Transportation Research Part C 86 (2018) 346–359

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Impact of combined alignments on lane departure: A simulator study for mountainous freeways

Yixin Chen[a,b], Mohammed Quddus[c], Xuesong Wang[a,d,e,*]

[a] Key Laboratory of Road and Traffic Engineering, Ministry of Education, Shanghai 201804, China
[b] School of Highway, Chang'an University, Xi'an 710064, Shaanxi, China
[c] School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom
[d] School of Transportation Engineering, Tongji University, Shanghai 201804, China
[e] National Engineering Laboratory for Integrated Optimization of Road Traffic and Safety Analysis Technologies, China

ARTICLE INFO

Keywords:
Mountainous freeways
Combined alignments
Lane departure
Mixed multinomial logit model
Driving simulator

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.

1. 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).

* Corresponding author at: School of Transportation Engineering, Tongji University, Shanghai 201804, China.
E-mail address: wangxs@tongji.edu.cn (X. Wang).

https://doi.org/10.1016/j.trc.2017.11.010
Received 18 April 2017; Received in revised form 7 November 2017; Accepted 10 November 2017

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.

2. 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.

2.1. 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 and La Cava (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, $10\ \text{km/h} \leq |\Delta V85| \leq 20$ km/h; and (iii) poor, $|\Delta V85| > 20$ km/h, in which $\Delta V85$ represents the 85 th percentile of the distribution of maximum vehicle speed on the adjacent road alignment segments (MOT, 2015).

2.2. 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).