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Quantifying the safety effects of horizontal curves on two-way, two-lane rural roads

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ABSTRACT

The objective of this study is to quantify the safety performance of horizontal curves on two-way, two-lane rural roads relative to tangent segments. Past research is limited by small samples sizes, outdated statistical evaluation methods, and unreported standard errors. This study overcomes these drawbacks by using the propensity scores-potential outcomes framework. The impact of adjacent curves on horizontal curve safety is also explored using a cross-sectional regression model of only horizontal curves. The models estimated in the present study used eight years of crash data (2005–2012) obtained from over 10,000 miles of state-owned two-lane rural roads in Pennsylvania. These data included information on roadway geometry (e.g., horizontal curvature, lane width, and shoulder width), traffic volume, roadside hazard rating, and the presence of various low-cost safety countermeasures (e.g., centerline and shoulder rumble strips, curve and intersection warning pavement markings, and aggressive driving pavement dots). Crash prediction is performed by means of mixed effects negative binomial regression using the explanatory variables noted previously, as well as attributes of adjacent horizontal curves. The results indicate that both the presence of a horizontal curve and its degree of curvature must be considered when predicting the frequency of total crashes on horizontal curves. Both are associated with an increase in crash frequency, which is consistent with previous findings in the literature. Mixed effects negative binomial regression models for total crash frequency on horizontal curves indicate that the distance to adjacent curves is not statistically significant. However, the degree of curvature of adjacent curves in close proximity (within 0.75 miles) was found to be statistically significant and negatively correlated with crash frequency on the subject curve. This is logical, as drivers exiting a sharp curve are likely to be driving slower and with more awareness as they approach the next horizontal curve.

1. Introduction

Highway safety is a significant concern for transportation professionals in the United States. Despite a steady decline in highway fatalities over recent years, the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) reported over 32,000 fatalities resulting from nearly 30,000 fatal crashes on US roadways in 2011 (National Highway Traffic Safety Administration, 2014). Over 50% of traffic fatalities occur in rural areas, particularly on two-lane rural roads (National Highway Traffic Safety Administration, 2013), and horizontal curves appear to be one of the most hazardous locations on these facilities. In fact, more than 25% of all fatal crashes in the United States are related to horizontal curves (Federal Highway Administration, 2014b). This is disproportional to the actual number of crashes observed at these locations; e.g., the NHTSA data shows that 8386 (21.6%) traffic fatalities in 2012 occurred when a vehicle was negotiating a horizontal curve, although horizontal curve crashes accounted for only 5.2% of total crashes. Horizontal curves pose a significant safety risk due to the differentiation in roadway alignment, which forces drivers to deviate from their original path. Failure to adjust for this differentiation can lead to vehicles leaving their lane and either colliding with an oncoming vehicle or departing the roadway altogether, both of which have high potential for a severe crash. Thus, the most typical crash types on horizontal curves are single-vehicle roadway departure crashes (also known as run-off road crashes, ROR) and head-on crashes (Torbic et al., 2004).

Unsurprisingly, much attention and effort has been placed on developing countermeasures to reduce crash frequency and severity at horizontal curves on two-lane rural roadways. Volume 7

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of NCHRP Report 500 summarizes many curve safety treatments, including improved signage and delineation, high-friction pavements, and wider clear zones (Torbic et al., 2004). The report suggests treating curve safety as a two-pronged effort that requires treatments to:

1. Keep vehicles from departing their lane, crossing the centerline or leaving the roadway; and
2. Eliminate obstacles to reduce the risk of a vehicle striking an object once a vehicle has left the roadway.

Countermeasures to satisfy these objectives are generally costly to implement. Unfortunately, most transportation agencies operate under a restrictive budget and are faced with the daunting task of identifying the most effective ways to utilize available funding to improve traffic safety on an entire roadway network. For states with a highly curvilinear network, such as Pennsylvania, a significant challenge becomes identifying specific curves that have the potential for safety improvement. Implementing some of the countermeasures described above will be most effective if deployed at locations with the greatest potential for safety improvement. These sites may be identified using the crash frequency prediction tools in the Highway Safety Manual (HSM) via Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs). Unfortunately, a review of the Federal Highway Administration's (FHWA) CMF Clearinghouse reveals a lack of quality CMFs for horizontal curves on two-lane rural roads. Although several high-quality CMFs exist for the implementation of specific countermeasures on horizontal curves (e.g., rumble strips on horizontal curves), CMFs for horizontal curve safety performance (as opposed to tangent segments) on two-lane rural roads are all rated with 3 or fewer stars on a 5-star scale due to small datasets, outdated methodologies (such as simple cross-sectional analyses), and no standard errors provided. Further, recent research has suggested that the safety performance of horizontal curves is related to the presence of adjacent horizontal curves (Findley et al., 2012; Khan et al., 2013), but these impacts are not well understood.

In light of this, the objective of this paper is to develop a high-quality CMF for horizontal curves that uses a statistical causal inference technique (the propensity scores-potential outcomes method) and overcomes the limitations of existing CMFs. In addition, the impacts of adjacent curves on horizontal curve crash frequency are explored in more detail using a cross-sectional regression model of curve data.

The remainder of this article is divided into five sections. First, CMFs for horizontal curvature in the literature are reviewed. This is followed by a discussion of the methodology used to estimate the CMFs in the present study, along with the empirical setting. The results are presented and discussed and, finally, conclusions drawn.

2. Horizontal curve CMFs

SPFs provided in the HSM typically assume roadway segments are tangent sections as a baseline condition. Therefore, expected crash frequencies must be modified by a CMF to predict crash frequencies on horizontal curves. The existing CMF for horizontal curves on two-lane rural roads was developed by (Harwood et al., 2000), which used expert judgment to modify the statistical models estimated in (Zegeer et al., 1992). The resulting CMF is:

$$\boldsymbol{CMF} = \frac{1.55 \times \boldsymbol{L_C} + 80.2/\mathrm{R} - 0.012 \times \boldsymbol{S}}{1.55 \times \boldsymbol{L_C}} \quad (1)$$

where:

CMF — Crash Modification Factor for the horizontal curve,
L_C — length of curve [miles],
R —curve radius [feet], and
S —presence of a spiral transition on the curve [1 if present, 0.5 if only on one end; 0 otherwise].

Although included in the HSM, this CMF is not rated in the FHWA *CMF Clearinghouse* (Federal Highway Administration, 2014a), which serves as the most comprehensive repository of CMFs for use by transportation professionals and provides an indication of the reliability of the CMFs. Two factors contribute to the lack of quality rating of this CMF: (1) the original CMF reported in (Zegeer et al., 1992) did not provide a standard error; and, (2) it was then modified based on expert judgment. Further, the data used by (Zegeer et al., 1992) are more than 20 years old, meaning that driving conditions are potentially different now than described by the data used in this study. For example, the fleet of vehicles and population of drivers have changed significantly during this time.

Other CMFs for horizontal curves on two-lane rural roads are provided in the *CMF Clearinghouse* but these are generally low quality. In fact, none of the CMFs for horizontal curves on two-lane rural roads are provided the highest quality ratings of 4- or 5-stars, while 43 CMFs are rated 3-stars or less. Some reasons provided on the CMF Clearinghouse for the low scores include lack of reported standard error (Harwood et al., 2000; Labi, 2011), failure to report traffic volumes (Jang et al., 2010), and limitation of data sources (Acqua and Russo, 2011; Bauer and Harwood, 2013).

Despite the lack of high-quality CMFs for horizontal curves on two-lane rural roads, there seems to be general agreement on how horizontal curvature impacts safety at these locations. A synthesis of studies of horizontal curve safety in ten countries on three continents (North America, Europe, and Australia) revealed a consistent inverse relationship between radius of curvature and safety at all locations (Elvik, 2013). That is, crash frequency generally increases as the radius decreases, as expected from intuition and from Eq. (1). For the majority of the studies, the relative crash rate on curves increases rapidly as curve radius decreases below 200 m (~656 ft). For radii larger than 200 m, curves seem to have a much smaller impact on safety.

Many existing studies have examined the interaction of horizontal curvature with other geometric features, such as: vertical alignment (Acqua and Russo, 2011; Bauer and Harwood, 2013), functional classification of the roadway (Labi, 2011), and driveway density (Fitzpatrick et al., 2010). Two pioneering efforts have recently attempted to examine how the presence of nearby horizontal curves impacts safety at a particular curve location. (Khan et al., 2013) developed safety models for horizontal curves on undivided rural roads of the Wisconsin State Trunk Network using GUIDE (Generalized, Unbiased, Interaction Detection and Estimation). This regression tree analysis revealed that fewer crashes were expected on curves with shorter upstream tangent sections. Perhaps one reason for this finding is the issue of driver expectancy: drivers traveling on roadways with curves in closer proximity are more expectant of curves and are more likely to traverse them safely. (Findley et al., 2012) attempted to model curve safety as a function of the spatial relationship between consecutive curves using data from two-lane rural roads in North Carolina. The authors defined the nearest adjacent curve (in either the upstream or downstream direction) as the proximal curve and the nearest adjacent curve in the other direction as the distal curve. Negative binomial regression was then used to model crash frequency as a function of curve features and distance to distal and proximal curves. The models revealed that crash frequency increased as the distance to proximal and distal curves increased up to some point. However, the authors used data from just two, two-lane rural roadways, so the resulting model suffers from small sample size and thus the results may not be applicable to other roadways. Furthermore, both of these studies considered only the presence of adjacent curves and failed to consider the geometric features of the adjacent curves