Impact Area and Speed Effects on Powered Two-Wheeler Crash Fatality and Injury Risk

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ABSTRACT

The primary objective of this study was to evaluate the fatality risk of powered two-wheeler (PTW) riders across different impact orientations while controlling for different opponent vehicle (OV) types. For the crash configurations with higher fatality rate, the secondary objective was to create an initial speed–fatality prediction model specific to the United States. Data from the NHTSA Crash Reporting Sampling System and the Fatality Analysis Reporting System from 2017 to 2020 was used to estimate the odds of the different possible vehicle combinations and orientations in PTW-OV crashes. Binary logistic regression was then used to model the speed–fatality risk relationship for the configurations with the highest fatality odds. Results showed that collisions with heavy trucks were more likely to be fatal for PTW riders than those with other OV types. Additionally, the most dangerous impact orientations were found to be those where the PTW impacted the OVs front or sides, with fatality odds respectively four and five times higher than when the OV rear-end was impacted. The high variability in the odds of different crash configurations suggests the importance of considering the impact orientation factor in future injury prediction models. The speed–fatality prediction models developed for head-on and side crashes could provide an initial tool to evaluate the effectiveness of advanced rider assistance systems and other safety countermeasures in the US, particularly those that result in speed reductions.

INTRODUCTION

Motorcycles and mopeds, often referred to as powered two-wheelers (PTWs), have become increasingly important for personal mobility worldwide. In the US, for example, the number of registered PTW has nearly doubled, from 4.3 billion in 2002 to 8.6 billion in 2021 (Teoh, et al., 2021), and similar trends have been recorded in Australia (+30.6 % from 2007 to 2012 (ABS, 2013)), Sweden (+50% from 2000 to 2013 (STA, et al., 2020)), and Italy (+44% from 2004 to 2016 (ACEM, 2018)). Understandably, this trend has raised concerns over the potential hazards associated with these vehicles, since in the US, for example, motorcycle riders represent 14% of all traffic fatalities despite only accounting for 3% of the total registered vehicles (NHTSA, 2021). Several factors have been linked to the higher PTW risk of injury crashes. Among these factors, crash configuration, opponent vehicle (OV) type, and relative speed have been identified as key (Wali, et al., 2018; Li, et al., 2021; Chawla, et al., 2019; Fredriksson, et al., 2015).

In recent years, research started exploring the injury likelihood of different PTW–OV crash scenarios, often by simulating collisions between different vehicle types. Xiao et al. (2020), for instance, conducted multibody simulations of three crash scenarios in which the front of a

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passenger vehicle collided with a PTW, obtaining different head injury probabilities across the scenarios. Similarly, Serre et al. (2010) simulated a lateral impact configuration (i.e., front of the PTW colliding with the side of the OV) and emphasized that there may be differences in injury outcomes depending on the impact location and the OV type. Therefore, in a subsequent study (2012), they performed a retrospective analysis of aggregated French crash data, analyzing the frequencies of different PTW-OV impact orientations. In this work, however, they did not assess the injury likelihood associated with the various orientations. Thus, there is need for a rigorous retrospective study based on real-world crash data that, identifying the most dangerous orientations and opponent vehicle types, assists in focusing further research and prioritizing the development of effective safety countermeasures.

In the same way, an increase in impact speed has often been correlated with an increase in injury outcomes (Fredriksson, et al., 2015; 2016). This relationship has been attributed to several factors, including the reduced effectiveness of protective gear in high-speed crashes (Carroll, et al., 2022), altered mechanisms of injury during collisions (Petit, et al., 2020), and limited time to perform avoidance maneuvers (Li, et al., 2021). Advanced Rider Assistance Systems (ARAS) could play an important role in reducing the PTW speed before the impact (e.g., Motorcycle Autonomous Emergency Braking (Savino, et al., 2014)) or in improving the PTW stability during emergency braking (e.g., Anti-lock Braking Systems (Rizzi, et al., 2016)). However, to estimate the potential benefit of these systems (e.g., (Lucci, et al., 2022)), new injury prediction models that rely on rigorous crash retrospective analysis are necessary (Savino, et al., 2020). To date, injury prediction models based on relative speed have been constructed by Otte et al. (2015), Ding et al. (2019), and Lubbe et al. (2022), using data from the German In-Depth Accident Study (GIDAS) crash database. However, given the differences in traffic environments and vehicle types across countries, the authors cautioned against the direct application of these models in other contexts. Specifically to the US, Bambach et al. (2011) used National Highway Traffic Safety Administration (NHTSA) crash data to build an injury prediction model for crashes into roadside barriers, however, no consideration was provided to crashes involving passenger vehicles. Additionally, due to data limitations, they used the travel speed as their metric, although standard ISO 12353-1 suggests using the relative speed, as it is representative of crash energy (ISO, 2020).

Motivated by these gaps, the first part of this study aims to evaluate the fatality risk of PTW riders in collisions with different OV body types, to provide a preliminary foundation for further analysis investigating possible countermeasures specific to OV body type. To accomplish this aim, the most common impact orientations and their corresponding fatality odds have been assessed using national-representative crash data. The second part of this study selected several dangerous impact orientations and developed proof-of-concept speed-based fatality prediction models specific to the US.

METHODS

Data sources

The NHTSA Crash Reporting Sampling System (CRSS, 2020) and the Fatality Analysis Reporting System (FARS, 2020) were used to perform the calculations. CRSS provides a sampling

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of police-reported crashes involving all categories of motor vehicles and injury levels, whereas FARS is a census of all fatal crashes occurring in the United States.

Information on accidents, vehicles, and people involved in crashes from 2017 to 2020 were extracted from both datasets. Adjustments for differences in the coded variables between the two datasets and between different years were made, and the CRSS cases were weighted to represent the entire crash population. Table 1 provides an overview of the two datasets.

Table 1: Comparison of the CRSS and FARS datasets

2017 - 2020	**FARS (US fatality census)**	**CRSS (US national crash estimation)**
Crashes frequency	137,732	25,193,379
Vehicles involved	211,309	44,886,299
People involved	338,912	60,403,288
PTW crash frequency	20,168	369,697
Vehicles involved in PTW crashes (PTW subset)	34,309 (20,983)	602,245 (377,728)
People involved in PTW crashes (PTW rider and passenger subset)	43,254 (23,136)	714,193 (407,117)

"Impact area" fatal risk

To compare fatalities across different OV types, two-vehicle crashes were sub-selected from both datasets and the vehicles involved in each crash were coupled based on their respective crash ID. Vehicle types were grouped following CRSS definitions (2020 p. 104-107).

The "Initial Contact Point" variable (Figure 1) was coupled for each crash and used to assess the fatality odds of each possible orientation.

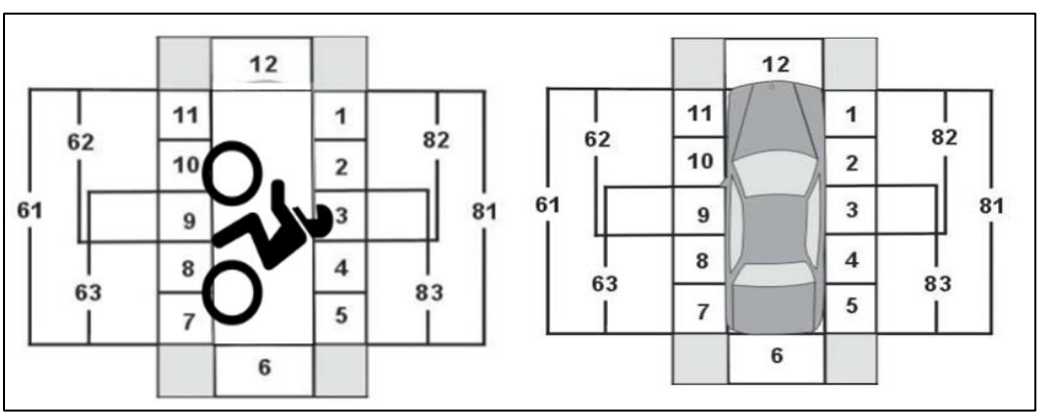

Figure 1: "Initial Contact Point" variable values (CRSS, 2020)

To reduce the number of potential orientations, the variable values ranging from 1 to 12 were aggregated into eight groups:

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- “12” → Front
- “6” → Rear
- “1” and “2” → Right front
- “3” → Right center
- “4” and “5” → Right rear,
- “7” and “8” → Left front,
- “9” → Left center
- “10” → Left rear

Additionally, if the contact point was associated with a value that belonged to more than one sector (variable values 61, 62, 63, 81, 82, 83), it was randomly assigned to one of the relevant aggregated groups – e.g., “62” randomly assigned to “9”, “10”, or “11”.

The fatality odds were assessed across combinations of the eight different orientations. Fata events were obtained from FARS and exposure (i.e., non-fatal crashes) were obtained from CRSS. As an example, Table 2 summarizes the event and exposure data for the configurations illustrated in Figure 2.

Table 2 : Sample contingency table used to estimate fatality odds

	Event	**Exposure**	
“OV / PTW”	FARS (fatal)	CRSS-FARS (non-fatal)	CRSS (total)
Front / Front	1,393	9,124	10,517
Rear / Front	906	30,658	31,564

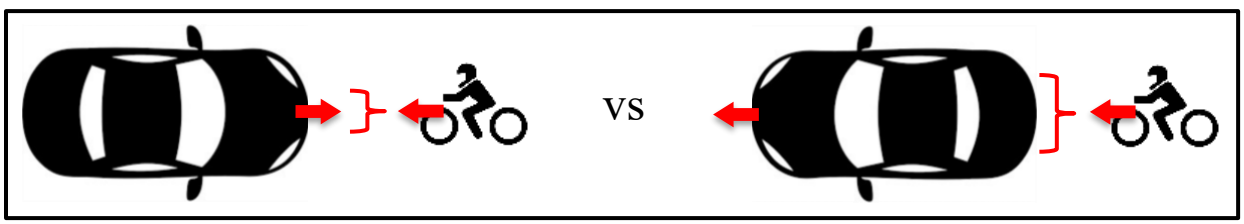

Figure 2: Configurations used in Table 2, left is Front/Front OV/PTW, right is Rear/Front OV/PTW

“Relative speed” fatal risk

Binary logistic regression (Eq. 1) was used to model the speed–fatal likelihood relationship for the configuration with the highest fatality odds.

$$logit(p) = \beta_0 + \beta_1 x \tag{1}$$

where:

- p represents the probability of the fatality occurring → $p = 1/(1 + e^{-logit(p)})$;
- x is the predictor variable; and
- β_0 and β_1 are the intercept term and the slope coefficient for the regression model, respectively.

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The predictor variable used for head-on crashes was the relative speed, estimated by summing the travel speeds of both vehicles involved. Due to a lack of data regarding the angle of the crash, the relative speed for angle crashes was not estimated. Instead, a 90° crash was assumed for all angle crashes. Therefore, for these scenarios, the travel speed of the motorcycle was used as a predictor variable. In addition, the estimated fatal cases in the CRSS dataset were substituted with the corresponding actual fatal crashes recorded in FARS to improve the injury risk estimation.

RESULTS

The distribution of vehicle combinations across fatal and non-fatal crashes showed large variation as a function of OV (Table 3). Notably, about 15% of the total crashes between a PTW and a medium/heavy truck and between a PTW and a bus resulted in fatalities. These percentages roughly doubled the next highest ratio observed (involving light trucks and PTWs).

Table 3: Distribution of vehicle combinations in two-vehicle PTW crashes

Vehicle combinations	**FARS (%)**	**CRSS (%)**	**Ratio (%)**
Automobiles / PTW	3,627 (42.0%)	91,390 (54.0%)	4.0
Utility Vehicles / PTW	1,989 (23.0%)	36,040 (21.3%)	5.5
Light Trucks / PTW	1,612 (18.7%)	21,883 (12.9%)	7.4
Van-based Light Trucks / PTW	444 (5.1%)	8,303 (4.9%)	5.3
Medium/Heavy Trucks / PTW	720 (8.3%)	4,111 (2.4%)	17.5
Buses / PTW	65 (0.8%)	481 (0.3%)	13.5
Other vehicles / PTW	173 (2.0%)	6.888 (4.1%)	2.5
Total	8,630 (100%)	169,094 (100%)	5.1

The proportion of fatalities for each vehicle combination also differed by impact orientation. As an example, Table 4 shows the top five most frequent impact orientations for fatalities resulting from the "Medium/Heavy Trucks/PTW" vehicle combination. In this crash situation, fatalities in crashes between the PTW front and the front or rear of the OV were the most common, accounting for nearly a third of the fatalities occurring in this scenario.

Table 4: Most common impact orientations in “Medium/Heavy Trucks / PTW” fatalities

Impact Orientations *“OV / PTW”*	**Fatalities (%)**
Rear/Front	18.1%
Front/Front	12.6%
Rear Right/Front	10.3%
Rear Left/Front	8.6%
Front Left/Front	8.6%

More generally, impact orientation had a large influence on the likelihood of a fatal crash (Table 5 shows the ten most common impact orientations based on crash frequency). The first contact area listed on the table is the initial contact point for the OV, whereas the second contact area is the initial contact point for the PTW. The “Rear / Front” orientation was selected as baseline for the odds estimation since it represented the most common configuration based on crash frequency.

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Table 5: Odds ratio (95% Confidence Interval; CI) for the ten most common impact orientations; color coding maps to the magnitude of the odds ratio observed

Impact orientations ***"OV / PTW"***	**FARS**	**CRSS**	**OR (95% CI)** **Baseline: "Rear / Front"**
Rear / Front	906	31,564	1
Front / Rear	522	18,251	1.00 (0.89 – 1.11)
Front Left / Front	709	12,746	1.99 (1.80 – 2.20)
Rear Right / Front	691	12,493	1.98 (1.79 – 2.19)
Front / Front	1,393	10,517	5.17 (4.74 – 5.63)
Front Right / Front	950	8,931	4.03 (3.67 – 4.43)
Center Left / Front	767	8,803	3.23 (2.92 – 3.57)
Center Right / Front	1,030	8,251	4.83 (4.40 – 5.30)
Rear Left / Front	325	5,004	2.35 (2.06 – 2.68)
Front / Center Left	252	4,858	1.85 (1.60 – 2.14)

The injury risk curve modelling the PTW fatality risk as a function of the relative crash speed for head-on crashes, which had the highest odds ratio across the impact orientations, was statistically significant (Figure 3). The model shows a 50% fatality risk at a relative crash speed of 150 kph.

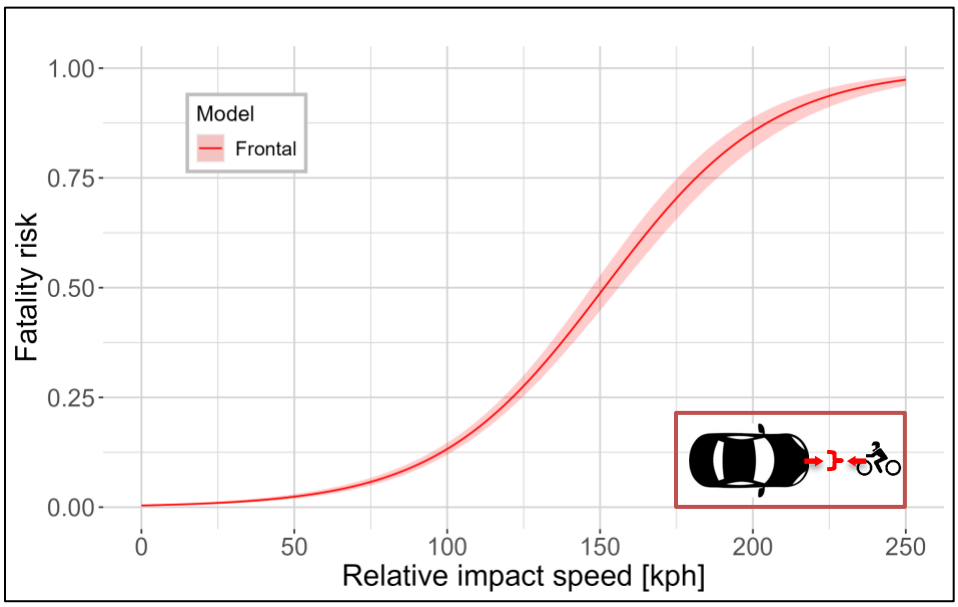

Figure 3: Injury curve risk for head on crashes - relative crash speed used as predictor variable

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Given the high odds of fatality observed for lateral impacts (particularly right-side impacts), injury risk curves were also developed for cases when the PTW collided with the central left or right side of the occupant vehicle (Figure 4). The models were statistically significant ($p<0.001$). For these curves, the 50% fatality risk was observed around 110 kph.

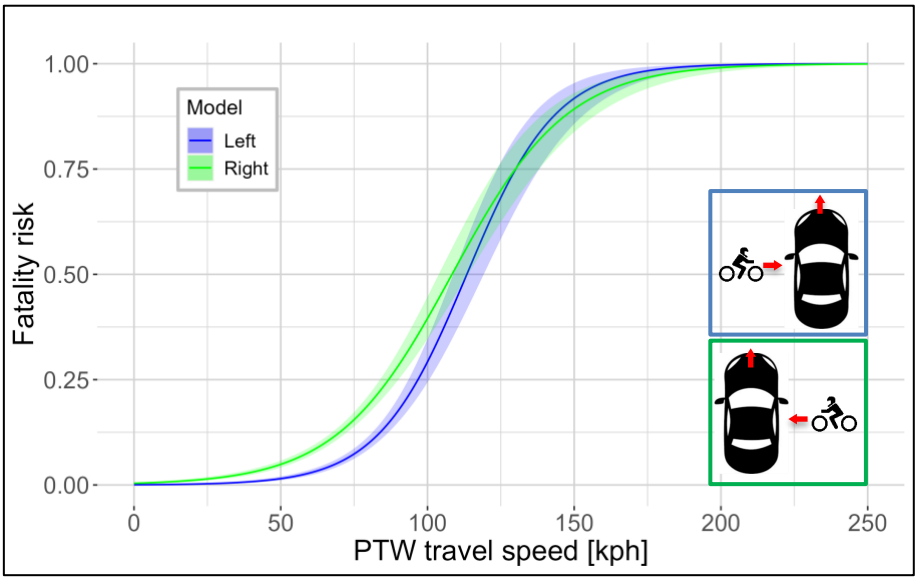

Figure 4: Injury curve risk for left/right angle crashes – PTW travel speed used as predictor variable

DISCUSSION

The analysis of the vehicle combinations in PTW crashes highlighted that collisions between PTWs and passenger cars alone accounted for the majority of the crashes (52.8%). However, "Medium/Heavy Trucks / PTW" crashes resulted in over four times the fatality risk, with 16.9% of these crashes being fatal. These results are aligned with Serre et al., who estimated that 64% of total PTW crashes in France occurred with a passenger vehicle but reported that PTW-heavy vehicle collisions accounted for 6.5% of the total fatalities while representing only 1.7% of the total crashes (Serre, et al., 2012). Fredriksonn et al. obtained similar results while considering crashes that occurred in two specific German regions; they estimated that 46% of the recorded injury crashes occurred in PTW-car collisions (Fredriksson, et al., 2016) and 14% of the PTW fatalities occurred in collisions with heavy vehicles (Fredriksson, et al., 2015). Differences in proportions of these crashes and fatalities between these previous studies and the current investigation could be attributed to country differences in fleet composition and vehicle design. In turn, these differences provide motivation for the development of new injury prediction models specific to the US. Interestingly, Fredriksonn et al. also analyzed several reconstructed PTW–heavy vehicle crashes and found that, in 45% of these cases, the heavy vehicle ran over the PTW (Fredriksson, et al., 2015). Although the two datasets used in this investigation do not support a direct comparison, examination of the most common impact orientations suggests that 30.7% of the US heavy vehicle – PTW fatalities occur due to front- or rear-end collisions. This observation may support further efforts in improving the front/rear design of heavy vehicles (e.g., Xiao et al. (2020)) to make them more compatible with PTWs and their riders.

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The analysis of the top-ten impact configurations revealed that eight of the ten most common orientations were collisions in which the *front* of the PTW collided with the OV. Additionally, crashes where the front of the PTW collided with the front or right side of the OV ("Front / Front" and "Center right / Front") obtained significantly higher odds—5.17 and 4.83—than crashes where the PTW collided with the rear of the OV ("Rear / Front"). For the first case ("Front / Front"), the injury risk curve showed that PTW riders have a 50% fatal probability when involved in head–on crash at a relative crash speed of 150 kph. This result highlights the potential benefit of forward-scanning protection systems such as collision warning or autonomous emergency braking systems in PTW fleet. For example, considering an expected speed reduction of 10-15.8 kph (Lucci, et al., 2022), the PTW autonomous emergency braking may reduce the fatality risk for US PTW riders by about 12.5%. Future US-based injury prediction models should focus on incorporating a wider range of crash orientations (e.g., Ding et al. (2019)) and considering other potentially important factors in the model (e.g., rider age; Lubbe et al. (2022)).

For crashes where the front of the PTW collided with the left/right side of the occupant vehicle, no influence of the PTW travel speed was found that could explain the higher odds ratios obtained for right-side crashes. While further analyses are required to identify other potential factors, it should be noted that fatalities where the PTW front collided with the right side of the OV almost doubled the opposite configuration – i.e., when the PTW front collided with the left side of the OV – suggesting for a possible correlation with the intersection design and the dynamics of the crash. Additionally, among the top-five dangerous crash scenarios for both right and left lateral crashes, the turn-across and turn-into path resulted in the two highest fatality rates. These types of scenarios have also been proven to be high-risk configurations for car-to-car crashes. In the past, intersection driver assistance systems (I-ADAS) and automated emergency braking (AEB) have been proposed to mitigate associated fatalities (Bareiss, et al., 2019; Sander, et al., 2019). Therefore, further adoption of similar systems in PTWs could potentially provide significant benefits in crashes associated with these scenarios. Finally, the common dynamics of both configurations (i.e., PTW going straight and occupant vehicle turning left) could suggest that PTW visibility, intersection design, and PTW difficulties in performing stable emergency braking maneuvers could be main contributing factors for these types of crashes.

CONCLUSIONS

Given the increasing concern over the potential hazards associated with PTW crashes, this study aimed to address some of the gaps in the existing literature by: 1) investigating the fatality risk of PTW riders across different occupant vehicle (OV) types and different impact orientations, 2) proposing a new injury prediction model for the configurations with the highest fatality odds. The study showed that collisions involving PTWs and passenger cars were the most common, while PTW collisions with heavy vehicles had the highest proportions of fatalities. Considering that the fatalities in crashes with heavy vehicles were often in front-to-front or rear-end impacts, further improvements in the front and rear design of these vehicles could therefore potentially reduce fatalities of US PTW riders. Additionally, although these findings are consistent with previous studies conducted in France and Germany, the relative proportions were different, suggesting differences between the US and the European contexts. This observation highlights the necessity for injury prediction models specific to the US.

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The analysis of impact orientations revealed that head-on crashes and side-angle crashes had significantly higher fatality odds than other configurations. Thus, the second part of the study aimed to provide an initial speed-fatality prediction model for these orientations using US national crash data. Although future studies would benefit from more precise crash data, the model results provide an initial tool to assess the effectiveness of crash speed reduction countermeasures and could provide a new instrument for further discussions concerning US speed limits.

In addition to quantifying a significant relationship between PTW travel speed and fatalities in side-angle crashes, our investigation identified turn-across and turn-into paths as high-risk scenarios. The common design of these configurations (i.e., PTW going straight and the OV turning left) could suggest potential improvements in intersection design and in methods to increase PTW visibility. Additionally, this result also suggests an initial framework for future assessments of PTW intersection-ARAS that mitigate the fatality and injury outcomes of these scenarios.

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