Correlation between crash avoidance maneuvers and injury severity sustained by motorcyclists in single-vehicle crashes

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Objective: In order to improve motorcycle safety, this article examines the correlation between crash avoidance maneuvers and injury severity sustained by motorcyclists, under multiple precrash conditions.

Method: Ten-year crash data for single-vehicle motorcycle crashes from the General Estimates Systems (GES) were analyzed, using partial proportional odds models (i.e., generalized ordered logit models).

Results: The modeling results show that "braking (no lock-up)" is associated with a higher probability of increased severity, whereas "braking (lock-up)" is associated with a higher probability of decreased severity, under all precrash conditions. "Steering" is associated with a higher probability of reduced injury severity when other vehicles are encroaching, whereas it is correlated with high injury severity when motorcycles are traveling off the edge of the road. The results also show that a large number of motorcyclists did not perform any crash avoidance maneuvers or conducted crash avoidance maneuvers that are significantly associated with high injury severity.

Conclusions: In general, this study suggests that precrash maneuvers are an important factor associated with motorcyclists' injury severity. To improve motorcycle safety, training/educational programs should be considered to improve safety awareness and adjust driving habits of motorcyclists. Anti-lock brakes and such systems are also promising, because they could effectively prevent brake lock-up and assist motorcyclists in maneuvering during critical conditions. This study also provides valuable information for the design of motorcycle training curriculum.

Introduction

Motorcyclists are much more vulnerable, compared to other passenger car occupants. The injury and fatality rates of motorcyclists were 30 and 5 times higher than those of passenger car occupants in the United States in 2011 (NHTSA 2011). Thus, motorcycle safety needs to be improved.

Over the past few years, an ample body of research has been done on motorcycle crashes, in terms of examining factors associated with crash risk and injury severity of motorcyclists. The related factors include alcohol and drug use (Chang and Astrachan 1988; Hundley et al. 2004; Lin and Kraus 2009; Luna et al. 1984; NHTSA 2011; Savolainen and Mannering 2007b; Waller et al. 1986; A. F. Williams 2006; Zambon and Hasselberg 2006); night, dawn, and weekends (Donate-Lopez et al. 2007); young drivers (Baker et al. 1992; Keall and Newstead 2012; Lardelli-Claret et al. 2005; Lin et al. 2003); male drivers (Donate-Lopez et al. 2010); fuel system leaks and low conspicuity (Hurt et al. 1981); speeding (Riffat et al. 2012); intersections (Clabaux et al. 2012; de Lapparent 2006); few riding experiences (Lin et al. 2003; Lin and Kraus 2009; Wong et al. 1990); failure to use headlights (Quddus et al. 2002; Yuan 2000); driving without a license (Dandona et al. 2006; NHTSA 2011; Reeder et al. 1996); failure to wear a helmet (Eastridge et al. 2006; Goslar et al. 2008; Hundley et al. 2004; Kelly et al. 1991); horizontal and vertical curves; and divided highways (Geedipally et al. 2011). It should be noted that mixed results were also found for some of the factors. For instance, motorcyclists with more riding experience were more likely to be involved in severe crashes (Savolainen and Mannering 2007b), possibly due to their lower risk perception and greater self-confidence (Lin et al. 2009). Adverse road conditions were found to be correlated with a reduced risk of motorcycle injuries (Quddus et al. 2002), possibly due to failure to consider exposures (Fuster et al. 2013).

Although motorcycle safety has been widely studied, there are still some potentially important factors that need to be examined. Precrash avoidance maneuvers are such a factor that deserves more research attention (Kuang et al. 2015). Regarding precrash avoidance behaviors, Kaplan and Prato (2012)
conducted a statistical analysis to examine how they are correlated with injury severity sustained by drivers in single-vehicle crashes. It was found that the majority of drivers failed to apply evasive actions before crashes. Moreover, most drivers failed to take the evasive actions correlated with decreased injury severity. These findings are considered to be useful for developing educational programs and precrash warning systems. However, Kaplan and Prato (2012) excluded motorcycle crashes from their study, because they pointed out that motorcyclists need to be examined separately, due to the differences in maneuvering. In order to fill the gap, this research is conducted to explore the relationship between injury severity of motorcyclists and their precrash avoidance maneuvers.

**Method**

**Data**

The General Estimates Systems (GES) crash database, maintained by the NHTSA’s National Center, were used for this study. The GES database is considered a reliable data source for crash modeling (Daniello and Gabler 2011; Kaplan and Prato 2012). Data were collected from the police accident reports from 400 police agencies and then recoded by trained personnel. Data were initially examined to ensure validity and consistency during the coding phase. After coding, a full examination was conducted to make reliable and trustworthy data available to researchers, manufacturers, insurance companies, and governments. It contains probability samples from roughly 6 million annual police-reported crashes in the United States. Thus, the national crash characteristics can be estimated from the probability samples, using a weight variable provided by the GES, which is the inverse of the probabilities of selection in the sampling process.

More than 10,000 single-vehicle motorcycle crashes from years 2001 to 2010 were extracted from the GES. Crash records including unknown or missing values were excluded (N = 6,653), resulting in a total of 3,440 available records (the unweighted data), representing 153,324 motorcyclists (the weighted data) involved in crashes. It should be noted that most crashes were excluded because they lack the details on precrash conditions (e.g., critical events or crash avoidance maneuvers). Because the GES database is based on nationwide police-reported data, precrash conditions and maneuvers were identified based on on-site witnesses and obvious field evidence. If these were missing or unclear, details could not be recorded. Thus, it is reasonably believed that the remaining 3,440 cases were mostly accurately reported. The remaining cases were also compared with the excluded cases. Chi-square tests were conducted and there were no statistically significant differences in the distribution of injury outcomes between the two. Thus, the remaining cases can be considered valid.

The available crash records were further divided into 4 groups per a coded variable “critical events,” which refers to the events leading to the vehicle’s first impact (no secondary events are considered). The 4 groups are “loss of control” (N = 943), “traveling off the edge of the road” (N = 637), “other vehicle encroaching” (N = 1,505), and “animal encounter and object presence” (N = 355). For each group, a statistical analysis was applied to examine the correlation between injury severity and precrash actions of motorcyclists. The precrash actions in the GES were coded as the variable “crash avoidance maneuvers.” In this study, crash avoidance maneuvers were classified into 6 types: “no avoidance maneuvers,” “braking (lock-up),” “steering,” “braking and steering,” and “other maneuvers.” The other maneuvers category includes accelerating, accelerating and steering, and actions that were not recorded in detail. All precrash actions were determined by police based on on-site witnesses and field evidence. Note that “braking” and “steering” are both sole maneuvers, whereas “braking and steering” is a combined maneuver. Thus, although the 3 could be somewhat correlated, they are mutually exclusive.

**The model**

In this study, injury severity of motorcyclists is coded on a 4-point scale from the lowest to the highest level: 0 = no and slight injury, 1 = nonincapacitating injury, 2 = incapacitating injury, and 3 = fatality. Though previous research (Farmer 2003) indicated that police-reported data may suffer from the misclassification of injury severity, it is still believed that the GES data are carefully prescreened and coded to ensure validity and reliability. Moreover, because motorcyclists are more vulnerable than drivers of other vehicles due to less protection, the signs of injuries could be more evident. There is still no clear evidence in research that motorcyclists’ injury severity is largely misrepresented. Thus, injury categories in this study are not combined in order to explore relationships between factors and various severity levels. In fact, the relationship between a factor and any pair of injury outcomes (i.e., injury severity) could vary, and this study attempts to reveal such relationships by incorporating partial proportional odds models.

Because injury severity is a categorical and ordinal variable, a proportional odds model is more suitable than binary and multinomial models, which ignore the ordering of categories. (Jang et al. 2010). An ordered logit model is a proportional odds model that can be specified as

\[
P(y_i > j) = \frac{\exp (X_i \beta - \mu_j)}{1 + \exp (X_i \beta - \mu_j)}; \ j = 1, 2, \ldots, M - 1, \ (1)
\]

where \( j \) is a category of injury severity, \( X_i \) is a vector of explanatory variables, \( \beta \) is a vector of parameters of explanatory variables that need to be estimated, \( \mu_j \) are cut points for the thresholds of the ordered logit model, and \( M \) is the number of categories for the response variables.

For proportional odds models, there is an important assumption that the relationship between any pair of outcome categories is equal. If this assumption, also called the parallel line assumption, is violated by some of explanatory variables, the proportional odds model can lead to incorrect, incomplete, or even misleading results (Kaplan and Prato 2012). In this case, a partial proportional odds model can be used to address this issue. Partial proportional odds models are less restrictive than proportional odds models (e.g., ordered logit and ordered probit models), which require all variables to follow the parallel line assumption, and more parsimonious than binary models.
and multinomial logit/probit models, which do not consider the ordering of categories (R. Williams 2006). For a partial proportional odds model (e.g., a generalized ordered logit model), the probability of crash injury for a given crash can be specified as

\[
P(y_i > j) = \frac{\exp(X_i^j \beta_1 + X_i^j \beta_2 - \mu_j)}{1 + \exp(X_i^j \beta_1 + X_i^j \beta_2 - \mu_j)}; \quad j = 1, 2, \ldots, M - 1, \tag{2}
\]

where \( \beta_1 \) is a vector of parameters that does not violate the parallel line assumption and is associated with a subset of explanatory variables \( (X_i) \), and \( \beta_2 \) is a vector of parameters that vary according to the cut point of the partial proportional odds model and is associated with a subset of other explanatory variables \( (X_i) \).

The probability of injury severity has a closed-form expression and maximum likelihood allows model estimations by incorporating weights (i.e., weighted sample data; Williams 2006). The log-likelihood function can be expressed by

\[
\ln (L) = \sum_{n=1}^{N} \sum_{j=1}^{J} k_{nj} w_n \ln P(y_i > j) \tag{3}
\]

where \( \ln(L) \) is the log-likelihood function, \( w_n \) is the GES weight of crash \( n \), \( k_{nj} \) is equal to 1 if crash \( n \) results in severity level \( j \) and 0 otherwise, and \( N \) is the number of crashes. The GES weights are normalized to make their sum equal to the total number of observations.

The likelihood ratio index, which is called the pseudo \( R^2 \) measure, can be calculated by (Train 2003)

\[
R^2 = 1 - \frac{\ln L_a}{\ln L_0} \tag{4}
\]

where \( \ln L_a \) is the log-likelihood value of the models with all predictors, and \( \ln L_0 \) is the log-likelihood value of the models without predictors (i.e., intercept only). The pseudo \( R^2 \) is improved when the value of the index increases from 0 to 1.

The Akaike information criterion (AIC) is used to measure the model fit (Train 2003):

\[
AIC = 2k - 2\ln (L_a) \tag{5}
\]

where \( k \) is the total number of estimated parameters.

**Results**

In the study, partial proportional odds models with logit functions (i.e., generalized ordered logit models) were developed for the 4 event groups, considering the weighted crash data. According to previous research by Kaplan and Prato (2010), separate models were built instead of an integrated model, considering that the relationships between precrash maneuvers and injury severity could vary by event type. The modeling results also prove such differences. Partial proportional odds models with probit functions were also applied to fit the data. By comparing AIC, partial proportional odds models with logit functions were determined to be better with lower AIC values for all four event groups. The parallel line assumptions for each variable were tested using a series of Wald tests. A description of the characteristics of the weighted data is shown in Table A1 (see online supplement). The modeling results are shown in Tables 1, 2, 3, and 4, where factors with \( P \)-values less than .05 were determined to be significant and included. The coefficients indicate how factors are correlated with injury severity of motorcyclists: A positive value means that the factor is associated with increased injury severity; a negative value indicates that the factor is associated with decreased injury severity.

**Loss of control**

Table 1 shows the modeling results for loss of control events. Braking (no lock-up) is associated with a higher probability of decreased injury severity, with strengthened effect of increasing severity levels. Steering and breaking (lock-up) are correlated with a higher probability of increased injury severity, with a heightened effect trending toward higher severity levels. The finding could be reasonable. When a motorcyclist loses control of his motorcycle, he could panic and thus take actions such as oversteering or excessive braking. Such actions could lead to the lock-up of motorcycle wheels. To be more specific, oversteering could cause the rear wheel to slip because the forces required for motorcycle equilibrium exceed the tire friction. In this case, the motorcycle could easily fall to the ground (Cossalter 2006). Similarly, excessive braking could lock both the front and rear wheels. Thus, the rear wheel would skid and the front wheel would easily tuck under, causing the motorcyclist to fall off (New Zealand Motorcycle Safety Consultants 2013). On the contrary, if the motorcyclist were able to successfully control the speed without brake lock-up, the risk of being severely injured could be reduced. Note that precrash speed could be correlated with

| Variable | Categories | 0 and 1 | 1 and 2 | 2 and 3 |
|----------|------------|--------|--------|--------|
| Road alignment | Curve | 0.083 | 0.083 | 0.083 |
| Road profile | Straight\(^a\) | — | — | — |
| Grade | Level\(^b\) | 0.588 | 0.588 | 0.588 |
| Surface condition | Slippery | 0.441 | 0.441 | 0.441 |
| Weather condition | Dry\(^b\) | — | — | — |
| Alcohol | Alcohol related | 0.337 | 0.455 | 0.721 |
| Helmet | No alcohol\(^b\) | — | — | — |
| Helmet use | No helmet | 0.295 | 0.411 | 0.498 |
| Field of vision | Helmet obstruction | 0.623 | 0.601 | 0.704 |
| Lighting | Clear sight\(^b\) | — | — | — |
| Daylight\(^b\) | Dark, no light | 0.355 | 0.332 | 0.471 |
| Avoidance maneuver | Braking no lock-up | — | — | — |
| Braking lock-up | — | — | — |
| Steering | 0.183 | 0.332 | 0.621 |
| No maneuvers\(^b\) | — | — | — |
| Log likelihood | Pseudo \( R^2 \) | —74,032.630.2648943 | — |

\(^a\) = none or slight, \(^b\) = incapacitating, \( 2 = \) incapacitating, \( 3 = \) fatal. \( \text{Base category.} \)
Table 2. Partial proportional odds model estimates—critical event: Traveling off the edge of the road.

| Variable              | Categories         | Coefficient\(^b\) between |
|-----------------------|--------------------|---------------------------|
| Road alignment        | Curve              | 0.284                     |
|                       | Straight\(^b\)     | —                         |
| Road profile          | Grade              | 0.196                     |
|                       | Level\(^b\)        | —                         |
| Surface condition     | Slippery           | 0.651                     |
|                       | —                  | 0.721                     |
|                       |                    | 1.017                     |
| Weather condition     | Dry\(^b\)          | —                         |
|                       | Adverse            | 0.762                     |
| Alcohol               | Nonadverse\(^b\)   | —                         |
|                       | Alcohol related    | 0.420                     |
|                       | No alcohol\(^b\)   | —                         |
| Helmet                | No helmet          | 0.166                     |
|                       | Helmet use\(^b\)   | —                         |
| Field of vision       | Obstruction        | 0.485                     |
|                       | Clear sight\(^b\)  | —                         |
|                       | Dark, no light     | 0.431                     |
|                       | Daylight\(^b\)     | —                         |
| Avoidance maneuver    | Braking no lock-up | −0.503                    |
|                       | Braking lock-up    | −0.532                    |
|                       | Steering           | 0.361                     |
|                       | Braking and steering | 0.428                  |
|                       | No maneuvers\(^b\) | —                         |
| Log likelihood        |                    | −54,023,240.2883637       |
| Pseudo \(R\)^2        |                    |                           |
| Number of crashes     |                    |                           |

\(^a\)= none or slight, \(1=\) nonincapacitating, \(2=\) incapacitating, \(3=\) fatal. \(^b\)= Base category.

Table 3. Partial proportional odds model estimates—critical event: Other vehicle encroaching.

| Variable              | Categories         | Coefficient\(^b\) between |
|-----------------------|--------------------|---------------------------|
| Road alignment        | Curve              | 0.196                     |
|                       | Straight\(^b\)     | —                         |
| Road profile          | Grade              | 0.179                     |
|                       | Level\(^b\)        | —                         |
| Surface condition     | Slippery           | 0.320                     |
|                       | —                  | 0.320                     |
|                       |                    | 0.320                     |
| Weather condition     | Dry\(^b\)          | —                         |
|                       | Adverse            | 0.669                     |
| Alcohol               | Nonadverse\(^b\)   | —                         |
|                       | Alcohol related    | 0.729                     |
|                       | No alcohol\(^b\)   | —                         |
| Helmet                | No helmet          | 0.272                     |
|                       | Helmet use\(^b\)   | —                         |
| Field of vision       | Obstruction        | 0.248                     |
|                       | Clear sight\(^b\)  | —                         |
|                       | Undivided          | 0.221                     |
|                       | Divided\(^b\)      | —                         |
| Avoidance maneuver    | Braking no lock-up | −0.479                    |
|                       | Braking lock-up    | 0.216                     |
|                       | Steering           | −0.232                    |
|                       | Other              | −0.203                    |
|                       | No maneuvers\(^b\) | —                         |
| Driver's age          | <25                | 0.292                     |
|                       | 25–34              | 0.194                     |
|                       | >54\(^b\)          | —                         |
| Log likelihood        |                    | −134,342.060.18361505     |
| Pseudo \(R\)^2        |                    |                           |
| Number of crashes     |                    |                           |

\(^a\)= none or slight, \(1=\) nonincapacitating, \(2=\) incapacitating, \(3=\) fatal. \(^b\)= Base category.

Brake lock-up. Unfortunately, precrash speed cannot be examined because such data are largely missing in the GES.

Other factors are also correlated with injury severity of motorcyclists. Among them, uneven roads, adverse weather, slippery road surfaces, visual obstructions, alcohol consumption, failure to wear a helmet, and dark roads without lighting are significantly associated with higher probability of high injury severity. Those findings are consistent with prior research (Geedipally et al. 2011; Goslar et al. 2008; Williams 2006).

**Traveling off the edge of the road**

Table 2 shows the estimates for traveling off the edge of the road events. Braking (no lock-up) is associated with a higher probability of reduced injury severity, whereas braking (lock-up) is associated with a higher probability of high injury severity.

Steering is significantly associated with a higher probability of high injury severity, with a weakened effect in the transition toward higher severity levels. Braking and steering is correlated with a higher probability of increased injury severity. This finding is surprising because we believe that a combination of braking and steering could effectively reduce injury severity. More details of this maneuver type could help to reveal true effects of this factor and other unobserved factors. The results here indicate that any precrash maneuvers associated with steering could be linked to increased injury severity of motorcyclists.

Curvy roads, uneven roads, slippery road surface, adverse weather, alcohol consumption, failure to wear a helmet, visual obstruction, undivided roads, and dark roads without lighting are also significantly correlated with increased risk of more severe injuries.

**Other vehicle encroaching**

Table 3 presents the modeling results for other vehicle encroaching events. Braking (no lock-up) is correlated with higher probability of low injury severity. Steering and other maneuvers are both associated with higher probability of decreased injury severity, with a weakened and constant effect trending toward higher severity levels. Braking (lock-up) is linked to higher probability of high injury severity. Braking and steering was not found to be significantly correlated with motorcyclists’ injury severity. Noted that because the GES database does not include details on braking and steering, mechanical failures such as brake lock-up could occur during the maneuver, causing this type to be insignificant. Again, more details may help to better reveal the implication of such maneuvers.

Other variables were also found to be significant. Among them, curvy roads, uneven roads, slippery road surface, adverse weather, alcohol consumption, failure to wear a helmet, visual
Table 4 shows the modeling results for animal encounter and object presence. As expected, braking (no lock-up) is associated with higher probability of decreased injury severity, with a bolstered effect trending toward higher severity levels. Though simply braking may not always be safe to avoid collisions, it could effectively lower precrash speed and thus mitigate injury severity. Braking (lock-up) is linked to higher probability of high injury severity, with a heightened effect in the transition toward higher severity levels. As discussed earlier, brake lock-up could cause motorcycles to skid uncontrollably and fall to the ground.

Steering is associated with higher risk of high injury severity. When there are unexpected animals/objects in front of a motorcyclist, he could be caught off guard and oversteer at high speed, easily causing the motorcycle to unbalance. Moreover, without applying brakes, high precrash speeds could result in severe injuries when the motorcyclist hits the ground. Again, precrash speed data are largely missing, preventing us from exploring the relationships among precrash speed, maneuver type, and injury severity. Braking and steering and other maneuvers are both correlated with higher probability of low injury severity.

Other factors, including curvy roads, uneven roads, slippery road surface, adverse weather, younger motorcyclists, alcohol consumption, failure to wear a helmet, visual obstruction, and dark roads without lighting were found to be significantly correlated with increased probability of severe injuries, and motorcyclists who drive on weekends are less likely to be involved in severe crashes.

Discussion

This study examined the correlation between injury severity sustained by motorcyclists and their precrash actions using 10-year data on single-vehicle motorcycle crashes from the GES database. Partial proportional odds models (i.e., generalized ordered logit models) were developed separately for 4 precrash critical event types: loss of control, traveling off the edge of the road, other vehicle encroaching, and animal encounter and objects presence.

According to the modeling results, braking (no lock-up) is associated with a higher probability of lower injury severity, whereas braking (lock-up) is correlated with higher chances of increased injury severity, across all event types. Steering appears to be dangerous to motorcyclists under most precrash conditions, including traveling off the edge of the road, other vehicles encroaching, and animal encounter and objects presence. Braking and steering is associated with a higher probability of decreased injury severity when motorcyclists encounter animals or objects ahead. However, when motorcycles travel off the edge of the road, braking and steering is linked to a higher probability of increased injury severity.

It should be noted that motorcyclists were largely found to fail to react before crashes. To make it worse, many motorcyclists took evasive actions significantly associated with high injury severity. For instance, when loss of control occurred, 61.3% of the motorcyclists did not react and 13.9% reacted in such a way as to cause braking lock-up. Only 12.1% of the motorcyclists managed to apply brakes without causing lock-up. For the event animal encounter and object presence, only 3.7% of the motorcyclists made the attempts of braking and steering, correlated with low injury severity, whereas 24.8% of motorcyclists conducted steering, associated with high injury severity.

The findings suggest that motorcycle safety could be improved if motorcyclists better understood the safety implications of precrash actions under various conditions and adjusted their current driving habits. Educational/training programs may be considered as an option. It should be recognized that mixed results have been found on the effectiveness of motorcycle training programs. Some previous studies have shown that motorcycle training is effective in improving motorcycle safety (Baer et al. 2005; Baldi et al. 2005; Billheimer 1998; Davis 1997; McDavid et al. 1989), whereas others found otherwise (Jonah et al. 1982; Mayhew 2007; Rutter and Quine 1996; Savolainen 2007). Thus, one may argue that there was no concrete evidence that training
programs are necessary to improve motorcycle safety. Nevertheless, motorcyclists are strongly recommended to take training programs due to the following reasons:

1. In this study, motorcyclists were largely found to take no or even high risk-associated maneuvers, increasing their risks of being injured. In recent years, training programs have been proven to increase the use of protective equipment among motorcyclists (Mortimer 1998; Savolainen and Mannering 2007a) and adjust hazards perception and riding maneuvers (Crundall et al. 2014; Woratanarat et al. 2013), indicating its potential to increase motorcycle safety.

2. Instead of examining training curriculums, according to Haworth et al. (1999), previous evaluations on training programs are typically based on changes in crash rates. Daniello et al. (2009) also concluded that the findings of previous studies could be a reflection of the methods rather than the effectiveness of training itself. To date, few investigations were conducted directly on training curriculums to justify their effectiveness. According to our study, under different critical conditions, different types of crash avoidance behaviors could be correlated with varied injury outcomes. Thus, improved curriculum targeting training motorcyclists under specific critical conditions may help them develop required skills and driving habits to avoid crashes or alleviate injury severity. Moreover, training curricula need to be carefully designed and they can benefit from the results of this research as an input for the design of experiments.

3. According to Baldi et al. (2005), states in the United States have their own training programs, indicating different levels of training quality. Thus, it is necessary to develop a high-quality nationwide training program quality. The research has provided valuable information for developing a standard driving program, as well as driving guidance, under emergency conditions for motorcyclists.

In addition, motorcycle equipment should be considered. Anti-lock brakes have been proven to effectively prevent brake lock-up and thus mitigate injury severity (Rizzi et al. 2009; Roll et al. 2009; Teoh 2011). However, such equipment has not been globally deployed. Because brake lock-up has been found to be associated with high injury severity across all precrash conditions, anti-lock brakes are suggested to be mandatorily deployed. Similar systems, such as following distance warning systems, roll stability systems, and electronic stability control systems, could also be considered for motorcycles. A collision warning system has been deployed in Yamaha’s ASV-2 prototype vehicles (Bayly et al. 2007). Such systems are expected to assist motorcyclists in avoiding crashes.

In general, this study suggests that precrash maneuvers are an important factor associated with motorcyclists’ injury severity. To improve motorcycle safety, training/educational programs should be considered to improve safety awareness and adjust driving habits of motorcyclists (according to some previous research). Anti-lock brakes and similar systems are also promising, because they could effectively prevent brake lock-up and assist motorcyclists in maneuvering during critical conditions. This study provides valuable information for the design of motorcycle training curriculum. Some limitations should also be recognized. First, the statistical models in this study only explain correlations instead of causation. Thus, further in-depth studies should be focused on the effectiveness of the suggested avoidance maneuvers. Second, the correlation between braking and steering and injury severity needs to be further examined. The current crash records and details of such maneuvers are very limited. It is believed that such a maneuver is much more complicated than other types because it combines 2 major evasive actions. Third, some factors may not be considered in the study, such as precrash speed, motorcycle size, and improved motorcycle technology. Those factors, as well as some explanatory variables, may be correlated with injury severity. Unfortunately, the current GES does not include those variables. Fourth, because there is no variable indicating the information of motorcycle training in the GES database, the correlation between training and injury severity cannot be directly revealed. Different training programs need to be thoroughly and carefully investigated for their true safety effects. Moreover, though providing some useful information, this study could only be considered as a starting point for the research on the design of training curricula. Future research could focus on examining factors associated with various precrash maneuvers under different critical conditions. With more detailed information, motorcycle training curriculum can be further improved. The authors suggest that further research be focused on these topics.

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