Accident Analysis and Prevention 77 (2015) 105–112

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

# Influence of horizontally curved roadway section characteristics on motorcycle-to-barrier crash frequency

Douglas J. Gabauer *, Xiaolong Li

*Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA 17837, USA*

ARTICLE INFO

*Article history:*
Received 19 December 2014
Received in revised form 8 February 2015
Accepted 10 February 2015
Available online 18 February 2015

*Keywords:*
Motorcycle crash
Longitudinal barriers
Horizontal curves
Roadway characteristics

ABSTRACT

The purpose of this study was to investigate motorcycle-to-barrier crash frequency on horizontally curved roadway sections in Washington State using police-reported crash data linked with roadway data and augmented with barrier presence information. Data included 4915 horizontal curved roadway sections with 252 of these sections experiencing 329 motorcycle-to-barrier crashes between 2002 and 2011. Negative binomial regression was used to predict motorcycle-to-barrier crash frequency using horizontal curvature and other roadway characteristics. Based on the model results, the strongest predictor of crash frequency was found to be curve radius. This supports a motorcycle-to-barrier crash countermeasure placement criterion based, at the very least, on horizontal curve radius. With respect to the existing horizontal curve criterion of 820 feet or less, curves meeting this criterion were found to increase motorcycle-to-barrier crash frequency rate by a factor of 10 compared to curves not meeting this criterion. Other statistically significant predictors were curve length, traffic volume and the location of adjacent curves. Assuming curves of identical radius, the model results suggest that longer curves, those with higher traffic volume, and those that have no adjacent curved sections within 300 feet of either curve end would likely be better candidates for a motorcycle-to-barrier crash countermeasure.



## 1. Introduction

Motorcycle impacts into traffic barriers, such as w-beam guardrails and concrete barriers, produce particularly severe rider injuries, even when compared to other types of motorcycle crashes (Daniello and Gabler, 2011a). Although not a frequently occurring type of motorcycle crash, they now comprise the largest proportion of guardrail fatalities of any single vehicle type in the US (Gabler, 2007). The majority of the published research to date has focused on determining the characteristics of these crashes as well as the associated rider injury mechanisms and injury consequences (Ouellet, 1982; Bryden and Fortuniewicz, 1986; Koch and Brendicke, 1988; Hell and Lob, 1993; Gibson and Benetatos, 2000; Association of European Motorcycle Manufacturers (ACEM), 2004; Bambach et al., 2012; Daniello and Gabler, 2011b, 2012). In addition, several alternative barrier designs and barrier retrofit devices have been developed to reduce rider injury severity in the event of a motorcycle impact (Koch and Schueler, 1987; Ellmers, 1997; Mulvihill and Corben, 2004; Janssen et al., 2005; Candappa et al., 2005).

While a number of the developed "motorcycle-friendly" barriers have been field-installed, researchers have indicated that these devices are cost effective only at locations predisposed to this crash type (Koch and Schueler, 1987; Domham, 1987). The influence of specific roadway design elements on the incidence of motorcycle-to-barrier crashes, however, is not well understood. As a result, roadway designers have little guidance on where to locate these countermeasures to maximize the effectiveness of each field-installed device. Anecdotal evidence from previous studies indicates motorcycle-to-barrier crashes may occur more frequently on curved roadway sections (Berg et al., 2005; Jama et al., 2011). Although this suggests that curved locations may be good candidates for "motorcycle-friendly" barriers, there is only a single quantitative placement guideline present in published literature (Elliot et al., 2003) with regard to curved sections and none with respect to other roadway geometrics or features. Also, there were no studies found in the available literature specifically investigating how roadway characteristics affect the likelihood that a given roadway section will or will not experience a motorcycle-to-barrier crash.

* Corresponding author. Tel.: +1 570 577 2902; fax: +1 570 577 3415.
*E-mail address:* doug.gabauer@bucknell.edu (D.J. Gabauer).

http://dx.doi.org/10.1016/j.aap.2015.02.006
0001-4575/

## 2. Objective

The purpose of this study was to examine the influence of roadway design elements on the frequency of motorcycle-to-barrier crashes occurring on horizontally curved sections. Specific objectives were to (1) compare characteristics of horizontal curve sites with and without motorcycle-to-barrier crashes and (2) develop a statistical model to investigate how curvature and other roadway curve features affect the occurrence of this crash type.

## 3. Previous research

### 3.1. Studies specific to motorcycle-to-barrier crashes

Several previous studies specific to motorcycle-to-barrier crashes provided anecdotal insight into roadway characteristics associated with this crash type. At least two studies reported that curved roadway sections experienced a higher proportion of motorcycle-to-barrier crashes. Berg et al. (2005) found that 60 percent of the 57 motorcycle-to-barrier crashes investigated, including various injury severity levels, occurred within curved sections. Examining 77 fatal motorcycle-to-barrier crashes in Australia and New Zealand, Jama et al. (2011) reported that 81 percent involved a horizontal curve with an approximately equal distribution of right and left hand curves. Other studies indicated somewhat differing results regarding curved sections. Based on 8 barrier impact fatalities occurring in New South Wales, Gibson and Benetatos (2000) reported half involved the rider leaving the roadway in a curved section. A previous study by Gabauer (2014) examined police-reported motorcycle-to-barrier crashes occurring in Ohio and Washington State over a 12-year and 10-year period, respectively. Based on the 1511 crashes, 40 percent of motorcycle-to-barrier crashes in Washington State were on curved sections compared to a mere 19 percent of these crashes in Ohio. When compared to all single vehicle motorcycle and all multiple vehicle crashes involving motorcycles, however, motorcycle-to-barrier crashes were found to be overrepresented on curved sections in both states.

Even fewer studies provided curve-specific details beyond a curve/no curve indication. Domham (1987) noted that none of 22 motorcycle-to-barrier crashes in Germany occurred on a horizontal curve with the smallest radius. Based on the reported results of French motorcycle-to-barrier crash study, Elliot et al. (2003) suggested motorcycle-to-barrier countermeasures are appropriate on horizontal curves with radius less than 250 m (820 feet); this was the only quantitative recommendation found in the literature specific to the motorcycle-to-barrier crash mode. The previous study by Gabauer (2014) reported mean horizontal curve radius and mean vertical grade for motorcycle-to-barrier crashes in addition to other roadway characteristics such as mean shoulder width, median width, and annual average daily traffic (AADT). A primary finding with regard to horizontal curvature was that motorcycle-to-barrier crashes were significantly more likely on smaller radius horizontal curves compared to all other single vehicle motorcycle crashes. With respect to the Elliot et al. (2003) recommendation, the author found less than 45 percent of motorcycle-to-barrier crashes occurred on a curved section or within 90 m (300 feet) of either end of a curve meeting the 250 m (820 foot) criterion. Considering only crashes occurring within the curved sections reduced this percentage to less than 25 percent of the total motorcycle-to-barrier crashes in either state. Although the study presented more detailed roadway information for this crash type, barrier presence data was unavailable. This data limitation prevented a distinction between sections with a barrier present but no motorcycle-to-barrier crashes from sections with no barrier present and thus no possibility of a crash of this type. As a result, a full analysis of the effect of roadway characteristics on crash frequency was not possible.

### 3.2. Relevant general motorcycle crash study results

A number of crash studies not specific to the motorcycle-to-barrier crash mode also provided information related to the influence of roadway alignment on either crash frequency or crash severity, or both. Similar to the studies specific to motorcycle-to-barrier crashes, though, the majority of the results were predominately general in nature, e.g., distinguishing curved sections from tangent sections but no specific curve radius data. The majority of the studies suggested that horizontal curves increased the likelihood (Kim et al., 2002; Association of European Motorcycle Manufacturers (ACEM), 2004; Preusser et al., 1995) and the severity (Savolainen and Mannering, 2007; Kim et al., 2002; Quddus et al., 2002) of either single vehicle motorcycle crashes or all motorcycle crashes. There were two recent crash studies found with more specific alignment data for horizontal curves on rural two-lane highways; one focusing on driver injury severity in all single vehicle crashes (Schneider et al., 2009) and another specific to single vehicle motorcycle crashes (Schneider et al., 2010).

Schneider et al. (2009) used multinomial logit analysis to examine roadway, driver, environmental and vehicle factors affecting horizontal curve crash severity. Data included 10,029 single vehicle crashes in Texas which contained 354 single vehicle motorcycle crashes. Horizontal curves were categorized based on radius with ‘small’ curves having radii less than 500 feet, ‘large’ curves having radii greater than 2800 feet, and ‘medium’ curves having radii between the small and large ranges. Compared to all other vehicle types, fatal and incapacitating motorcycle injuries were found to be approximately 6 times as likely, irrespective of curve category. Non-incapacitating motorcycle rider injuries were also found to be between 73 and 98 percent more likely than for drivers of all other vehicle types negotiating a curved section. Trees were the only fixed object specifically noted as producing higher severity injuries but this finding applied to all vehicle types; results specific only to motorcycle-to-barrier crashes were not reported.

Schneider et al. (2010) used a negative binomial model to investigate roadway geometry effects on single vehicle motorcycle crashes in Ohio. The analysis was based on 225 motorcycle crashes which had occurred on 30,379 rural two-lane highway horizontal curves over a seven year study period. Horizontal curve length, horizontal curve radius, distance beyond either curve end-point, roadway shoulder width, and total segment average daily traffic (ADT) were all found to have a statistically significant effect on motorcycle crash occurrence. Longer, higher speed curves and smaller radius curves were both found to increase motorcycle crash frequency on a given segment. Curves were also found to influence crash risk on adjacent tangent sections for up to 300 feet but with decreasing crash risk as a motorcyclist moved farther from a curved section. A percentage point increase in total ADT was estimated to increase motorcycle crash frequency by 0.43 percent. In addition, roadway sections with shoulders less than 6 feet in width were found to increase motorcycle crash risk by approximately 50 percent. Similar to the previous Schneider et al. (2009) study, motorcycle-to-barrier crashes were not specifically addressed.

## 4. Methodology

The overall study approach was to investigate motorcycle-to-barrier crash frequency on horizontally curved roadway sections in a single state using police-reported crash data linked with roadway data. The available roadway data was augmented with barrier presence information obtained through a satellite/street view photography approach (Google Maps/Street View). Using the available combined dataset, a statistical model was developed to examine the influence of the curved section geometric characteristics on motorcycle-to-barrier crash frequency while controlling for other potentially confounding roadway factors. MATLAB (MathWorks, Natick, MA) was used to facilitate the review of street view photography while SAS V9.4 (SAS Institute, Cary, NC) was used to perform the data processing and statistical analyses.

### *4.1. Data sources and preparation*

Crash and roadway data for Washington State was obtained from the Highway Safety Information System (HSIS). HSIS is a multi-state database maintained by the Federal Highway Administration (FHWA) containing linked crash, roadway inventory, and traffic volume data (Federal Highway Administration (FHWA), 2011a). Washington HSIS contains 7220 roadway miles and approximately 48,000 crashes per year (Council and Mohamedshah, 2009). The HSIS road mileage includes approximately one fourth of the 26,400 miles of non-local roadways in the state (Federal Highway Administration (FHWA), 2011b) and is predominately comprised of state and interstate roadways. Also, the HSIS crashes represent about one-third of the approximately 130,000 police-reported crashes in the state each year (Council and Mohamedshah, 2009).

Although the Washington HSIS data provided detailed geometry for each curved roadway section, the data does not include roadside feature existence information. As sections without barriers will not experience any motorcycle-to-barrier crashes, it was important to identify barrier presence for each curved roadway section so that the analysis could be limited to only those sections with a barrier. The following subsections provide additional details on crash data processing, collection of the barrier presence information, and creation of the final datasets used for statistical model development.

#### *4.1.1. Crash data selection and roadway data matching*

Selected crash data included motorcycle, scooter, and moped crashes occurring from 2002 through 2011. Initial analysis indicated scooters and mopeds comprised less than 2 percent of all Washington crashes available and, as a result, have been excluded from further analysis. After exclusion of scooters and mopeds, the dataset was reduced to single vehicle motorcycle crashes involving one or more longitudinal traffic barrier impacts. Longitudinal barrier crashes were selected using the available HSIS object struck variables. The barrier related object struck codes separate barriers by type (guardrail or concrete barrier) and impact location (barrier face or end). For the purpose of this study, any impact to either barrier type or impact location was considered a longitudinal barrier impact. This barrier impact could occur in either or both of the two available object struck variables for a particular crash. For the available single vehicle motorcycle-to-barrier crashes in each year, structured query language was used to merge the crash, vehicle, roadway, curve, grade, and ramp information into a single table by matching the road inventory variables and ensuring that the milepost was between the beginning and end of the road/curve/grade segment.

The available single vehicle motorcycle-to-barrier crashes were then further limited to those occurring on non-tangent, e.g., horizontally curved, mainline roadway sections. While there were a number of crashes occurring on ramp sections, these were excluded as the associated roadway data for these sections lacked sufficient detail. As an example, HSIS ramp file data did not indicate curve presence or curve radius for non-tangent ramp sections. After the matching process was complete for each suitable crash, sections with multiple crashes were identified and the total number of crashes per section was noted. Based on the findings of Schneider et al. (2010), crashes occurring on a tangent section but within 300 feet of either end of a horizontal curve were grouped with the associated horizontal curve. A revised HSIS curve file was then developed by amending the HSIS 2011 curve file with the information on total number of motorcycle-to-barrier crashes. Using the beginning/ending milepost information in the entire file, “isolated” curves were then identified. Isolated curves were those with at least 300 feet of tangent section at both ends of the curve.

#### *4.1.2. Determination of barrier presence*

Using the available geospatial coordinates, a MATLAB program extracted at least one Google Street View image for each curve location. Additional images were extracted in the following cases: (1) an initial Street View image was not available, (2) vehicles or objects were blocking the view of the roadside and/or median, or (3) barrier presence and/or type was difficult to discern. Based on the image(s) for each curve, barrier presence (present, no barrier, or unable to determine), barrier type (w-beam, concrete, or cable) and barrier location (e.g., curve inside, curve outside, median) were coded. Note that the barrier presence determination was made based on the most recent Street View image(s) to coincide with the use of the 2011HSIS curve data. The option to view images over time with Street View was not used as its availability for the subject locations was limited and rarely spanned the entire 10 year study period. Instead, the HSIS date change variable was used to compute observation time for each available curve section.

#### *4.1.3. Data merging for final data set creation*

The barrier presence information from Section 4.1.2 was combined with the curve data from Section 4.1.1 using structured query language. The matching procedure required an exact route number match, the beginning/end mileposts matching within 80 feet, and the curve radii matching within 5 feet. Each curve section was then matched with associated HSIS road and grade data. This matching process required two iterations as curved sections were not always within the boundaries of one roadway and/or grade section. Matches were first made with curved sections completely contained within a road/grade segment, e.g., an exact route number match and the beginning/ending mileposts of the curve section matching or within the beginning/ending mileposts of the road/grade section. A second iteration matched curved sections spanning more than one road/grade segment with the first appropriate road/grade segment. Curved sections spanning more than one grade segment were flagged for vertical curvature as Washington HSIS does not contain vertical curve presence or length data.

The final dataset included the matched GIS and HSIS curve sections, the total number of motorcycle-to-barrier crashes per section, and the associated roadway and grade data. The final dataset included 13,912 curves, representing approximately a 90 percent match rate with the available HSIS curve data. A number of sections were excluded from further analysis due to no matching roadway/grade information (120 sections) or an inability to determine barrier presence or absence (435 sections). There were also a small number of sections (36) where the barrier presence data indicated no barrier but a motorcycle-to-barrier crash had been reported in HSIS. For these sections, the HSIS data was assumed correct and the associated barrier presence indicator was changed accordingly.

### 4.2. Data analysis and model development

#### 4.2.1. Comparison of curves with and without motorcycle-to-barrier crashes

Using the final dataset described above, descriptive statistics were generated for four horizontal curve groups: (1) sections with no barrier present, (2) sections with one or more barriers present, (3) sections with barriers present experiencing one or more motorcycle-to-barrier crashes, and (4) sections with barriers present but no motorcycle-to-barrier crashes. For each category, various alignment and roadway characteristics were reported. Alignment characteristics included mean radius, curve length, central angle and vertical grade along with the number of sections with radius less than 250 m (820 feet), grades in excess of 3 percent, a vertical curve present, and the number of isolated curves. General roadway characteristics included mean posted speed and AADT along with number of lanes, median presence (divided/undivided), shoulder width, a rural/urban designation, and roadway functional classification. Shoulder width was grouped into three categories: less than 2 feet, greater than or equal to 2 feet but less than 10 feet, and greater than or equal to 10 feet, based loosely on American Association of State Highway and Transportation Officials (American Association of State Highway and Transportation Officials (AASHTO), 2011) shoulder width guidance. Posted speed limit was divided into two groups based on the AASHTO distinction between high speed, e.g., 50 mph and above, and low speed, e.g., 45 mph and lower, roadways (2011). Note that the speed limit data was obtained from the HSIS curve file and accounts for posted speed reductions typical of smaller radius curves. To further examine curve radius, cumulative distributions were plotted for all curved sections with barrier present, curved sections with barrier present and no motorcycle-to-barrier crashes, and curved sections with one or more motorcycle-to-barrier crashes. For sections containing barriers, summary data on barrier type and location was also reported.

#### 4.2.2. Statistical model development

Two primary statistical models, the negative binomial and zero-inflated negative binomial, were used to model motorcycle-to-barrier crash frequency on horizontally curved sections. Negative binomial (NB) models are generally preferred for modeling data where the variance is greater than the mean (Washington et al., 2011). This is often true of crash data and numerous researchers have applied NB models to study crash frequency (Miaou, 1994; Shankar et al., 1995; Abdel-Aty and Radwan, 2000; Carson and Mannering, 2001; Schneider et al., 2010). Zero-inflated negative binomial (ZINB) models have also been applied to study crashes (Shankar et al., 1997; Carson and Mannering, 2001; Lee et al., 2002) and are useful when a large number of zeros are present in the data, potentially arising from differing phenomena (Washington et al., 2011). Although the identification of barrier presence eliminated the possibility of having a zero motorcycle-to-barrier count due to the inclusion of sections without barrier, excess zeros may be present for other reasons. One example could be a section with zero motorcycle volume. While HSIS contains AADT data for all vehicle types, the motorcycle vehicle volume is not known and could vary significantly from the total AADT in a given roadway section.

All models were developed with the number of motorcycle-to-barrier crashes occurring on a given horizontally curved roadway section as the dependent variable. Continuous predictor variables included horizontal curve radius, normalized horizontal curve radius, AADT, curve length and percent grade. The normalized radius was computed by dividing the curve radius by the recommended minimum radius based on Washington State (Washington DOT, 2012) geometric design standards. The minimum radius was selected using a design speed equal to the posted speed limit and using the largest permissible superelevation, as superelevation data were not universally available in the HSIS data. Natural logarithm transformed versions of the continuous variables were also explored during model development as well as interactions between horizontal curve radius and vertical grade. Categorical predictor variables included number of lanes, shoulder width, vertical curve presence, isolated curve indication, divided/undivided indication with categories as discussed previously in Section 4.2.1. While rider characteristics were available for crash-involved riders, the corresponding characteristics for non-crash-involved riders were not available in HSIS and thus rider characteristics were not included in the developed models. Additional information on the rider characteristics for motorcycle-to-barrier crashes can be found in the previous study by Gabauer (2014).

Several initial NB models were developed using combinations of the available predictor variables and two versions of the final dataset: (1) the full dataset including sections with observation times less than the full study period and (2) a smaller dataset only including only sections with no change noted during the full study period. For models using the first dataset, only crashes occurring after the noted change date were included for those sections and the model used the SAS offset option to account for differing section observation times. Models using the second dataset were explored since the number of changed sections (465) was such a small subset of the available data (5380 sections). Initial models with both datasets revealed very little difference between the time-variant models and the models developed using the smaller time-constant dataset. As there were no changes to the variables that were statistically significant and only very small changes to the estimates for each coefficient, the model results presented herein were those based on the smaller time-constant dataset.

A final NB model was selected based on comparing the full log likelihood, Akaike's Information Criterion (AIC), and the Bayesian Information Criterion (BIC) fit statistics of each developed model. A corresponding ZINB model was developed based on the final NB model with the natural logarithm of the curve radius, natural logarithm of the AADT, and area type serving as zero model parameters. Selection of these parameters was based the initial NB model results and the assumption that curve radius, area type, as well as total traffic volume likely influence the proportion of motorcycles in the traffic stream, e.g., more motorcyclists may use rural roadways with tighter curves and less traffic volume. The Vuong test statistic was used to determine if the ZINB model provided an improved fit over the final NB model. The computed Vuong test statistic was 1.34 ($P = 0.18$) indicating that the ZINB model was closer to the true model but not by a statistically significant margin. As a result, the final NB model was selected over the ZINB model. The estimated parameters of the final NB model were then used to examine the relationship between the roadway characteristics and the frequency of motorcycle-to-barrier crashes on curved sections. Estimated percentage increases or decreases in crash frequency associated with a specific predictor were computed by exponentiation of the corresponding coefficient and subtracting 1.0 from the result prior to converting to a percentage value.

## 5. Results

There were a total of 556 motorcycle-to-barrier crashes available in the Washington HSIS data from 2002 through 2011; 421 of these were mainline, e.g., non-ramp, crashes. A total of 344 of the mainline crashes occurred either within a curved section (234 crashes) or on a tangent section but within 300 feet of a horizontal curve end (110 crashes); the remaining 77 occurred on a tangent section not within 300 feet of a horizontal curve end. Comparing the HSIS and GIS curve datasets resulted in matching curve data for 329 of the 344 available curve crashes. The matched 329 crashes occurred on 252 curved sections; 204 sections with one crash and 48 sections experiencing multiple crashes (range: 2–6 crashes; mean: 2.6). The final matched dataset of all curved sections included 13,357 horizontally curved roadway sections with less than half of these (5380) containing at least one barrier.

### 5.1. Comparison of curves with and without barrier crashes

Table 1 summarizes the alignment and roadway characteristics for the available Washington HSIS horizontally curved roadway segments in each of the four categories. In general, curved roadway sections with barrier present were shorter in length, had smaller radii, larger central angles, and steeper vertical grades than curved sections without a barrier. The majority of the available curved sections were on high speed, undivided roadways in rural areas. Approximately 82 percent of sections with barrier had posted speed greater than 45 mph, 85 percent were undivided and 81 percent were in a rural area. The percentages were similar for non-barrier sections; 75 percent, 93 percent, and 88 percent, respectively. The presence of barrier on a curved section also coincided with higher traffic volume as the mean AADT was more than double than that of curves without barrier present. Curved sections with barrier were also more frequently principal arterials (53 percent vs. 35 percent), had shoulder widths of 10 feet or more (16 percent vs. 8 percent), and had 4 or more lanes (7.6 percent vs. 1.2 percent).

Of the curved sections with barrier, there were differences observed between sections with one or more motorcycle-to-barrier crashes present and those sections with none. The mean radius for curves experiencing at least one crash was approximately 60 percent of the mean radius of curves not experiencing any crashes of this type. Also, crashes were overrepresented on sections with radius less than 820 feet; 56 percent of those with crashes had radius less than 820 feet compared to 30 percent for curves with barrier but no crashes. Crashes were also overrepresented on isolated curves, curves with a vertical curve present, and curves with a grade of 3 percent or higher, although to a much lesser extent than observed with horizontal curvature. Mean AADT of curved sections with a crash was approximately double that of curves with no crashes. Approximately 37 percent of curves with one or more crashes were in urban areas compared with 18 percent of curves with no crash present. Functional classification and shoulder width proportions were approximately equal between curves with and without a motorcycle-to-barrier crash. Curves with crashes contained a higher percentage of sections with 4 or more lanes (15.5 percent) compared to curves without crashes (7.2 percent). It should also be noted that curved sections with barrier had, on average, a higher number of all motorcycle crashes present: 0.24 crashes per section for those with barrier compared to 0.10 crashes per section for those without barrier.

Table 2 provides barrier-specific details for the horizontal curves with at least one barrier present. For undivided roads, there was an approximately even split between barriers located on the outside of the curve, e.g., right-hand side of a curve to the left, and the inside of the curve. A smaller proportion of sections had barrier on both sides of the curved section. For divided roadway sections, approximately one third had barriers in the median only, another third had barriers at all possible positions, and the remaining third had some combination of barrier presence possibilities. The identified barriers were predominately w-beam guardrails and

**Table 1**
Horizontal curve alignment and roadway characteristics by barrier presence and motorcycle-to-barrier crash presence (Washington State HSIS 2002–2011 crash data).

| Parameter (units; a count if no units identified) | All horizontal curves | | All horizontal curves with barriers | |
|---|---|---|---|---|
| | No barrier present | Barrier present | 1 or more motorcycle-to-barrier crashes[a] | No Crashes |
| All | 7977 | 5380 | 252 | 5128 |
| Alignment characteristics | | | | |
| Mean radius (feet) | 2740 | 2458 | 1485 | 2506 |
| Mean length (feet) | 708 | 650 | 683 | 648 |
| Mean central angle (°) | 25.5 | 28.2 | 49.6 | 27.2 |
| Radius < 820 feet | 1994 | 1678 | 142 | 1536 |
| Mean grade (%) | 1.90 | 2.61 | 2.86 | 2.6 |
| Grade ≥ 3% | 2023 | 2197 | 116 | 2081 |
| Vertical curve present | 3609 | 2096 | 106 | 1990 |
| Isolated curve | 5026 | 2818 | 138 | 2680 |
| Roadway characteristics | | | | |
| Mean posted speed (mph) | 51.3 | 53.2 | 51.6 | 53.3 |
| Posted speed > 45 mph | 5962 | 4422 | 192 | 4230 |
| Mean AADT (vpd) | 5,609 | 14,763 | 28,236 | 14,101 |
| Undivided roadways | 7447 | 4599 | 192 | 4242 |
| Urban area | 958 | 1031 | 93 | 938 |
| Functional classification | | | | |
| Principal arterial | 2775 | 2834 | 133 | 2701 |
| Minor arterial | 2670 | 1617 | 86 | 1531 |
| Collector | 2532 | 929 | 33 | 896 |
| Shoulder width | | | | |
| Less than 2 feet | 935 | 391 | 24 | 367 |
| ≥2 and <10 feet | 6394 | 4103 | 178 | 3925 |
| ≥10 feet | 648 | 886 | 50 | 836 |
| Number of lanes | | | | |
| 1–2 lanes | 7091 | 4240 | 174 | 4066 |
| 3–4 lanes | 789 | 733 | 39 | 694 |
| More than 4 lanes | 97 | 407 | 39 | 368 |

[a] Defined as HSIS variables OBJECT 1 or OBJECT 2 = 31, 32, 34, 35, 36.

**Table 2**
Barrier location and type distribution for horizontally curved HSIS sections in Washington State.

| Parameter | Curves with one or more barriers | |
|---|---|---|
| | *n* | (%) |
| All | 5380 | 100 |
| Barrier location | | |
| Undivided roads | 4599 | 85.5 |
| Inner curve only | 1701 | 37.0 |
| Outer curve only | 2034 | 44.2 |
| Both sides | 864 | 18.8 |
| Divided roadway | 781 | 14.5 |
| Median only | 277 | 35.5 |
| Inner only | 29 | 3.7 |
| Outer only | 29 | 3.7 |
| Median + inner | 52 | 6.7 |
| Median + outer | 76 | 9.7 |
| Inner + outer | 31 | 4.0 |
| All possible | 287 | 36.7 |
| Barrier type (all locations) | 6934 | 100 |
| W-beam | 5376 | 77.5 |
| Concrete | 1443 | 20.8 |
| Cable | 115 | 1.7 |
| Barrier location/type | | |
| Roadside | 6247 | 90.1 |
| Median | 687 | 9.9 |

located on the roadside. Based on the available motorcycle-to-barrier crashes, approximately 74 percent involved an impact with a metal barrier and the remaining 26 percent with a concrete barrier. Note that any one of the 5380 sections can have more than one barrier section present resulting in a total of nearly 7000 individual barrier sections.

Based on the available HSIS curve change information, the vast majority (4915 sections; 91 percent) of the sections remained unchanged during the study period resulting in a mean observation time of 9.49 years. Of the changed sections, 445 experienced no crashes. The remaining 20 sections experienced a total of 28 crashes; 15 sites with one motorcycle-to-barrier crash and 5 sites with multiple crashes. A total of 6 sites had crashes occurring after the change date of the section (8 crashes total) while 14 sites had crashes occur before the change to the section (20 crashes total).

Cumulative curve radius distributions for all Washington HSIS curves with barrier present, all curves with barrier present and no motorcycle-to-barrier crashes, and curves with one or more motorcycle-to-barrier crashes are shown in Fig. 1. The cumulative distributions for all curves and curves without motorcycle-to-barrier crashes were nearly identical. For curves with motorcycle-to-barrier crashes present, two-thirds of the sections had a radius of 1044 feet or less while 90 percent had a radius of 2800 feet or less. Considering all Washington horizontal curves with barrier present, approximately 40 and 73 percent have radius less than 1044 feet and 2800 feet, respectively.

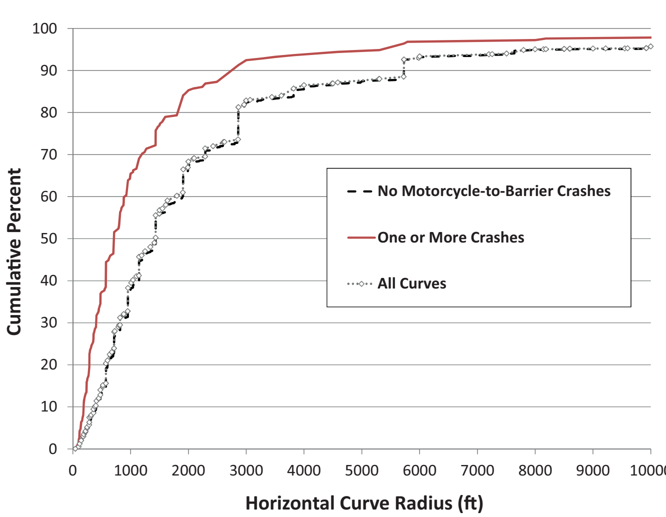


**Fig. 1.** Horizontal Curve Radius Cumulative Distributions: All Washington HSIS Curves with Barrier Present and by Motorcycle-to-Barrier Crash Presence.

### 5.2. Statistical model results

The final NB model results for the statistically significant and nearly statistically significant predictors are shown in Table 3; this combination of predictor variables resulted in the best fit to the available data. Natural logarithm transforms of curve radius, curve length, and AADT, as well as the presence of another curve end within 300 feet of the subject curve were found to have a statistically significant effect on motorcycle-to-barrier crash frequency. Increases in curve length and AADT were found to increase motorcycle-to-barrier crash frequency. A one unit increase in the natural logarithm of the curve length and AADT were estimated to result in 58 percent and 87 percent more crashes, respectively. An increase in curve radius was found to decrease crash frequency with a one unit increase in the logarithm of curve radius resulting in an estimated 80 percent reduction. Compared to isolated curves, non-isolated curves were found to reduce crash frequency by approximately 54 percent. Area type was found to have a nearly statistically significant effect. Compared to horizontal curves in urban areas, curves in rural areas were found to reduce crash frequency by 36 percent. The interaction between roadway grade and horizontal curve radius was not found to be statistically significant in the final model or any of the other initial models developed.

As part of the model development, separate NB models were developed (full model results not shown) using the other curve radius criteria: the normalized radius, an indicator for curves with radius less than 820 feet, and the small/medium/large categories from Schneider et al. (2009). Compared to large curves (radius > 2800 feet), small and medium curves were found to be 43 and 4.7 times more likely to experience a motorcycle-to-barrier crash, respectively. Curves meeting the 820 foot criterion were found to have 10 times the rate of these crashes compared to curves not meeting this criterion. A unit increase in the normalized radius criterion was found to result in 47 percent less motorcycle-to-barrier crashes.

## 6. Discussion

The purpose of this study was to investigate motorcycle-to-barrier crash frequency on horizontally curved roadway sections in Washington State using police-reported crash data linked with roadway data. Based on the available data, only a small subset (4.7 percent) of horizontal curves with a barrier present experienced at least one motorcycle-to-barrier crash and less than 1 percent experienced multiple motorcycle-to-barrier crashes. This fact reinforced the importance of careful selection of the location of motorcycle-to-barrier crash countermeasures. Crashes occurring on a curved section or within 300 feet of a curve end represented more than half of all the motorcycle-to-barrier crashes available; the remaining crashes were split between ramp crashes (24 percent) and tangent section crashes not within 300 feet of a curve end (14 percent). These results were similar to the approximately 60 percent curve proportion reported by Berg et al. (2005) and by Daniello and Gabler (2011b) for New Jersey and North Carolina. Note that the proportion drops to 42 percent in the present study if the crashes within 300 feet of a curve end are omitted. While

**Table 3**
Final negative binomial model results predicting motorcycle-to-barrier crash frequency.

| Parameter | Coefficient | Standard error | Wald chi-square | *P*-value |
|---|---|---|---|---|
| Constant | 1.367 | 0.843 | 2.63 | 0.105 |
| Natural log of the curve radius (feet) | −1.637 | 0.116 | 199 | <0.001 |
| Natural log of the total AADT (vpd) | 0.461 | 0.079 | 34.5 | <0.001 |
| Natural log of the curve length (feet) | 0.626 | 0.114 | 30.2 | <0.001 |
| Non-isolated curve indicator | −0.761 | 0.168 | 20.6 | <0.001 |
| Rural area indicator | −0.455 | 0.234 | 3.8 | 0.052 |

Note: *n*: 4519; log likelihood: −947.97; $\chi2$/DF: 1.208; dispersion: 3.043 [95% CI: 2.12–4.36].

curved sections may be of interest to motorcycle-to-barrier crashes, it is important to note that other sites may also be of interest, especially ramp sections. Previous research suggests that these crashes are overrepresented on ramp sections (Quincy et al., 1988; Gabauer, 2014).

Comparing horizontal curves experiencing at least one motorcycle-to-barrier crash to curved sections with barrier present but no crashes, the largest differences were found in curve radius and traffic volume. Curves experiencing crashes of this type had smaller radii which was likely a result of the increasing difficulty maneuvering the motorcycle as curve radius decreases. Higher traffic volume was also generally associated with more motorcycle-to-barrier crashes likely due to an increased exposure, i.e. more motorcycle riders passing the barrier. Other less prominent differences suggested curved sections with at least one motorcycle-to-barrier crash were more frequently in urban areas and on sections with 4 or more lanes. This may be an extension of the higher traffic volume observation above, as urban areas and roadways with more lanes likely have higher volumes, or it could simply be an artifact of the available dataset. In terms of barrier type, the proportions of barrier types identified on all curves were approximately equal barrier type proportions in the available motorcycle-to-barrier crashes occurring on or near horizontally curved sections (74 percent metal barrier; 26 percent concrete). This suggested that no one barrier type on curved sections was more frequently associated with these crashes.

The final negative binomial model results suggested isolated curves, decreases in curve radius, increases in traffic volume, and increases curve length increased the risk of motorcycle-to-barrier crashes on a given horizontal curve section. These findings were generally intuitive and echoed the traffic volume and curve radius findings from the descriptive statistics comparison. Similar to the curve radius, the curve length findings likely reflect that the difficulty maneuvering a motorcycle through a curve of a particular radius increases as the curve length increases. The isolated curve findings may be linked to rider expectation; riders experiencing many curved sections in succession may be more capable of traversing a curve compared to riders that only very sporadically experience a curved roadway section. In general, the findings were similar to the Schneider et al. (2010) study which found single vehicle motorcycle crash frequency increased with increases in traffic volume, increases in curve length, and decreases in curve radius. Isolated vs. non-isolated curves were not explored in the Schneider et al. (2010) study as only isolated curved sections were included in the analysis. Unlike the Schneider et al. (2010) study, a significant relationship was not found with regard to shoulder width. This could be an artifact of examining a different crash subset, motorcycle-to-barrier crashes as opposed to all single vehicle motorcycle crashes, or the use of differing shoulder width categories.

The strongest predictor of motorcycle-to-barrier crash frequency was curve radius which supports a countermeasure placement criterion based, at the very least, on horizontal curve radius. This prediction strength was true for all variants of curve radius used in the model development. The results presented herein could be used by transportation agencies to set an appropriate threshold radius value similar to the 250 m (820 feet) value proposed by Elliot et al. (2003). Other important variables that may aid roadway designers with countermeasure placement include curve length, traffic volume, and the location of adjacent curve sections. Assuming curved sections of identical radius, the model results suggest that longer curves, those with higher traffic volume, and those that have no adjacent curved sections within 300 feet of either curve end would likely be better candidates for a motorcycle-to-barrier crash countermeasure. While these quantifiable characteristics do provide countermeasure placement guidance, it should be noted that other considerations may also be of importance. For instance, road sections recognized as popular motorcycle routes likely have an increased risk of motorcycle-to-barrier crashes and may warrant separate consideration. If these motorcycle routes are known, consideration of the curved sections on those routes in combination with the findings herein may provide better guidance than simply applying the curve section property findings to all available roadway sections in a given jurisdiction.

Limitations of the study were primarily associated with the available and collected data. The analysis included data only from a single state. As previous research (Gabauer, 2014; Daniello and Gabler, 2011b) suggests that motorcycle-to-barrier crash experience may vary by state, care should be exercised when applying these results to areas that have a vastly different motorcycle-to-barrier crash experience than Washington State. Also, total roadway section volume was used as a surrogate measure of motorcycle traffic volume, as this data was not available. Although there is likely a relationship between these two quantities, they may not be proportional for all roadway sections. Total volume, however, was a significant factor in the developed models suggesting that motorcycle exposure may be captured, at least in part, by total traffic volume. Nevertheless, future studies should use motorcycle traffic volume should it be available. With respect to the determination of barrier presence using Google Street View, there were sections where no barrier was coded yet HSIS data indicated a motorcycle-to-barrier crash. This does suggest a level of uncertainty in the barrier determination approach with these cases representing about 10 percent of the available curve crashes.

## 7. Conclusions

The purpose of this study was to investigate motorcycle-to-barrier crash frequency on horizontally curved roadway sections in Washington State using police-reported crash data linked with roadway data. The available HSIS crash and roadway data was augmented with barrier presence information using a street view image approach. Data included 4915 horizontal curved roadway sections with 252 of these sections experiencing 329 motorcycle-to-barrier crashes between 2002 and 2011. Negative binomial regression was ultimately used to predict motorcycle-to-barrier crash frequency using available horizontal curvature and other roadway feature information.

The developed model results suggested isolated curves, decreases in curve radius, increases in traffic volume, and increases curve length increased the risk of motorcycle-to-barrier crashes on a given horizontal curve section. The strongest predictor of crash frequency was found to be curve radius which supports a motorcycle-to-barrier crash countermeasure placement criterion based, at the very least, on horizontal curve radius. With respect to the existing horizontal curve criterion of 820 feet or less (Elliot et al., 2003), curves meeting this criterion were found to increase crash frequency rate by a factor of 10 compared to curves not meeting this criterion. Curves with radius less than 500 feet were found to be more than 40 times more likely to experience a motorcycle-to-barrier crash than a curve with radius in excess of 2800 feet. Given curves of identical radius, the model results also suggested that longer curves, those with higher traffic volume, and those that have no adjacent curved sections within 300 feet of either curve end would likely be better candidates for a motorcycle-to-barrier crash countermeasure.

## Acknowledgements

The authors would like to acknowledge the FHWA staff for the provision of the HSIS data. This study was in part funded through National Cooperative Highway Research Program (NCHRP) Project 22-26.

## References

Abdel-Aty, M.A., Radwan, A.E., 2000. Modeling traffic accident occurrence and involvement. Accid. Anal. Prev. 32 (5), 633–642.
American Association of State Highway and Transportation Officials (AASHTO), 2011. A Policy on Geometric Design of Highways and Streets, sixth ed. AASHTO, Washington, DC.
Association of European Motorcycle Manufacturers (ACEM), 2004. MAIDS: In-Depth Investigation of Accidents Involving Powered Two Wheelers: Final Report, Version 2.0. Association of European Motorcycle Manufacturers (ACEM).
Bambach, M.R., Grzebieta, R.H., McIntosh, A.S., 2012. Injury typology of fatal motorcycle collisions with roadside barriers in Australia and New Zealand. Accid. Anal. Prev. 49, 253–260.
Berg, F.A., Rucker, P., Gartner, M., Konig, J., Grzebieta, R.H., Zou, R., 2005. Motorcycle impacts into roadside barriers – real world accident studies, crash tests, and simulations carried out in Germany and Australia. Proceedings of the 19th International Technical Conference on ESV, Washington, pp. 1–13.
Bryden, J.E., Fortuniewicz, J.S., 1986. Traffic barrier performance related to vehicle size and type. Transport. Res. Rec. 1065, 69–78.
Candappa, N., Mulvihill, C., Corben, B., Lenné, M., 2005. Ameliorating motorcyclist injury risk from flexible barrier collisions in Victoria. Proceedings of the Australasian Road Safety Research, Policing and Education Conference, Wellington, pp. 1–10.
Carson, J., Mannering, F., 2001. The effect of ice warning signs on accident frequencies and severities. Accid. Anal. Prev. 33 (1), 99–109.
Council, F.M., Mohamedshah, Y.M., 2009. Highway Safety Information System: Guidebook for the Washington State Data Files. Federal Highway Administration, Washington, DC.
Daniello, A., Gabler, H.C., 2011a. Fatality risk in motorcycle collisions with roadside objects in the United States. Accid. Anal. Prev. 43, 1167–1170.
Daniello, A., Gabler, H.C., 2011b. Effect of barrier type on injury severity in motorcycle-to-barrier collisions in North Carolina, Texas, and New Jersey. Transport. Res. Rec. 2262, 144–151.
Daniello, A., Gabler, H.C., 2012. Characteristics of injuries in motorcycle-to-barrier collisions in Maryland. Transport. Res. Rec. 2281, 92–98.
Domham, M., 1987. Guardrails and passive safety for motorcyclists. Proceedings of the Stapp Car Crash Conference, SAE Paper No. 870242 .
Elliot, M.A., Baughan, C.J., Broughton, J., Chinn, B., Grayson, G.B., Knowles, J., Smith, L. R., Simpson, H., 2003. Motorcycle safety: a scoping study. RL Report TRL581. Road Safety Division, Department of Transport.
Ellmers, U., 1997. Guardrail post-protection for improving the safety of motorcycle riders. Proceedings of the Traffic Safety on Two Continents Conference, Lisbon, Portugal, pp. 141–151.
Federal Highway Administration (FHWA), 2011a. HSIS: Highway Safety Information System. FHWA-HRT-11-031. US Department of Transportation, Washington, DC.
Federal Highway Administration (FHWA), 2011b. Highway Statistics 2011. US Department of Transportation, Washington, DC. https://www.fhwa.dot.gov/policyinformation/statistics/2011/.
Gabauer, D.J., 2014. Characterization of roadway geometry associated with motorcycle crashes into longitudinal barriers. J. Transport. Saf. Secur. doi:http://dx.doi.org/10.1080/19439962.2014.984886.
Gabler, H.C., 2007. The risk of fatality in motorcycle crashes with roadside barriers. Proceedings of the 20th International Technical Conference on ESV, Lyons, France Paper 07-0474.
Gibson, T., Benetatos, E., 2000. Motorcycles and Crash Barriers. NSW Motorcycle Council, Sydney.
Hell, W., Lob, G., 1993. Typical injury patterns of motorcyclists in different crash types – effectiveness and improvements of countermeasures. Proceedings of the 37th Annual Meeting of the Association for the Advancement of Automotive Medicine, San Antonio, Texas, pp. 77–98.
Jama, H.H., Grzebieta, R.H., Friswell, R., McIntosh, A.S., 2011. Characteristics of fatal motorcycle crashes into roadside safety barriers in Australia and New Zealand. Accid. Anal. Prev. 43 (3), 652–660.
Janssen, E., Scippa, A., Baldanzini, N., Pierini, M., 2005. Advanced Passive Safety Network (APSN): Standard and research activities conducted on motorcycles, infrastructure, protective clothing, and helmets. Report D12, Sixth Framework Program.
Kim, K., Boski, J., Yamashita, E., 2002. Typology of motorcycle crashes: rider characteristics, environmental factors, and spatial patterns. Transport. Res. Rec. 1818, 47–53.
Koch, H., Brendicke, R., 1988. Motorcycle accidents with guardrails. Proceedings of Road Safety in Europe, Gothenburg, Sweden.
Koch, H., Schueler, F., 1987. Reduction of injury severity involving guardrails by the use of additional w-beams, impact attenuators, and 'sigma-posts' as a contribution to the passive safety of motorcyclists. Proceedings of the 11th International Technical Conference on ESV 878–883.
Lee, A.H., Stevenson, M.R., Wang, K., Yau, K.K.W., 2002. Modeling young driver motor vehicle crashes: data with extra zeros. Accid. Anal. Prev. 34 (4), 515–521.
Miaou, S.-P., 1994. The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions. Accid. Anal. Prev. 26 (4), 471–482.
Mulvihill, C., Corben, B., 2004. Motorcyclist Injury Risk With Flexible Wire Rope Barriers and Potential Mitigating Measures. Monash University Accident Research Center.
Ouellet, J.V., 1982. Environmental hazards in motorcycle accidents. Proceedings of the 26th Annual Meeting of the American Association for Automotive Medicine, Ottawa, Canada, pp. 117–129.
Preusser, D.F., Williams, A.F., Ulmer, R.G., 1995. Analysis of fatal motorcycle crashes: crash typing. Accid. Anal. Prev. 27 (6), 845–851.
Quddus, M.A., Noland, R.B., Chin, H.C., 2002. An analysis of motorcycle injury and vehicle damage severity using ordered probit models. J. Saf. Res. 33, 445–462.
Quincy, R., Vulin, D., Mounier, B., 1988. Motorcycle impacts with guardrails. Transportation Research Circular 341. Transportation Research Board, pp. 23–28.
Savolainen, P., Mannering, F., 2007. Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes. Accid. Anal. Prev. 39 (5), 955–963.
Schneider, W.H., Savolainen, P.T., Moore, D.N., 2010. Effects of horizontal curvature on single-vehicle motorcycle crashes along rural two-lane highways. Transport. Res. Rec. 2194, 91–98.
Schneider, W.H., Savolainen, P.T., Zimmerman, K., 2009. Driver injury severity resulting from single-vehicle crashes along horizontal curves on rural two-lane highways. Transport. Res. Rec. 2102, 85–92.
Shankar, V., Mannering, F., Barfield, W., 1995. Effect of roadway geometrics and environmental factors on rural freeway accident frequencies. Accid. Anal. Prev. 27 (3), 371–389.
Shankar, V., Milton, J., Mannering, F.L., 1997. Modeling accident frequency as zero-altered probability processes: an empirical inquiry. Accid. Anal. Prev. 29 (6), 829–837.
Washington DOT, 2012. Design Manual – Volume 1: Procedures, Publication M 22-01, Engineering and Regional Operations.