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Characterization of Motorcycle Encroachments in the US

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Characterization of Motorcycle Encroachments in the US

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ABSTRACT

In 2020, there were 5,579 motorcyclist fatalities in the US, which is the highest on record. Despite accounting for only 3% of registered vehicles, motorcycles are involved in 42% of fatal guardrail impacts. Roadside safety hardware testing guidelines are outlined in the Manual for Assessing Safety Hardware (MASH) for passenger vehicles and large trucks but these procedures do not include any motorcycle impacts. Although international test procedures for roadside hardware prescribe motorcycle crash tests, it is not known if the prescribed test conditions reflect the conditions at which motorcycles depart the roadway in the US. A better understanding of the characteristics of motorcycles departing the roadway in the US is needed prior to the development of motorcycle crash tests. This study used the NCHRP 17-88 database to compare the encroachment and impact characteristics of motorcycles, passenger vehicles, single-unit trucks, and tractor-trailer trucks.

Motorcycles were found to have a similar distribution impact angles to passenger vehicles with an 85th percentile of 24 degrees. The median and 85th percentile impact angle was found to be shallower for tractor-trailer trucks compared to motorcycles and passenger vehicles. Additionally, large trucks and motorcycles were found to rollover at a higher frequency than passenger vehicles. During the first event, almost 80% of motorcycles were upright. By the second event, almost 50% of motorcyclists were separated from the motorcycle. This indicates that a large percentage of riders lose contact with the motorcycle during the first event and are separated during any subsequent events. Based on these results, future motorcycle-barrier tests should consider an upright configuration and an impact angle of 24 degrees.

Keywords: Motorcycle, Encroachments, MASH, Barrier Design, Vulnerable Road Users

INTRODUCTION

In 2020, there were 5,579 motorcyclist fatalities in the US, which is the highest recorded since 1975 [1]. Motorcyclists are more vulnerable than passenger vehicle occupants due to the lack of protective structures, airbags, and seatbelts. While seatbelts are enforced by law for passenger vehicles in the US except for one state [2], only 19 states require motorcyclists to wear a helmet [1]. Among the fatal motorcycle crashes in 2020, only 60% of motorcyclists were wearing a helmet [1]. Previous research has demonstrated that motorcyclists are particularly vulnerable in roadside impacts, especially those involving longitudinal barriers. Despite accounting for only 3% of registered vehicles, motorcycles are involved in 42% of fatal guardrail impacts [3]. Gabler estimated that the fatality risk for motorcycle collisions with a guardrail was 81 times higher than that of passenger vehicles. Compared to other countries, there has been relatively little research on motorcycle-barrier impacts in the US. Similarly, other countries have developed and introduced motorcycle-barrier crash tests but there are currently no motorcycle-barrier test specifications in the US.

Testing Standards

The Manual for Assessing Safety Hardware (MASH) prescribes procedures for evaluating the safety performance of roadside hardware using full-scale crash tests [4]. MASH replaced the National Cooperative Highway Research Program (NCHRP) 350 Report [5] in 2009 with updated test impact conditions and vehicle masses. For longitudinal barriers, there are multiple test levels (TLs) specified for applications on differing road types with differing vehicle types present. MASH TL-3 is a 100 km/h impact at 25 degrees by two different passenger vehicles, a small car and large pickup truck. In addition to the passenger vehicle impacts, TL-4, TL-5, and TL-6 include an 80 km/h impact at 15 degrees of a single-unit truck (10,000 kg), a tractor-van trailer (36,000 kg), and a tractor-tank trailer (36,000 kg) respectively (Table 1). The MASH impact conditions are chosen based on the practical worst-case scenario of three factors: vehicle mass, impact velocity, and impact angle. For impact velocity and impact angle, MASH suggests that the practical worst-case scenario is the 85th percentile.

Table 1: MASH longitudinal barrier test conditions for passenger vehicles and large trucks in TL-3+ crash tests.

Test Vehicle	Impact Speed mph (km/h)	Impact Angle degrees	Minimum Impact Severity kip-ft (kJ)
Passenger Car 1,100 kg (TL-3+)	62.1 (100)	25	51.4 (69.7)
Pickup Truck 2,270 kg (TL-3+)	62.1 (100)	25	106.2 (144)
Single-Unit Truck 10,000 kg (TL-4+)	56 (90)	15	142.3 (193)
Tractor-Van Trailer 36,000 kg (TL-5+)	50 (80)	15	404.2 (548)
Tractor-Tank Trailer 36,000 kg (TL-6+)	50 (80)	15	404.2 (548)

Although US roadside hardware crash procedures currently do not prescribe the use of a motorcycle test vehicle, a number of international roadside crash test procedures exist, and several crash tests have been conducted with motorcycles for research purposes. In 1988 in France, Quincy et al. designed one of the first comprehensive motorcycle tests where a rider was ejected into the barrier to examine guardrail designs [6]. Test conditions were chosen to best replicate real-world crashes based on available data [6].

Expanding upon this work, Koch and Brendicke performed a crash test to examine guardrail impacts from motorcyclists [7]. Compared to earlier studies, the impact angle and impact speed were lowered to precisely investigate which portion of the guardrail causes injury when impacted by the rider. In 2007, Peldschus et al. summarized multiple studies that conducted motorcycle-barrier tests [8]. This includes a follow-on study by Quincy in 1998 at an increased impact speed and two different orientations of the Anthropomorphic Test Device (ATD) [9]. An Anthropomorphic Test Device is a tool commonly used in crash testing to measure potential human injury in different testing conditions. Gaertner et al completed two upright impact tests with shallower impact angles and a higher speed to test head and thorax injury response to impacts with barriers [10]. These test conditions were chosen to replicate common higher speed impacts that occur on the roadway. These tests have resulted in the implementation of CEN TS 1317-8 as the standard test for motorcycle protection systems on barriers in Europe [11]. Similar to many previous studies [12], CEN TS 1317-8 prescribes a 30 degree impact angle with the ATD striking the barrier head-first. The standard prescribes both a 60 km/h and a 70 km/h impact. One of the most recent studies was conducted by The Texas Transportation Institute (TTI) with similar testing conditions to evaluate motorcyclist injury prevention additions on current barriers [13]. TTI motorcycle testing conditions were specified by the Texas Department of Transportation and were chosen to represent real-world barrier impacts (Table 2).

Table 2: Global testing conditions used for motorcycle barrier crash testing

Research Institute	Position	Impact Speed mph (km/h)	Impact Angle degrees
Institut National de Recherche sur les Transports et leur Securite (INRETS) Quincy, R et al, 1988 [6]	Separated, ATD on back with head first	34.2 (55)	30
Laboratorie d'essais Inrets Eqquipments de la Route (LIER) Quincy R, 1998 [9]	Separated, ATD on back with head first	37.3 (60)	30
	Separated, ATD on back parallel to the barrier	37.3 (60)	30
National Swedish Road and Traffic Research Institute Koch and Brendicke, 1989 [7]	Separated, Cadaver on back with feet first	19.9 (32)	15
Texas A&M Transportation Institute Silvestri Dobrovolny et al, 2019 [13]	Upright	35 (56.3)	18
DEKRA & German Federal Highway Research Institute Gaertner et al 2006 [10]	Upright @ 45° roll	37.3 (60)	25
	Upright	37.3 (60)	12
Ministerio de Fomento CIDAUT 2005 [12]	Separated, ATD on back with head first	37.3 (60)	30
CEN TS 1317-8 [11]	Separated, ATD on back with head first	37.3 (60)	30
	Separated, ATD on back with head first	43.5 (70)	30

Crash and Encroachment Studies

The foundation for barrier test impact conditions is data from real-world encroachments, i.e. the vehicle leaves the traveled way, and real-world encroachment crashes. The current test conditions in MASH are based on the crash encroachments collected in the NCHRP 17-22 database. The NCHRP 17-22 dataset extracted encroachment data from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) case years 1997 to 2000 and a few cases from 2004 [14]. NASS/CDS is an in-depth, nationally representative dataset of crashes involving at least one passenger vehicle that was towed from the scene due to damage and contains detailed information on the environment conditions, the vehicle damage, and occupant injuries [15]. Despite the in-depth information, NASS/CDS captures very little information on the roadside. The NCHRP 17-22 dataset used the scaled NASS/CDS scene diagrams to measure the encroachment angles, lateral extent, and road geometry. Based on the vehicle deformation, the impact speed was reconstructed by the NCHRP 17-22 research team. As a follow-on study to NCHRP 17-22, the NCHRP 17-43 dataset continued extracting roadside encroachment data from more recent case years [16]. The NCHRP 17-43 database contains 1,581 roadside encroachments extracted from NASS/CDS case years 2011 to 2015.

Most encroachment studies, including NCHRP 17-22 and NCHRP 17-43, have focused on passenger vehicles while relatively few data collection studies have been conducted for motorcycles in the US. In contrast, there have been many data collection efforts focused on motorcycles in Europe and New Zealand [17, 18]. The first motorcycle in-depth crash data collection effort in the US was collected from 1976 to 1979 in Los Angeles [19]. This dataset included an on-scene crash investigation, an interview with the motorcyclist, and injury data. While this dataset is not specific to roadside encroachments, Ouellet [20] used the Hurt dataset to identify hazards for motorcyclists. Ouellet discussed that road and roadside designs focused on passenger vehicles may increase the risk of crashes for motorcyclists. A more recent data collection effort was conducted by Gabler et. al. in the NCHRP 22-26 project from 2010 to 2016 [21]. This project identified and collected in-depth data on 21 single-vehicle motorcycle-barrier crashes where a rider was admitted into a level I trauma center. In 2016, FHWA released the new Motorcycle Crash Causation Database (MCCS) [22]. This database is comprised of 351 injury crashes, of which 82 cases are single-vehicle motorcycle crashes that occurred in California.

Table 3. Summary of roadside encroachment, and crash datasets for motorcycles

Study	Years	Study Type / Location	# Encroachments / Crashes	Characteristics examined / Notes
Hurt Hurt, Oullet, and Thom, 1981 [19]	1976 to 1979	Crashes / California	900	In-depth
MAIDS ACEM, 2004 [17]	1999 to 2000	Crashes / EU countries	921	In-depth
CARE Stefan, Hoglinger, and Machata 2003 [18]	1991 to 2001	Crashes / EU countries	-	Focus on motorcycle crash trends
22-26 Gabler 2022 [21]	2010 to 2016	Run-off-road crashes / North Carolina	21	In-depth and admitted to a trauma center
MCCS [22]	2016	Crashes / California	351	In-depth investigation

Objective

The purpose of this study is to estimate the real-world impact conditions for motorcycle crashes and compare the encroachment characteristics to passenger cars, utility vehicles, vans, light trucks, single unit trucks and tractor-trailer trucks.

METHODS

The departure angle, posted speed, impact angle, road type, injury outcomes, and object struck were compared across motorcycles, passenger cars, vans, light trucks, single-unit trucks, and tractor-trailer trucks using the National Cooperative Highway Research Program (NCHRP) 17-88 database.

Data Sources

The NCHRP 17-88 database is a collection of encroachments and roadside crashes for the purpose of improving roadside design under development at Virginia Tech and Bucknell University. One of the most important features of the NCHRP 17-88 database is the inclusion of motorcycles and large trucks in addition to passenger vehicles. The NCHRP 17-88 database is comprised of roadside crashes and encroachments extracted from national, state, and naturalistic datasets. The NCHRP 17-88 data used for this analysis was extracted from the following datasets.

NCHRP 17-43: The National Cooperative Highway Research Program project 17-43 is a collection of roadside crash encroachments extracted from in-depth crash datasets [16]. The NCHRP 17-43 dataset includes roadside crashes from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) [15] and from the Crash Investigation Sampling System (CISS). Both NASS/CDS and CISS are in-depth crash datasets that are nationally representative of tow-away, passenger vehicle crashes in the US. NASS/CDS sampling ended in 2015 and was replaced by CISS in 2017. Therefore, NCHRP 17-43 includes cases from NASS/CDS case years 2011 to 2015 and from CISS case year 2017. NCHRP 17-43 includes detailed information on the roadway, roadside, and encroachment in roadside crashes involving a passenger vehicle that was towed away from the crash scene.

LTCCS: The Large Trucks Crash Causation Study contains detailed crash information for approximately 1,000 large truck crashes that occurred from 2001 to 2003. This in-depth crash dataset sampled large truck crashes that resulted in serious injury. This includes scaled scene diagrams that were used to extract trajectory information available in NCHRP 17-88.

MCCS: The Motorcycle Crash Causation Study contains detailed crash information for 351 motorcycle impacts, of which 82 are single-vehicle motorcycle crashes. These crashes were sampled from police-reported motorcycle crashes in California where the motorcyclist was transported to a level one trauma center.

NCHRP 22-26: The National Cooperative Highway Research Program project 22-26 collected in-depth data for crashes involved a motorcyclist that struck a roadside barrier and was transported to a level one trauma center.

Case Selection Criteria

The NCHRP 17-88 database contains 1,581 crashes incorporated from NCHRP 17-43, 124 crashes incorporated from LTCCS, 48 crashes from MCCS, and 21 from NCHRP 22-26. These in-depth crash datasets contain motorcycles, passenger cars, utility vehicles, vans, light trucks (pickups), single-unit trucks, and tractor trailer trucks. Because the dataset is still in development, not every data element is available for every case. Some additional data elements such as speed limit and object struck are being coded for the NCHRP 17-43 cases. Therefore, the case count is provided for each analyzed variable in Table 4. Partial departure crashes, where the subject vehicle impacted a roadside object without the vehicle center of gravity departing the roadway, were excluded from the analysis. When analyzing impact events, such as the object struck or the impact angle, only the first impact was considered. The subsequent impacts are affected by the first impact and that could lead to very unusual impact dynamics. For example, a vehicle that strikes a narrow object may yaw significantly due to the impact before striking a second object. In this analysis, when a vehicle split into multiple components, only the component that originally contained the driver is considered. For example, if a tractor-trailer truck is separated into the trailer and the cab, only the trajectory of the cab is considered. Additionally, if a motorcyclist is separated from the bike during a crash, the trajectory of the motorcyclist is considered.

Table 4: Data Availability

	Motorcycles	Passenger Cars	Utility Vehicles	Vans	Light Trucks	Single-Unit Trucks	Tractor Trailor Trucks
Source Dataset	MCCS + NCHRP 22-26	NCHRP 17-43	NCHRP 17-43	NCHRP 17-43	NCHRP 17-43	LTCCS	LTCCS
All Cases	69	977	305	69	230	38	86
Departure Angle	67	977	305	69	230	37	86
Impact Angle	67	977	305	69	230	38	85
Object Struck	65	744	230	53	174	38	86
Speed Limit	57	734	226	53	168	38	85
Rollover	63	733	225	54	172	38	86
Number of Lanes	67	977	305	69	230	38	86
Alignment	69	977	305	69	230	38	86

Encroachment and Impact Condition Characterization

Six vehicle types were considered: passenger cars, vans, light trucks, motorcycles, single-unit trucks, and tractor-trailer trucks. These vehicle categories are based on the terminology NHTSA uses in the source NASS/CDS dataset. Passenger cars include sedans, convertibles, and station wagons. Vans include mini-vans and van based light trucks. Utility vehicles include compact utility vehicles (CUVs), and sport utility vehicles (SUVs). Light trucks include pickup trucks and other trucks with a GVWR under 10,000 lb. NCHRP 17-43 data was merged with NASS/CDS to evaluate case weight in the context of passenger vehicles. Using case weights assigned in NASS/CDS allows frequency estimates to be nationally representative (Radja, 2016). The analysis of cases from LTCCS was unweighted and MCCS does not include any case weights. The cases from NCHRP 22-26 were combined with MCCS to increase the number of motorcycle crashes available for analysis. In this analysis, the departure angle, posted speed, impact angle, road type, and object struck were compared between the vehicle types. These comparisons help understand the differences in roadside impacts involving motorcycles due to their unique characteristics.

RESULTS

Impact and Departure Angles

For each type of vehicle, the departure angles on each side of the road were combined and plotted using a cumulative distribution function (CDF). All the departure cases included represent full road departures. Departures from both sides of the road occurred between 0 and 180 degrees with 0 degrees being tangent to the roadway in the direction of travel and 180 degrees being tangent to the roadway in the opposite direction.

Figure 1. The departure angle and the impact angles are measured relative to the roadway

In general, the distributions of departure angles corresponding to each vehicle type were nearly identical up to 13 degrees or roughly 65% (Figure 2). Single-unit trucks' 85th percentile departure angle was 33 degrees which was higher than the other vehicle types (Table 5). The distribution of motorcycle and tractor-trailer truck departure angles were very similar to each of the passenger vehicle types. The median motorcycle departure angle was 27 degrees. The largest motorcycle departure angles were much larger than those of passenger vehicles due to a control loss prior to the departure.

Figure 2: The distribution of departure angles in the NCHRP 17-88 database by vehicle type.

The distribution of impact angles was very similar across all vehicle types (Figure 3). The 85th percentile impact angles for motorcycles, passenger cars, utility vehicles, and light trucks were similar (Table 5). Vans tended to have higher impact angles than the other vehicle types.

Figure 3 : The distribution of impact angles in the NCHRP 17-88 database by vehicle type.

Table 5. Distribution of passenger vehicle, large truck, and motorcycle impact and departure angles from NCHRP 17-88 database by vehicle type.

	Departure Angle (degrees)			Impact Angle (degrees)		
	15th Percentile	Median	85th Percentile	15th Percentile	Median	85th Percentile
Motorcycles	4	11	24	2	8	24
Passenger Cars	5	11	22	4	12	26
Utility Vehicles	5	11	24	5	11	27
Vans	3	12	27	7	15	32
Light Trucks	5	11	22	4	11	23
Single-Unit Trucks	4	11	33	3	10	29
Tractor-Trailer Trucks	4	10	20	2	9	22

Event Characteristics

Ejection in passenger vehicles is relatively uncommon but occurs during nearly all motorcycle impacts. Within the NCRHP 17-88 database, motorcycles were classified at each event into three major positions. Motorcyclists can be in the upright position on the motorcycle, they can be coupled to the motorcycle but the motorcycle is laid down, or the motorcyclist can be separated from the motorcycle. An upright motorcyclist is attached to a motorcycle moving in standard upright motion, a down motorcyclist is attached to a motorcycle that is sliding or moving on its side, and a separated motorcyclist is completely removed from the motorcycle. Over 75% of recorded motorcycle crashes included multiple events. During the first event, almost 80% of cases were upright. By the second event, almost 50% of cases were separated. This indicates that a large percentage of riders lose contact with the motorcycle during the first event and are separated during any subsequent events (Figure 4).

Figure 4: Motorcyclist state prior to each impact event. The curves represent the transition of individual riders between states.

Overall, large trucks rollover and motorcycles transition to the down state at a rate much greater than passenger vehicles rollover. Approximately three-quarters of roadside crashes in a passenger car, utility vehicle, van, or light truck were non-rollover. In contrast, over 84% motorcycle, 88% of single unit truck, and 63% of tractor trailer truck roadside crashes were rollover (Figure 5). This difference is likely due to the different body types. Large trucks often have a higher center of gravity making it easier for them to rollover while motorcycles are less stable with only two wheels compared to a typical four-wheel passenger vehicle.

Figure 5: Percent of crashes involving a rollover by vehicle type.

The first roadside crash event for passenger vehicles typically involved fixed objects such as trees and poles. In contrast, the most common first roadside crash event for single unit and tractor trailer trucks involved concrete barriers, guardrails, or a rollover. For motorcycles, the most common objects contacted were curbs and the guardrail length of need (Table 6). Motorcycles likely have a larger percentage of recorded impacts with curbs due to their reduced size and lack of encompassing body. Curb impacts are likely not severe enough to be recorded as an event by the original crash investigator for larger vehicle types such as passenger vehicles and large trucks. Motorcycle impacts with guardrails are overrepresented in this dataset because of the sampling criteria of the NCHRP 22-26 project.

Table 6. Distribution of objects struck during first event by vehicle type for cases in NCHRP 17-88.

	Motorcycles	Passenger Cars	Utility	Vans	Light Trucks	Single-Unit Trucks	Trailer Trucks
Curb	28.3%	9.4%	7.2%	9.7%	9.4%	7.9%	0.0%
Guardrail	26.6%	8.9%	7.6%	0.5%	5.2%	10.5%	12.8%
Rollover	15.0%	4.8%	8.0%	2.7%	13.7%	39.5%	43.0%
Cable Barrier	3.3%	1.0%	3.0%	0.0%	0.0%	0.0%	0.0%
Concrete Barrier	3.3%	1.5%	1.3%	0.0%	0.3%	10.5%	15.1%
Poles/Trees	3.3%	40.4%	40.9%	51.9%	27.5%	10.5%	10.5%
Signpost	0.0%	7.9%	6.0%	0.5%	11.0%	5.3%	1.2%
All Others	20.2%	26.1%	26.0%	34.7%	32.9%	15.8%	17.4%

Road Characteristics

One contributor to the differences in roadside objects struck across the vehicle types is the road types commonly traveled by these vehicles. While passenger vehicle and motorcycle crashes were evenly distributed across most posted speed limits, large truck crashes were more frequent on higher speed roads (Table 7). Motorcycle and tractor-trailer truck crashes are significantly more common on divided roads, while passenger vehicle crashes are more common on undivided roads. Large truck road departure crashes occurred on higher speed, multilane roads more often than passenger vehicle and motorcycle road departure crashes. Over half of large truck road departure crashes occurred on roads with a speed limit of 55 mph (88 km/h) averaging more than two lanes in the direction of travel. In contrast, half of motorcycle and passenger vehicle crashes occur on roads with a speed limit of 40 mph (65 km/h), with passenger vehicles averaging significantly less than two lanes in the direction of travel. Single lane roads refer to undivided roads with two lanes, one in each direction of travel.

Table 7. Cumulative distribution of posted speed for cases in NCHRP 17-88 by vehicle type.

	Motorcycles	Passenger Cars	Utility	Vans	Light Trucks	Single-Unit Trucks	Trailer Trucks
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15	1.8%	3.6%	0.0%	0.0%	0.0%	0.0%	0.0%
20	1.8%	5.3%	0.3%	0.0%	0.9%	0.0%	0.0%
25	21.1%	27.8%	14.8%	23.1%	8.3%	5.3%	5.9%
30	28.0%	35.8%	37.0%	33.6%	19.1%	13.2%	9.4%
35	35.1%	54.2%	55.4%	39.2%	43.3%	21.1%	17.6%
40	43.9%	63.2%	64.4%	58.7%	45.6%	26.3%	18.8%
45	70.2%	80.0%	70.9%	87.6%	62.6%	39.5%	27.1%
50	73.7%	81.4%	76.4%	87.7%	71.7%	44.7%	35.3%
55	98.2%	91.4%	92.9%	97.0%	87.2%	76.3%	63.5%
60	100%	92.2%	95.2%	97.0%	89.0%	86.8%	75.3%
65	100%	96.6%	97.3%	97.6%	98.9%	89.5%	88.2%
70	100%	98.7%	99.9%	100%	99.6%	97.4%	95.3%
75	100%	100%	100%	100%	100%	100%	100%

Motorcycle crashes on curved roadways occurred at a frequency higher than other vehicle types. Over 65% of motorcycles crash on curved roadways, while all other vehicle types crash on curved roadways with a frequency less than 50% (Table 8). Previous motorcycle-barrier crash studies by Jama et. al. [23] and Berg et al. [24] also found that the majority of motorcycle crashes occurred on curves. Gabler et. al. 2007 found that 75% of fatal motorcycle-guardrail collisions occurred on a curve [3]. Furthermore, motorcycle crashes occurred on roads with a smaller radius of curvature (Figure 6).

Table 8. Distribution of roadway alignments by vehicle type for crashes in NCHRP 17-88.

	Straight Road	Curved Road
Motorcycles	34.8%	65.2%
Passenger Cars	57.0%	43.0%
Utility	62.1%	37.9%
Vans	50.4%	49.6%
Light Trucks	58.0%	42.0%
Single-Unit Trucks	63.2%	36.8%
Trailer Trucks	52.3%	47.7%

Figure 6: Distribution of roadway curvature radius by vehicle type in NCHRP 17-88.

Injury Outcomes

Injury outcomes were typically more severe for motorcycles and large trucks compared to passenger vehicles, with a dramatic difference in motorcycles. When a crash occurs, a KABCO injury designation is given by police on scene, while an AIS injury scores are assigned by medical professionals after triage. AIS levels are not recorded in LTCCS. On the AIS scale, motorcycle injuries are more common at the most severe designations of Critical and Maximum (Figure 7). Motorcycles have increased injury due to the lack of safety features that prevent injury in passenger vehicles like airbags and seatbelts.

Figure 7: Distribution of AIS injury reports by vehicle type in NCHRP 17-88.

DISCUSSION

Objects Struck

When studying objects struck, the percentages are relatively consistent across the different vehicle types, with a larger percentage of passenger vehicles striking poles and trees, motorcycles striking curbs, and a larger percentage of large trucks striking concrete barriers. The increase in curbs hit by motorcycles is likely due to the small body size and lack of an encompassing frame on motorcycles. Impacts with curbs are likely not severe enough to be recorded in standard impacts in large trucks or passenger vehicles. The higher number of concrete barriers hit by large trucks compared to other vehicle types could be due in part to large trucks primarily operating on higher speed limit multilane roads. In contrast, passenger vehicles were more likely to hit fixed objects such as poles and trees likely due to passenger vehicles traveling on lower speed limit, single lane roads. High speed limit, multilane roads are likely interstates with a designated clear zone and a greatly increased prevalence of concrete barriers. Single lane, low speed limit roadways have the potential to be much closer to fixed objects, increasing the frequency that vehicles collide with said objects.

Barrier Impact Tests

The motorcycle impact angles were very similar to passenger cars and light trucks, which are the current MASH test vehicles (Table 9). The passenger car and light trucks 85th percentile impact angles were very similar to the MASH test criteria. The 85th percentile impact angle for large trucks, both single unit and tractor trailer trucks, was higher than the MASH test conditions. This is likely due to LTCCS sampling higher severity crashes.

Table 9: Distribution of passenger vehicle, large truck, and motorcycle impact angles from NCHRP 17-88 database by vehicle type.

	Impact Angle (degrees)				
	Passenger Vehicle	**Light Trucks**	**Single-Unit Truck**	**Tractor-Trailer Truck**	**Motorcycle**
15th Percentile	4	4	3	2	2
Median	12	11	10	9	10
85th Percentile	26	13	29	22	24
MASH Testing Guidelines	25	25	15	15	-

Previous studies have performed motorcycle impacts in upright and separated crash conditions because motorcyclists were often ejected from their motorcycle. This study found that during the first impact, the majority of motorcycles were upright. In only 20% of these first impacts, either the motorcycle was down with the rider still on the motorcycle or the rider had separated from the motorcycle. To date, this down but coupled with the rider configuration has not been performed with physical testing. After the first impact, the majority of riders have been separated from their motorcycle. After three impacts, no motorcycles remained upright. Future motorcycle-barrier crash tests should alter the configuration of the motorcycle and the motorcyclist depending on the intended installation type. If the barrier is likely to be the first impact once installed, then an impact with the motorcycle in the upright position would be the most representative. However, if the barrier is likely to be the second impact, such as an installation behind a curb, then an impact test with the motorcyclist separated from the motorcycle would be most representative.

The MASH testing impact angle for sedans and pickup trucks was very close to the 85th percentile impact angle in the NCHRP 17-88 database. If MASH were to adopt a similar practical worst-case scenario (85th percentile) for motorcycle crashes, the impact angle would be 24 degrees. This is lower than the 30-degree impact angle in CEN 1317 part 8, the currently adopted standard in Europe. Based on the motorcycle impacts in the NCHRP 17-88 database, the majority of riders are upright on the motorcycle just prior to the first impact event. MASH could prioritize tests with an upright configuration to most closely match the roadside impacts observed in the US. This would be different from head-first, prone position of the rider alone during the impact test prescribed in CEN 13-17 part 8. However, this test would be very similar to the upright test conducted at TTI [13].

Limitations

The in-depth data from MCCS was combined with NCHRP 22-26 to increase the sample size of motorcycle impacts in the NCHRP 17-88 database. The NCHRP 22-26 dataset only contained motorcycle-barrier impacts, of which the majority were guardrails. The combination of the two datasets nearly doubled the number of motorcycle cases which was a priority. Despite the NCHRP 17-88 database containing every available in-depth motorcycle roadside crash case since 2000, the sample of motorcycle crashes is still small. The results from these motorcycle barrier crashes may not generalize outside of the collection area (California and North Carolina). However, until additional motorcycle crash data is collected, this study represents the largest analysis of motorcycle impact conditions.

The passenger vehicle cases are derived from the NASS/CDS dataset which samples crashes where a passenger vehicle was towed due to damage. Unlike NASS/CDS, the NCHRP 22-26, MCCS, and LTCCS sampling criteria included either transfer to a trauma center or a serious injury. This difference in sampling criteria results in the motorcycle and large truck cases being more severe than the passenger vehicle crashes. This may indicate that this analysis may have higher impact angles compared to all large truck roadside crashes. Because motorcyclists are highly susceptible to injury during a crash, the difference between this study's impact conditions and those of all roadside motorcycle crashes may be small.

CONCLUSIONS

This study analyzed the largest collection of in-depth motorcycle crash data and compared the impact conditions to passenger vehicles, motorcycles, and large trucks. Tractor-trailer trucks consistently had lower departure and impact angles compared to passenger vehicles while motorcycles tended to have very similar departure and impact angles compared to passenger vehicles. The higher center of mass in large trucks and the decreased stability of motorcycles resulted in a much higher frequency of rollover in the sampled road departure crashes. Additionally, it was found that motorcyclists are typically upright during the first impact event. By the second impact event, the majority of motorcyclists were separated from the motorcycle. Passenger Vehicle and Large Truck testing standards are determined by the 85th percentile of impact angles in the US. Following this precedent, future motorcycle-barrier impact studies should consider a 24 degree impact angle. Additionally, the vast majority of 17-88 motorcycle crashes were upright during the first impact. Testing should consider testing in the upright configuration at a 24 degree impact angle to most closely reflect current crashes occurring on the roadway. Future research should focus on collecting additional motorcycle crash data to support further research efforts improving roadside infrastructure for motorcyclists.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: L.E. Riexinger, D.J. Gabauer; data collection: M. Daanen; analysis and interpretation of results: M. Daanen, L.E. Riexinger; draft manuscript preparation: M. Daanen, L.E. Riexinger, D.J. Gabauer. All authors reviewed the results and approved the final version of the manuscript. The authors do not have any conflicts of interest to declare.

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