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Safety performance functions for horizontal curves and tangents on two lane, two way rural roads

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ABSTRACT

Horizontal curves on two-way, two-lane rural roads pose critical safety concerns. Accurate prediction of safety performance at these locations is vital to properly allocate resources as a part of any safety management process. The current method of predicting safety performance on horizontal curves relies on the application of a safety performance function (SPF) developed using only tangent sections and adjusting this value using a crash modification factor (CMF). However, this process inherently assumes that safety performance on curves and tangent sections share the same general functional relationships with variables included in the SPF, notably traffic volumes and segment length, even though research suggests otherwise. In light of this, the goal of this paper is to systematically study the relationship between safety performance and traffic volumes on horizontal curves of two-lane, two-way rural roads and to compare this to the safety performance of tangent sections. The propensity scores-potential outcomes framework is used to help ensure similarity between tangent and curve sections considered in the study, while mixed-effects negative binomial regression is used to quantify safety performance. The results reveal that safety performance on horizontal curves differs significantly from that on tangent sections with respect to both traffic volumes and segment length. Significant differences were also found between the safety performance on tangents and curves relative to other roadway features. These results suggest that curve-specific SPFs should be considered in the next edition of the Highway Safety Manual.

1. Introduction

Horizontal curves require drivers to deviate from their current path and thus pose a safety risk. Glennon et al. (Glennon et al., 1985) found that crash rates on two-lane rural highways are three times higher, and that roadway departure crashes are four times more frequent, on horizontal curves than along tangent road segments. A study by Hummer et al. (Hummer et al., 2010) found that crashes on horizontal curves have a fatality rate that is three times higher than the fatality rate on all roads. Collectively, these statistics indicate that accurate prediction of crash frequency along horizontal curves is required for transportation agencies to identify hazardous roadway segments. Inaccurate predictions can lead to inefficient use of resources when developing and implementing countermeasures.

The current method to estimate safety performance of horizontal curves on two-lane, two-way rural highways (TLTWRHs) requires application of a Crash Modification Factor (CMF) to adjust the crash frequency predicted from a Safety Performance Function (SPF) developed for tangent sections of similar roadway types. The SPF and CMF recommended in the Highway Safety Manual (3) are presented in Eqs. (1) and (2), respectively:

$$SPF_{TLTWRH} = (AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}) \times C_x \quad \text{and} \tag{1}$$

$$CMF_{HC,TLTWRH} = \frac{1.5 \times L_c + 80.2/R - 0.012 \times S}{1.5 \times L_c} \tag{2}$$

where SPF_{TLTWRH} represents the annual expected crash frequency for a tangent section [crashes/year]; $CMF_{HC,TLTWRH}$ is a scalar multiplier applied to SPF_{TLTWRH} that represents the CMF for horizontal curves; $AADT$ is the average annual daily traffic [veh/day]; L and L_c represent the segment and curve length, respectively [mi]; R is the horizontal curve radius [ft]; S represents the presence of a spiral transition curve; and, C_x is a calibration factor for site type x. Eq. (1) reveals that crash frequency on tangent sections of TLTWRHs are expected to increase linearly with traffic volumes and segment length, while Eq. (2) reveals that the proportional change in safety performance between horizontal curve and tangent sections is a function of only curve radius, length and presence of a spiral transition. Additional CMFs for horizontal curves of

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TLTWRHs exist as functions of curve radius or its inverse degree of curvature (Elvik, 2013; Harwood et al., 2000; Zegeer et al., 1992), vertical grade (Bauer and Harwood, 2013; Dell'Acqua and Russo, 2011), roadway functional class (Labi, 2011), driveway density (Fitzpatrick et al., 2010), and geometry of adjacent horizontal curves (Findley et al., 2012; Gooch et al., 2016; Khan et al., 2013). None of these existing CMFs include traffic volume, which implies that the relationship between traffic volume and safety performance is the same on curve and tangent road segments of TWTLRHs. So, for instance, if the HSM SPF is applied, safety performance on horizontal curves of TWTLRHs will also be expected to increase linearly with traffic volumes.

However, previous research suggests that the relationship between safety performance and traffic volumes might differ on tangent and curve sections of TLTWRHs. Persaud, Retting and Lyon (Persaud et al., 2000) developed separate SPFs for tangent and curve sections of two-lane rural roads using generalized linear modeling. These SPFs are shown in Eqs. (3) and (4), respectively:

$$CF_{tangent} = AADT^{0.914} \times L \times e^{(-7.678)} \quad \text{and} \tag{3}$$

$$CF_{curve} = AADT^{0.761} \times L^{0.648} \times e^{(-6.912+789\times\frac{L}{R})}, \text{ where} \tag{4}$$

where $CF_{tangent}$ and CF_{curve} represents annual expected crash frequency for tangent and curve segments [crashes/year], respectively; and, L and R represent the segment length and horizontal curve radius, respectively [km]. Comparison of Eqs. (3) and (4) reveals large (statistically significant) differences between the coefficients associated with traffic volumes and roadway lengths between the tangent and horizontal curve models. The traffic volume coefficient for the horizontal curve SPF is similar to those provided by a more recent study that developed SPFs for horizontal curve sections of TLTWRHs using GUIDE regression algorithms (Khan et al., 2013). These studies provide some evidence to suggest that the relationship between safety performance and traffic volumes on TLTWRHs is significantly different for curves than for tangent segments, and that curve-specific SPFs might be needed to accurately predict crash frequency on TLTWRHs. Unfortunately, the relationships in (Persaud et al., 2000) were developed using data from Ontario obtained nearly 30 years ago so it is not clear if the differences between curve and tangent safety performance with respect to traffic volumes still hold. More importantly, differences between tangent and curve sections with respect to other features, such as cross-section, roadside features, or the presence of other safety improvements (e.g., rumble strips), were not explicitly accounted for in the analysis, which might contribute to the differences in AADT coefficients.

The goal of this paper is to systematically study the relationship between safety performance and traffic volumes on tangent and horizontal curve sections of TLTWRHs to determine if curve-specific SPFs are warranted. An extensive database of state-owned, two-lane, two-way rural roads in Pennsylvania, consisting of more than 29,400 mile-years of data from 2005 to 2012, was used. The propensity scores-potential outcomes (PSPO) framework was applied to simulate a randomized experiment that reduces potential biases that might exist across the individual tangent and curve database. Separate SPFs were developed for each section type using negative binomial regression and the results compared to explore the effects of traffic volume—as well as other characteristics—on safety performance of tangents and curves. The prediction accuracy of curve-specific SPFs was compared with current crash prediction methods for horizontal curves that apply CMFs to tangent-specific SPFs. As will be shown, the results suggest that curve-specific SPFs more accurately describe safety performance of horizontal curves on two-lane rural roads and should be considered in future editions of the HSM.

The remainder of this paper is organized into four sections. The next section describes the analytical methodology used to match tangent and curve sections, estimate the corresponding SPFs and quantify prediction accuracy. The next section describes the data that were used in this study. This is followed by the modeling results and discussion of the results. Finally, concluding remarks are provided.

2. Methodology

Separate SPFs were estimated for horizontal curve and tangent segments. The propensity score matching was performed to ensure similarity between the two roadway section types. This reduced the potential for bias between the horizontal curve and tangent samples used for modeling, helping to better isolate the effect of the horizontal curve by mimicking a randomized experiment.

2.1. Propensity scores – potential outcomes framework

The propensity scores-potential outcomes (PSPO) framework is a method of causal inference used for improving quasi-experimental studies (Dehejia and Wahba, 2002). In highway safety research, PSPO has gained traction as a tool for estimating CMFs using cross-sectional data. CMFs that have been estimated using the PSPO framework include signal installation (Aul and Davis, 2006), pavement marking retroreflectivity (Karwa et al., 2011), design exceptions (Wood and Porter, 2013), intersection lighting (Sasidharan and Donnell, 2013), and lane widths on urban streets (Wood et al., 2015). The method involves using characteristics of individual observations to predict the likelihood, or *propensity*, that an observation has been treated with some feature (Rosenbaum and Rubin, 1983). These propensity scores are then used to match treated observations with untreated observations. This mimics a randomized experiment by accounting for the non-random assignment of the treatment to an observation by reducing correlation between the treatment and explanatory variables between two samples (i.e., selection bias) (Guo and Fraser, 2010; Hirano et al., 2003; Holmes, 2013). For the purposes of this study, the "treatment" is defined as the presence of a horizontal curve, because the goal is to compare safety performance between horizontal curves and tangents sections.

Three assumptions are necessary for valid causal inference when using the propensity scores-potential outcomes framework (Guo and Fraser, 2010; Hirano et al., 2003; Rubin, 1980):

1 *Stable Unit Treatment Value Assumption (SUTVA):* The application of a treatment to one entity does not affect the outcome for any other entities. SUTVA is valid in this case because the presence of a horizontal curve is based on each site's geometry and independent of the geometry of other sites.
2 *Positivity:* The probability of each site in the analysis receiving the treatment is greater than zero, meaning each site has unobserved outcomes in the other group.
3 *Unconfoundedness:* The treatment is conditionally independent of the potential outcomes for a given set of covariates. For this analysis, it is assumed that all confounding variables are measured and able to be used for the analysis.

2.1.1. Estimating propensity scores

The propensity score is the probability that an observation will receive the treatment based on known characteristics (Holmes, 2013). In this study, a binary logit model was used to estimate the propensity scores. The functional form that describes the conditional probability is shown in Eq. (5):

$$P\left(HC_i \middle| X_i = x_i\right) = E(HC_i) = \frac{e^{x_i\beta_i}}{1 + e^{x_i\beta_i}} \tag{5}$$

where HC is the presence of a horizontal curve (1 if present; 0 otherwise); x is a vector of covariates; i is the observation number; and, β is the vector of estimated coefficients. When estimating this model, variables should be considered based on their relationship to the treatment and not on statistical significance, as omitted variable bias can arise

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