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Examining vehicle operating speeds on rural two-lane curves using naturalistic driving data

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ABSTRACT

Horizontal curves have been shown to exhibit crash rates significantly higher than comparable tangent segments. Extensive research has investigated the causes of crashes on horizontal curves, particularly the curve navigation process and driver speed selection. Research in this area has generally been limited by the nature of the data, which is often inhibited by practical constraints as to the number of locations and drivers that can be observed. This study overcomes these hurdles through the use of naturalistic driving data, providing insights on how drivers navigate and react to curves on rural two-lane highways. Nearly 10,000 vehicle traces were collected from 202 drivers on 219 horizontal curves as a part of this study. All driving traces were collected on rural two-lane highways with prevailing posted speed limits of 45 mph or 55 mph, as well as a diverse range of curve advisory speeds. Regression models are estimated via generalized estimating equations to discern those factors affecting mean speeds on curves. A log-linear relationship was found between curve radius and mean vehicle speed, with speeds relatively stable on radii of 900–1000 ft. or more, decreasing more rapidly as radii decreased below this range. Drivers were found to reduce speeds when curve advisories were present, but the magnitude of these reductions was much less than suggested by the advisory signs. Speeds were significantly lower when a W1-6 curve arrow sign was present adjusting for the curve radius. There were also some differences in speeds based on driver age and gender. Ultimately, this paper provides insights into driver curve navigation and demonstrates the potential of high-fidelity naturalistic driving data to assess speed management and geometric design on horizontal curves.

1. Introduction

Prior research has demonstrated that crash rates are three to four times higher on horizontal curves than similar tangent segments (Glennon et al., 1985; Hummer et al., 2010). A total of 7911 fatal crashes were reported on horizontal curves in the U.S. in 2015 and most of them occurred in rural area (NHTSA, 2017). Speeding has long been recognized as one of the most important contributing factors to crashes on horizontal curves (Fitzpatrick et al., 2000; Zegeer et al., 1992).

To this end, the ability to predict the operating speed on horizontal curves plays a critical role in assessing roadway design consistency, which refers to the degree to which roadway design aligns with drivers' expectations. Under ideal conditions, the speed limits at horizontal curves should be established such that they are approximately equal to the 85th percentile of vehicle operating speeds. Design consistency is another topic that has been studied extensively (Fitzpatrick et al., 2000; Lamm et al., 1988; Camacho-Torregrosa et al., 2013; and Wu et al., 2013). Inconsistency between the design speed and operating speeds has been shown to result in heightened crash risk (Anderson and Krammes, 2000; Donnell et al., 2009; Gibreel et al., 1999; Montella and Imbriani, 2015). Historically, research in this area has examined operational characteristics along curves using speed measurements conducted at point locations using devices such as pneumatic tubes or radar (Bonneson and Pratt, 2009; Fitzpatrick et al., 2000). However, this form of data collection introduces practical limitations as to the number of curve locations that can be studied. Furthermore, such data collection methods inhibit access to potentially important characteristics related to the driver and the vehicle.

With the recent development of in-vehicle data collection technologies and advances in high-performance computing, large-scale naturalistic driving study datasets create an opportunity to overcome these barriers and allow for a more rigorous assessment of driver behavior on horizontal curves under real-world conditions. Naturalistic driving research provides an unobtrusive observation method allowing researchers to study daily driving behaviors under natural settings without any experimental control (Dingus et al., 2014; PROLOGUE,

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2009; Schagen and Sagberg, 2012). The second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) involved the collection of extensive data from approximately 3150 drivers over a three-year period from October 2010 to November 2013. Study participants were sampled from six states, including Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. Numerous data elements were collected about the study participants, in addition to high-fidelity information from in-vehicle cameras and sensors that documented the participants' daily driving activities. The detailed information provides opportunities for safety analyses that are not possible under traditional safety study frameworks.

The objective of this paper is to examine vehicle speed on rural two-lane horizontal curves as a function of driver characteristics, roadway geometry, posted speed limit, and the presence of supplemental traffic control devices (e.g., advisory speeds, chevrons) using the SHRP2 NDS data. The study focuses on those curves where the prevailing statutory (posted) speed limit is set at either 45 mph or 55 mph. In this paper, posted speed limit refers to the regulatory speed limit sign, which means driver should never exceed this speed limit under any circumstances and the sign has white background. In contrast, advisory speed limit is the recommended speed limit which is not enforced as posted speed limit. The sign has yellow background and suggests drivers to reduce speed for unsafe conditions such as sharp curve radius ahead and bad weather conditions.

This paper first briefly reviews the extant research literature focused on driver speed selection on horizontal curves in Section 2. Section 3 provides a discussion of data collection, aggregation, and post-processing procedures. Section 4 provides an overview of the statistical methods, which involved the estimation of generalized estimating equations (GEE). Section 5 presents the analysis results, along with a discussion of key findings and design implications, including insights as to the relationship between driver speed selection and curve geometry. Additional information is provided as to lessons learned from working with the naturalistic driving study data

2. Literature review

Speeding has been identified as one of the most important contributing factors to roadway departure crashes on horizontal curves (Fitzpatrick et al., 2000; Zegeer et al., 1992). Given this relationship, a substantial amount of research has focused on better understanding how vehicle speeds vary based on roadway geometry. Collectively, these studies have found curve radius, deflection angle, curve length, superelevation and upstream tangent speeds to be the primary factors influencing driver speed selection on horizontal curves (Bonneson and Pratt (2009); Fitzpatrick et al., 2000; Hallmark et al., 2013; Hauer, 1999; Krammes et al., 1995; Lamm et al., 1988; Montella and Imbriani, 2015; Schurr et al., 2002).

The basic curve equation from the American Association of State Highway and Transportation Officials' *A Policy on Geometric Design of Highways and Streets* relates vehicle speed to curve radius, superelevation rate, and side friction demand as shown in Eq. (1):

$$V = \sqrt{15R\left(\frac{0.01e + f}{1 - 0.01ef}\right)} \tag{1}$$

where:

V = vehicle speed (mph);
R = curve radius (ft);
e = rate of roadway superelevation (percent); and
f = side friction demand factor (or lateral acceleration).

From a design perspective, appropriate values are selected for design speed, superelevation, and side friction in order to determine a minimum curve radius. In practice, operating speeds are dictated by driver steering effort, tire and pavement conditions, and other factors. Several studies have been conducted to predict operating speeds based on curve geometry and roadway characteristics.

Bonneson and Pratt (2009) predicted vehicle speeds on 55 horizontal curves on rural two-lane highways. A total of 6677 passenger cars were observed and a speed prediction model was developed based on curve radius, curve length, width of traffic lanes and shoulders, superelevation, and vertical grade. The results showed that drivers tended to tolerate higher rates of lateral acceleration on curves with smaller radii.

The tangent distance between consecutive curves was found to have a significant impact on vehicle speed in a study Findley et al. (2012), which examined spatial relationships between successive curves in consideration of factors such as tangent distance, curve direction, radius, and length. The results showed upstream tangent distance to the adjacent curve to be a reliable indicator of crash rates.

Fitzpatrick et al. (2000) developed a regression model for vehicle speeds as a function of roadway geometry along rural two-lane highways using data collected from 176 sites across six states, including Minnesota, New York, Pennsylvania, Oregon, Washington, and Texas. More than 100 observations were collected at each site, with speed data collected by a combination of radar guns and on-pavement piezoelectric sensors. No significant speed reductions were found when the curve radius was larger than 800 m (2625 ft.) and the study also did not find any significant impacts of spiral curves on 85th percentile vehicle speeds.

Schurr et al. (2002) examined the relationship of curve design, operating speed, and posted speed limit at 56 sites in Nebraska. Speed data were collected by detectors installed at the entry and mid-point of the curves. Several linear regression models were estimated to predict vehicle speeds based on a number of explanatory variables. The study found vehicle speeds were highly correlated with deflection angle, curve length, posted speed limit, vertical grade, and annual average daily traffic. Drivers were only found to reduce their speeds when curve radius was less than 350 m (1148 ft.).

Bella, 2013 assessed driver behavior on curves with different roadway configurations. The results showed behavior was influenced by cross-sectional characteristics and geometric design elements, but not by the roadside environment (e.g., presence of guardrail) or the vehicle's lateral position within the curve. This study also showed drivers had a tendency to cut the curves (i.e., encroach on the centerline or edgeline) on both left-turn and right-turn curves.

Anderson and Krammes (2000) evaluated the relationship between speed reductions and crash rates on 1126 curves. Speed reduction was calculated as the difference between the 85th percentile speeds on the preceding tangent section and the midpoint of the curve. The results showed that crashes generally increased when there was a more pronounced reduction between the tangent and curve speeds.

Prior research has also included evaluations of different types of speed reduction countermeasures on curves. For example, Charlton (2007) tested two groups of treatments in a driving simulator. Chevron signs and rumble strips were found to reduce vehicle speeds effectively. Chevron is the yellow arrow signs that installed on curves to help show the delineation of the curve. In contrast, advanced curve signs and advisory speed warnings were found to have little impact on vehicle speeds.

Table 1 provides a summary of the aforementioned regression models relating operating speeds to various geometric characteristics. A majority of the studies found curve radius, curve length, deflection angle, and vertical slope to have significant impacts on vehicle speeds during curve navigation. As the data for these studies were generally collected using on-road or roadside equipment, there is limited knowledge as to the degree to which speed selection is affected by other potentially important factors such as the presence of lead vehicles, as well as how speeds vary within and between individual drivers. In addition, the analysis of drivers at specific curves also introduces sample size limitations, which introduce potential concerns when extrapolating results outside of the sample locations. This study addresses