Driver performance at horizontal curves: Bridging critical research gaps to increase safety

Alyssa Ryan[1], Emily Hennessy, Chengbo Ai, Wooseong Kwon, Cole Fitzpatrick, Michael Knodler

Department of Civil & Architectural Engineering & Mechanics, University of Arizona, 324F Civil Engineering Building, 1209 E. 2nd Street, Tucson AZ, USA 85721, alyssaryan@arizona.edu
Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 142 Marston Hall, 130 Natural Resources Road, Amherst, MA, USA 01003, ehennessy@umass.edu
Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 142A Marston Hall, 130 Natural Resources Road, Amherst, MA, USA 01003, chengbo.ai@umass.edu
Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 34 Marston Hall, 130 Natural Resources Road, Amherst, MA, USA 01003, wkwon@umass.edu
Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 128A Marston Hall, 130 Natural Resources Road, Amherst, MA, USA 01003, cfitzpat@umass.edu
Department of Civil and Environmental Engineering, University of Massachusetts Amherst, 214B Marston Hall, 130 Natural Resources Road, Amherst, MA, USA 01003, mknodler@umass.edu

Abstract

Horizontal curve segments are locations of critical safety concern given their high crash rates. Extensive research has identified that behavioral factors influence the occurrence of such crashes. However, the most beneficial countermeasure for a curve is not always implemented or is implemented inefficiently due to a lack of full understanding of driver behavior at curves compared to tangent roadway segments. The aim of this research is to identify the conditions that impact safety at curve locations compared to tangent segment locations. This is completed through a literature review of current research relating to curve safety issues and a safety analysis of curve and tangent segment data using a novel dataset that includes curve data throughout a region. The results of this study revealed several factors that cause horizontal curves to have a higher crash rate related to driver performance, including the increased task load and demand required at curve segments compared to tangent segments, and that horizontal curve segments have an increased rate of crashes per mile with an increasing AADT compared to tangent segments. Further, horizontal curve segments along one-way operations are of increased safety concern for drivers compared to tangent segments and two-way operations. The results of this study present the conditions that can be more carefully considered in future studies and analyses to consider the human factor cause behind the increased safety issue at curve segments.

Keywords: horizontal curve; crash rate; countermeasure development; traffic volume

[1] * Corresponding author. Tel.: +1 520-626-8462
E-mail address: alyssaryan@arizona.edu

1. Introduction

Horizontal curves have disproportionately high crash rates and have been recognized as high safety risk locations for decades [1, 2]. In 2019, an estimated 36,120 people were killed in motor vehicle crashes on U.S. roadways [3]. Horizontal curves alone are typically associated with over 25 percent of all fatal crashes on roadways [4]. Extensive research has identified that behavioral factors influence the occurrence of such crashes, e.g. inappropriate speed monitoring, poor lane positioning, etc. [5, 6]. Curve negotiation requires increased attention, creating a higher driver workload [7]. To assist drivers in these situations, perceptual countermeasures can offer guidance, leading drivers to anticipate a curve more accurately. However, the most beneficial countermeasure for a curve is not always implemented or is implemented inefficiently due to a lack of full understanding of driver behavior at curves compared to tangent roadway segments. The aim of this research is to identify the factors that impact safety at curve locations compared to tangent segment locations through a thorough review of current literature relating to curve safety issues and a new safety analysis of curve and tangent segment data using a novel dataset that includes curve data throughout an expansive region.

1.1 Horizontal Curve Safety

Horizontal curves are curves that “change the alignment or direction of the road" [8]. Safety is a significant concern at horizontal curve locations, especially in rural areas. Horizontal curve segment crashes have an average fatality rate more than three times the fatality rate of all crashes on all roads and are estimated to account for nearly 25 percent of all people who die each year on U.S. roadways [4, 9]. The safety risk on horizontal curves has been found to be influenced by a number of factors, including the deflection angle, super-elevation, road surface friction, distance to and radius of adjacent curves, use of signage, and radius [10]. Further, driver performance along horizontal curves in varying roadway environments is directly connected to this issue [2, 7].

Several variables of curves influence crash rates. Elvik (2019) reviewed previous studies and found that the shorter the mean distance between horizontal curves of a given radius, the lower the crash rate [10]. Further, neighboring curves of sharper curves, or those with a smaller radius, were found to be associated with a lower crash rate than those neighboring curves with a larger radius.

1.2 Road Environment & Safety

In driving environments, consistency is linked with safety, as sudden changes in roadway characteristics lead to crashes from speeding errors or driving maneuvers. It has long been established that consistent design improves the safety and flow of traffic operations [12], and the most consistent sections of roadways are the straight tangent segments between horizontal and vertical curves.

Curved sections of roadway represent a higher risk to drivers due to increased vehicular centripetal forces, increased driver demand, and roadway characteristics [9]. Because of these factors, crash rates on horizontal curves are 1.5 to 4 times higher than those of tangent sections [13]. An analysis of 51,000 horizontal curves across North Carolina concluded that crashes resulting in severe injury or fatalities were overrepresented along horizontal curves when compared to tangent sections. These more severe outcomes are linked to the types of crashes which are more prevalent along horizontal curves, such as crashes along grades, rural locations, inclement weather, fixed object crashes, and those with overturned vehicles [9]. Horizontal curves are also associated with roadway departure crashes, which Glennon et al. (1985) noted occur on two-lane rural highways four times as frequently as on comparable tangent segments [14].

Tangent roadway sections can be described as independent or non-independent based on which sequences control the design process. Independent tangents are controlled by the tangent-to-curve sequence, where non-independent tangents are controlled by the curve-to-curve sequence [15]. Sight distance, tangent length, and curve spacing all factor into the independence of a tangent section, while the safety performance of horizontal curves differs with respect to traffic volumes, segment lengths, and additional roadway features [16]. These tangent curve elements are critical to driver behavior and speed through horizontal curves. Wood and Donnell (2014) observed that insufficient driver sight distance is more probable on horizontal curve approaches than inside the curves themselves, and concluded that horizontal sight lines should be considered beyond the curves [17]. These studies show that while tangent sections are safer than horizontal curves, their characteristics have a significant effect on the safety of the curves they connect.

Gooch et al. (2018) completed an extensive analysis of two-lane two-way rural roads which concluded that applying crash modification factors to tangent sections does not adequately model the safety performance of horizontal curves [16]. This conclusion indicates that the safety performance of tangents and horizontal curves are not yet defined with proper specificity, and that research is needed to better understand which performance factors of horizontal curves increase their risk.

1.3 Risk and Demand while Driving

Several theories explain why people adjust their behavior while driving. Jiang et al. (1992) provides a review of many of these theories [18]. The theory of risk homeostasis is of particular concern at horizontal curve locations. This theory suggests all people adjust their behavior in response to their desired level of perceived risk [12, 13]. At any moment in time, Widle (1982) suggests a road user perceives a certain level of subjective risk and compares it with the level that they would like to accept, or their “target risk." If the level of risk is perceived to be higher or lower than their target level of risk, the individual will attempt to eliminate this discrepancy [19]. In these instances, the way in which a driver behaves and performs on the road is affected by three skills: perceptual skills determine the level of subjective risk compared to objective risk, decisional skills determine what should be done to produce the desired adjustment, and vehicle handling skills determine if the road user has the ability to carry out what should be done for the desired adjustment [19]. These skills can differ depending on the driver. For example, young/novice drivers tend to overestimate their skill level [21–23]. Further, overconfident drivers have shown to adapt their driving behavior less in complex traffic situations than other drivers and thus, are less adequate in their adaptation in new environments [24].

Wilde (1982) originally assumed that these feelings of risk were the same as drivers' estimates of the probability of crashing. However, Fuller (2005) concluded these two were not the same. Drivers may target a level of risk, but that is not to say they target a level of crash involvement [25]. The two statistical risks will only begin to converge when task demand approaches capability and the driver speculates there will be no unexpected increase in demand and no unexpected decrease in capability [25]. This is due to the relationship between feelings of risk and the perception of task difficulty. As a driving task, or vehicle handing task, becomes more difficult, the margin between what must be done, and a driver's capability shrinks. The driver then becomes closer to losing control [25]. Thus, if a driver feels their task difficulty is increasing and they are aware of their capabilities, then their feeling of risk also increases.

Driver task, or vehicle handling, demand is affected by a number of interacting elements. Environmental factors such as visibility, road alignment, road signs, road surfaces, curve radii, and so on, impact demand. Other road users and operational features of vehicles also impact demand. Further, the elements that drivers have direct control over impact their demand, such as their speed and trajectory. Thus, in driving situations where a change of safety needs to be evaluated due to these changing factors, a driver is tasked with determining their perceived risk, deciding how to produce their desired risk adjustment, and carrying out the adjustment. One common circumstance of change for drivers is during the transition from a tangent section to a curved section. McDonald and Ellis (1975) found that negotiating curves requires more cognitive demand than tangent sections [7]. Thus, during the transition, drivers need to evaluate geometric factors before adapting their speed and steering to conform to the new conditions.

1.4 Driver Performance and Behavior along Horizontal Curves

Driver performance on horizontal curves has been shown to be influenced by a number of factors including the perceived level of risk, curve radius, and tangent length. Curve negotiation requires that drivers anticipate the curve through the adjustment of their speed and lane position to accommodate the severity of the curve [26]. This event requires enhanced attention compared to tangent sections, given the need for drivers to evaluate geometric factors before adapting their speed and steering to conform to the new roadway condition [7]. Speeds have been found to be underestimated by drivers at curves [27], particularly during the approach section [28].

Edge lines along curves have been shown to visually guide driver steering and reduce crashes [29, 30]. However, drivers still continue to travel differently along curves than tangent sections with edge lines. In a simulation study by Coutton-Jean et al. (2009), drivers did not remain in the middle of the lane during curve negotiation, but rather traveled on the outside of the lane on their approach to the curve and then cut into the curve, passing through the middle at the entry of the curve [29]. These “cutting" paths have been reported by other studies and it is theorized that such a trajectory allows drivers to maintain a higher speed through the curve [31].

Several studies have found that driver speed on horizontal curves is influenced by the radius. Research by Calvi (2015) found that drivers drove at higher average speeds at wider curves [32]. Montella (2015) found that on smaller radius curves, deceleration ended closer to the center of the curve, while acceleration started closer to the end of the curve [33]. When the curve radius was increased, the end point of deceleration was further towards the start of the curve, while the beginning of acceleration began further towards the center of the curve [33]. Bella (2014b) found the speed at the curve midpoint was affected solely by the radius, not by the curve direction [34].

While previous studies have the ability to offer insight into the expected performance of drivers at horizontal curves, it is critical to acknowledge that horizontal curve speeds can be impacted by their location. In challenging local or regional road conditions, design standards are often lowered to reduce cost and environmental disturbance. Lower design standards of horizontal curve alignment often take the shape of curves designed with a reduced design speed compared to their adjacent tangent sections [35]. Given this discrepancy, advisory speeds are posted together with warning signs at these locations. However, as stated, previous research has indicted that advance warning signs at curves, even with advisory speed plates, do not provide an adequate safety improvement [29, 30]. This issue becomes exacerbated by the underestimation of speed by drivers. Perception of vehicle speed by a drivers has been shown to be underestimated on straight roadways, particularly at faster speeds or after deceleration [38–41]. Milošević and Milić (1990) found speed underestimation to be true at curves as well [27]. Given the increased driver task demand required at curves, speed perception underestimation could increase crash risk, particularly at sharp curves [7, 20]. The perception of curves themselves by drivers further exacerbates this issue. Overall, the dynamics of driver speeds at horizontal curves are complex and must be further considered in future research.

1.5 Curve Perception

Drivers behave differently along curves depending on their perception of a given curve. Results from Fildes and Triggs (1985) suggest that drivers are predominately influenced by a curve's deflection angle and less by a curve's radius. In their study, small-radius bends were judged by subjects as less curved. Small deflection angle curves were also seen as less curved than large angle curves, even though the angle alone does not physically influence the amount of curvature of an arc [11]. Overall, their research concluded that drivers primarily make their judgement of a curve on the basis of a curve's deflection angle, while the radius of a curve is likely to be misinterpreted by drivers [11]. Available sight distance has also been shown to influence driver perception of a curve. In a subjective perception evaluation from a simulator study, Moreno et al. (2013) found that sharper curves and curves with shorter available sight distances were perceived as less favorable to drivers [42].

Vertical curvature in combination with horizontal curvature has been shown in literature to influence perception of a horizontal curve. On horizontal and crest curve combinations, the radius of the curve has been found to be perceived by drivers as being shorter than it actually is [34].

2. Methodology

A series of research tasks were developed to investigate horizontal curve safety compared to safety at tangent segments. The following section outlines the tasks that were employed to address the research aims.

2.1 Literature Review

A literature review was performed to identify the influential factors that impact the safety at horizontal curves that have been revealed to date, as presented in the introduction of this paper. Both field studies and simulator studies were identified through this literature review to uncover the relationship between human factors, the environment, and horizontal curves to assist in the development of future research and countermeasures for horizontal curves. The literature review informed the rest of the analysis.

2.2 Data Description

This research considered a novel data set of horizontal curves across the state of Massachusetts, derived from vehicle GPS trajectory data in a process first established by Ai and Tsai (2015) [43]. The trajectory data was segmented and clustered into either tangent sections or one of the following four types of horizontal curves: simple, compound, reverse, and spiral. Once categorized, the radius of each curve was calculated using circular or spiral fittings, as applicable. These identified tangent and curved roadway segments were then used for this analysis. Crash data for Massachusetts was collected through the MassDOT IMPACT data tool for the years 2014 through 2017 [44]. Roadway inventory data for all state roadway was collected from the Massachusetts Department of Transportation [45]. Figure 1 presents the 2017 crash data in Massachusetts with the curve segment data.

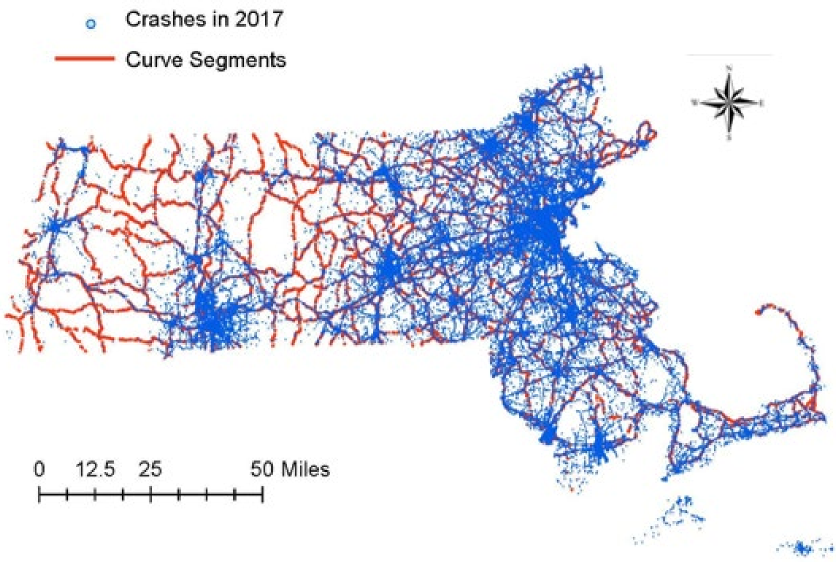

Figure 1: Massachusetts curve segments and crashes in 2017

2.3 Spatial Analysis & Modeling Approach

Spatial analysis using ArcGIS was performed to identify the crashes that were correlated with different roadway segments. To begin, tangent sections between curve segments were created using Massachusetts road data and the horizontal curve data. Following, crashes for each year were connected to the nearest segments for both tangent and curve segments. All crashes within a 200-foot buffer of each segment were consider correlated with that segment. The 200-ft distance was determined based on previous horizontal curve and crash literature [46–48]. Each segment was then combined with the correlated crash data and roadway inventory data for that given segment. To identify the crash value associated with each roadway segment, each crash was assigned an equivalent property damage only (EPDO) crash value based upon the severity of each crash. In Massachusetts, different severities of crashes are weighted differently, often for identifying areas in need of countermeasure implementation. Property damage only (PDO) crashes are weighted at a level of 1, while injury, severe injury, and fatal injury crashes are weighted at a level of 21. This weighting method used in Massachusetts was developed to avoid only “chasing fatal crashes,” as the difference between an injury crash and fatal crash can sometimes be due to a single factor, such as emergency services arrival time [38, 39]. It has been proven to be a more effective method than typical EPDO weighting methods in crash modeling [51].

A model was built to determine the different environmental conditions leading to higher severity crashes at horizontal curves and tangent sections. Specifically, a generalized linear regression model was developed predict the EPDO crash points per mile on a segment that included the annual average daily traffic (AADT) count in vehicles, roadway operation (one-way or two-way), and segment type (horizontal curve or tangent), given the availability in the roadway inventory data and previous literature. Interaction between the segment type and the other factors were included in the final model. Given the exponential increase in crashes and to account for the segments with an EPDO value of zero crashes per mile, a log transformation of the EPDO rate plus one was included as part of the model. Finally, rows with missing values of the factors to be included in the regression and outliers were identified and excluded from analysis prior to modeling. Linear regression was implemented using R. The final dataset that was analyzed consisted of 324,336 segments, with 15.5 percent being curve segments. The final model is presented below.

$$log(EPDO\ crashes\ per\ mile + 1) \sim (segment\ type * roadway\ operation) + (segment\ type * AADT)$$

3. Results

The regression model coefficient results are presented in Table 1. As shown, all terms were statistically significant in the model. Figures 2 and 3 present the interaction of the segment type with AADT and the roadway operation. The results are discussed in more detail in the following discussion section.

Table 1: Model Coefficient Summary

Term	Coefficient	Standard Error of Coefficient	P-Value
Constant	0.522	0.0068	0.000
Segment type (reference = tangent)	0.468	0.0168	0.000
Roadway operation (reference = two-way)	0.416	0.0266	0.000
AADT	0.000053	0.0000004	0.000
Segment type * Roadway operation	0.935	0.0785	0.000
Segment type * AADT	0.000056	0.000001	0.000

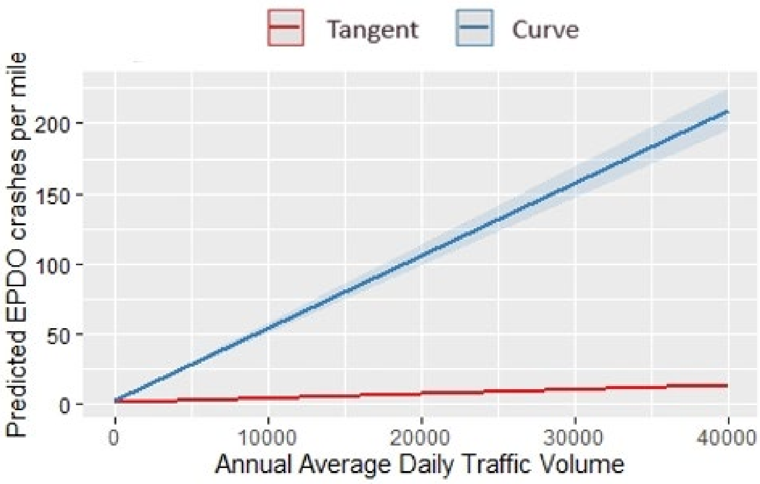

Figure 2: Probability of EPDO crashes per mile depending upon traffic volume and segment type

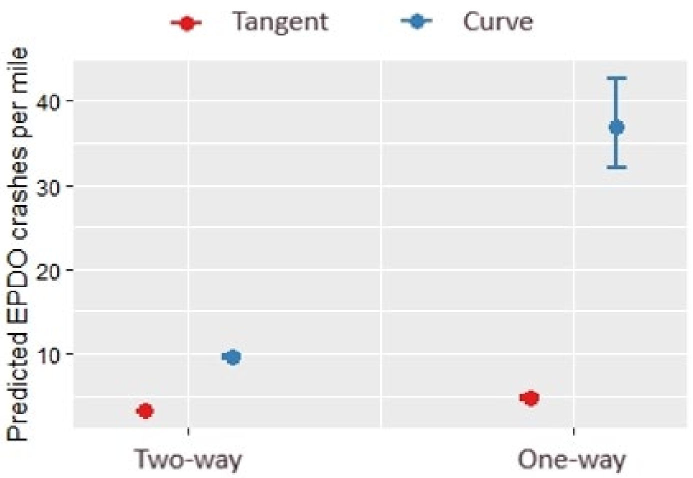

Figure 3: Probability of EPDO crashes per mile depending upon road operation and segment type

4. Discussion

Previous literature has found that horizontal curves remain a significant safety issue given the increase of higher severity crashes at these locations compared to tangent sections. Perception of risk and task demand create environments that make it difficult for drivers to transverse curves in a safe manner. The lateral position and speeds of drivers are then influenced by their perceived risk depending on the curve environment, such as the radius, length, and number of lanes, among others. However, while several studies have proven the specific safety issues and in turn, types of countermeasures that should be placed at horizontal curves, it is not yet clear how the likelihood of higher severity crashes at horizontal curves is influenced by different roadway environments and conditions from a large-scale case study with recent data. This study using a novel dataset of curve data revealed that horizontal curve segments have higher crash points than tangent segments even in cases accounting for the operational roadway type, speed limit, and AADT, as presented in Table 1 and aligning with previous literature. The interaction of variables with the segment type in the model allowed for a deeper understanding of the relationship differences in crash points that occur at both tangent and curve segments, as presented in Figures 2 through 4.

As the AADT volume of a segment increased, the EPDO crash points per mile increased at a faster rate for curve segments than tangent segments, as presented in Figure 2. It is known from previous research that while the crash point value increases as traffic volume increases, the crash point value increases at a lower rate per vehicle added [52]. This is also depicted in Figure 2, aligning the findings of this study with previous literature. The contribution of this study to literature is that this is true for both horizontal curve segments and tangent segments, though curve segments still maintain a higher crash point value. Thus, it is critical for future research to consider the safety of curves in areas of high AADT compared to tangent segments. In terms of operation, horizontal curve segments were found to have a higher crash point value per mile than tangent segments in both one-way and two-way operations, as presented in Figure 3. This is likely connected to the operation of one-way conditions on high-speed highway road segments, where higher severity crashes are more likely. Human performance in one-way operation conditions should be considered in future research, especially for curve segments, to identify the cause of this increased safety issue.

5. Conclusions

Horizontal curve segments have been shown in previous literature to be areas of higher safety concern. Thus, this study aimed to identify the safety issues that have been uncovered to date in current literature pertaining to horizontal curves as compared to tangent segments. This study revealed several factors that cause horizontal curves to have a higher crash point value related to driver performance, including the increased task load and demand required at curve segments compared to tangent segments. The literature review in this study may assist with the development of safety countermeasures for horizontal curve segments. Using a novel horizontal curve dataset in Massachusetts, the results of this study also revealed that horizontal curve segments have an increased rate of crashes per mile with an increasing AADT compared to tangent segments. Further, horizontal curve segments along one-way operations are of increased safety concern for drivers compared to tangent segments and two-way operations. Thus, these conditions should be more carefully considered in future studies and analyses to consider the human factor causes behind this increased safety issue.

It is noted that this study had limitations which should be considered in future research. To begin, this study was limited in scope to the region of Massachusetts highways given the availability of the curve data and inventory data. This study also did not include all factors that may impact the crash point value of a given segment, such as crash factors and roadway condition factors. Future research should consider a larger scope to identify the specific conditions that lead to an increased crash rate at horizontal curves of different types, among other related topics.

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