World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:17, No:3, 2023

Optimal Design of Motorcycle Crash Bar Using CAD and Finite Element Analysis

Sharon S. Wu, Yong S. Park

***Abstract*—**This project aims to study and evaluate the motorcycle crash bar, which is used to reduce injuries caused by side impacts to the motorcycle, and then develop an improved design using the engineering design process theory based on the current benchmark crash bar in order to lower the severity of motorcycle crash injuries. For this purpose, simulations for the crash bar are set up so that it travels at an angle towards a fixed concrete wall and collides at certain velocities. 3D CAD models are first designed in SolidWorks and dynamic crash simulations are then carried out using ANSYS to determine the lowest maximum Von-Mises stress over time and deformations by adjusting the parameters used in manufacturing the crash bar, including the velocity of the crash, material used, geometries with various radius fillets, and different thicknesses for the bar. The results of the simulation are used to determine the optimum parameters for a safer crash bar to withstand higher stress and deformation. Specifically, the von-Mises stress was reduced by at least 75% compared with the benchmark design by choosing aluminum alloy and a true unibar design.

***Keywords*—**Crash bar, crash simulation, engineering design, motorcycle safety.

I. INTRODUCTION

THE motorcycle fatalities, though not necessarily more common than other motor vehicle accidents, can be more devastating. Looking at their per vehicle mile traveled in 2016, fatalities occurred 28 times more frequently than passenger car fatalities in vehicle crashes. In addition, 37% of the motorcycle riders involved in fatal crashes were speeding, which was the highest of any type of vehicle [1].

A multitude of studies over the last 30 years have attempted to determine the events and actions leading up to a crash. Most of them were done at least 10 years ago and have offered inconclusive results [2]-[6]. However, the Motorcycle Safety Foundation (MSF) recently sponsored the first large-scale naturalistic motorcycle study to collect data on 100 riders over a period of time [5]. The findings showed that one of the most common risk factors that led to single-vehicle crashes and near crashes were riders negotiating curves. This led to impacts to the motorcycle sides and the undercarriage.

In this paper, the motorcycle crash bar was chosen for study based on the statistical data above to reduce the injuries in the leg area from riders making high speed turns and the engineering design process was utilized to evaluate and optimize the crash bar design. This study can then provide a framework for future studies that can be done to adjust additional parameters.

II. CONCEPT GENERATION

After speaking with a local motorcycle shop owner, the Lindby Custom Unibar was selected for benchmarking purposes (see Figs. 1 and 2). The Lindby crash bar was chosen since it was a popular standard bar and the ratings were very high. This crash bar is made from steel, has fixed geometry, 18 inches long, 1 ¼-inch inner diameter, and 0.12-inch wall thickness tubing. The name suggests that it is a unibody design, but because crash bars are usually add-on parts after a bike has completed manufacturing, there needed to be a way for drivers to install these and slip through the motorcycle body [7]. This study will suggest designs with true unibody structures and make recommendations for how to attach these to a motorcycle.

Fig. 1 Picture of Lindby Custom Unibar

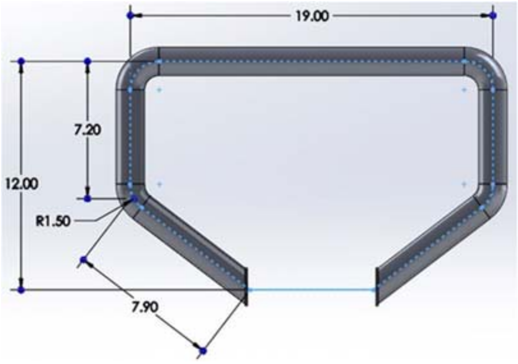


Fig. 2 Dimensions for benchmark crash bar from SolidWorks

TABLE I
PARAMETERS USED IN CAD AND FINITE ELEMENT ANALYSIS (FEA) SIMULATIONS

Geometry	Materials	Thickness (mm)
Existing	steel alloy	3.05
A	aluminum alloy	2.54
B	titanium alloy	3.81

S. S. Wu. is with the Mechanical Engineering Department at California State University, Fullerton, CA 92831 USA.

Y. S. Park is with the Mechanical Engineering Department at California State University, Fullerton, CA 92831 USA. (e-mail: yopark@fullerton.edu)

Using the product specifications of the benchmark, the study designs used and modified the following parameters to set as independent variables: geometry, material, and wall thickness (see Table I).

III. CONCEPT SELECTION

In SolidWorks, variations of geometry designs were drawn based on the benchmark's existing dimensions. Initially, just the first three geometries (Existing, A, and B) were drawn to run simulations. Afterwards, two more CAD designs (D, B2) were drawn and imported into ANSYS. A mock wall was built at 0.1 inches from the right side of the bar. This distance needed to be small so that the simulation run time would be reasonable. Then for the variations on geometry, dimensions for the corner radii, overall length, and curvature of the bottom half of the part were all changed, and the goal was to see what kind of differences these changes would make in lowering the stress and deformation (see Figs. 3-7). Also, a true unibody design would be able to better absorb the impact energy, so the first variation (variation A) was to connect the two ends of the existing design and make it a true unibody design. The second variation (variation B) was purposely drawn to be radically different from the benchmark design, to find out how much stress and deformation would change with a much more rounded geometry.

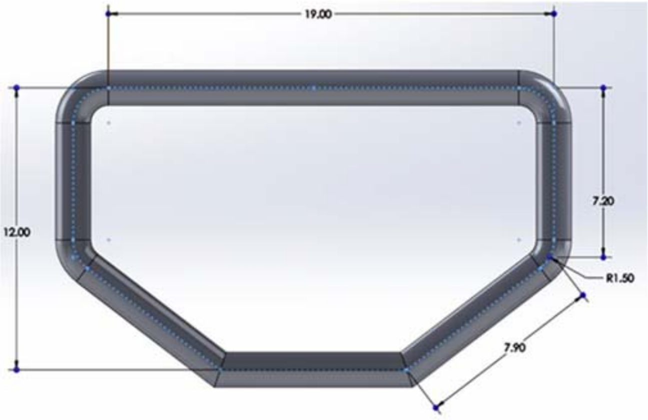


Fig. 3 Dimensions of variation A

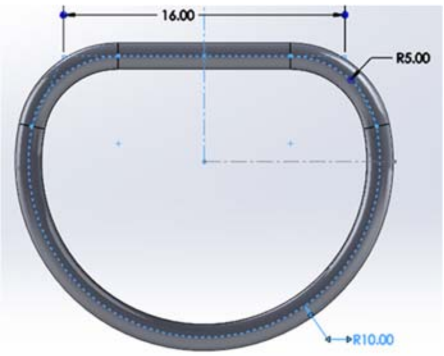


Fig. 4 Dimensions of variation B

There are some existing models out there with similar dimensions, but none of them has this true unibody design. Therefore, all the variations have 1.25-inch inner diameter and their varied shapes are based on those popular basic designs on the market, with the exception that they are designed to be true unibody parts.

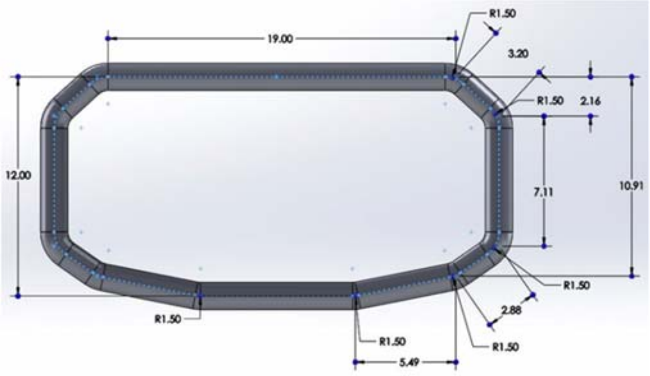


Fig. 5 Dimensions of variation C

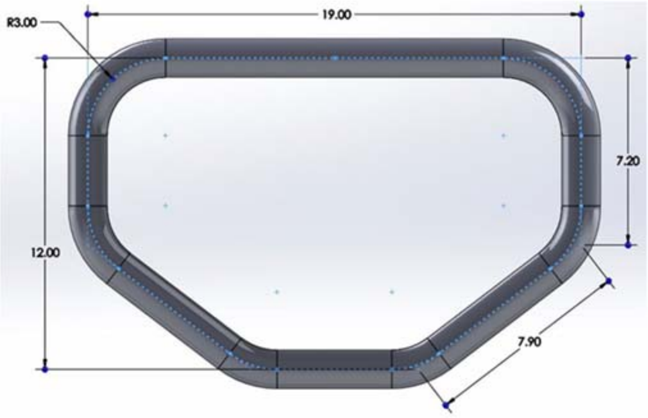


Fig. 6 Dimensions of variation D

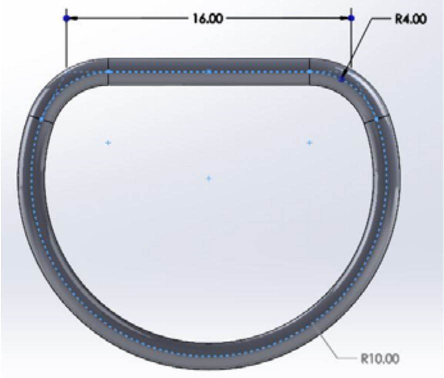


Fig. 7 Dimensions of variation B2

IV. FINITE ELEMENT ANALYSIS USING ANSYS

By using the Explicit Dynamics solver in ANSYS, crash bars could be tested under dynamic loadings with respect to time. Within ANSYS Workbench, the designs were categorized by the five geometries and three material types. A second Workbench file was used for the wall thickness later.

As well as setting up the geometry, material, and thickness, the explicit dynamics solver required a velocity and endtime. So that these simulations could be as close to real world as possible, four different velocities were chosen: 25 mph (11.18 m/s) as the typical speed limit for residential areas, 40 mph (17.88 m/s) as the typical speed limit for city streets, 65 mph (29.06 m/s) as the typical speed limit for highways, and 80 mph (35.76 m/s) as the velocity generally considered as speeding.

In the Workbench, each geometry and material system needed to have three additional dependent systems linked to each previous system (see Fig. 8). By doing so, these additional connected systems could share the material data and geometry but keep a separate solver model for each different velocity. Each material needed three systems with its own connected sub-systems for velocities.

Within the Model outline (see Fig. 9), the parameters and settings for this study were set up to reflect our inputs. Starting with the geometry, there were two bodies: the crash bar and the wall. First, the material for the crash bar was selected to be "Structural Steel" and the wall was selected to be "Concrete." In practice, the wall's material did not affect the simulation because it was set to be a fixed object that could not move regardless of the material assigned. Then, the mesh was set to system default, as it was not the purpose of this study.

Next in the outline are the four velocities set up earlier by linking multiple systems together in Workbench. As shown in the outline tree, these velocities all share the same geometry and mesh and can run as one simulation. These velocity parameters were specifically for the dynamic analysis portion of the simulation. To mimic a real crash, these velocities were set to be in the X and negative Z-direction only and fixed in the Y-direction. Movement in the X and negative Z-directions was chosen based on how in general, a motorcycle would crash forward and downward towards the ground. In the "Analysis Settings" the endtime was chosen to be 0.001-sec based on the general default for many simulations.

Lastly, the "Solutions" section needed to be set up to find Equivalent Stress, Total Deformation, and Directional Deformation in the X-axis. Within the Equivalent Stress and Directional Deformation in the X-axis solutions, the main results to obtain were the changes in the X- axis deformation and stress over the entire time period of the simulation. This allowed for results that were tracked more easily and consistently across all the different geometries, materials, and thicknesses.

Fig. 8 The entire connected system of the benchmark (existing) design in steel with four velocities

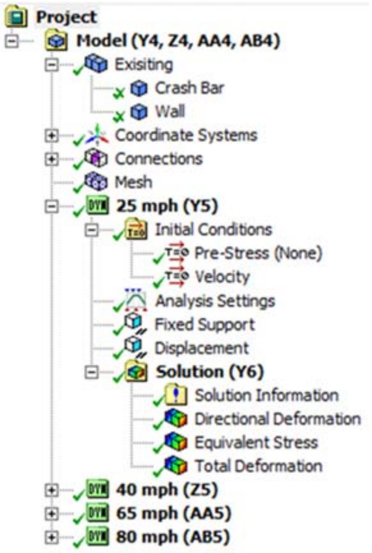


Fig. 9 Project outline from ANSYS showing bodies, mesh, velocities, and solutions

A total of twenty simulations were completed, each with four different velocities. Part I of the first simulations consisted of the benchmark geometry and material, five geometry variations (A, B, C, D, B2), three materials for each variation (Steel, Aluminum, Titanium), and part II simulations were of the four different thicknesses (0.10", 0.15", 0.20", 0.50") using the best geometry and material combination from part I. An example of the mesh and project outline is shown in Fig. 10.

V. RESULTS

From simulations part I, Table II shows the "Maximum von-Mises Stress Over Time" for all the geometries and materials. The cells highlighted in gray indicate the lowest value in its category.

Since Aluminum and variation D (see Table II) showed the highest reductions, these two were used for testing the third parameter – thickness – in a second simulation. Table III shows the results from testing the various thicknesses. The velocities were kept constant as before, and the 0.12-in results came from variation D from the first simulation using aluminum. The lowest values are indicated by a gray highlight.

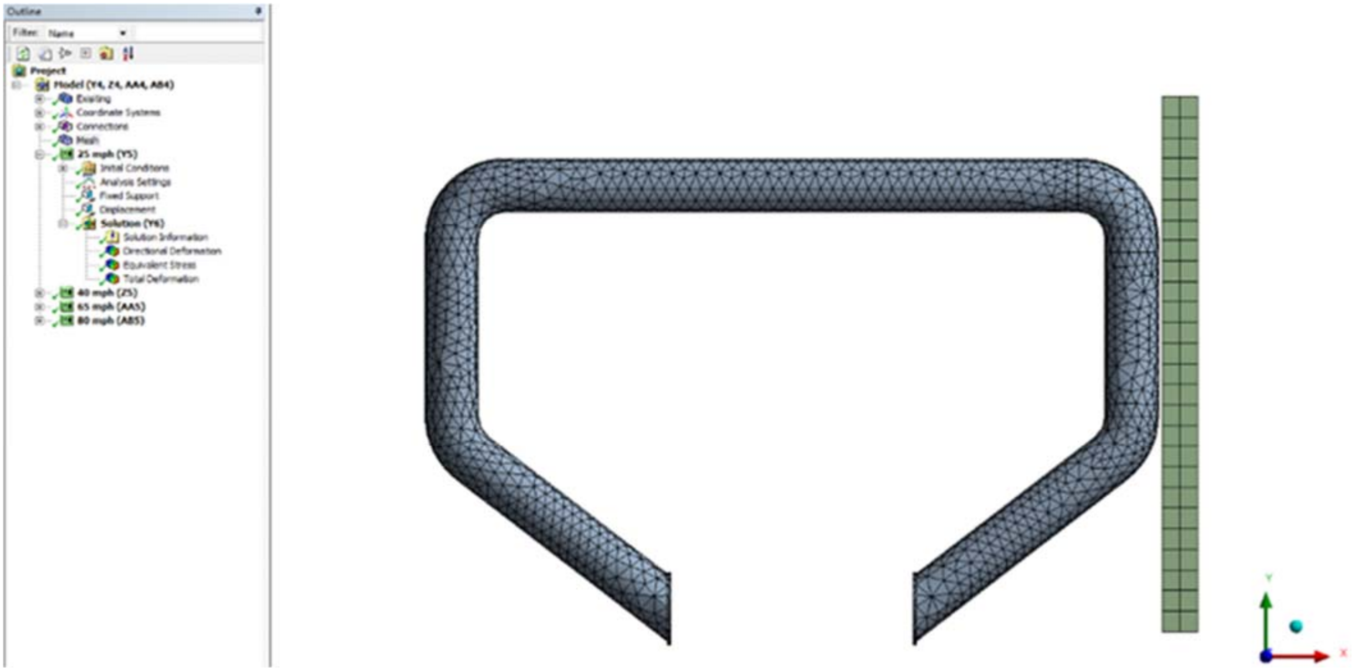
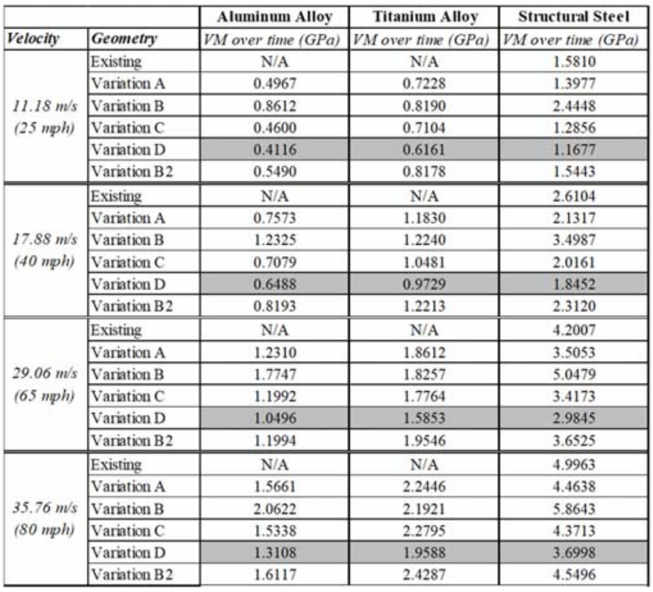
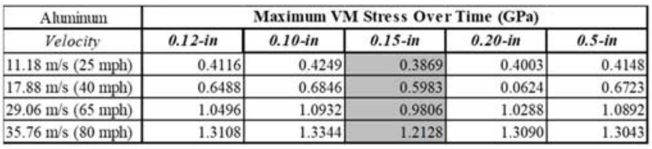


Fig. 10 Auto-completed mesh and wall with project outline on the left



		Aluminum Alloy	**Titanium Alloy**	**Structural Steel**
Velocity	***Geometry***	*VM over time (GPa)*	*VM over time (GPa)*	*VM over time (GPa)*
11.18 m/s (25 mph)	Existing	N/A	N/A	1.5810
	Variation A	0.4967	0.7228	1.3977
	Variation B	0.8612	0.8190	2.4448
	Variation C	0.4600	0.7104	1.2856
	Variation D	0.4116	0.6161	1.1677
	Variation B2	0.5490	0.8178	1.5443
17.88 m/s (40 mph)	Existing	N/A	N/A	2.6104
	Variation A	0.7573	1.1830	2.1317
	Variation B	1.2325	1.2240	3.4987
	Variation C	0.7079	1.0481	2.0161
	Variation D	0.6488	0.9729	1.8452
	Variation B2	0.8193	1.2213	2.3120
29.06 m/s (65 mph)	Existing	N/A	N/A	4.2007
	Variation A	1.2310	1.8612	3.5053
	Variation B	1.7747	1.8257	5.0479
	Variation C	1.1992	1.7764	3.4173
	Variation D	1.0496	1.5853	2.9845
	Variation B2	1.1994	1.9546	3.6525
35.76 m/s (80 mph)	Existing	N/A	N/A	4.9963
	Variation A	1.5661	2.2446	4.4638
	Variation B	2.0622	2.1921	5.8643
	Variation C	1.5338	2.2795	4.3713
	Variation D	1.3108	1.9588	3.6998
	Variation B2	1.6117	2.4287	4.5496

Fig. 11 Obtained results of maximum von-Mises stress over time



Aluminum	**Maximum VM Stress Over Time (GPa)**				
Velocity	***0.12-in***	***0.10-in***	***0.15-in***	***0.20-in***	***0.5-in***
11.18 m/s (25 mph)	0.4116	0.4249	0.3869	0.4003	0.4148
17.88 m/s (40 mph)	0.6488	0.6846	0.5983	0.0624	0.6723
29.06 m/s (65 mph)	1.0496	1.0932	0.9806	1.0288	1.0892
35.76 m/s (80 mph)	1.3108	1.3344	1.2128	1.3090	1.3043

Fig. 12 Obtained results of maximum von-Mises stress over time of various wall thicknesses using aluminum and variation D

VI. CONCLUSIONS

In Table II, we evaluate the results of maximum von-Mises stress over time. Variation D has the lowest maximum von-Mises stress over time for all the four velocities. Even though some of the other geometries had more rounded corners and overall rounder shapes, the impact from hitting the wall created stress concentrations resulted in higher stress for other radii corners and shapes. Combined with aluminum, variation D was the best design with the highest reduction in maximum von-Mises stress over time. Even though titanium is stronger than aluminum, the best results were still when aluminum was used because of its better ability to deform and absorb the energy upon impact.

After the results for part I of the simulations were gathered, the last parameter for thickness was tested using the best design so far: variation D and aluminum. After running simulations for the 4 additional wall thicknesses, the best thickness for lowest maximum von-Mises stress over time (see Table III) was 0.15-inch wall thickness, as shown by the least maximum von-Mises stress over time.

By using the engineering design process, this study has found that through understanding the motorcycle background, problem definition, morphological chart, and concept generation using CAD and FEA, the best design found for a motorcycle crash bar is using aluminum as the material, the unibody geometry using dimensions from variation D, and a 0.15-inch wall thickness for the tubing. Not only has this research provided a framework for future studies that should be done on improving the safety benefits of motorcycle accessories, this has also contributed to filling the vacancy in the low number of modern research done on reducing the severity of lower body injuries for motorcyclists.

VII. LIMITATIONS AND FUTURE RESEARCH

Usually when motorcycles are manufactured, the crash bar is considered an accessory that riders would buy separately at a shop. The bar itself is not usually included as part of the bike itself and can cost upwards of $500. The bar would be installed to the bike by the owner after purchasing, so the geometry would have to be open-ended for it to be looped into and mounted to the body. This design is not ideal as proven by the simulations, so the recommendation would be for motorcycle makers to include the bar as part of the manufacturing process, instead of as an accessory.

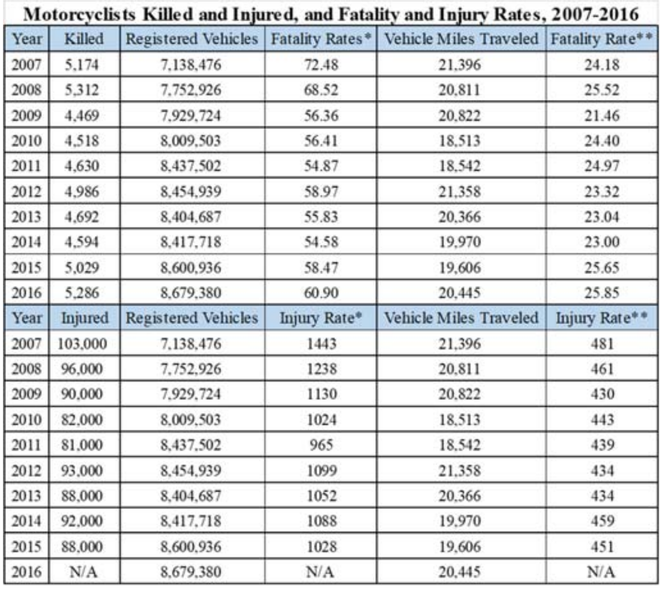
In the simulation setup, the crash location of the bar was kept against the flat lateral surface on the right-hand side. Although the velocity moved in the X and –Z direction, the force was still upon the smooth side of the bar. It was meant to emulate the bar landing on that specific location. If the impact was against one of its rounded corners, the results of the simulation may emerge differently, and further simulations should address how this impact location changes the stress and deformation of the design.

The simulations looked like the crash bar bounced off the wall without much visible deformation. In the real world, the part would crumple and have immense physical damage from the impact. One of the reasons the crash bar simply looked like it bounced off and did not crumple was because in the simulation environment, the software assumes that the part is a perfectly manufactured bar, without any imperfections or weaknesses from manufacturing. It is considered a perfect geometry in the utmost ideal circumstances.

Other future studies should investigate the wide variety of materials that exist today, including complex composite materials that only elongate in one direction, or materials that have positive Poisson's ratio. The inner diameter and cross-sectional area were also left unchanged for the purposes of this study, but there is potential to find a better design here as well.

APPENDIX

Appendix A: Data from NHTSA on the Fatality and Jury Rates for Motorcyclists, 2007-2016 [1]

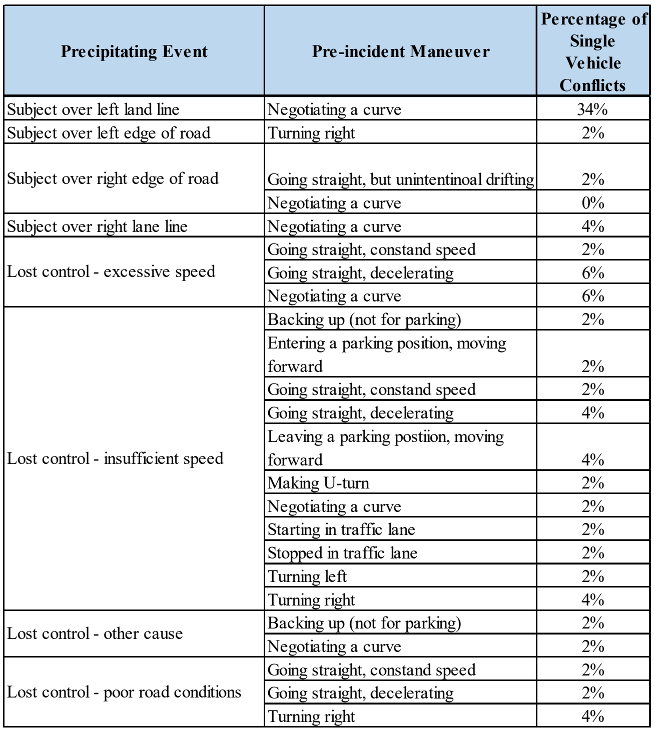


Motorcyclists Killed and Injured, and Fatality and Injury Rates, 2007-2016

Year	Killed	Registered Vehicles	Fatality Rates*	Vehicle Miles Traveled	Fatality Rate**
2007	5,174	7,138,476	72.48	21,396	24.18
2008	5,312	7,752,926	68.52	20,811	25.52
2009	4,469	7,929,724	56.36	20,822	21.46
2010	4,518	8,009,503	56.41	18,513	24.40
2011	4,630	8,437,502	54.87	18,542	24.97
2012	4,986	8,454,939	58.97	21,358	23.32
2013	4,692	8,404,687	55.83	20,366	23.04
2014	4,594	8,417,718	54.58	19,970	23.00
2015	5,029	8,600,936	58.47	19,606	25.65
2016	5,286	8,679,380	60.90	20,445	25.85
Year	Injured	Registered Vehicles	Injury Rate*	Vehicle Miles Traveled	Injury Rate**
2007	103,000	7,138,476	1443	21,396	481
2008	96,000	7,752,926	1238	20,811	461
2009	90,000	7,929,724	1130	20,822	430
2010	82,000	8,009,503	1024	18,513	443
2011	81,000	8,437,502	965	18,542	439
2012	93,000	8,454,939	1099	21,358	434
2013	88,000	8,404,687	1052	20,366	434
2014	92,000	8,417,718	1088	19,970	459
2015	88,000	8,600,936	1028	19,606	451
2016	N/A	8,679,380	N/A	20,445	N/A

Fig. 13 Data of motorcyclists fatalities and injuries from 2007 to 2016

Appendix B: Data from MSF Study on Events Immediately before an Accident, 2019 [5]



Precipitating Event	Pre-incident Maneuver	Percentage of Single Vehicle Conflicts
Subject over left land line	Negotiating a curve	34%
Subject over left edge of road	Turning right	2%
Subject over right edge of road	Going straight, but unintentinoal drifting	2%
	Negotiating a curve	0%
Subject over right lane line	Negotiating a curve	4%
Lost control - excessive speed	Going straight, constant speed	2%
	Going straight, decelerating	6%
	Negotiating a curve	6%
Lost control - insufficient speed	Backing up (not for parking)	2%
	Entering a parking position, moving forward	2%
	Going straight, constant speed	2%
	Going straight, decelerating	4%
	Leaving a parking postiion, moving forward	4%
	Making U-turn	2%
	Negotiating a curve	2%
	Starting in traffic lane	2%
	Stopped in traffic lane	2%
	Turning left	2%
	Turning right	4%
Lost control - other cause	Backing up (not for parking)	2%
	Negotiating a curve	2%
Lost control - poor road conditions	Going straight, constant speed	2%
	Going straight, decelerating	2%
	Turning right	4%

Fig. 14 Percentages of single vehicle conflicts shown with their corresponding event scenarios

REFERENCES

[1] National Center for Statistics and Analysis. (2018a). Motorcycles: 2016 data. (Updated, Traffic Safety Facts, Report No. DOT HS 812 492),

Washington, DC: National Highway Traffic Safety Administration.

[2] Kostyniuk, L. P., & Nation, A. D. (2006). Motorcycle Crash Trends in Michigan: 2001-2005. 75.

[3] Lin, M.-R., Chang, S.-H., Pai, L., & Keyl, P. M. (2003). A longitudinal study of risk factors for motorcycle crashes among junior college students in Taiwan. Accident Analysis & Prevention, 35.

[4] Lin, M. R., & Kraus, J. F. (2009). A review of risk factors and patterns of motorcycle injuries. Accid Anal Prev, 41(4), 710-722. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/19540959. doi:10.1016/j.aap.2009.03.010

[5] Nazemetz, J. W., Bents, F. D., Perry, J. G., Thor, C., & Tan, C. (2019). Motorcycle Crash Causation Study: Final Report.

[6] Westat and Dynamic Science, I. (2010). Motorcycle Crash Causes and Outcomes: Pilot Study. 233.

[7] Lindby. Retrieved from https://www.lindbycustom.com/cart/UNIBAR/UNIBAR-1411-For-Harley-Davidson-All-Softail-Models-2000-2017-p152c34.html