Safety Effects of Horizontal Curve Design on Motorcycle Crash Frequency on Rural Two-Lane Undivided Highways in Florida

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ABSTRACT
The association between horizontal curve design (e.g., radius and type) on rural two-lane undivided highways and motorcycle crash frequency is not well-documented in existing reports and publications. This study aimed to investigate the effects of the design parameters and associated factors on the occurrence of motorcycle crashes considering the issue of unobserved heterogeneity. A random parameters negative binomial regression model was developed based on 431 motorcycle crashes, which were collected on 2,179 horizontal curves along two-lane undivided highways in Florida for a period of 11 years (2005–2015). Four normally-distributed random parameters (logarithm of curve radius, reverse curves, pavement condition, and rough pavement indicator) were identified to represent their heterogeneity caused by unobserved factors over time, space, and/or individuals. The major conclusions are the following: (1) An increase in curve radius, on average, significantly and near-logarithmically decreases the motorcycle crash frequency on rural two-lanes undivided highways. This effect is more significant when the curve radius is less than 2,000 ft. (2) 74.8% of reverse curves tend to decrease the motorcycle crash frequency on rural two-lane undivided highways; the remaining 25.2% have an opposite effect. On average, the likelihood of motorcycle crashes on reverse-curves is reduced by 39%. (3) The crash modification function (CMF) for curve radius on rural two-lane undivided highways was established, given the radius of 5,000 ft as the baseline, as a power formula, \( CMF = \left(\frac{Radius}{5000}\right)^{-0.208} \).

Keywords: Motorcycle, Crash frequency, Horizontal curve, Random parameters, Un-observed heterogeneity, Negative Binomial, Crash Modification Function/Factor
INTRODUCTION

In the United States, although motorcycles comprise only 3% of registered vehicle and less than 1% of vehicle miles traveled, the percentage of motorcyclist fatalities as a portion of total traffic deaths grew from 7% in 2000 to 14% in 2014 (1). As shown in a National Highway Traffic Safety Administration (NHTSA) report, motorcyclists in the US are 30 times more likely than car passengers to be fatally injured in traffic crashes (2). As the state with the second highest number of registered motorcycles, Florida has experienced a significant increase in the number of motorcyclist fatalities, from a record low of 246 in 2001 to 550 in 2015. According to the Florida Department of Health, in 2013, Florida hospitalization charges from motorcycle crashes exceeded $500 million (3). It is worth noting that motorcycle crashes are over-represented on horizontal curves in Florida, especially for fatal crashes. Curved roadway segments—comprising around 6% of total mileages in Florida—accounted for 57% of fatal single-motorcycle crashes and 36% of incapacitating single-motorcycle crashes (4).

Horizontal curves on rural two-lane undivided (RTU) highways are more dangerous to motorcyclists compared to other roadway facilities. Zegeer et al. (5) indicated that crash rates on horizontal curves are 1.5–4.0 times greater than those on tangents of rural two-lane highways. In addition, it has been estimated that there are more than 10 million horizontal curves in the US on two-lane highways alone (6).

The causes of safety hazards to motorcyclists on RTU horizontal curves are (7) (1) the relatively high speed and low standards of horizontal alignment design on RTU highways; (2) complex riding maneuvers required for negotiation of curves, e.g., turning maneuvers in limited space, counterweighting techniques, etc.; (3) reduced sight distance on curves that weaken rider perception; and (4) for some riders, the attraction of sharp curves to risk-seeking behavior for aggressive riders, especially on RTU highways. These factors may cause erroneous riding behaviors (e.g., underestimation of curve sharpness, excessive speed, erroneous lean angle, flawed trajectory, etc.) when negotiating curves, resulting in an increased number of motorcycle crashes on RTU curves. However, the occurrence of motorcycle crashes is a joint consequence from a complex process involving various factors, some of which can be observed (usually obtained from police accident reports or roadway characteristics inventories) and others cannot. The safety effect of a contributing factor may be random rather than fixed if heterogeneity (over time, space, or individuals) exists in unobserved factors that are related to the contributing factor (8).

Many efforts have been made to address motorcycle safety in terms of crash frequency (9–19) and injury severity (4, 7, 20–22). Previous studies on the factors contributing to motorcycle crash occurrence (frequency or crash rate) are summarized in Table 1. Only a few studies were found to investigate the relationship between horizontal curve design parameters and motorcycle crash occurrence. Schneider et al. (9) evaluated the impacts of horizontal curves and other geometric characteristics on the frequency of motorcycle crashes along rural two-lane highways in Ohio using the negative binomial model with the full Bayesian estimation. They found that both the radius and length of each horizontal curve significantly influence the occurrence of motorcycle crashes, and an increase of 1% in the radius tends to decrease average single-motorcycle crash frequency by 0.74%. Gabauer and Li (10) investigated motorcycle-to-barrier crash frequency on horizontally-curved roadway sections in Washington and concluded that curve length, traffic volume, and location of adjacent curves can significantly affect the occurrence of motorcycle-to-barrier crash. Chen et al. (11) conducted a motorcycle safety investigation at an exit ramp section and concluded that ramp type, ramp length, and reverse curvature are the major factors contributing to motorcycle crashes. In summary, the safety effects...
of RTU horizontal curve design parameters on motorcycle crash frequency were not well-documented. Thus, it is essential to seek insight into the association of horizontal curve design parameters (e.g., curve radius, length, and type) and motorcycle crash frequency.

### TABLE 1 Summary of Previous Studies on Motorcycle Crash Frequency

<table>
<thead>
<tr>
<th>Category</th>
<th>Factors</th>
<th>Effectiveness &amp; References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve Characteristics</td>
<td>Curve radius</td>
<td>1% increase in radius tends to decrease average single-motorcycle crash frequency by 0.74% (9). Horizontal curves of 820 ft or less increase average motorcycle-to-barrier crash frequency by factor of 10 compared to curves not meeting this criterion (10).</td>
</tr>
<tr>
<td></td>
<td>Curve type</td>
<td>Isolated curves—curves having no adjacent curved sections within 300 ft of either curve end—increase risk of motorcycle-to-barrier crashes (10).</td>
</tr>
<tr>
<td></td>
<td>Segment length</td>
<td>1% increase in curve length results in increase in average frequency of single-motorcycle crashes by 0.39% (9). Long horizontal curves increase motorcycle-to-barrier crashes (10). Increasing road length increases motorcycle crash frequency (12). 0.1-mile increase of ramp length will lead to 5% increase in motorcycle crashes occurring on ramps (11).</td>
</tr>
<tr>
<td>Geometric Characteristics</td>
<td>Number of lanes</td>
<td>Greater number of lanes decreases likelihood of intersection-related motorcycle crashes (13–15); additional lane increases number of motorcycle crashes occurring on four-legged signalized intersections by ~13% (16).</td>
</tr>
<tr>
<td></td>
<td>Lane width</td>
<td>Wider lane decreases likelihood of intersection-related motorcycle crashes (13, 15).</td>
</tr>
<tr>
<td></td>
<td>Shoulder width</td>
<td>Narrow shoulder (≤ 6 ft) increases average single motorcycle crashes by 52.24% (9). Likelihood of motorcycle crashes decreases with increase of shoulder width (13–15, 17).</td>
</tr>
<tr>
<td></td>
<td>Access density</td>
<td>Higher access density increases motorcycle crash frequency (12, 18).</td>
</tr>
<tr>
<td>Pavement Characteristics</td>
<td>Pavement roughness</td>
<td>Likelihood of motorcycle crashes increases with increase of International Roughness Index of pavement (14).</td>
</tr>
<tr>
<td>Traffic Characteristics</td>
<td>Annual average daily traffic (AADT)</td>
<td>1% increase in AADT results in increase of single-motorcycle crash frequency by 0.43% (9). Increasing AADT increases risk of motorcycle-to-barrier crashes (10), likelihood of intersection-related motorcycle crashes (13, 15, 16, 19), and motorcycle crash frequency (11, 12, 18).</td>
</tr>
<tr>
<td></td>
<td>Truck volume</td>
<td>2% increase in heavy vehicle traffic may increase motorcycle accidents by ~28% (17).</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>10 km/h increase in approach speed expected to cause 27% increase in non-signalized intersection-related motorcycle crashes (13); 5 mph increase in posted speed limit will result in 7% increase in ramp-related motorcycle crashes (11). Higher imposed speed limits increase likelihood of intersection-related motorcycle crashes (15, 16, 19). Higher speed or greater speed variation increase likelihood of motorcycle crashes (12, 17).</td>
</tr>
</tbody>
</table>

The primary objective of this study was to investigate the effects of horizontal curve design parameters on the occurrence of motorcycle crashes along RTU highways in Florida. This study aimed to (1) quantify the effects of horizontal curves on the occurrence of motorcycle crashes, (2) identify factors contributing to motorcycle crash frequency on horizontally-curved segments on RTU highways, and (3) address the unobserved heterogeneity issues in curve-related motorcycle crashes using a random-parameters model.

### DATA COLLECTION

The data set developed for this study was compiled from two major sources. Data from the first source, the Florida Roadway Characteristics Inventory (RCI) database, which contains
comprehensive roadway information, was scanned, and 8,597 horizontal curves with a 300-ft buffer on each end were identified. Among these horizontal curves, 2,492 horizontal curves are located on RTU highways. Curves in which a signalized intersection was present were excluded. Information on geometry, traffic, and pavement data were extracted from the RCI database for each identified RTU curve. The types of horizontal curve are classified as reverse curve and non-reverse curve. A reverse curve consists of two jointed simple curves, but curving in opposite directions. A non-reverse curve could be a simple curve or a compound curve that consists of two or more simple curves with deflections in the same direction immediately adjacent to each other. The types of horizontal curves are shown in Figure 1.

The second source was the Crash Analysis and Reporting (CAR) system maintained by the Florida Department of Transportation (FDOT). In total, 439 motorcycle crashes for 11 years (2005–2015) were spatially matched to the identified RTU horizontal curves. The descriptive statistics of the collected data are shown in Table 2.

### TABLE 2 Descriptive Statistics of Curvature, Geometric, Pavement, and Traffic Variables

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent Variable: number of motorcycle crashes per 11 years</td>
<td>0.198</td>
<td>0.581</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Logarithm value of curve radius in log (ft)</td>
<td>8.239</td>
<td>0.969</td>
<td>4.54</td>
<td>13.44</td>
</tr>
<tr>
<td>Reverse curve indicator (1 if reverse curve, 0 otherwise)</td>
<td>0.190</td>
<td>0.393</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Curve length in miles</td>
<td>0.350</td>
<td>0.225</td>
<td>0.08</td>
<td>6.07</td>
</tr>
<tr>
<td>Shoulder width in ft</td>
<td>11.928</td>
<td>2.766</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Auxiliary lane indicator (1 if auxiliary lane exists in curve segment, 0 otherwise)</td>
<td>0.024</td>
<td>0.153</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Grade indicator (1 if vertical grade is present, 0 otherwise)</td>
<td>0.114</td>
<td>0.318</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Access density: number of junctions per mile</td>
<td>3.026</td>
<td>4.731</td>
<td>0</td>
<td>48</td>
</tr>
<tr>
<td>11-year average pavement condition (scale 0–5)</td>
<td>3.798</td>
<td>0.420</td>
<td>2.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Pavement roughness indicator (1 if 11-year average international roughness index (IRI) is greater than 75 in./mi, 0 otherwise)</td>
<td>0.309</td>
<td>0.462</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Average annual daily traffic (AADT) in thousands of vehicles per day</td>
<td>4.269</td>
<td>2.959</td>
<td>0.46</td>
<td>25.18</td>
</tr>
</tbody>
</table>


STATISTICAL METHODOLOGY

A wide range of statistical regression methodologies has been developed to describe the relationship between crash frequency and a set of explanatory variables. These methodologies were comprehensively reviewed and assessed by two reviewed papers (23, 24). In this study, the random-parameters negative binomial (RPNB) model was used to assess the factors that determine the occurrence of motorcycle crashes.

Negative Binomial (Poisson-Gamma) Model

The negative binomial (NB) model is an extension of the Possion model to address over-dispersion in crash data (23, 24). The Possion regression model can be written as:

\[
P(y_i) = \frac{\exp(-\lambda_i)\lambda_i^{y_i}}{y_i!}
\]

where \( P(y_i) \) is the probability of curve segment \( i \) having \( y_i \) crashes per a given period and \( \lambda_i \) is the Possion parameter for curve segment \( i \), which is equal to curve segment \( i \)th expected number of crashes per a given period, \( E[y_i] \). The Possion regression model can be estimated by specifying the Possion parameter \( \lambda_i \) as a function of explanatory variables by typically using a log-linear function:

\[
\lambda_i = \exp(\beta X_i)
\]

where \( X_i \) is a vector of explanatory variables and \( \beta \) is the vector of regression coefficients (25). In this study, the Possion model is not appropriate because the mean (0.198) of motorcycle crashes is significantly less than the variance (0.338 = 0.581²). To address this over-dispersion issue, the NB model can be derived as

\[
\lambda_i = \exp(\beta X_i + \epsilon_i)
\]

where \( \exp(\epsilon_i) \) is a gamma-distributed error term with mean 1 and variance \( \alpha \). The addition of this term allows the variance to differ from the mean as \( \text{VAR}[y_i] = E[y_i][1 + \alpha E[y_i]] = E[y_i] + \alpha E[y_i]^2 \). The negative binomial probability density function can be described as

\[
P(y_i) = \left(\frac{1/\alpha}{(1/\alpha) + \lambda_i}\right)^{1/\alpha} \frac{\Gamma[(1/\alpha) + y_i]}{\Gamma(1/\alpha)y_i!} \left(\frac{\lambda_i}{(1/\alpha) + \lambda_i}\right)^{\gamma_i}
\]

where \( \Gamma(\cdot) \) is a gamma function.

Random-Parameters Negative Binomial Model

The occurrence of a motorcycle crash is a complicated outcome that involves complex interactions between human factors and roadway characteristics, vehicle features, traffic attributes, and environmental conditions (8). Sample data for crash modeling usually are retrieved from police accident reports and RCI files; it is impossible to include all factors influencing the occurrence of a traffic crash in these databases over time, space, and individuals. The unobserved factors, correlated with the observed variables, potentially can cause the issue of
unobserved heterogeneity—that is, differences among crash observations that are not measured. Traditional statistical methods (e.g., NB model) cannot address the issue of unobserved heterogeneity and may lead to biased and inconsistent parameter estimation, erroneous inferences, and inefficiency predictions (8). To resolve this issue, the random-parameters negative binomial (RPNB) model was developed to allow some parameters to vary across crash observations, rather than fixed in traditional models. The equation of regression coefficients for random parameters model is given as

$$\beta_i = \beta + \varphi_i$$ (5)

where $\varphi_i$ is a randomly distributed term with mean 0 and variance $\sigma^2$. With this, the log-likelihood function can be shown as

$$LL(\beta) = \sum \ln \int_{\varphi_i} f(\varphi_i) P_i(y_i | \varphi_i) d\varphi_i$$ (6)

where $f(\cdot)$ is the probability function of the $\varphi_i$. Since Equation 6 cannot be derived to a closed form, the simulated maximum likelihood approach with a Halton sequence was used to estimate the model parameters (26).

**Model Interpretation**

Unlike fixed parameters, the sign of a random parameter cannot be used directly to interpret the effect of the parameter. Alternatively, the probability of which parameter is positive or negative was used to indicate different influences on the occurrence of motorcycle crashes. Assume a random parameter ($\beta_i$) obeys a given distribution with parameter $\theta$, the probability of its coefficient $\beta_i < 0$ can be calculated as

$$P(\beta_i < 0) = F(\beta_i < 0 | \theta)$$

$$P(\beta_i > 0) = 1 - F(\beta_i < 0 | \theta)$$ (7)

where $F(\cdot)$ is the cumulative distribution function of the parameter $\beta_i$. The parameter effects can be interpreted as the likelihood of the parameter to decrease motorcycle crash frequency is $P(\beta_i < 0)$ and the likelihood to increase motorcycle crash frequency is $P(\beta_i > 0)$.

Marginal effects were used to quantify the impacts of an explanatory variable in the estimated model. For a continuous variable, marginal effects reflect the effect of a “one unit” change in the $k$th explanatory variable ($x_{ik}$) on the expected number of accidents ($\lambda_i$) per a given period for the $i$th observation (25). They can be computed as

$$ME_{x_{ik}}^{\lambda_i} = \frac{\partial \lambda_i}{\partial x_{ik}}$$ (8)

**MODEL ESTIMATION**

The software package NLOGIT 5 (27) was used to estimate the NB and RPNB models based on the collected data. In the estimation of the RPNB model, several assumptions (normal, lognormal, triangular, uniform distribution) on the random parameters’ distribution were tested for different variables using the simulated maximize likelihood approach. Finally, four normally-
distributed random parameters (curve radius, reverse curve, pavement condition, pavement roughness) were identified after 200 Halton draws.

A likelihood ratio test with the null hypothesis that two models are statistically equivalent was performed between the NB and RPNB models (25), as shown in Equation 9.

\[
\chi^2 = -2 [LL(\beta^{NB}) - LL(\beta^{RPNB})]
\] (9)

where \(LL(\beta^{NB})\) is the log likelihood at convergence of the NB model (-1075.03) and \(LL(\beta^{RPNB})\) is the log likelihood at convergence of the RPNB model (-1068.38). The chi-square statistic for the likelihood ratio test with four degrees of freedom gave a value greater than the 99% confidence limit (\(\chi^2 = 13.30\)). It indicates that the RPNB model is statistically superior to the corresponding NB model. The estimated RPNB model, along with average marginal effects, is presented in Table 3.

**TABLE 3 Random-Parameters Negative Binomial Regression Model for Motorcycle Crash Frequency on Rural Two-Lane Undivided Highways**

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Estimated Parameter</th>
<th>t-Statistic</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant</strong></td>
<td>-2.771</td>
<td>-3.78</td>
<td></td>
</tr>
<tr>
<td><strong>Curve characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logarithm value of curve radius in log(ft)</td>
<td>-0.208</td>
<td>-3.29</td>
<td>-0.027</td>
</tr>
<tr>
<td>Standard deviation of parameter distribution</td>
<td>(0.047)</td>
<td>(6.42)</td>
<td></td>
</tr>
<tr>
<td>Reverse curve indicator (1 if reverse curve presents, 0 otherwise)</td>
<td>-0.490</td>
<td>-2.61</td>
<td>-0.064</td>
</tr>
<tr>
<td>Standard deviation of parameter distribution</td>
<td>(0.734)</td>
<td>(4.78)</td>
<td></td>
</tr>
<tr>
<td><strong>Geometric characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary lane indicator (1 if auxiliary lane is present in curve segment, 0 otherwise)</td>
<td>0.777</td>
<td>2.59</td>
<td>0.101</td>
</tr>
<tr>
<td>Grade indicator (1 if vertical grade is present, 0 otherwise)</td>
<td>0.409</td>
<td>2.40</td>
<td>0.053</td>
</tr>
<tr>
<td>Access density: number of junctions per mile</td>
<td>0.061</td>
<td>5.10</td>
<td>0.008</td>
</tr>
<tr>
<td><strong>Pavement characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11-year average pavement condition (scale 0–5)</td>
<td>0.318</td>
<td>2.38</td>
<td>0.041</td>
</tr>
<tr>
<td>Standard deviation of parameter distribution</td>
<td>(0.034)</td>
<td>(2.21)</td>
<td></td>
</tr>
<tr>
<td>Pavement roughness indicator (1 if 11-year average international roughness index (IRI) is greater than 75 in./mi, 0 otherwise)</td>
<td>0.007</td>
<td>0.05</td>
<td>0.001</td>
</tr>
<tr>
<td>Standard deviation of parameter distribution</td>
<td>(0.507)</td>
<td>(4.86)</td>
<td></td>
</tr>
<tr>
<td><strong>Traffic characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average annual daily traffic (AADT) in thousands of vehicles per day</td>
<td>0.165</td>
<td>8.93</td>
<td>0.021</td>
</tr>
<tr>
<td><strong>Overdispersion parameter (\alpha)</strong></td>
<td>0.745</td>
<td>5.29</td>
<td></td>
</tr>
</tbody>
</table>

| Number of observations | 2179 |
| Log-likelihood with constant only | -1249.37 |
| Log-likelihood at convergence | -1068.38 |
| McFadden pseudo R-squared (\(\rho^2\)) | 0.145 |
DISCUSSION

Curve Radius and Type
The logarithm of the curve radius is a random parameter that is normally distributed, with a mean of -0.208 and standard deviation of 0.047. This indicates that increasing the curve radius nearly always decreases the motorcycle crash frequency (less than 0.05% of the distribution would have a positive value) but with varying magnitude across the population of RTU roadway segments. The increase of curve radius can reduce the risk factors for motorcyclists, such as speed variation, poor sight distance, and complexity of negotiation maneuvers. Schneider et al. (9) found a similar result, that sharper curves might attract motorcyclists who exhibit greater risk-taking behavior.

The reverse curve indicator produced a normally-distributed negative parameter with a mean of -0.490 and a standard deviation of 0.734, suggesting that for 74.8% of roadway segments, the presence of reverse curves tends to result in a decrease in motorcycle crash frequency. For the remaining roadway segments, the presence of reverse curves tends to result in an increase in motorcycle crash frequency. This is perhaps because a great portion of motorcycle riders (~74.8%) would become more alert and take safety-orientation behaviors (e.g., slow speed) to compensate for the difficulty of negotiating reverse curves. Other riders still suffer the risk caused by reverse curve, such as frequent adjustments of riding posture, poor sight distance, etc. Gabauer and Li (10) reported a similar finding, that the isolated curves (simple curves) increase the risk of motorcycle-to-barrier crashes but their effects are fixed. Marginal effects show that the presence of reverse curves results in an average 0.064 decrease in the number of motorcycle crashes per 11 years.

Figure 2 presents the expected motorcycle crash frequency (per 11 years) by curve radius and type, holding other factors at their average over sample observations. The relationship between motorcycle crash frequency and curve radius is near-logarithmic. The expected motorcycle crash frequency decreases rapidly with an increase in radius if the curve is sharp (radius < 1,000 ft). When the radius exceeds 1,000 ft but is less than 3,000 ft, the decrease slope is smaller than sharp curves but still higher than a flat curve (radius > 3,000 ft). It is also obvious that the presence of reverse curve can significantly decrease the motorcycle crash frequency at each radius level.
Since some geometric factors (e.g., shoulder width) may vary with the increase in curve length, curve length was not treated as an exposure variable that be assumed to have a linear relationship with expected crash frequency. The RPNB model shows that the length of horizontal curve is a positive fixed parameter, which indicates that the average number of motorcycle crashes increases with an increase in curve length because motorcycle riders would gain more exposure time with increase of curve length. This finding is in line with several previous studies (9, 12). The marginal effects show that a 1-mile increase in curve length on RTU highways results in an average increase of 0.138 motorcycle crashes per 11 years.

Geometric Characteristics
Auxiliary lanes, linking access points and, consequently, increasing potential traffic conflicts, were found to increase the probability of motorcycle crash occurrence on RTU curves. Marginal effects show that the presence of auxiliary lanes would increase the average number of motorcycle crashes on RTU highways by 0.101 (per 11 years).

The vertical grade variable produced a positive fixed parameter that increases motorcycle crash frequency by 0.053 crashes per 11 years. The interaction between horizontal curves and vertical slope can significantly decrease the sight distance and increase the complexity of riding maneuvers. The safety effects of horizontal curve and grade combinations on rural two-lane highways were discussed in a previous study (28) in which the authors found that short horizontal curves at sharp vertical curves are associated with higher crash frequencies for all vehicles.

The number of junctions (access points) per mile on horizontal curves is a positive fixed parameter, since high access density may introduce more traffic conflicts. This finding also is consistent with previous studies (12, 18). Marginal effects show that each additional junction per mile can result in an increase of 0.008 motorcycle crashes per 11 years on RTU roads.
Pavement Characteristics

The pavement condition variable ranges from 0 (completely deteriorated) to 5 (excellent pavement condition). This variable produced a normally-distributed negative parameter, with a mean of 0.318 and a standard deviation of 0.034, suggesting that for nearly all RTU curves, the number of motorcycle crashes increases when the pavement conditions become better. This finding seems counterintuitive and could be related to a variety of unobserved factors. For example, one possible unobserved factor is related to motorcyclist risk-compensation behavior; that is, motorcyclists who believe pavement quality is good tend to take risky behaviors, such as higher speed and less alertness. Similar findings about the effects of good pavement condition tending to increase vehicle crash frequency were found in two previous studies (29, 30).

Another indicator of pavement condition is the International Roughness Index (IRI), which measures roughness of road surface. In Florida, the IRI is measured in inches per mile, with lower values indicating a smoother surface. The RPNB model shows that a rough-pavement (IRI > 75 in./mi) is a random positive parameter, with a mean of 0.007 and a standard deviation of 0.507, suggesting that 50.6% of RTU curves with rough pavement tend to increase motorcycle crash frequency.

Traffic Volume

AADT has a positive fixed parameter, indicating that a growth of 1,000 vehicles per day increases the expected number of motorcycle crashes by 0.021 per 11 years. This finding is consistent with previous studies (11, 12, 18).

CRASH MODIFICATION FUNCTION

The crash modification function (CMF) for horizontal curve radius describes the risk of curve radius in terms of motorcycle crash frequency relative to a baseline. Assuming that the curve radius of 5,000 ft is the baseline, the crash modification function can be derived from the estimated model (Table 3) as

\[
CMF = \frac{\lambda(R_i | X)}{\lambda(R_0 | X)} = \frac{\text{EXP}(-0.208 \times \ln(R_i) + \hat{\beta}X)}{\text{EXP}(-0.208 \times \ln(R_0) + \hat{\beta}X)} = \left( \frac{R_i}{5000} \right)^{-0.208}
\]  

where \(\lambda(R_i | X)\) is the expected number of motorcycle crashes along curve segment \(i\) with radius \(R_i\); \(R_0\) is 5,000 ft, the baseline of CMF; -0.208 is the estimated parameter of radius in Table 3; \(X\) represents the vector of the other variables; and \(\hat{\beta}\) is the vector of estimated parameters for the other variables. The curve of the CMF for horizontal curve radius is shown in Figure 3. The CMF curve has a similar nonlinear tendency with the curve of curve radius—expected motorcycle crash frequency. The safety performance in reducing motorcycle crashes is more significant in the low range of curve radius. For example, the expected motorcycle crash frequencies for horizontal curves of 150, 500, and 1,000 ft are, respectively, 2.07, 1.61, and 1.40 times as many as the frequency for the radius 5,000 ft. In other words, if decreasing the radius from 5,000 ft to 150 ft, 500 ft, and 1,000 ft, the expected motorcycle crash frequency will increase by 107%, 61%, and 40%, respectively. If increase the radius from 5,000 ft to 6,000 ft, the percent of expected motorcycle crash frequency is only decreasing by 4%.
The crash modification factor for reverse curve indicates the relative change of expected motorcycle crash frequency comparing reverse curves with non-reverse curves (simple or compound curves, Figure 1).

\[
CMF = \frac{\lambda(\text{Reverse} | \vec{X})}{\lambda(\text{Non-reverse} | \vec{X})} = \frac{\exp(-0.490 \times 1 + \beta \vec{X})}{\exp(-0.490 \times 0 + \beta \vec{X})} = \exp(-0.490) \approx 0.61 \tag{11}
\]

where \(\lambda(\text{Reverse} | \vec{X})\) is the expected number of crashes along a reverse curve; \(\lambda(\text{Non-reverse} | \vec{X})\) is the expected number of crashes along a non-reverse curve; -0.490 is the estimated parameter of reverse curve in Table 3; \(\vec{X}\) represents the vector of the other variables; and \(\vec{\beta}\) is the vector of estimated parameters for the other variables. The crash modification factor of curve type indicates that the number of motorcycle crashes would decrease 39% when a reverse curve is present on RTU roads.

**CONCLUSIONS AND RECOMMENDATIONS**

This study quantified the effects of horizontal curve parameters and contributing factors on the occurrence of motorcycle crashes on rural two-lane undivided (RTU) roads using the random parameters negative binomial (RPNB) model. Based on the discussion, the following conclusions can be obtained:

- Horizontal curve radius significantly influences motorcycle crash occurrence on RTU roads. Although curve radius is a random parameter, nearly all RTU curves (>99%) tend to decrease motorcycle crash frequency with an increase in curve radius. The average marginal effects of horizontal curve radius suggest a logarithmic association between curve radius and motorcycle crash frequency: the expected motorcycle crash frequency decreases (increases) rapidly with an increase (decrease) in curve radius when the curve

**FIGURE 3 Crash Modification Function by Curve Radius**

The crash modification factor for reverse curve indicates the relative change of expected motorcycle crash frequency comparing reverse curves with non-reverse curves (simple or compound curves, Figure 1).
radius in a low range; this trend (decrease) becomes progressively slower with the radius increase.

- Based on the developed RPNB model, the crash modification function (CMF) for horizontal curve radius on RTU roads was established as a power function of the quotient of curve radius \( CMF_{\text{for Radius}} = \left(\frac{R}{5000}\right)^{0.208} \).

- Reverse curve was identified as a random parameter. On 74.8% of roadway segments, the presence of a reverse curve tends to result in a decrease in motorcycle crash frequency. On average, the presence of a reverse curve decreases the expected motorcycle crash frequency on RTU roads by 39% \( (CMF_{\text{for Reverse Curve}} = 1 – 39\% = 61\%) \).

- The presence of auxiliary lanes, vertical slope, high access density, and growth of AADT can significantly increase the number of motorcycle crashes. Pavement condition and rough pavement indicator were found to have random effects on motorcycle crashes caused by unobserved factors over time, space, and individuals. The number of motorcycle crashes tends to increase on nearly all RTU curves with good pavement conditions and 50.6% of RTU curves with rough pavement. This finding revealed motorcyclist significant risk-compensation behaviors with high-quality pavement on horizontal curves.

- It is interesting to compare the effects of horizontal curve design between frequency and severity. A random parameter negative binomial (RPNB) model, predicting the frequency of all motorcycle crashes on rural two-lane undivided horizontal curves, shows that sharp curves \( (\text{radius}<1,500\ \text{ft}) \) are more likely to increase both the likelihood of motorcycle crash occurrence and the probability of motorcycle crash severe injury on horizontal curves. Curve type has different impacts: reverse curves tend to decrease the likelihood of motorcycle crash frequency on curves and increase the probability of severe injury in a single-motorcycle crash on curves. Similarly, good pavement conditions tend to increase motorcyclist safety-compensation effects, thus raising both motorcycle crash frequency and severity on horizontal curves.

### Recommendations

A strategic framework from 3Es (Engineering, Education, and Enforcement) is necessary to be developed for addressing the motorcycle safety issues identified in this study. As described in “FHWA-SA-15-084 Low-Cost Treatments for Horizontal Curve Safety 2016” \( (31) \), various engineering countermeasures (e.g., pavement markings, traffic control signs, pavement treatments, roadside improvements, ITS devices) have been developed to alert motorists of the presence and/or risk of horizontal curves and control their speed/trojectory in curve negotiation.

However, these treatments that aim to improve vehicle safety on curves are not necessarily aimed to be motorcycle-friendly because of the special characteristics and significant risk-compensation of motorcycles and motorcyclists. Additional assessments on these treatments are required for implementing motorcycle-friendly treatments to improve road safety on horizontal curves.

Education programs (e.g., training courses, education campaigns, safety coalitions) are effective for improving motorcyclist behaviors in curve negotiation, which is the primary contributing factor in a motorcycle crash. Education programs aim to (1) increase rider awareness on the risk of horizontal curves, (2) improve rider skills in negotiation with horizontal curves, and (3) alleviate injury severity by using safety equipment. Enforcement, especially for speeding, also is effective in reducing motorcycle crash and fatalities on horizontal curves.
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