weather conditions may affect the combined alignments and the possible influence of gender with a balance of male and female drivers.

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Fig. 1 Tongji driving simulator and experiment simulation scene

Fig. 2 Road cross section and segment length

Fig. 3 Schematic diagram of a lane departure scenario

Fig. 4 Lane departure classifications for the two datasets

Fig. 5 Estimated probabilities for departure to the left with left-turn curve and downward-slope on Lane 1 (vertical grade <= -2%)

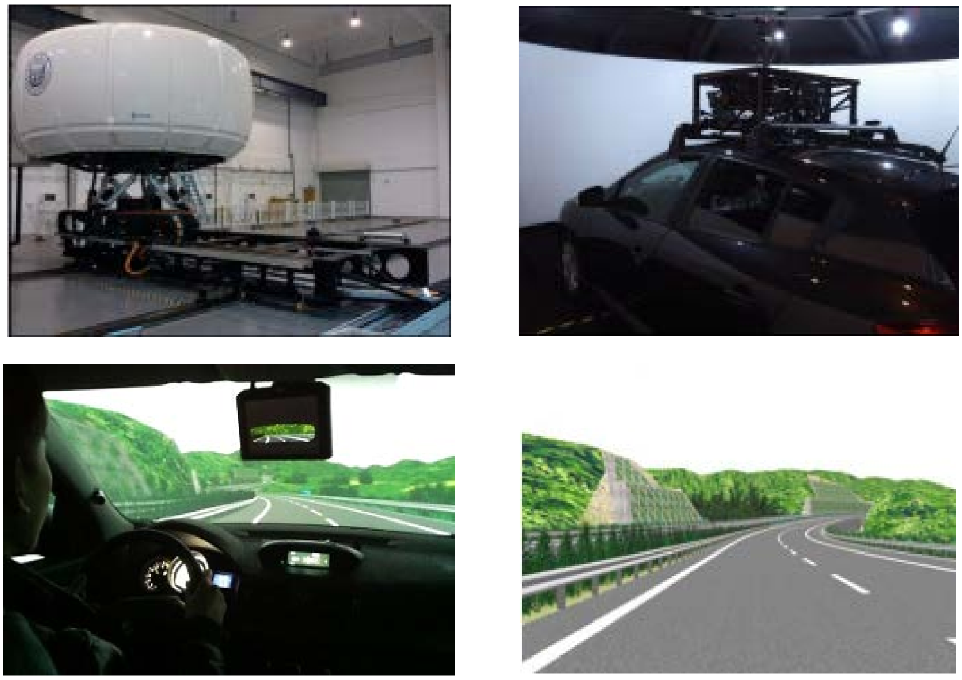
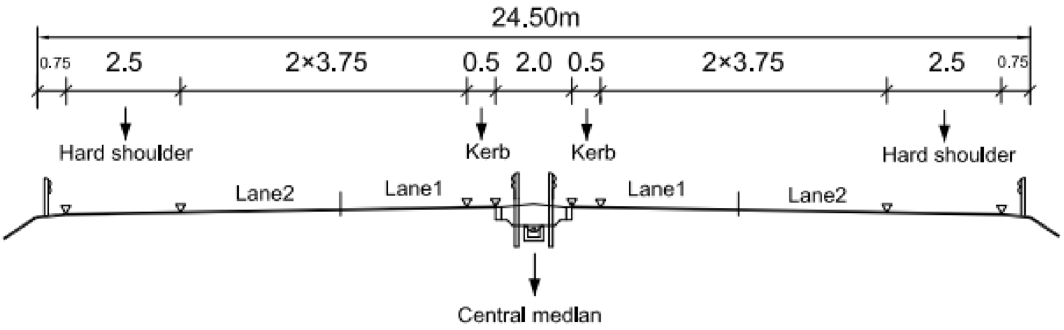
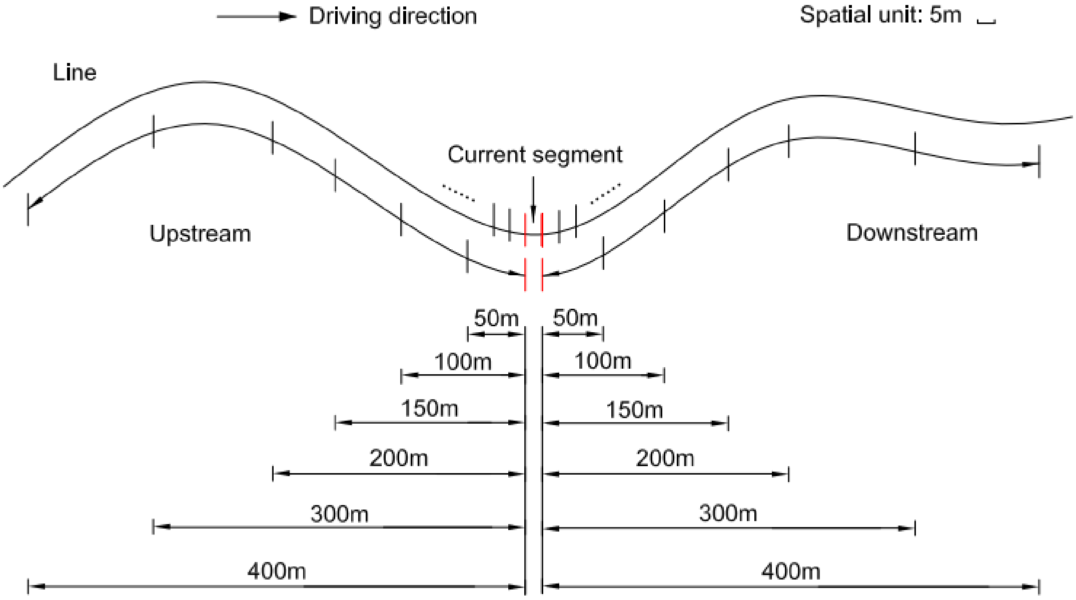


Fig. 1 Tongji driving simulator and experiment simulation scene



(a) Cross-section



(b) A bird's-eye view of a stretch of the studied road alignment

Fig. 2 Road cross section and segment length

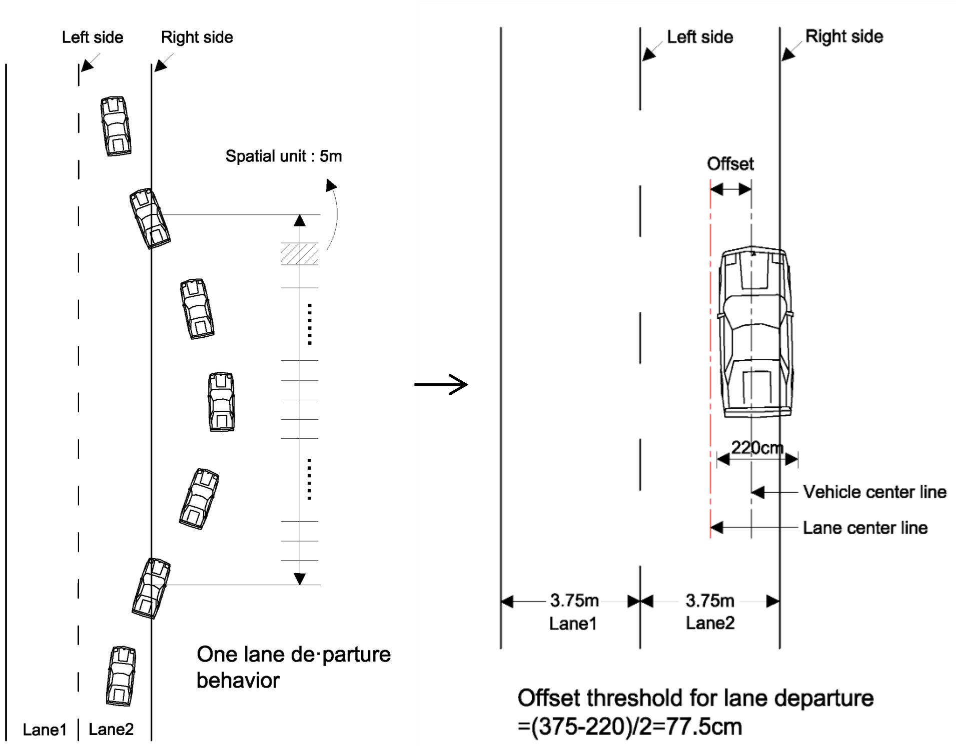
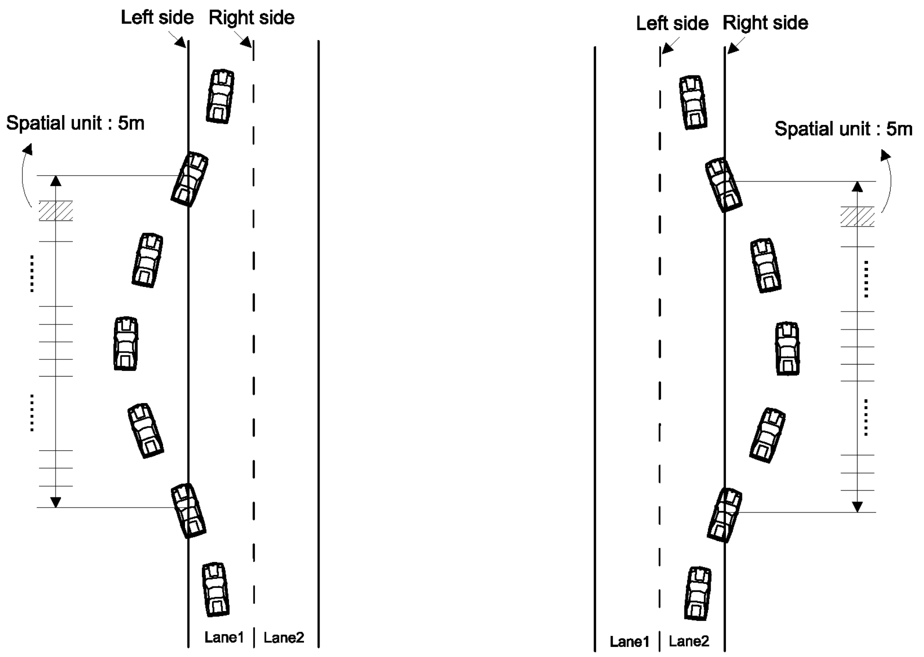
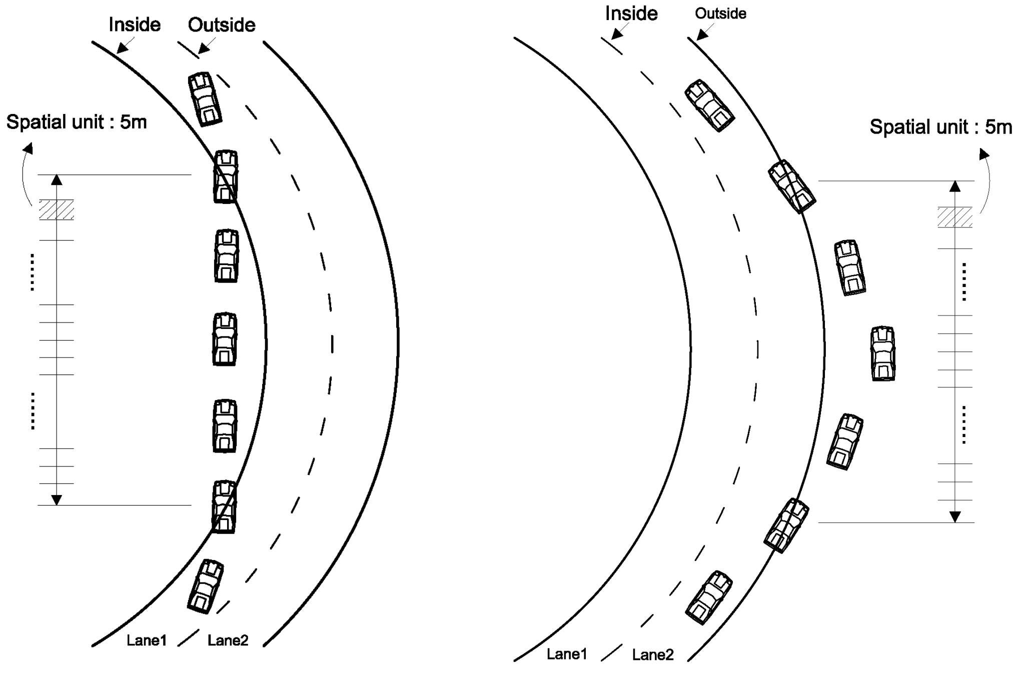


Fig. 3 Schematic diagram of a lane departure scenario

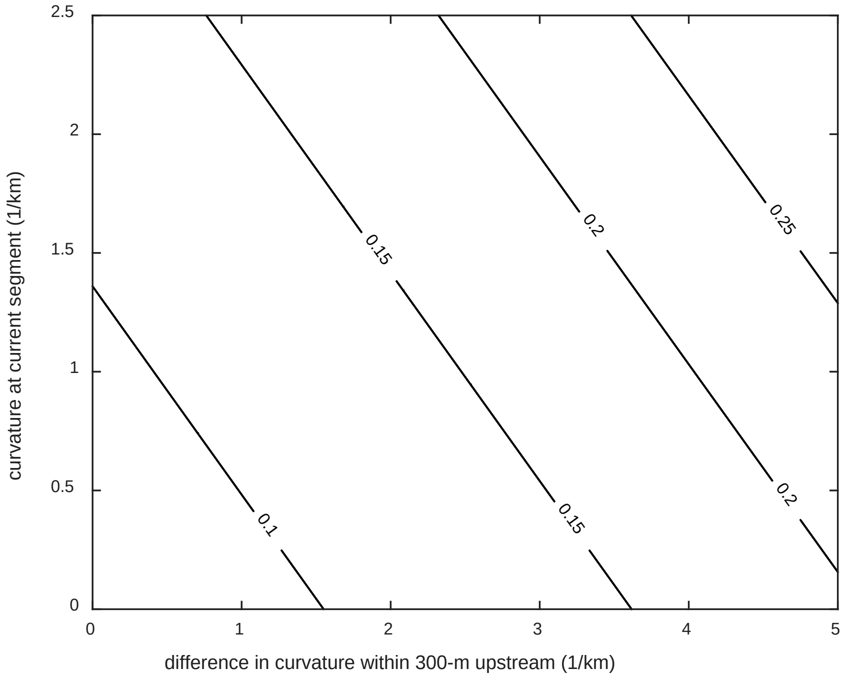


(a)Lane departure to the left (all-alignments) (b)Lane departure to the right (all-alignments)

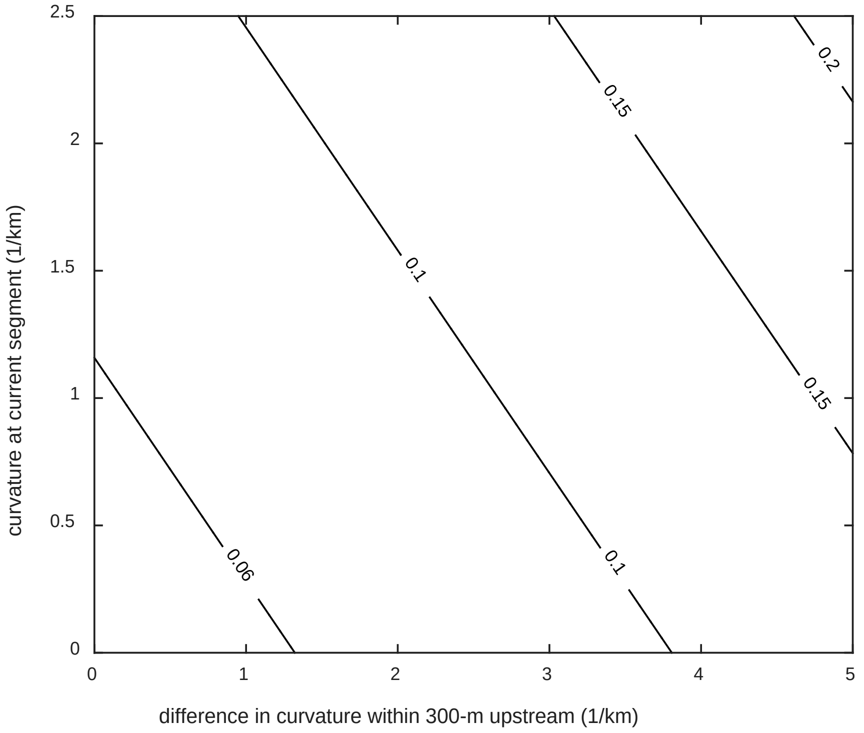


(c)Lane departure to the inside (curves-only) (d)Lane departure to the outside (curves-only)

Fig. 4 Lane departure classifications for the two datasets



(a) ***AvgSpeedU300***=100km/h



(b) ***AvgSpeedU300***=80km/h

Fig. 5 Estimated probabilities for departure to the left with left-turn curve and downward-slope on Lane 1 (vertical grade <= -2%)

Table 1 Descriptive statistics for alignment variables and vehicle operational data

(a) **Continuous variables**

Variables	Description	Mean	S.D	Min	Max
Characteristics of the current segment					
Curvature_C	Absolute value of the horizontal curve at the current segment (1/km)	0.33	0.62	0.0	2.5
Grade_ Northbound	Longitudinal grade of the vertical alignment	-0.0053	0.025	-0.06	0.04
Grade_ Southbound	Longitudinal grade of the vertical alignment	0.0053	0.025	0.06	-0.04
Speed	Driving speed at the current segment (km/h), design speed is 100 km/h	96.31	11.04	50.54	143.41
Visibility	Visibility distance at the current segment (m)	274.78	116.65	47.50	420.00
Characteristics of adjacent upstream and downstream alignments （Using 300-m upstream adjacent alignment as an example）					
AvgC_U300	Average horizontal curvature(1/km)	0.33	0.62	0.0	2.5
MaxC_U300	Maximum horizontal curvature(1/km)	0.64	0.79	0.0	2.5
MinC_U300	Minimum horizontal curvature(1/km)	0.28	0.78	0.0	2.4
DiffC_U300	Difference between maximum and minimum horizontal curvature (1/km)	1.17	1.23	0.00	5.00
NumC_U300	Number of successive curves	1.53	1.16	0	5
AvgS_U300	Average vertical grade	-0.5%	2.5%	-6.0%	4.0%
MaxS_U300	Maximum vertical grade	0.4%	2.0%	-6.0%	4.0%
MinS_U300	Minimal vertical grade	-1.5%	2.6%	-6.0%	3.0%
DiffS_U300	Difference between maximum and minimum vertical grade	1.9%	1.9%	0.0%	8.1%
PuS_U300	Proportion of upward slope	48.4%	45.0%	0.0%	100%
PdS_U300	Proportion of downward slope	51.6%	45.0%	0.0%	100%
AvgSpeedU300	Average driving speed within 300-m upstream adjacent segment (km/h)	96.30	10.78	51.07	143.11

(b) Categorical variables

Variables	Description	Statistic
Curve_Direction	Straight segment, left-turn curve or right-turn curve of the road	Straight: 30.94%
		Left-turn: 31.32%
		Right-turn: 37.73%
Horizontal_Type	Type of horizontal alignment: tangent; circular curve; approach transition curve; departure transition curve	Tangent: 37.7%;
		Circular curve: 32.7%
		Approach transition curve: 14.8%
		Departure transition curve: 14.6%
Lane	Travelling lane: Lane 1 borders the median and Lane 2 borders the hard shoulder	Lane 1: 76.17%
		Lane 2: 23.83%
Slope_Type (outbound)	Slope type of the segment: flat grades	Level or flat: 61%

	(-2%≤grade≤2%), downward slope (< -2%), upward slope (> 2%); four additional degrees of slope type were considered, with thresholds ±1%,±1.5%, ±2.5% and ±3%	Downward slope(< -2%):25.6%
		Upward slope(> 2%): 13.4%

Table 2 Lane departure statistics

Statistic		Dataset I (all-alignments)		Dataset II (curves-only)	
		Lane departure to the left	*Lane departure to the right*	*Lane departure to the inside*	*Lane departure to the outside*
Departure behaviors (30 drivers)		697	750	943	217
Average length of lane departure along the road (m)		65.5	82.0	72.8	63.2
Lane offset value (m)	Min	0.775	0.775	0.775	0.775
	Max	2.156	2.285	2.243	2.281
	Mean	0.939	1.010	0.980	1.003

Table 3 Modelling results for Dataset I (all-alignments) for lane departures to the left and right

Variables	*Parameters*	*Std. Err*	*p-value*
Category 1: ***Lane Keeping (reference)***			
Category 2: ***Lane Departure to the Left***			
Driving on a left-turn curve (vs straight segment), standard deviation for random parameter	2.463 (1.625)	0.164 (0.102)	0.000 (0.000)
Driving on a right-turn curve (vs straight segment), fixed parameter	-0.351	0.169	0.034
Downward slope <-2%(vs flat segment), fixed parameter	-0.230	0.102	0.024
Driving in Lane 1 (bordering the median) vs Lane 2 (bordering the shoulder), fixed parameter	-2.262	0.109	0.000
Horizontal curvature at the current segment, fixed parameter	0.226	0.078	0.004
Difference in curvature (max-min) within 300-m upstream adjacent segment, fixed parameter	0.257	0.040	0.000
Average speed within 300-m upstream adjacent segment, standard deviation for random parameter	0.025 (0.012)	0.004 (0.001)	0.000 (0.000)
Alternative specific constant, fixed parameter	-5.011	0.449	0.000
Category 3: ***Lane Departure to the Right***			
Driving on a left-turn curve, standard deviation for random parameter	-1.047 (0.794)	0.159 (0.145)	0.000 (0.000)
Driving on a right-turn curve, fixed parameter	0.678	0.120	0.000
Upward slope “>2%” vs flat segment, fixed parameter	-0.205	0.092	0.026
Driving in Lane 1 (bordering the median) vs Lane 2 (bordering the shoulder), fixed parameter	1.691	0.211	0.000
Horizontal curvature at the current segment, fixed parameter	0.211	0.080	0.008
Difference in curvature (max-min) within 300-m upstream adjacent segment, fixed parameter	0.162	0.037	0.000
Average speed within 300-m upstream adjacent segment, standard deviation for random parameter	-0.018 (0.013)	0.004 (0.001)	0.000 (0.000)
Intercept	-4.075	0.424	0.000
Overall			
Number of events	53001		
Log-likelihood	-4893.7139		
LR chiSq	726.76		
Prob> chiSq	0.000		

Table 4 Modelling results for Dataset II (curves-only) for lane departures to the inside and outside

Variables	*Parameters*	*Std. Err*	*p-value*
Category 1: ***Lane Keeping (reference)***			
Category 2: ***Lane Departure to the Inside***			
Downward slope <-2% (vs flat segment), fixed parameter	-0.201	0.088	0.022
Upward slope “>2%” (vs flat segment), fixed parameter	-0.162	0.081	0.047
Driving in Lane 1 (bordering the median) vs Lane 2 (bordering the shoulder), standard deviation for random parameter	-0.355 (0.527)	0.107 (0.063)	0.001 (0.000)
Horizontal curvature at the current segment, fixed parameter	0.192	0.061	0.002
Difference in curvature (max-min) within 300-m upstream adjacent segment, fixed parameter	0.281	0.031	0.000
Intercept	-2.736	0.108	0.000
Category 3: ***Lane Departure to the Outside***			
Driving in Lane 1 (bordering the median) vs Lane 2 (bordering the shoulder), standard deviation for random parameter	-1.152 (0.637)	0.301 (0.131)	0.000 (0.000)
Speed at the current segment, standard deviation for random parameter	0.026 (0.014)	0.009 (0.002)	0.003 (0.000)
Intercept	-5.957	0.860	0.000
Overall			
Number of events	33783		
Log-likelihood	-3989.00		
LR chiSq	260.69		
Prob> chiSq	0.000		

Table 5 Statistics for speed of lane departure on a curve

Category	Speed(km/h)					
	Mean	Min	15%	50%	85%	Max
Lane keeping	94.9	51.7	84.0	95.2	105.3	143.0
Lane departure to the inside	92.8	50.5	82.5	93.7	102.0	129.6
Lane departure to the outside	97.3	67.4	89.6	97.3	104.4	123.3

Table 6 Statistics for speed on slope

Category	Speed(km/h)					
	Mean	**Min**	**15%**	**50%**	**85%**	**Max**
Downward slope (grade<-2%)	95.2	54.1	83.3	95.8	106.2	137.6
Upward slope (grade>2%)	97.2	60.9	86.9	98.0	110.1	142.1
Flat grades (-2%⩽grade⩽2%)	96.9	53.5	86.1	96.8	107.6	143.0