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Crashes and near-crashes on horizontal curves along rural two-lane highways: Analysis of naturalistic driving data

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A B S T R A C T

Prior research has shown the probability of a crash occurring on horizontal curves to be significantly higher than on similar tangent segments, and a disproportionally higher number of curve-related crashes occurred in rural areas. Challenges arise when analyzing the safety of horizontal curves due to imprecision in integrating information as to the temporal and spatial characteristics of each crash with specific curves. The second Strategic Highway Research Program (SHRP 2) conducted a large-scale naturalistic driving study (NDS), which provides a unique opportunity to better understand the contributing factors leading to crash or near-crash events. This study utilizes high-resolution behavioral data from the NDS to identify factors associated with 108 safety critical events (i.e., crashes or near-crashes) on rural two-lane curves. A case-control approach is utilized wherein these events are compared to 216 normal, baseline-driving events. The variables examined in this study include driver demographic characteristics, details of the traffic environment and roadway geometry, as well as driver behaviors such as in-vehicle distractions. Logistic regression models are estimated to discern those factors affecting the likelihood of a driver being crash-involved. These factors include high-risk behaviors, such as speeding and visual distractions, as well as curve design elements and other roadway characteristics such as pavement surface conditions. This paper also discusses limitations and lessons learned from working with the SHRP 2 NDS data.

1. Introduction

The safety of horizontal curves has drawn significant interest in the research literature (Bonneson et al., 2009; Felipe et al., 2007; Schurr, McCoy, Pesti, & Huff, 2002). Curves are shown to experience disproportionately higher crash rates than similar tangent roadways. The Federal Highway Administration (FHWA) notes that crash rates on horizontal curves are three times higher than crash rates on tangent segments (FHWA, 2014). A total of 7911 fatal crashes occurred on horizontal curves in 2015 (National Highway Traffic Safety Administration (NHTSA), 2015). These types of crashes account for about one quarter of all motor-vehicle fatalities annually in the United States. The majority of curve-related crashes occur in rural areas, especially on rural two-lane highways.

An extensive number of prior studies have sought to understand the relationship between crash risk and horizontal curve characteristics. This includes various studies that have investigated the relationships between crash frequency or severity and curve characteristics, such as radius/degree of the curve and the curve length (Council, 1998; Khan, Bill, Chitturi, & Noyce, 2013; Schneider, Zimmerman, Savolainen, & Moore, 2010; Suh, Park, Park, & Chon, 2006; Torbic et al., 2004). Collectively, research has shown crashes occur more frequently and more severely on curves. Additional research has examined how these increased crash risks are affected by drivers' curve negotiation behavior from a human factors perspective. The research has shown drivers to have difficulty in effectively recognizing the presence and sharpness of upcoming curves due to visual distortion (Charlton, 2007; Hassan & Easa, 2003; Hong, Iwasaki, Furuichi, & Kadoma, 2006; Kandil, Rotter, & Lappe, 2010; Mars, 2008; Shinar, Mcdowell, & Rockwell, 1977; Suh et al., 2006; Wooldridge, Fitzpatrick, Koppa, & Bauer, 2000; Zakowska, 2000). Additional studies have focused on driver speed selection while navigating curves with various geometric characteristics. The research has shown mean and 85th percentile speeds to be impacted by the curve radius, the curve length, the tangent distance, and the speed limits. (Bella, 2007; Bonneson & Pratt, 2009; Collins, Fitzpatrick, Bauer, & Harwood, 2007; Donnell, Ni, Adolini, & Elefteriadou, 2001; Felipe & Navin, 2007; Fitzpatrick et al., 1999; Montella, Pariota, Galante, Imbriani, & Mauriello, 2014; Schurr et al., 2002). Several studies have also examined vehicle lateral position during curve navigation. These studies have contrasted patterns of curve trajectories, showing drivers to exhibit curve cutting, swinging, drifting, and correcting in contrast to ideal behavior (Abele & Møller, 2011; Bella, 2013; Bertola, Balk, & Shurbutt, 2012; Charlton, 2007; Gunay & Woodward, 2007; Hallmark,

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2014; Reymond, Kemeny, Droulez, & Berthoz, 2001; Spacek, 2005; Suh et al., 2006; Taylor, Abu-Lebdeh, & Rai, 2005).

While above-mentioned studies have provided important insights into the factors affecting safety on horizontal curves, some important gaps remain in the literature. While driver behavior has been shown to contribute to >90% of all crashes (NHTSA, 2008; Rumar, Evans, & Schwing, 1985; Salmon, Regan, & Johnston, 2005; Spainhour, Brill, Sobanjo, Wekezer, & Mtenga, 2005; Treat et al., 1979), research has been somewhat limited as to how curve geometries affect driver behavior and crash risk at a fine level of detail. For example, much of the extant research in this area focuses on analyses of police-reported crash data. However, crash report forms often have limited information as to driver behavior during the period immediately preceding a crash. This is exacerbated by the fact that crash reports are difficult to integrate with associated roadway characteristics due to the lack of temporal and spatial accuracy. Driver behavior on curves has also been assessed through driving simulator studies, though these studies can be criticized as to their validity in replicating real-world behaviors (Casali & Frank, 1986; Fisher, Rizzo, Caird, & Lee, 2011).

Naturalistic driving studies (NDS) have emerged as an innovative means to observe real-world driving behavior with the potential to provide important insights that are not possible through alternative study designs. NDS provides an unobtrusive observation method to study driver behavior in natural settings without any experiment controls (Dingus et al., 2014; PROLOGUE, 2009; Schagen & Sagberg, 2012). Such studies allow researchers to observe how drivers naturally interact with other vehicles, roadway characteristics, and traffic environments.

The study described in this paper utilizes data collected as a part of the NDS conducted through the second Strategic Highway Research Program (SHRP2) to better understand the role of driver behavior in crash and near-crash events. The SHRP2 NDS involved continuous monitoring of more than 3000 drivers, resulting in unparalleled information as to how driver behavior varies with respect to the driving environment, providing unique opportunities to better understand how driver behavior and other factors affect crash risk. The SHRP2 NDS provides a variety of pre-crash information that is not available in police-reported crash data. For example, details as to in-vehicle distractions can be discerned from in-vehicle driver face cameras. External factors, such as traffic flow and pavement conditions, can also be determined from the accompanying forward road-view video. Detailed vehicle information is also available through 10-Hz vehicle Controller Area Network (CAN) bus signals, allowing for determination of speed, acceleration, yaw rate, and other kinematic data. These critical variables are generally difficult to collect using traditional study designs. Ultimately, the study demonstrates how NDS data can be exploited to examine safety issues on rural two-lane curves.

2. Data

2.1. SHRP2 NDS overview

The SHRP2 NDS resulted in the collection of detailed data from more than 3000 drivers from October 2010 to November 2013 (Dingus et al., 2014). More than 5 million trips and 1 million h of driving data were collected across study sites in six states in the United States, including Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington.

The data collected as a part of the SHRP2 NDS includes extensive information detailing the drivers and vehicles involved in the study. In addition, summary information is provided for a sample of the 5 million trips that were conducted over the course of the NDS. This includes general information as to roadway and traffic characteristics, as well as aggregate-level summaries of operational data (e.g., speed, acceleration) and driver behavior (e.g., seatbelt use, cell phone use) over the course of each trip. More detailed information is provided for specific events, which are vehicle traces of approximately 20-second in length. Trips may include multiple events, with each event being classified as a crash, near-crash, or baseline event. These events are defined in Table 1.

Table 1
Definitions of event types (SHRP2 NDS website, 2015).

Event type	Description
Crash	*Any contacts that the subject vehicle has with an object, either moving or fixed, at any speed in which kinetic energy is measurably transferred or dissipated. Also includes non-premeditated departures of the roadway where at least one tire leaves the paved or intended travel surface of the road.*
Near-crash	*Any circumstance that requires a rapid evasive maneuver by the subject vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. Near Crashes must meet the following four criteria: 1) Not a Crash; 2) Not pre-meditated; 3) Evasion required; 4) Rapidity required.*
Safety critical event	*The combination of all crash and near-crash events were referred as safety critical event in this study.*
Baseline	*An epoch of data selected for comparison to any of the conflict types listed above rather than due to the presence of conflict. For SHRP2, these baselines are 21 s long and were randomly selected with a goal of 20,000 baselines, a minimum of 1 baseline per driver.*

Given the relatively small number of crash events occurring along horizontal curves on two-lane highways within the NDS data, both crash and near-crash events were combined and are classified as "safety critical events" in the remainder of this paper. Several prior studies have shown near-crash events to be a reasonable crash surrogate in naturalistic driving studies (Wu, Aguero-Valverde, & Jovanis, 2014; Wu & Jovanis, 2012, 2013). In addition to the safety critical events, a sample of baseline events were included as a control to represent normal driving activities. The baseline events were sampled from normal driving activities in proportion to the number of miles driven by each driver over the course of the study period. An alternative is to use lane encroachment as a surrogate for lane departure crashes, but the lateral position measurement was found to contain large number of missing values and outliers, so lane encroachment is not used in this study.

In addition to the general driver, vehicle, trip, and event information described previously, forward roadway-view videos were also utilized to examine pre-crash scenarios for better understanding the causes of crash and near-crash events. The forward roadway view videos were manually reviewed by our own research team to extract roadway and traffic-related information.

Safety critical and baseline events are available on the SHRP2 InSight website (https://insight.shrp2nds.us/home), which was developed and is hosted by VTTI. Data reductionists at the Virginia Tech Transportation Institute (VTTI) manually coded the event detail data. Over 76 variables were reduced and are available including crash type, severity, driver actions, presence of passengers, environmental factors, event narrative, etc. A brief video clip of the forward roadway is included along with graphical display of select vehicle kinematics (i.e., speed, acceleration, distance into trip, wiper status). High-level roadway and traffic characteristics are also included such as intersection type, traffic control, alignment, and level of service. This information is provided in an Event Detail Table, which can be sorted using various filters such as the type of roadway.

Filters were used to first select roadway departure events. This was accomplished using incident type (i.e., road departure left) or precipitating event (i.e., subject over left lane line). A total of 1631 roadway departure crashes and near-crashes were identified from the Event Detail Table. Next safety critical events were filtered by setting number of lanes (i.e., Lanes = 2). No variable exists which specifically identifies an event as rural so the variable for locality was set to "open country" or "open residential." Presence of a curve was identified through a variable for alignment which indicated curve left or curve right.

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