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Addressing the Motorcyclist Advisory Council Recommendations:

Synthesis on Barrier Design for Motorcyclist Safety

U.S. Department of Transportation
Federal Highway Administration

ZERO IS OUR GOAL
A SAFE SYSTEM IS HOW WE GET THERE

Technical Documentation Page

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16. Abstract

The purpose of roadside barrier systems is to reduce the severity of injuries and number of fatalities by controlling and mitigating crash forces. While barrier systems have been designed and proven to be beneficial for motor vehicles they do not currently address the problems associated with motorcycle crashes. This synthesis of research presented in this report concludes that motorcyclists are more vulnerable than drivers of motor vehicles and that motorcyclists are more likely to be severely injured when they crash into a barrier system. Addressing the challenges associated with barrier systems is critical for reducing the severity of injurious and number of fatalities associated with motorcyclist-barrier crashes. The synthesis report summarized several new barriers and retrofit systems currently used or under development that are specifically intended to improve motorcyclist safety in addition to retaining the existing benefit for motor vehicles. This synthesis report identifies current research proposals and research gaps that should be considered for future research projects. A significant gap is the lack of testing standards and protocols in the United States to verify the safety advantages of roadside barriers for motorcyclists. The final portion of this report summarizes testing parameters to be considered for both upright and sliding impacts into roadside safety barriers that should be investigated during the planning, development, and research of testing standards in the United States.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device
CALTRANS	California Department of Transportation
CBP	Crash Barrier Protection
CDC	Center for Disease Control
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CODES	Crash Outcome Data Evaluation Systems
CRIS	Crash Records Information System (for Texas)
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FSI	Fatal-Serious-Injury Ratio
GES	General Estimates System
GIDAS	German In-Depth Accident Study
HIC	Head Injury Criteria
ISO	International Organization for Standardization
ISPE	In-Service Performance Evaluation
LIER	Laboratoire d'essais INRETS Equipment de la Route
MASH	Manual for Assessing Safety Hardware
MAC	Motorcyclist Advisory Council
MC	Motorcycle
MGS	Midwest Guardrail System
MPS	Motorcycle Protection System
MUTCD	Manual of Uniform Traffic Control Devices
NCDOT	North Carolina Department of Transportation
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NSW	New South Wales
OV	Opposing Vehicle
PDO	Property Damage Only
RDG	Roadside Design Guide
SMV	Single Motor Vehicle
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation
UNE	Una Norma Española (Spanish Association for Standardization)

CHAPTER 1. INTRODUCTION

The design, construction, maintenance, and retrofit of roadway facilities requires an inclusive approach that considers the interactions between a vehicle and the roadway. This approach is essential so that the facility can provide the safest possible driving environment. As part of this balanced approach, there is a need to comprehensively understand how the candidate design vehicle characteristics may differ and how these differences can be expected to influence vehicle operations on the roadway. Historically, the typical design vehicle primarily considered for road design has been the passenger car. In some cases, a heavy vehicle may have also been considered when weighing issues such as acceleration from a stopped condition. Unfortunately, the direct inclusion of motorcycles as potential design vehicles has been limited.

MOTORCYCLE SAFETY CONSIDERATIONS

To consider fully how to best accommodate motorcycle safety, there is a need to first assess the nature of this issue by contrasting motorcycle crash statistics to those of other road users. This information can then be used to help leverage ways to better address issues unique to motorcycle crash characteristics.

Motorcycle Crashes

The examination of crash statistics highlights the need for more direct inclusion of motorcycle-related considerations and how these challenges can be addressed as part of the roadway project development process. More than 14 percent of fatalities in the United States (U.S.) are attributed to motorcyclists (NHTSA, 2017), yet motorcycles make up only three percent of registered vehicles and only 0.6 percent of vehicle miles traveled (NHTSA, 2017). Based on a U.S. study conducted in 2019 using data acquired from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES), there were 5,172 motorcyclists killed in 2017 (NHTSA, 2019). These statistics demonstrate that motorcyclists have a greater likelihood of being involved in a fatal or serious injury crash when compared to passenger cars. Because a motorcycle is one of the most vulnerable motor vehicles on the road, there is a clear need to provide targeted research to determine ways to safely accommodate motorcycles and reduce crash severity associated with these vehicles.

A recent study conducted by the Federal Highway Administration (FHWA) reported that there was a 34 percent **decrease** in the number of passenger car and light truck fatalities between 1994 and 2014 (Nazemetz et al., 2019). In that same timeframe motorcyclist fatalities **doubled** (Nazemetz et al., 2019). These findings indicate that although measures have been taken to improve safety overall for motorists in the past 20 years, safety specific to motorcyclists appears to have been overlooked. Of course, the number of motorcyclist fatalities are much smaller as they make up a small percent of the total motoring public. These trends are disconcerting. NHTSA data shows that overall motorcyclists are 37 times more likely to be killed than car occupants per distance traveled (NHTSA, 2008).

European transportation agencies have also recognized the need to address motorcycle safety. Research from 23,000 crashes in the United Kingdom indicated that motorcyclists were more vulnerable than passenger car occupants with a 15 times greater chance of being involved in a fatal crash than that of a car occupant (Williams 2004). A 2018 European Commission study indicated 15 percent of all road fatalities were motorcyclists. The data also showed that 11 motorcyclists per 100,000 registered two-wheelers were involved in a fatal crash compared to five car drivers per 100,000 registered cars.

A study by Williams et al. (2008) analyzed information from 110 of the 278 police files relating to fatal crashes as documented within the Transport Research Laboratory's collection for pre-impact motion of motorcycles. Based on the analysis by Williams et al., motorcyclists were the most vulnerable road users observed in the study with a 27.2 percent fatality or serious injury rate as compared to 12.8 percent for car occupants.

A study conducted by Frederickson and Sui (2015) used data from the German In-Depth Accident Study (GIDAS) for the period 1999-2014. Frederickson and Sui compiled data for 3361 total motorcycle crashes and 79 fatal crashes in Dresden and Hanover. They identified that the most common cause of injury for single vehicle motorcycle crashes involved hitting a guardrail or a tree. The injuries related to fatal crashes involved 48 percent head injuries, 23 percent thorax (chest), 10 percent spine, and 4 percent other.

Wilson et al. (2019) conducted a study to analyze Texas motorcycle crash data with a goal of using their findings to further development of freeway ramp concrete barrier systems. The authors attempted to identify relevant factors related to crashes in which a motorcycle impacted a road safety barrier on flyover/connecters or on curves. Their analysis focused on the distribution of fatal and incapacitating motorcycle injury crashes that occurred in Texas from the year 2014 to 2016. Wilson et al. reported that 40 percent of the observed injury crashes where a motorcycle impacted a flyover or connector were fatal (leaving 60 percent to be classified as incapacitating). For these fatal or injury crashes, 3 fatal and 6 incapacitating crashes resulted from an overturned motorcycle. Guardrail, retaining walls, median barriers, and bridge rails were classified as the harmful object struck for 3 to 4 fatal or incapacitating injury crashes. Locations with curvature included 26 percent of the crashes resulting in fatalities with the remaining 74 percent resulting in incapacitating injuries.

An effective approach to identifying ways to improve motorcycle safety is to analyze safety data and determine how the areas of roadway geometrics, roadway construction and maintenance, barrier design, pavement design and materials, and automated and connected vehicle enhancements can collectively be improved to enhance motorcycle safety performance. This report focuses on candidate roadside barrier safety performance as it relates to the motorcycle-barrier crash condition.

Motorcycle-Barrier Crashes

The placement of a roadside barrier is intended to enhance roadside safety by minimizing the likelihood that an errant vehicle will run off the road and impact a rigid obstacle such as a tree. The barrier itself, if not installed correctly or as per roadside design guidelines recommend, could in some cases cause more harm than the obstacle it is intended to shield. For this reason, it is important to understand how a vehicle will respond upon impact with a roadside barrier.

An emerging concern is the effect of roadside barriers specific to motorcyclist safety. Barriers represent a small proportion of all crashes, but there is a much greater risk of a fatality for motorcyclists than for car occupants (15 times greater in Europe and 80 times for the steel guardrail in the United States) (Grzebieta et al., 2013). A review by Nazemetz et al. (2019) of the FHWA Motorcycle Crash Causation Study (MCCS) data of 351 crashes indicated that guardrail and traffic sign supports were one of the most harmful motorcycle crash events. Data from a soon to be released report for the NCHRP 22-26 study specifically looked at motorcycles and barriers and found that in the US motorcycle-guardrails crashes are responsible for more fatal crashes than any other vehicle-guardrail crash (Gabler, 2020). From 2001 through 2006, there were a total of 1,462 cases of roadside fatalities that involved a motorcycle in Australia and New Zealand with 78 of those cases positively identified as involving a roadside safety barrier (Bambach et al., 2010).

The following sections in this chapter review the influence of motorcyclist positions associated with a motorcycle-barrier crash and associated helmet use performance due to a motorcycle-barrier collision. Chapter 2 of this report further identifies barrier types in greater detail and provides a synthesis of their role in the safety performance of motorcycle-barrier crashes. Common barrier systems include concrete barriers, guardrails (also sometimes referred to as "guiderails"), and cable barriers. In addition, discrete barrier elements such as sign posts can be obstacles when impacted by a motorcycle or motorcyclist. These roadside treatments are typically constructed as safety enhancements to mitigate the injury to vehicle occupants, yet in some cases they may create new safety risks for motorcyclists. To better understand these potentials risks, there is a need to further examine the characteristic of these crashes as well as understand the role that the motorcyclist's position at the time of the crash and helmet use could have on the overall crash condition.

Common Motorcyclist Position

Gabler (2007) reported that guardrail collisions (12 percent fatality risk) pose a greater risk for motorcyclists than concrete barrier collisions (8 percent fatality risk). Similarly, research by Daniello and Gabler (2011) suggests that motorcycle crashes into guardrail systems are reported to be more harmful for riders when compared to crashes into concrete barriers. Based on the position of the motorcyclist, motorcycle-barrier crashes that involved concrete barriers had more instances of riders vaulting over the barrier. For collisions with guardrail, however, Daniello et al. (2013) observed riders more frequently slid into the guardrail.

Vehicles can impact barriers at different angles and speeds and these impact positions can result in different crash outcomes. Similarly, the method of impact into barriers by motorcyclists can be different. Examples of ways in which motorcyclists may hit a barrier includes upright impact at different angles, ejection from the motorcycle after striking a barrier, or sliding into a barrier. A research study by Daniello et al. (2013) analyzed police reports to examine rider trajectories for collisions that involved barriers in New Jersey between 2007 and 2011. The total number of single-vehicle motorcycle-to-barrier collisions were 442 with 430 of those crashes analyzed and the barriers identified for 342 of them. Barrier type was identified using Google Street View, as barrier type in the crash reports was not always present or accurate. Motorcycles most often (26.9 percent of the time) impacted a barrier while the motorcycle was in an upright position.

Crashes between motorcycles and barriers where the motorcyclist vaulted over the barrier occurred 12.2 percent of the time, while crashes where the motorcyclist slid into the barrier occurred 16.6 percent of the time. Crashes in which a rider was ejected from a motorcycle after colliding with a barrier were 2.91 times more likely to have a serious injury than crashes in which a rider struck upright and was not separated from a motorcycle. Also, if a rider was ejected into a barrier then there was an increased chance of serious injury (4.73 times as likely to be seriously injured).

Data extracted from a database that extended across England, Scotland, and Wales for the years 1992 to 2005 included 110 fatal motorcycle-guardrail related crashes with sufficient data for analysis. In 58 of the 110 crashes, the motorcyclist was upright when he or she hit the barrier, and the majority of the upright crashes involved the rail and not a post. In the 33 crashes that involved sliding, the motorcyclists were more likely to have struck a post first instead of the rail. In the remaining fatal crashes, the analysts were not able to determine the location of the rider at impact (Williams 2008).

This research suggests that motorcyclist riding position upon impact with a barrier can influence the type of injury sustained; however, injury type is not perfectly correlated with riding position upon impact and, in fact, there are injury types that are prevalent across different impact riding positions. As an example, Williams et al. (2008) concluded that regardless of the first barrier element in contact with a motorcyclist during an impact, head injuries and severe injuries were represented as the most common cause of motorcycle crash fatalities. Bambach et al. (2012) provided a case series analysis study conducted with crash data from Australia and New Zealand of motorcyclists who were fatally injured following a collision with a roadside barrier from 2001 to 2006. The thorax region had the highest incident of injury followed by the head region (Bambach et al., 2012). In fatal motorcycle crashes in single and multi-vehicle crash modes, head injuries predominated all other injuries. The injury profiles were similar with motorcyclists that slid into a barrier or collided with a barrier in an upright position.

Helmet Use

Based on information provided by the Centers for Disease Control and Prevention (CDC), helmets are an important and proven protection device. NHTSA (2019) estimated that motorcycle helmets helped save the lives of 1872 motorcyclists in 2017. NHTSA further estimated that helmets reduced the likelihood of fatal injury by 37 percent for motorcycle riders and 41 percent for their passengers. Additionally, research by Derrick and Faucher (2009) and Liu et al. (2008) determined that helmets reduced the risk of a head injury by 69 percent.

The general consensus among motorcycle safety stakeholders suggests that helmets are considered essential safety protective gear for motorcyclists; however, it is important to understand how barrier type or design may influence the likelihood of an injury as it relates to helmet use. Daniello and Gabler (2012) determined that injuries due to motorcycle-barrier crashes commonly affect the upper and/or lower extremities. Bambach et al. (2012) further determined that the motorcyclist's thorax region experienced the highest incidence of maximum injury in fatal motorcycle-barrier crashes. It is important to note that studies have shown wearing a helmet does not guarantee a risk-free impact between motorcycle and barrier; however, some personal protective gear may serve as a safety countermeasure (e.g., motorcyclist armored vest). Research has shown that protective body armor can reduce injuries from motorcycle crashes, in general (de Rome et al., 2011). Daniello and Gabler (2011) concluded that there is no statistical difference regarding the odds of severe injury for helmeted or unhelmeted motorcyclists when a collision occurs with a cable barrier or a guardrail. This observation seems logical given that the majority of injuries due to crashes into this type of barrier appear to result in injuries to the motorcyclists' extremities.

Daniello and Gabler (2011) further determined that if a rider was helmeted, the odds of severe injury in guardrail collisions were 1.419 times as great as the odds of severe injury in concrete barrier collisions. In addition, the odds of severe injury for helmeted riders in collisions with metal barriers were found to be significantly greater (at the 0.05 level) than the odds of severe injury in concrete barrier collisions. Analyses of riders with and without helmets showed no statistical difference at the 0.05 level in the odds of severe injury between collisions with a cable barrier and collisions with a guardrail; however, their study only included a small number of cable barrier collisions in the analysis when compared with the number of guardrail collisions.

CHAPTER CONCLUDING COMMENTS

Common roadside safety devices have historically targeted passenger cars and other motor vehicles with four or more wheels. When a motorcycle comes into contact with one of these roadside devices, the roadside barrier may not always function as a safety device. From a study by Daniello and Gabler (2011), the researchers analyzed 951 motorcycle-barrier collisions including guardrails, cable barriers, and concrete barriers. Of these devices, guardrail systems had greater odds of resulting in severe injury for riders when compared to injuries associated with crashes into concrete barriers. There is a need to understand better how the role of roadside barriers may differ for motorcycle-barrier crashes when contrasted to crashes between other vehicles and barriers. In addition, the rider position upon impact and the role of the motorcycle helmet are two elements that should be considered with assessing how to optimize roadway safety for motorcyclists while also balancing the safety needs of all users.

CHAPTER 2. ROADSIDE BARRIERS AND MOTORCYCLES

Chapter 1 identified some of the safety concerns associated with motorcycle crashes with particular attention to injury level for crashes into roadside barriers. As documented in the American Association of State Highway and Transportation Officials (AASHTO*)* Roadside Design Guide (2011), transportation agencies in the U.S. typically deploy one of the following three types of roadside safety barriers, examples of rigid barriers (typically concrete), semi-rigid barriers (typically guardrail systems), and flexible barriers (typically cable or wire rope systems) are shown in Figures 1-3, respectively.

Figure 1. Example of a Concrete (rigid) Barrier.

Figure 2. Example of a Guardrail with Steel Posts.

©GGfGA

Figure 3. Example of Cable Barrier.

These barrier systems are intended to enhance safety by protecting/shielding vehicles from conditions along the roadside which may be harmful to a driver if they leave the roadway, such as traffic signs, bridge piers or steep drop-offs. Roadside safety barriers can be placed on the outside of a roadway or in a median of a divided roadway. Some traffic signs can be designed so they do not need to be protected by barriers (e.g., breakaway posts), but then the posts themselves can still be struck. Roadside safety barriers are designed to contain and redirect vehicles. In most cases the barriers only serve their intended purpose if they maintain the vehicle (and therefore the occupants) on the impact side of the barrier. This is obviously a challenge in a motorcycle impact at any kind of speed, as the rider can be separated from a motorcycle much easier than a passenger can be ejected from a vehicle.

For a particular situation, the type of barrier used on a roadway is dependent upon the cost-effectiveness of the barrier, the amount of space available and potentially the type of obstacle being shielded (AASHTO, 2018). In the U.S., these barrier systems are tested and need to comply with the *Manual for Assessing Safety Hardware* (MASH) standards (AASHTO, 2016) prior to installation on the National Highway System (NHS) roadways. The U.S. MASH criteria addresses a broad range of motor vehicles with different test levels and configurations including testing a barrier system with passenger cars, pickup trucks, single unit trucks, tractor trailers, and tractor tank trailers. However, MASH does not provide any guidelines or protocols to test motorcycles against a barrier system. To date, there has not been a systematic approach developed in the U.S. for similar testing protocols related to motorcycle safety.

Roadside safety barriers are recommended when it is determined that a barrier poses less of a threat to a vehicle than the obstacle it is protecting. As noted, this consideration has been focused on cars and trucks, not motorcycles. The different barrier types have different configurations and therefore different concerns related to motorcycles.

CONTRASTING MOTORCYCLIST FATALITIES AND INJURIES BASED ON BARRIER TYPES

It has been observed that motorcyclists are the leading source of fatalities associated with guardrail crashes in the U.S. In 2005, motorcyclists suffered more fatalities (224) than were experienced by passenger car occupants (171), or persons involved in any other type of single vehicle crash involving guardrails (Gabler et al., 2007). NCHRP Project 22-26, Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers, specifically focused on crashes involving roadside barriers. Although the final report is not yet public, it has been presented that the study identified that motorcycle and barrier crashes remain an issue, as in 2017 motorcyclists accounted for 40 percent of guardrail related fatalities, while only 3 percent of vehicles registered for use (Gabler et al., 2020).

Motorcyclists also have a high number of incapacitating injuries from crashes involving barriers. This has been documented in a few studies using U.S. data. The proportion of single vehicle motorcycle crashes that resulted in a fatality or incapacitating injury from an impact into a roadside barrier was 32 percent in Washington State and 57 percent in Ohio (Gabaeur, 2014). Similar studies using data from North Carolina, Texas, and New Jersey identified an average value of 37 percent of the barrier related crashes resulted in a fatality or incapacitating injury (Daniello & Gabler, 2011). Obviously, roadside barrier impacts by motorcycles have lethal consequences, but there are also different types of roadside barriers. To look at the motorcycle-barrier issue closer the type of barrier needs to be considered.

U.S. Studies Related to Barrier Type

Some limited studies have been conducted in the U.S. to specifically understand motorcycle barrier crashes and barrier type. Daniello and Gabler (2011) conducted a study to determine which type of barrier carries a higher risk for motorcyclists. The study consisted of an analysis of motorcycle crashes into barriers for three states: North Carolina, Texas, and New Jersey. This study used Google Earth to identify barrier type since this information was not available in the police crash reports. Of the 951 motorcycle-barrier crashes they found 38 percent involved rigid barriers (concrete), 57 percent involved semi-rigid barriers (guardrail), and 5 percent involved flexible barriers (cable). They also assessed injury severity patterns in collisions with each barrier type. They identified that 36.5 percent of the rigid barrier crashes were fatal, similarly 40 percent of the guardrail and cable crashes were also fatal. They found that crashes involving a guardrail were 1.4 times as likely to result in severe injury (i.e., killed or incapacitated) as compared to rigid barrier for helmeted riders. There was not a statistical difference for riders without helmets. They also did not observe a statistical difference between guardrails and cable barriers.

Guardrails themselves can come in different types. An ongoing study with the Texas Department of Transportation (TxDOT) (Dobrovolny, 2021) found 689 of the total 68,838 reportable crashes from 2010-2017 involved a motorcycle making contact with a guardrail as determined by the Texas Crash Records Information System (CRIS) analysis. 94 percent of those crashes were classified as Single Motor Vehicle (SMV). Of those 646 SMV motorcycle crashes involving a guardrail, 109 resulted in a fatality and 215 resulted in an incapacitating injury. These serious SMV motorcycle crashes involving guardrails occurred on 174 different roadways. To identify the types of guardrails involved in the crashes, the research team viewed each crash site using Google Earth. Two types of guardrail with different types of post, wood posts and steel posts, were identified. Of those guardrails which were involved with fatal or incapacitating injury SMV motorcycle crashes, 75 percent were constructed with wood posts. But, the steel posts had a higher rate of fatal crashes compared to the guardrail with wooden posts.

European and other Non U.S. Studies Related to Barrier Type

This section examines research performed in Europe related to barrier type, realizing that barrier types in these areas may be slightly different than in the U.S. The locations include Australia and nearby New Zealand, Sweden, Germany, and England.

A study performed using data from motorcycle crashes with roadside objects in New Zealand that specifically examined fatal crashes identified 77 percent that involved a guardrail, 10 percent concrete barrier, and 8 percent a wire rope. The percentage of the different barrier types in New Zealand was not specifically presented, but they did note that the barriers involved in the fatal crashes were related to the volume of the type of barrier on the roadway, so the percentages identified were in line with the exposure risks (Bambach et al., 2012b). Another study by the same author using data from New South Wales, Australia from 2001 to 2009 found that 38 percent involved guardrails and posts while only 3 percent involved concrete barriers. As in the case for New Zealand, the percent of the different barrier types in New South Wales was not identified. They did conclude that based on the data concrete barrier collisions resulted in fewer serious injuries as compared to guardrail (Bambach et al., 2013).

Sweden found that barrier crashes involving guardrail and wire rope barriers were similar when comparing the severity of the crashes. Rizzi et al. (2012) analyzed police reported crashes of motorcycles into road barriers between 2003 and 2010 in Sweden using the Fatal-Serious-Injury Ratio (FSI) for different types of barriers. The FSI ratio is represented as the ratio of the number of fatal and severely injured motorcyclists to the number of injured motorcyclists. The study outcomes suggest that there was no statistically significant difference between FSI ratios for guardrail type barriers and wire rope barriers, although these FSI ratios were generally high (above 50 percent).

Outcomes of a crash statistics analysis conducted by Williams et al. (2008) indicated that in England, there was a slightly increased serious injury or fatality risk to motorcyclists from impacts with wire rope barriers (a 66.7 percent risk from wire rope compared to 58.3 percent for all barriers). The risk was higher in Scotland with a 100 percent risk from wire rope and 58.3 percent from all barriers. However, there was less than a 1 percent impact per year between motorcyclists and wire rope safety fences, so the data itself was limited.

Without the protection of a surrounding vehicle, motorcyclists have a higher likelihood of fatal or serious injuries in a crash. Different barriers, barrier material types, locations on the road, and even the rider's position impacting roadside barriers are variables that further change the likelihood of crash outcomes. The Federation of European Motorcyclist association (FEMA) has reported that concrete barriers have some benefits over guardrails in that they have a larger surface area to spread out any impact. They also note the concern of the safety of the cable barriers by many motorcycle association's in Europe. Due to the very thin nature of the cable barriers, there is a perception that the impact on a motorcyclist is potentially worse than a guardrail impact. FEMA noted anecdotal concerns with cable barrier impacts in their 2012 document "Standards for Road Restraint Systems for Motorcycles". The FEMA document also referenced the aforementioned studies by Williams in England and Scotland that found fatality rates higher for wire rope barrier crashes as compared to other type barrier crashes (FEMA, 2012). It should be noted that the previously mentioned Rizzi study using data from Sweden and the soon to be published NCHRP 22-26 project with data from the US both were not available when the 2012 FEMA document was published. The newer studies (i.e., Sweden and U.S.) both indicate that there is not a significant safety difference between guardrail and the cable/wire rope barrier.

Both as related to the volume and severity, guardrail, and in particular guardrail posts, pose a specific concern for motorcyclists in crashes. While recent crash data analysis indicates that there is no significant safety difference between guardrail and cable barrier types, motorcyclists generally have a higher concern with the cable barriers. This may be due to the fact that guardrail is ubiquitous, while cable barriers are just starting to be installed in larger numbers.

Motorcycle Riders Injuries Related to Barrier Crashes

Daniello and Gabler (2012) offer an example of the types of injuries associated when a motorcyclist strikes a barrier. The authors examined motorcycle crashes from 2006 to 2008 in Maryland using the Crash Outcome Data Evaluation System (CODES) to better understand the type, relative frequency, and severity of injures associated with this crash type. As a reference, CODES data links police-reported crashes with hospital data to provide detailed information about the injuries inflicted during a collision. Their results found four main crash modes for motorcyclists that included single-vehicle barrier collisions, single-vehicle fixed-object collisions, multivehicle collisions, and single-vehicle overturn-only. More than 70 percent of motorcyclists involved in the analyzed crashes suffered an injury to the upper or lower extremities, making this the most commonly injured body region for crashes. The authors also found that motorcyclists involved in barrier collisions were 2.15 times more likely to suffer a serious thorax (chest) injury than overturn-only collisions.

A study using motorcycle-barrier crash data from Sweden found the injury severity increased when the rider separated from the motorcycle prior to the crash and slid as compared to the riders that impacted the barrier upright (Rizzi, 2012). The authors also noted that previous crash tests using anthropomorphic test devices (also known as test dummies) supported that, at similar speeds, an upright barrier crash was more survivable than sliding into a barrier.

Research conducted by Bambach et al. (2014) investigated the crash mechanics and injury causation of motorcyclist fatalities in Australia and New Zealand between 2001 and 2006. Only crashes into a roadside safety barrier were used for the research project. Of the 20 fatal crashes, half of the motorcyclists slid into the barriers and the other half impacted the barrier in an upright crash posture, two types of position impacts that have been identified previously. Approximately half of those impacting the barrier in an upright position slid along the top of the barrier. After evaluating the crashes, the mean pre-crash speed and impact angle were determined to be 100km/h and 15 degrees respectively, and the thorax regions had the highest incidence of maximum injury followed by the head region.

BARRIER TYPES AND MOTORCYCLES

Each of the barrier types have potential benefits as well as limitations that should be considered when evaluating safety performance of motorcycles and their interaction with barriers. Rigid (e.g., concrete) barriers are the most expensive to install but typically have the least long-term maintenance. For concrete barriers, motorcycle riders are mainly observed to be ejected or vaulted to the other side of the barrier. Semi-rigid systems, such as guardrails, are the most used safety barrier systems in the US. Research shows that motorcycle crashes involving riders include both sliding into the guardrail and crashing into it in an upright stance. For discrete elements (e.g., sign posts), and what has been reported in cable barrier crashes so far, the interaction of rider is primarily in the form of a head-on collision. This report separates cable barrier and discrete posts into two categories due to the current perception in the motorcycle community that cable barrier is not just a post impact concern.

The next section describes some of the issues particular to the different barrier types and potential countermeasures that have been found in the research to address the concern. The following categories and sub-categories related to crash impact will be described:

- Rigid Barriers (Concrete)
  - Ejection over barrier
- Semi-Rigid (Guardrail)
  - Sliding (discrete post impact)
  - Upright (lacerations, tears or snagging with post top due to sliding on top rails)
- Flexible (Wire Cable)
- Unprotected Posts (discrete post impact)

Rigid Barriers

Rigid barriers are typically used in areas with limited lateral clearance as they are designed to allow minimum deflection after impact with vehicles. ©Texas A&M Transportation Institute

Figure 4 depicts an example of a rigid concrete barrier. Concrete barriers are a type of rigid barrier provided in the form of continuous sections joined to provide a smooth containing surface.

Concrete barrier systems are often built to a height of 32 inches. Some systems might be as tall as 54 inches. During impact of a motorcycle, however, the limited barrier height likely does not contain the impacting upright motorcycle rider. Depending on the mode of impact, this could result in the impacting rider being ejected from the motorcycle and landing on the opposite side of the barrier. For concrete barriers in a median that could mean being thrown into on-coming traffic. Concrete barriers can also usually be found around curves, on hills, and on bridges, etc. which presents the problem if a motorcyclist is thrown over the barrier, the ejected rider would be left potentially falling to his or her death after ejection from the motorcycle. These barriers present other issues for motorcyclists such as redirection into traffic. This type of crash could also lead to a fatal injury, especially if the rider loses control of the motorcycle and is redirected into the travel lane of a high-volume roadway.

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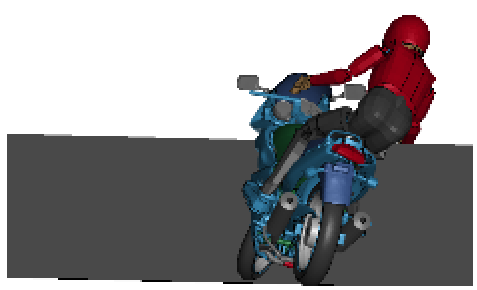
Figure 4. Rigid Concrete Barrier.

Issue: Concrete barriers provide relatively less threat to motorcyclists considering there is a smooth surface for the rider to slide after impact. However, the sliding rider impact and lack of containment can still be a problem for such barriers.

Concerns associated with concrete barriers include:

- Impact into the rigid structure
- Crashes can result in the ejection of the upright motorcycle rider over the barrier possibly resulting in striking the object the safety barrier was designed to protect against. Figure 5 shows a simulation of a motorcycle impact of a concrete barrier leading to the rider being ejected over the barrier.
- Redirection of the motorcyclist back into the traffic stream.

Potential Countermeasure: Continuous protection on the top of the barrier can be provided to prevent the rider ejection over the barrier. Such protection can help contain the rider after upright motorcycle impact.



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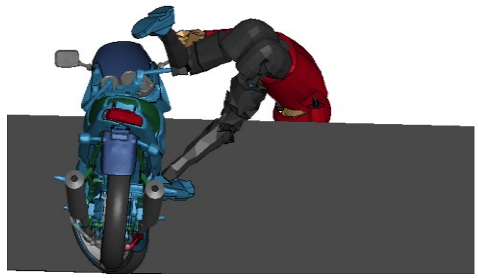
A. Motorcyclist impacting a concrete barrier



B. Motorcyclist being ejected and vaulting over a concrete barrier

C. Motorcyclist being ejected over a concrete barrier

Figure 5. Example of Simulated Motorcylist Impact With a Concrete Barrier.

Research on this type of containment system is underway at the Texas A&M Transportation Institute (Dobrovolny, 2021). Researchers are working with TxDOT engineers to develop computer simulation plans that include proposed nominal impact conditions (e.g., speed and angle), critical impact points, and Anthropomorphic Test Device (ATD) containment and redirection. This is important since U.S. standards for motorcycle testing do not exist. A chain link fence system was preferred over other options since it was more economical with good availability, ease of installation, and ease of maintenance. Seven pendulum tests were performed and determined a 2x2 chain link mesh size, and top and bottom steel horizontal rails with discrete steel connections spaced at approximately 1 ft. The simulation used a 32 in high concrete barrier installation that was rigidly installed and had a radius of curvature of 500ft. A retrofit U-shaped post design minimized the likelihood of an errant upright motorcycle rider directly impacting the discrete posts of the chain link fence system. The simulation showed no interaction between the ATD and the retrofitted U-shaped post. The U-shaped off-set posts were designed with the distance from the barriers similar to the distance a road sign would be if attached to the concrete barrier. See Figure 6 and Figure 7 for the design.

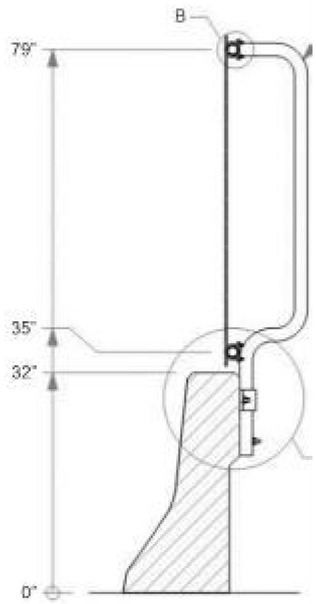


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Figure 6. Design of Retrofitted U-Shape Post with Barrier.


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Figure 7. Tested Retrofitted Design on the Test Site.

The photos presented in Figure 8 show a motorcycle test conducted at TTI's testing facility. Figure 8C, shows that the motorcyclist does not come in contact with the posts which was a concern of which the engineers and reseachers were mindful. The retrofitted U-Shaped Post and mesh fence containment system was considered suitable for implantation at locations where an upright motorcycle rider containment option is need and/or desired. MASH TL-3 compliance testing is still needed to evaluate the structural integrity of the system, occupant risk, and vehicle deformation.

A. Crash test picture of ATD with motorcycle impacting chain fence (front view).

B. Crash test picture of ATD with motorcycle impacting chain fence (side view).

C. Crash test picture of ATD with motorcycle impacting chain fence (perspective view).

D. Crash test picture of ATD with motorcycle after impacting chaining fence (perspective view).

Figure 8. Sequential Images of Crash Test of a Motorcycle into a Fence.

Semi-Rigid Guardrail Systems

Semi-rigid barriers are designed to allow higher deflection of the system under impact loading due to vehicles as compared to rigid barriers. The Midwest Guardrail System (MGS) as shown in Figure 9 is a typical example of a semi-rigid barrier. Guardrail type roadside barriers are the most common barrier type employed. A crash of a motorcycle into a semi-rigid barrier could be expected to result in injuries including lacerations due to the motorcyclist sliding on top of the rail or severe injuries due to the motorcyclist directly impacting a guardrail post. Therefore, semi-rigid barrier motorcycle impacts are further classified as guardrail system post-beam (sliding) and guardrail system post-beam (upright).

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Figure 9. Semi-Rigid Midwest Guardrail System.

Guardrails (Post-Beam Systems) – Sliding

Issue: The typical guardrail system used in the U.S. as a roadside safety barrier consists mainly of two elements: the longitudinal rail which is continuous, and the discrete posts (with or without a blockout) to support the rail. Guardrails have been designed and tested to redirect and contain motorized vehicles such as cars and trucks; however, as indicated earlier it is not necessarily a suitable option if the primary goal is to mitigate motorcyclist injuries.

A problem associated with existing guardrail options is that discrete posts serve as a fixed object against which a sliding rider can impact, potentially resulting in a serious injury or fatality. A depiction of a three-dimensional simulation/model of an ATD sliding into a discrete post can be seen in Figure 10.

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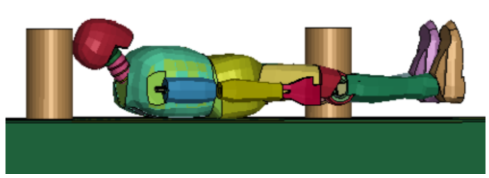
A. Simulated ATD sliding into a discrete post.



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B. Simulated ATD impacting a discrete post.

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C. Simulated ATD redirected update to top of discrete post after impacting a discrete post.

Figure 10. Impact of Anthropomorphic Test Device into Discrete Post.

Potential Countermeasure: Options which provide bottom protection to the guardrail systems to prevent or cushion rider interaction with discrete elements of the guardrail, such as posts, can be adopted to enhance motorcycle safety (see Figure 11 as an example). The protection can be related to the post themselves (non-continuous) or continuous along the bottom portion of the rail such that it covers the posts and in between the posts. Continuous protection systems also can contain a rider from going between posts, under the guardrail, and striking the object the guardrail was installed to protect. Continuous systems are referred to as Motorcycle Protection Systems (MPS) in this report (Europe also uses the term rub rail).

- Lower Rails: MPS or continuous rails made of different materials such as plastic or metal are available to install as a bottom protecting option for the guardrail systems. See Figure 11 which shows the crash test simulation pictures of an ATD impacting a lower rail and being redirected. As shown in the figure, adding lower rails allows a motorcyclist to slide along the bottom rail, instead of impacting a discrete post, to help mitigate serious motorcyclist injuries.
- Post Attenuators: Devices covering the discrete posts can be provided to mitigate injuries due to sliding rider impacts. This is a non-continuous protection covering only the posts.

MPS systems address the sliding motorcyclist problem by redirection, containment, energy dissipation, preventing head on collision with discrete posts, and minimizing rider interaction with the posts. However, providing protection for only the lower portion of a guardrail would not address the problems associated with upright position impacts and containment.

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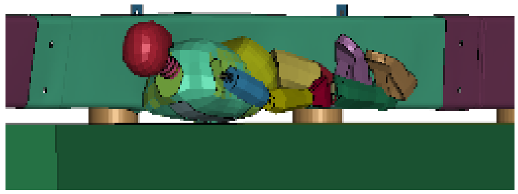
A. Simulated ATD impacting bottom rail protection.



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B. Simulated ATD redirected after impacting bottom protection rail.

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C. Simulated ATD redirected away from bottom rail after impacting.

Figure 11. Crash Test Simulation with Continuous MPS to Address Sliding Motorcyclist Impact with Discrete Posts.

U.S. States Experience with Motorcycle Protection Systems (MPS)

Several state DOTs have recently installed MPS systems (produced as Barrier System's DR-46 Motorcycle Barrier Attenuator). The results have not been formally documented in research reports due to the recent time frame. The information shared here was from unpublished work and personal correspondence.

California: The roadside safety research group in CalTrans have shared information about their experience with installation of a MPS in California. They used a commercially available barrier termed DR-46. After the installation in 2011-2012, the barrier did not experience any impacts until May 2019. Researchers believe that the system served the function of preventing any negative motorcyclist impacts on the roadside system. The yellow color of the barrier system is also considered as a possible factor to attract rider attention and prevent crashes (Personal communication between C. Dobrovolny and B. Meline [CalTrans], May 24, 2019).

North Carolina: Considering the results obtained by the MPS installed in California, NCDOT also decided to install MPSs on critical roadway sections to control motorcyclist injuries and fatalities. NCDOT had previously performed other motorcycle specific countermeasures along NC 143, Cherohala Skyway, such as paving shoulders and improving curve warning signage, but they were still experiencing motorcycle crashes. This roadway is known by the motorcycle community as part of a motorcycle route known as the “Tail of the Dragon/Cherohala Skyway”. In 2017, a review of five-year data on guardrail crashes identified 31 motorcycle crashes involving roadside barriers (guardrail). Out of those 31 crashes, 2 resulted in a fatality and 11 in an incapacitating injury. As a part of a safety project, NCDOT installed approximately 3,500 feet of an MPS (also DR-46) on six hot-spot locations in this high incident corridor. However, due to the recent installation (December 2018), it is difficult to determine the effectiveness of the MPS in reducing crashes and injuries involving motorcycles. NCDOT received a very positive response from the motorcycle community for undertaking this safety project. Further, they felt that the maintenance and installation of the MPS was also fairly simple and quick. The information included in this section was retrieved from an AFB20 committee presentation by Mr. Bucky Galloway from the North Carolina Department of Transportation (see Galloway, 2020).

Utah: The Utah Department of Transportation (UDOT) has taken significant steps to mitigate motorcyclists’ injuries due to discrete guardrail element impacts. UDOT installed commercially available MPS (also DR-46) on a section of State Route 35. Crash data collected by UDOT suggests an improvement after installment of the MPS. Although not analyzed statistically, the data reveals that before installing the barrier during a 6-year period, motorcycle crashes resulted in 12 injuries and 1 fatality. After installing the MPS, within a 3-year period, there has been only 1 reported motorcyclist injury. Since the DR-46 is not currently sold in the U.S., procurement of the MPS was difficult and involved sole source issues. Also, the DR-46 required being removed every winter so the snowplows would not damage it, as it is installed very close to the ground. Utah DOT retrofitted another guardrail installation on SR 191 by using a standard W-beam rail that was powder coated yellow, similar in color to the DR-46, and mounting it below the regular guardrail, similar to where a DR-46 would be installed, but a little higher so it did not need to be removed for snow plowing, as illustrated in Figure 12. Data collected by UDOT for this retrofit showed good results. In the 5 year period before installation of the MPS, 5 motorcycle injuries were reported within the roadway section. After installation, during a 3-year period, no injuries were reported.

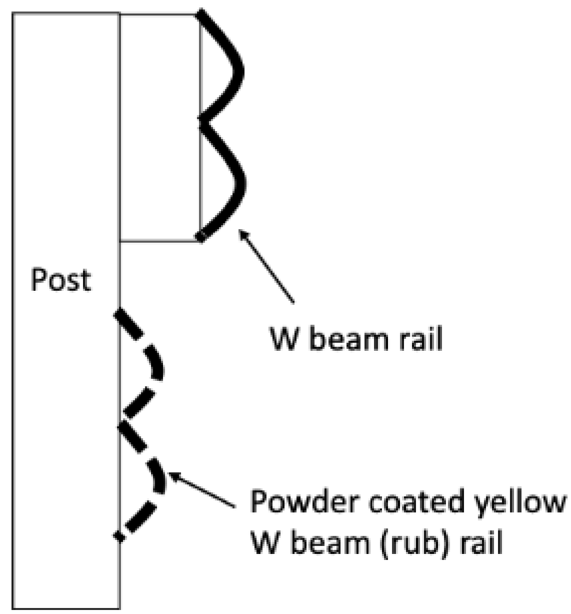

Figure 12. Illustration of Retrofitted Guardrail.

Similar to the powder coated rail retrofit, the UDOT also installed galvanized W-beam rub rail on a guardrail system on SR 167, but this added rub rail was not powder coated yellow, it was the same color as the original guardrail. Data showed that before installation, during an 8-year period, motorcycle impacts resulted in 2 fatalities and 19 injuries. After installation of the MPS, during a 2-year period, motorcycle crashes resulted in 2 fatalities and 8 injuries. No studies have examined the effectiveness of this MPS design. This does emphasize that as more MPS are installed, more in-depth analyses, like the types of crashes (i.e., sliding or vaulting over the top) are needed to understand their potential benefits and limitations. The information in this section was retrieved from a TRB AFB20 committee presentation by Mr. Debenham from UDOT (see Debenham, 2020).

Non-U.S. Experience with Motorcycle Protection Systems (MPS)

France was an early adopter of testing retrofitted guardrails with a lower beam for the protection of motorcyclists. They actually used ATDs in their MPS studies in 1979 and 1980. Germany also has a long history of use, the Bundesanstalt für Strassenwesen (BASt) (the German equivalent of FHWA) reported installing 80 kilometers of MPS in 1984 as part of an experimental effort (Domhan, 1987). Impact tests performed for the BASt using the "Schweizer Kastenprofil" or swiss box profile rub rail confirmed that the risk of injury to motorcyclists with the modified guardrail system was lower than without the retrofit (Berg et al. 2005).

In 2012, FEMA identified the variety of testing protocols used in Europe for evaluation of MPS (FEMA, 2012). FEMA identified that the French L.I.E.R. (Laboratoire d'essais INRETS Equipment de la Route) test protocol was used in France and Portugal. The MPS evaluation standard that is used in Spain is similar to the French version. The Spanish version is from Asociación Española de Normalización y Certificación (AENOR) and is known as UNE 135900. Italy and Germany both used a protocol from BASt. FEMA has recommended a more coordinated effort for approval of MPS by adopting a common European standard (EN 1317-8). Additional information on the existing European standards can be found in Chapter 3. Note that EN 1317-8 was recently (2019) changed to CEN/TS 17342:2019 – European Standard for Motorcycle road restraint systems.

It has been reported that Norway has developed guidance for the locations of MPS, and that Spain, Portugal, Germany, Australia and New Zealand are also pursuing retrofitting of guardrails with MPS (Nordqvist, 2016).

South Australia performed a case study of two different motorcycle protection systems (flexible fabric and steel mesh) in a popular location for motorcyclists, especially for weekend travel in the mountainous Adelaide Hills area. The specific installations were on Gorge Road and Cudlee Creek Road. Historically (2001-2010 data) over 40 percent of the casualty (i.e., injury and fatal) crashes on these two roads were due to motorcycles, and 34 percent of those motorcycle crashes involved impacting the guardrail (termed guard fence in Australia). After MPS installation, no serious or fatal injury crashes were recorded on either road that involved a guardrail. There were, however, 20 motorcycle crashes with 2 of the crashes reported to have involved the guardrail. One of the guardrail crashes was Property Damage Only (PDO) and the other involved a minor injury. Although not enough time had passed to evaluate the installations for a true before/after comparison, there was evidence that indicated the single crash resulting in PDO could have otherwise resulted in much worse injury without the MPS. In addition, there was not enough data to compare the fabric and steel MPS systems, but vandalism was noted as a significant concern for the fabric MPS, as it was slashed in several places shortly after installation (Anderson et al., 2012). Figure 13 and 14 show two different views of the fabric MPS.

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Figure 13. Back View of Fabric MPS.

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Figure 14. Front View of Fabric MPS.

TRL of the Transport Research Foundation identified a number of proprietary motorcycle protection systems in use (Williams 2008). Some of the systems were designed to be retrofitted on existing guardrails (e.g., BikeGuard, DR46, Ercawn Motard, MotorRail, MOTO-SHIELD, Mototub, SP4) and others were guardrail systems specifically made for motorcyclist protection (e.g., CUSTOM [Containment Urban System for Motorcyclists]).

The Center for Road Safety in Austrlia has documented the results of MPS crash tested for both motorcycle and vehicle impacts. Three different types of MPS were added to a standard W-beam guardrail. Each of the MPS systems were tested, along with the standard W-beam guardrail without the MPS as a comparison. Testing was performed in accordance with the European test standard for motorcycle testing EN 1317-8 (described in more detail in Chapter 3). The passenger car test was based on NCHRP 350 Test 3-11(2000 kg pickup truck, 100 km/h at an angle of 25 degrees) but it used a 1600 kg sedan instead of a 2000 kg pickup truck. The standard W-beam guardrail did not meet the motorcycle safety criteria (EN1317-8) but passed the passenger car safety criteria (NCHRP 350 modified). All three of the MPS passed the performance criteria used for passenger car safety, but only two of the three MPS met the motorcycle safety criteria (Baker et al. 2017). This indicates that MPS can be installed without causing undue harm to passenger vehicles.

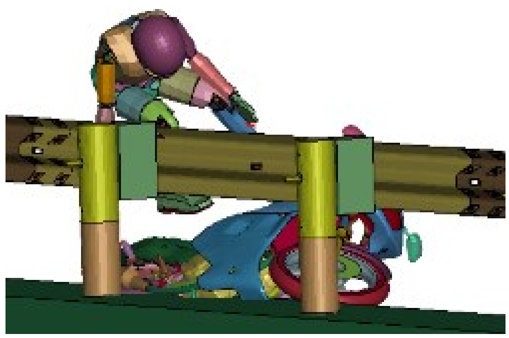
MPS can also attempt to specifically address head on collision related injuries with discrete elements such as the posts of the guardrails while sliding into it. TRL also described products designed to cover discrete posts that are designed using foam type material to absorb forces on an object (e.g., helmet or head) as it collides with a post (Williams 2008).

Guardrails (Post-Beam Systems) – Upright

Issue: Similar to guardrails described for the sliding motorcyclist problem, W-beam guardrail systems also pose a risk for a rider impacting it in an upright configuration (Figure 15 depicts two W-beam guardrail system concerns for upright riders). Issues associated with existing guardrail options when a rider is impacting the rail in an upright position include:

- Longitudinal rails can result in severe head injuries and lacerations for the rider, while impacting in an upright position, the rider can slide along the top of the guardrail impacting several posts before finally resting on either side of the system.

- Severe injuries can occur after rider impact with the guardrail system due to ejection on the other side of the system.



A. Simulated ATD striking and then vaulting over a W rail.

B. Simulated ATD striking a W rail and then impacting their head on the discrete post.

Figure 15. Motorcyclist Impacting the Rail and Discrete Posts of a Guardrail System.

Potential Countermeasure: Continuous or non-continuous options which provide top protection to the guardrail systems to prevent rider interaction with longitudinal rail edges, and discrete elements of the guardrail, such as top of the posts, can be adopted to motorcyclists' impact with guardrails. The MPS noted earlier do not provide protection to riders from guardrail elements such as the top of the posts. Similar to bottom protection plates, a continuous bent plate can be provided on the top covering the posts which allows the rider to slide without severe injuries. Figure 16 shows a guardrail top with protected longitudinal rails. The crash test is a part of an ongoing TxDOT project aiming to retrofit guardrail systems for motorcycle safety (Dobrovolny, 2019).

Top Rail: Has a smooth vertex on top that will help provide flexibility and dissipation of energy during impact with the rider.

Bottom Rail: Uses the opportunity for dissipation of energy of impact by accommodating small deformations and rotation during impact event. This also minimizes the distance between the flat bottom rail and the existing MGS rail.

Figure 16 shows a crash test of an ATD at TTI's testing facility. An important question that needed to be addressed before the crash test was conducted was the criteria for the Upright Motorcycle Test. There were 2 performance indicators to be considered: the severity levels (that focus on head injury criteria (HIC) and neck forces) and ejection during the test since the ATD is not allowed to remain trapped or suffer any detachments of limbs.

<u>Recommended Testing</u>: The following tests were recommended to address the priority need of the study:

1. MASH test 3-10 (passenger car)
2. MASH test 3-11 (pickup truck)
3. Upright motorcycle test with seated ATD rider
4. Sliding ATD test aiming at mid-span between posts
5. Sliding ATD test aimed at discreet post

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A. Side view of an ATD sliding on top of an MPS during a Texas A&M Transportation Institute crash test.

B. Perspective view of an ATD sliding on top of an MPS during a Texas A&M Transportation Institute crash test.

Figure 16. ATD Sliding Along the Top of a TxDOT MPS in a Texas A&M Transportation Institute Crash Test (Dobrovolny et al., 2019).

Flexible Cable Barriers

Flexible barriers (see Figure 17 as an example) are designed to allow even higher deflection than semi-rigid barriers. Consequently, a flexible barrier allows energy dissipation mainly through deflection of the system. Cable barriers and weak post W beam guardrail systems are examples of flexible barriers. While weak post guardrail poses the concern of impacting the rails as noted previously, cable barriers also pose a concern for impacting the thin cables. Decapitations and amputations have been reported in the literature related to extreme speeds and cable barriers in Australia and New Zealand, but the same study also identified decapitations and amputations based on guardrail impacts (Bambach et al., 2010).

Signposts have similarities to posts used in flexible barrier systems. A motorcycle crash into a flexible barrier or a signpost can result in severe injuries due to the motorcyclist directly impacting a post. Cable barriers typically have smaller posts that are spaced farther apart than guardrail, which would respectively lessen the severity and chance of impact with a cable barrier post as compared to guardrails.

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Figure 17. Flexible Barrier – Cable Rope Barrier.

Issue: Cable barriers are provided with continuous rope-wire elements acting as a beam to contain motor vehicles. However, these rope-wires are perceived to induce a "cheese-cutter" effect on motorcyclists when impacting such barriers. The contact area with a motorcyclist would be concentrated in the small wire diameters upon impact. Although the wire-rope barriers are provided with continuous cables, they have a large portion of the posts exposed to the motorcyclist in case of an impact event. This can again result in discrete post impact resulting in fatalities.

Potential Countermeasure: Although the cable barriers are widely perceived as potentially harmful for motorcyclists, the data suggests that they have provided great benefits to reduce highly fatal cross over motor vehicle crash fatalities in both the U.S. and Europe (Grzebieta el al., 2009). The discrete posts can be provided with post caps to mitigate head injuries. However, this would not address the redirection and containment issue pertaining to sliding and upright motorcyclists and does not address the "cheese-slicer" perception. Since cable barriers are relatively new, and such a low but growing proportion of the overall volume of roadside barriers, additional research is potentially needed specifically related to cable barriers and motorcycle crashes. It is anticipated that the NCHRP 22-26 report will provide additional data on this topic, specifically as related to current conditions related to barriers in the U.S.

Motorbike writer.com (see Hinchliffe, 2012) recently shared that an Australian motorcycle and safety enthusiast is supporting what is being called the "Nelson comb". They note that "The device, made by Indian company TDCO Design, uses recycled plastic to form a hair "comb" that is inserted into the wire barrier with a bottom rail snapped into the bottom gap" (Hinchliffe, 2012). While the article also noted that there was an issue with safety due to the cable in cable barriers, they do not cite any references supporting the assertions. A depiction of the Nelson comb device can be found in Figure 18.

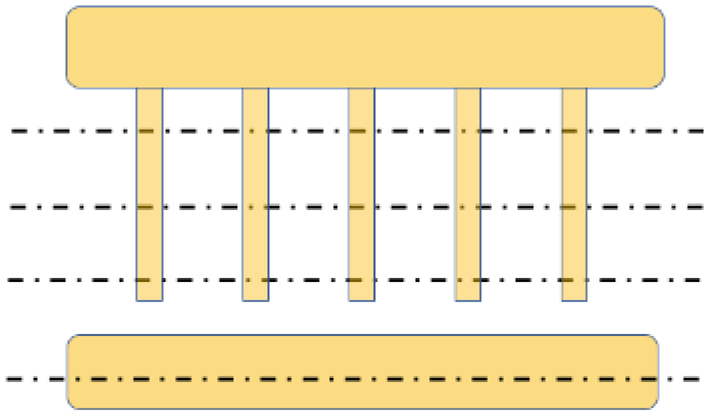

Figure 18. Depiction of the 'Nelson Comb'.

Signposts

Signposts that are not protected like shown in Figure 19, are required to be breakaway to prevent injury. Similar to barrier crash testing, breakaway testing only involves cars and vehicles.

Figure 19. Discrete Sign Post System.

Issue: Signposts essentially act as a discrete post element on the roadside. Hence, the problem is similar to sliding or upright riders impacting discrete posts. This can again lead to a fatal injury to a rider due to head on collision with the post.

Potential Countermeasure: Discrete protection similar to the discrete post elements noted previously could mitigate rider impact severity with the post. This would act like a post attenuator to absorb the head-on collision impact. However, it is noted that post attenuators will not address the redirection and containment issue pertaining to a sliding motorcyclist. It should also be noted that due to the vast amount of sign posts this would definitely be cost prohibitive.

IN-SERVICE PERFORMANCE EVALUATIONS (ISPE)

It is noted that even though several countries outside the U.S. have implemented the use of barriers on roadway sections, no studies or reports are available which illustrate in-service performance evaluations (ISPE) of those systems. Conducting an ISPE of existing motorcycle-friendly barriers is an important topic to address to understand if these systems serve their intended purpose. Not only would an ISPE indicate the adequacy of such barriers to motorcyclist impacts, but it would also provide an indication of whether they still meet current standards for vehicular impacts.

The objectives and need of developing ISPEs have been stated is the AASHTO Manual for Assessing Safety System (AASHTO, 2016), which is the latest U.S. standard for testing and evaluation of roadside safety hardware. This document highlights the importance of ISPEs by stating that "ISPE allows user agencies to identify overall impact performance of a feature as well as identify potential weakness or problems with the design" (AASHTO, 2016). It also states that ISPE will "demonstrate that design goals are achieved in the field and identify modifications that might improve performance" (AASHTO, 2016). Although the document refers to ISPEs specifically for vehicular impacts, the objectives and needs would remain for motorcycle impacts. Further, it is important to conduct ISPEs to ensure field performance of roadside safety devices which might be affected due to differences in crash testing and actual crashes such as field impact conditions, site conditions, configurations, etc. (AASHTO, 2016).

COST AND IMPLEMENTATION

Two primary considerations for many stakeholders are the costs to install and maintain "motorcycle friendly" barriers and their relative ease of implementation. Barriers that are costly and/or are difficult to implement will either be adopted very slowly or not adopted at all, thus limiting or even negating any potential advantages that the barriers may offer to motorcyclists.

A central finding from the work conducted here is that due to the new and somewhat novel nature of these barrier systems, there is little information readily available that can describe fully the range of installation and maintenance costs and ease of implementation. In the absence of conducting a large-scale survey of manufacturers and practitioners in the U.S. and abroad (e.g., Europe, Australia) the current work summarizes an example from the U.S. where information has been made available.

NCDOT installed the Lindsay Transportation Solutions' DR-46 Motorcycle Barrier Attenuator (MBA) in Graham County, NC in several curves along NC-143. The DR-46 MBA is a polyurethane barrier system that can be added with metal zip ties to an existing guardrail with on roadway curves that exhibited a documented pattern of guardrail crashes. It is also manufactured in yellow to provide a visual warning for motorcyclists. NCDOT indicated they were impressed with this barrier system (Galloway, 2020)

The cost of the DR-46 MBA was $30/lf, including delivery and NCDOT viewed the installation experience as extremely easy (Galloway, 2020). While NCDOT used a qualified guardrail installer for this project, it was noted that installers do not necessarily need to have a guardrail installation background to install this barrier system and that the NCDOT felt comfortable with their maintenance staff installing or replacing segments of the barrier system (personal communication with Mr. Bucky Galloway). As part of the project, NCDOT purchased additional DR-46 rail sections to be used when needed for replacement of damaged sections (Galloway, 2020).

A limitation noted by NCDOT was that if the height of the existing guardrail system was significantly lower than the NCHRP Report 350 height standard of 27 inches, the DR-46 would not fit between the bottom rail of the W-beam guardrail and the ground. This was one of several reasons why NCDOT made the decision to upgrade all the guardrails in the installation area where the DR-46 was installed (Galloway, 2020). Another option explored by NCDOT was to cut the shoulders around the guardrail to allow for sufficient space but they felt more comfortable upgrading the guardrail to MASH standards (personal communication with Mr. Bucky Galloway).

NCDOT did identify one challenge regarding the purchase of the motorcycle retrofit system. Specifically, because the purchase was a sole source procurement and the product was being purchased from Italy, the overseas shipping added costs and delays, and the sole source procurement created some issues that delayed the process by a few months (personal communication with Mr. Bucky Galloway). Utah addressed the sole source issue and cost of the DR-46 in their later installations by using a typical piece of W-beam guardrail, and installing it underneath the existing guardrail as shown in Figure 12. At the time (pre-MASH) it was considered a rub rail and did not need to be crash tested for passenger vehicles. If a retrofitted system like this was tested both for MASH and motorcycle safety it may be a potentially cost-effective measure to address motorcycle hot spots.

NCDOT noted maintenance issues that may be of interest for many U.S. States. NCDOT does not remove the barrier during the winter and, to date, has experienced minimal damage to the barrier from snow clearing operations. One of the main reasons NCDOT decided to leave the barrier in place during the winter is the fact that NC 143 does see a relatively high volume of motorcycle traffic on warm, dry weekends during winter months. An addendum to their comments indicated that while the section of NC 143 where the DR-46 is installed does receive above average snowfall for Western North Carolina, the amount does not compare to the large amounts of snow received by other parts of the U.S., such as the northern and Midwestern States, where more frequent snow removal may increase the amount of damage to the DR-46. Chapter 2 discussed the potential value of highlighting the lower guardrail with a contrasting color (yellow) to further influence motorcycle crash rates. To receive the full linear delineation benefit out of the yellow DR-46 rail, NCDOT found that there was a need to increase the number times that the area was mowed each season to reduce vegetation height.

As indicated in Chapter 2, the NCDOT saw an overall reduction in the severity of motorcycle crashes as well as an overall reduction in the frequency of motorcycle crashes along the portions of NC 143 where the DR-46 was installed. In addition, the motorcycle community expressed positive comments with this project and has been very vocal about their support for this and other projects that improve motorcycle safety.

CHAPTER CONCLUDING COMMENTS

Roadside barriers are necessary elements that are intended to protect a motorist that leaves the roadway from encountering an even more significant obstacle. But, since motorcycles are such a small minority of motorists on a typical roadway, barriers have traditionally been designed and built in the U.S. with the consideration of cars and trucks, not motorcycles.

This section has provided information on the different types of roadside barriers and how motorcycle impacts with these barriers differ. Potential countermeasures, such as motorcycle protection systems (MPS) for guardrails, have been identified as related to the type of impact as related to the barrier. Some promising installations of MPS have also been shared, while their time in service has been limited to date.

CHAPTER 3. NEXT STEPS AND POSSIBLE FUTURE ACTIVITES

A significant component associated with many motorcyclist crashes is the interaction between a motorcycle and an infrastructure-based element such as the roadway surface, lane striping, and signs and posts as examples. It is easy to envision a situation in which the risk of a motorcycle crash increases significantly due to pavement that is worn over long-term use and offers reduced traction. While it is easy to identify elements such as worn pavement as potentially contributing to motorcycle crashes, it is more challenging to appreciate those infrastructure-based countermeasures that are specifically designed to improve safety as potential contributors to reduced safety, particularly for motorcyclists.

This report focused on synthesizing research and engineering practices relative to roadside barrier design. As indicated in prior chapters of this report, barriers can have positive safety influence in a motor vehicles/barrier crash but can present significant safety issues for motorcyclists being lacerated when sliding across the top of a barrier, receiving significant thoracic injuries when impacting concrete barriers, colliding with the posts that support barriers, and vaulting over a barrier. The potential for barriers to reduce safety for motorcyclists is not insignificant and presents an engineering challenge to redesign barriers to improve the safety of motorcyclists but also retain the existing safety advantage for motor vehicles.

In response to this safety critical situation, the engineering and research community has developed or is in the process of developing "motorcycle friendly" barriers that are intended to minimize or eliminate motorcyclists' fatalities and serious injuries when impacting a barrier (see Chapter 2 of this report). While the new designs offer great promise, they represent an initial step in the longer quest for barriers to improve motorcyclist safety. Critical next steps include identifying what barrier related topics have been developed as problem statements and submitted for research funding and to identify potential barrier related research topics that could be developed into problem statements and submitted for future funding. Conducting research on the additional barrier-related topics would significantly advance not only how the field of motorcycle barrier design is approached but also, ultimately, the ability of the barriers to reduce the number of motorcyclists' lives lost.

CURRENT PROBLEM STATEMENTS

Research relative to design and effectiveness is critical for continually improving motorcyclist safety relative to barrier-motorcycle collisions. To gain a better understanding of what research should be funded as part of future projects, it is first important to examine what research has been conducted (see Chapters 1 and 2 in this report) and to then identify those research topics that have been proposed. In the course of the current project, one problem statement submitted to a federally funded program was identified along with a project that recently concluded but the results were not yet released.

Development of Guidance for Enhanced Delineation of Barriers and other Roadside Safety Hardware, Slopes, and Obstacles to Improve Visibility for Motorcycles.

Transportation agencies have encountered situations where enhanced continuous delineation of the face of existing roadside barriers appears to reduce crash and injury severity. At the recent

AKD20 Roadside Safety Conference (Debenham, 2020), the Utah DOT noted that their installations of a yellow powder coated metal motorcycle rub-rail under a standard W-beam guardrail on two state-maintained routes resulted in a significant reduction in motorcycle crashes and injuries. California Department of Transportation (CalTrans) installed the yellow colored DR-46 motorcycle attenuator rub-rail in a curve exhibiting a high number of motorcycle crashes and their evaluation, the number of motorcycle crashes in that curve reduced to zero. Similarly, yellow DR-46 rails installed by the North Carolina DOT showed promise in reducing motorcycle crashes, although the results are preliminary.

Based on preliminary before and after crash studies there appears to be an association between enhanced longitudinal delineation and crash and injury reductions; however, although this finding is encouraging, it is based on studies with limited experimental controls (e.g., multiple treatment locations, multiple control locations). Research and development in this area should examine the utility of enhanced continuous delineation as a first step but also develop guidance to assist state and local transportation agencies in determining enhanced practice solutions for delineating roadside safety barriers (and steep slopes). The guidance should be further implemented through an update of appropriate sections of the AASHTO RDG, Manual on Uniform Traffic Control Devices, and MASH.

The problem statement entitled "Development of Guidance for Enhanced Delineation of Barriers and other Roadside Safety Hardware, Slopes, and Hazards" was submitted to the American Association of State Highway and Transportation Officials Special Committee on Research and Innovation for the NCHRP fiscal year 2022 program.

Factors Contributing to Injurious and Fatal Motorcycle Crashes with Traffic Barriers

As indicated in prior sections of this report, relatively little research has been conducted on fatal and serious motorcycle collisions with barriers with some of this work being constrained by significant research limitations. To address this need, the project entitled "Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers" was funded through an NCHRP project (NCHRP 22-26) and conducted by the Virginia Polytechnic Institute and State University and was completed in November, 2020. The project is listed in this report as a problem statement because the final report was pending at the time of this report and has not yet been released.

The objective of the research project was to identify the range of factors contributing to motorcycle collisions with traffic barriers that resulted serious injuries and fatalities. The research examined impacts with a variety of barriers such as bridge rails, cable barriers, concrete barriers, crash cushions, and end terminals to understand better the association between barrier type and injurious and fatal crashes.

POTENTIAL RESEARCH TOPICS

The prior research projects, current projects, and existing problem statements summarized in this report support the notion that some tentative steps have been taken to address the potential benefit that redesigned barriers could offer for improving motorcyclist safety; however, the lack of an extensive list of projects and problem statements also suggests the need for additional research. The following potential research topics were identified through a gap analysis based on the results of the review of literature (summarized in Chapters 1 and 2 of this report) of motorcyclist injuries and fatalities sustained in barrier related crashes and through discussions with practitioners (e.g., state engineers). The gap analysis indicated there is an opportunity to address several important research topics through future funding, each of which are summarized below.

Development of a Motorcycle Testing Standard Addressing Motorcycle Testing and Impact Configurations in the U.S.

Research conducted by Grzebieta et al. (2013) reviewed the European Standard EN 1317-8 (European Committee for Standardization, 2012) with regard to Australian motorcyclist fatalities. The research identified the primary crash modes of sliding upright and ejection from a motorcycle and concluded that both an upright and sliding position of a motorcyclists while impacting a barrier were equally represented in the Australian-New Zealand crash data analysis. However, EN 1317-8 does not provide any specifications or criteria for specify thorax injuries (but it does contain a head injury criterion for sliding mechanisms). As indicated in Chapter 1, thorax injuries represent a significant motorcyclist injury type.

It is clear that there are several potential research topics associated with this area. First, research is needed to develop criteria for thorax injuries and an additional test using an ATD consisting of colliding with a barrier in an upright position. Second, relative to testing standards, it is noted that International standards (e.g., EN1317-8) do not contain test specifications and criteria for upright position (they do however address a sliding motorcyclist test design) thus necessitating research to examine this critical and common crash configuration. Lastly, there are no guidelines addressing proper testing and use of motorcycle retrofit barriers in the U.S. Research is needed to identify and validate appropriate standards for the U.S.

Research Examining In-Service Performance Evaluation

It is important to recognize that there may be differences in barrier performance between test and actual site installation locations due to varying impact conditions at the barrier installation site, differences in test and actual site conditions, and differences due to varying attention to installation details. Due to these differences, it is important to monitor actual installation to evaluate barrier performance and conduct evaluations of barriers that are currently in service. These evaluations are typically referred to as in-service performance evaluations (ISPE).

As per AASHTO'S Manual for Assessing Safety Hardware (MASH), Second Edition (AASHTO, 2016), the following are some of the objectives of an ISPE:

- To prove that the required design goals are obtained and to identify factors that could improve system performance,
- To obtain a wide range of information on collision-performance characteristics of barriers to determine failure/success ratios and associated damage repair costs,
- To determine factors that prevent a barrier from performing as anticipated,

- To determine the effect of climatic and associated environmental conditions on barrier performance,
- To identify the features of barrier systems that impact highway conditions and operations, and
- To obtain timely maintenance information about the system, damages, operations, etc.

Most importantly, ISPEs can help determine if installed barriers are serving the function for which they were intended which, relative to the current work, would include reducing the rate of motorcyclist serious injuries and fatalities due to motorcyclist-barrier collisions.

ISPEs can be performed by analyzing currently available crash data. Available data can be used to analyze pre-installation crashes for motorized (including motorcycles) and non-motorized vehicles (i.e., bicycles). The obtained data can then be employed to determine placement guidance and MPS system design addressing vehicular issues. Data after installation can be analyzed to indicate the degree of benefits or loss due to barrier installation. The conduct of such studies can contribute significantly to an overall data analytic approach and would facilitate system design and placement guidance.

A positive finding from the gap analysis is that some DOTs have started ISPEs of recently installed MPS to enhance motorcyclist safety. In addition, MASH has included a section for ISPE. However, given the overall lack of IPSEs conducted to date, there is a need to fund IPSE studies to understand fully the potential benefits of barriers for motorcycles but also all motorized vehicles.

Identification of Critical Locations to Implement Barrier Systems

State and Federal DOT resources and the potential benefits of barrier systems can be maximized by understanding and identifying appropriate locations deployment. For example, installing guardrail protection or barrier systems can be costly if installed across large areas so it may be important to focus on those areas that truly require a safety countermeasure. In addition, roadside barrier systems installed on curves can have different requirements than installations on straight roads and they may differ based on roadway characteristics, such as rural roads versus urban roads.

An ongoing study conducted by Dobrovolny and Goel (2021) for TxDOT involved investigating placement guidance based on crash severity models that included factors such as the roadway, roadside, operational, and environmental associated with severe motorcycle crashes involving fixed objects in Texas. Their research showed that roadside elements have a significant impact on crash severity. Using random forest and decision trees after conducting a regression analysis, a framework for identifying high-risk locations for motorcycle crashes was developed. The results of data mining were then used to identify potential sites for installing the MPS systems for enhancing motorcyclist safety. Critically, this work underscores the ability to focus installations and mitigation efforts on those sites most in need.

However, while the work conducted for the TxDOT is a promising start, there is a need to expand these efforts to a wider range of location characteristics, barrier types and treatments, and to different States that experience different geographical characteristics. With the development of new MPS for barriers, it is also important to develop placement guidance for installation at locations which are critical to motorcyclist safety.

Enhance the HSIS Database with information on Motorcycle Protection System Barriers and additional Motorcycle Crash Data

Installation of MPS in the U.S is a relatively recent practice performed by State DOTs. As a result, the availability of before and after MPS installation motorcycle-barrier crash data is scarce and challenges the ability to make sound decisions regarding barrier installation and retrofit. Motorcycle-barrier specific data itself is also very limited in the U.S., with the MCCS data only containing 351 crashes. The current MCCS data format also does not now clearly identify cable type barrier systems. Data on specific types of barrier are currently very difficult to compile, as evidenced by the number of research reports that noted they used Google-Earth to identify barrier type for each crash.

A more robust database of motorcycle-barrier crash related information would be a significant resource to address MPS placement guidance and ISPE. Moreover, a database would facilitate maximizing barrier effectiveness by addressing issues specific to certain regions or class of vehicles. It is anticipated that the results of the NCHRP 22-26 research project will provide some additional motorcycle crash data information. The Highway Safety Information System (HSIS) that currently houses the MCCS data is a potential home for this and other motorcycle specific data. There is a need to review the HSIS for future compatibility and potentially add some elements to the MCCS to specifically address cable barrier, which is seeing increased use in the U.S. The specific objectives of this work would include:

- Review the HSIS crash database to identify if it could act as a resource for various applications such as barrier design, crash data analysis, barrier placement guidance, performance evaluation, etc.
- Identify the feasibility of acquiring barrier specific information from other datasets (potentially from their asset management systems).
- Developing a guideline for implementation of motorcycle friendly barriers in the U.S by identifying best practices followed in the U.S or other countries.
- Understanding the barrier system implementation guidelines followed by states or countries who have experience with installing MPS on roads.
- Investigating if the practices followed by such countries or states address the needs of motorcycle safety.

TESTING STANDARDS AND PROTOCOLS

As stated earlier in this chapter, there are no U.S. based standards or protocols available to test a motorcycle or motorcyclist impact with a barrier system, regardless of whether they are designed for motor vehicles or designed/adapted for motorcycles. It will be helpful to examine existing standards and protocols for testing and evaluation of motorcyclists impacting barriers in Europe and elsewhere that may be considered as the basis for U.S. standards and protocols. It is noted that these standards primary exist in Europe (e.g., EN 1317-8) but they are not complete as evidenced by the lack of standards or protocols to test an upright motorcycle impact configuration (testing standards are available for evaluating barriers for sliding test configurations).

Existing Standards and Protocols

The existing standards and protocols include:

- L.I.E.R Protocol: Motorcyclist Safety Evaluation Regarding Barriers
- UNE 135900 Spanish Standard Protocol
- EN 1317-8 Road Restraint Systems
- ISO 13232 Test and Analysis Procedures for Research Evaluation of Rider Crash Protection Devices Fitted to Motorcycles
- FEMA Motorcyclists and Crash Barriers Project
- AS/NZS 3845 Australian/New Zealand Standard

L.I.E.R. Protocol (1998): Motorcyclist Safety Evaluation Regarding Safety Barriers.

The crash test agency was the Laboratoire d'essais INRETS Equipment de la Route Laboratory (L.I.E.R.), France. The L.I.E.R protocol consists of two tests with an ATD impacting a system in two configurations that include an ATD aligned with the path of travel and aimed offset from a post and an ATD aligned with the path of travel but parallel to the posts (see L.I.E.R., 1998). These tests are conducted with the ATD sliding across the ground surface. The test conditions are summarized below:

- Impact Speed: 60 km/h - 37.3 mi/h
- Impact Angle: 30°
- ATD: Standard ATD Model, with standard helmet and standard motorcyclist clothing
- Approval Criteria:
    - The occupant risk should be investigated through instruments included in the ATD. The resultant value for forces and moments should be within approved biomechanical limits. (L.I.E.R., 1998)
    - During the impact event, the impacting ATD shall not penetrate the impacted system, nor should remained trapped in the system. (L.I.E.R., 1998)

UNE – 135900 Spanish Standard Protocol

The crash test agency was the Spanish Ministry of Public Works. This test protocol is similar to the L.I.E.R protocol with some additional elements. In fact, the UNE protocol includes an additional test speed of 70 km/h that was added in revised UNE – 135900 (2008) as compared to 60 km/h in the L.I.E.R specification (AENOR, 2008). In this protocol, the discrete element protection systems (discontinuous systems) are also considered and a post-centered test and a head-first test with an impact offset with regard to a post. A second impact is conducted between two posts as compared to the L.I.E.R. protocol where it was conducted opposite to a post (rigid element). This protocol also provides an additional biomechanical acceptance criteria along with two different performance classes. The test conditions are summarized below:

- Impact Speed: 60 km/h - 37.3 mi/h; and 70 km/h (43.5 mi/h)
- Impact Angle: 30°
- ATD: Hybrid III 50th percentile male, with standard helmet and standard motorcyclist clothing
- Approval Criteria:
  - The evaluated barrier system should not yield to debris with a weight of more than 2 Kgs. (AENOR, 2008)
  - Degree of dynamic deflection and width of the system should not be more than the limits for impact of 4- wheel vehicles specified by UNE EN 1317-2. (AENOR, 2008)
  - ATD should have no noticeable intrusions with no breakage of bones (with an exception to clavicle). (AENOR, 2008)
  - ATD should not reveal any damage or tearing of the clothing used for ATD. (AENOR, 2008)

EN1317-8 Road Restraint Systems - Part 8: Motorcycle Road Restraint Systems which Reduce the Impact Severity of Motorcyclist Collisions with Safety Barriers, Technical Specification

The crash test agency is the Comité Européen de Normalisation (CEN) Technical Committee on Road Equipment (TC226). This specification (European Committee for Standardization, 2012) was an addition to the EN 1317 standard for testing MPS. It specifically considered the sliding motorcyclist position during impact for testing of the protection system. This standard is not mandatory throughout Europe due to lack of experience of some countries with this test specification. Hence, it was decided to accept the standard as a technical specification, thus each country is free to install a barrier which is considered to provide safety with/without compliance with this specification. The test conditions are summarized below:

- Impact Speed: 60 km/h - 37.3 mi/h; and 70 km/h (43.5 mi/h)
- Impact Angle: 30°
- ATD: Modified Hybrid III 50th percentile male, Motorcycle Helmet (polycarbonate shell) satisfying Regulation 22 of ECE/TRANS/505 requirements, and Complying EN 1621 – 1 requirements Motorcyclist Clothing
- Approval Criteria:
  - MPS: The test article shall not reveal any complete rupture for any of its longitudinal elements. (European Committee for Standardization, 2012)
  - ATD**:** It should not remain trapped in the system. There should be no complete detachment of the ATD. ATD parts such as head, neck, limb, etc. shall not become detached after the impact. However, the breaking of the ATD upper extremity and shoulder assembly due to failure of the frangible screws after impact is an exception. (European Committee for Standardization, 2012)

The full-scale crash tests are performed with an ATD sliding on its back with a helmet. The specification requires the ATD to be the hybrid III 50th percentile male. The specification evaluates the MPS performance based on two classes:

- Speed class – based on impact speed of tests.

- Severity level – based on biomechanical values obtained from ATD test measurements.

International Organization for Standardization 13232 Motorcycles-Test and Analysis Procedures for Research Evaluation of Rider Crash Protection Devices Fitted to Motorcycles

The crash test agency is the International Organization for Standardization (ISO). The test protocol standard consists of eight parts which are identified below from ISO 13232 (2005).

- Part 1: Definitions, symbols, and general considerations.
- Part 2: Definition of impact conditions in relation to accident data.
- Part 3: Motorcyclist anthropometric impact dummy.
- Part 4: Variables to be measured, instrumentation, and measurement procedures.
- Part 5: Injury indices and risk/benefit analysis.
- Part 6: Full-scale impact test procedures.
- Part 7: Standardized procedure for performing computer simulations of motorcycle impact tests.
- Part 8: Documentation and reporting.

ISO 13232 Part 2 greatly expands the number of impact configurations and test conditions (e.g., impact speed) to determine the severity of a motorcycle impact against an opposing vehicle (International Organization for Standardization, 2005). There are seven impact configurations and test conditions specified by ISO 13232 Part 2, which differ for 1) Occupant Vehicle Contact Location; 2) Relative Heading Angle, and 3) Occupant Vehicle/Motorcycle Speeds. In addition, ISO 13232 Part 2 recommends a Hybrid III 50th percentile male ATD with specific characteristics (e.g., sit/stand construction, standard non-sliding knees) and some additional modifications (e.g., ATD head skins, frangible knee assembly, and leg retaining cables). See Zellner et al. (1996) for a full list of additional ATD modifications.

FEMA Final report of the Motorcyclists and Crash Barriers Project, Federation of European Motorcyclist's Associations

The testing agency was BASt, the German Federal Highway Research Institute, who conducted work for FEMA (see FEMA, 2010). Their agency defined a test procedure for impact protectors which evaluated the deceleration value during the impact against a protector. The evaluation criteria was unique in that it specified a maximum of 60 g and, over 3 milliseconds, a measured g of 40. The authors defined two different classes of devices. Class 1 devices are those with a test impact speed of 12.4 mi/h (20 km/h) while Class 2 devices are those with an impact speed of 21.7 mi/h (35 km/h).

Australian/New Zealand Standard

The Australian/New Zealand standard (Standards Australia Limited/Standards New Zealand, 2015) consists of two portions that define requirements for road safety barrier systems. The first portion focuses on both permanent and temporary safety barrier systems. These systems include crash cushions, longitudinal barrier gates, longitudinal barriers, and terminals as examples. The second portion focuses on permanent and temporary roadside devices specifically for safety. These devices include examples such as bollards, pedestrian fences, attenuators affixed to truck and trailers, and support structures and poles for roadside signs.

Australian data revealed that out of half of the motorcyclists who crashed into a barrier in an upright position on a motorcycle, half of them slid on top (Grzebieta et al., 2013). Also, data shows that majority of motorcyclists suffered from serious thorax injuries (Bambach et al., 2012a). To address this situation, the Australian/New Zealand standard suggests that, apart from the HIC as considered by other standards, additional thorax compression criterion testing should be conducted. The Australian/New Zealand standard states that previous standards, such as the Spanish standard, L.I.E.R. testing protocol, and the EN1317-8 involved an ATD sliding into a barrier and did not consider motorcyclists impacting roadside barriers in an upright position. Thus, the barriers suggested by other standards may be less effective in preventing rider injuries while impacting barriers in the upright position. Newly retrofitted devices need to be crash tested with motor vehicles since the design of these devices are centered around critical posts and beams which can be less effective during barrier-motor vehicle collisions. Further research and development is needed to understand the risks of riders impacting barriers in an upright position and contacting the barrier on the top. It is noted that the Austroad research regarding road design and safety barrier assessment process is similar to the Australian/New Zealand standard with the exception that the Austroad guidelines provide specifications the variety of roadway and roadside configurations where roadside barrier systems may be installed.

Development of New U.S. Standards and Protocols

As evidenced to this point, the U.S does not have any standards or protocols which address the motorcycle safety issues for roadside barriers and, as a result, roadside safety barriers in the U.S. are not tested and evaluated to determine the extent to which they would provide a benefit to motorcyclists. It is recognized that the development of U.S.-based standards and protocols will require extensive planning, research, and evaluation which is beyond the scope of the current project and report. To facilitate future discussions that will lead to standards and protocols development for roadside barriers that consider motorcyclist safety, the following configuration considerations are identified. Specifically, it is recommended that both sliding and upright impact configurations be developed to evaluate motorcycle friendly roadside barriers. The following sections summarize the general considerations that should be examined relative these two impact configurations.

Considerations for an Upright Impact Configuration

It is important to consider an upright impact configuration when developing a new standard for mitigating injuries for motorcyclists while impacting barriers so that the incidence of head and thorax injuries can be addressed (Grzebieta et al., 2013). Table 1 summarizes the testing parameters, rational, and additional considerations that should be considered in the planning, development, and research of roadside safety barriers testing standards and protocols in the U.S.

It is important to note that the Critical Impact Point (CIP) for a crash test should be decided based on the type of the barrier used for testing. Since the barrier might be uniquely retrofitted with MPS, it is important consider the critical location for each barrier. The critical location is the location where the barrier provides highest probability for the test to fail The CIP can be determined by either parametric evaluation through simulations or by determining the point of maximum damage to the MPS and ATD. Further, it shall be determined so that the ATD has maximum interaction with the MPS to evaluate crashworthiness of the system. This can support a veridical test of the MPS ability to limit interaction of the ATD with discrete barrier elements (e.g., posts).

Table 1. Upright Impact Configuration Evaluation Parameters, Selection Rational, and Additional Considerations for Upright Motorcycle Testing and Evaluation Standard and Protocols.

Testing Parameters	**Selection Rational**	**Additional Considerations**
Impact Angle	The impact angle plays an important role in defining the trajectory of the rider and the interaction with the impacted barrier. In addition, it can play an important role in determining impact severity.	Potential sources would be real-world crash databases of motorcycle impacts against roadside hardware. A challenge is to have complete accident reconstruction of the vehicle kinematics for these crashes, which would likely be the best way to obtain the actual impact angle. It might be possible that police accident reconstruction is applied to fatal crashes, but there is a need for non-fatal crashes to also be examined.
Impact Speed	Impact speed is important to consider since it will determine the severity of the impact. Impact speed will also determine the rider behavior and interaction with the system.	Potential sources would be real-world crash databases of motorcycle impacts against roadside hardware. Impact speed can be determined by posted speed limit on crash road sections. However, the optimal method to determine exact speed would be through complete crash reconstruction.
Impact mode	The type of impact mode (sliding/upright) of the rider constitutes an essential input to properly replicate the real world rider's impact trajectories. In addition, the impact mode will serve to identify the critical retrofit aspects of the system investigated.	Potential sources include studies that determine through crash data analysis the upright impact mode.
Motorcycle Type	The type of motorcycle can play a considerable role in determining rider position while impacting a barrier. Sports, traditional, touring, and cruisers are examples of motorcycle types.	Potential sources would include real-world crash databases of motorcycle impacts against roadside barriers that specify motorcycle type.

Testing Parameters	Selection Rational	Additional Considerations
ATD	An ATD is recommended to be used for all tests due to its ability to record and provide data on its interaction with a crash barrier and barrier performance.	Studies and standards which recommend ATD to be used in crash tests should be reviewed. The ATD type which conforms to the U.S crash data and represents an average U.S motorcyclist should be used.
ATD Helmet	The helmet worn by an ATD used in a crash test should represent an average U.S motorcyclist. A certified DOT helmet commonly used by motorcyclists can be employed.	Examine available data to identify the particular type of certified helmet primarily used in the U.S. and by riders.
ATD Clothing	Standard motorcyclist clothing should be provided to represent an average U.S motorcyclist.	Commonly used motorcyclist clothing like leather jackets and pants have to be used during testing.
Roadside Hardware/Barrier Type	The roadside barrier to be tested should be should be identified and selected carefully to understand better the potential differences between rider impacts for different barrier type categories (e.g., concrete barriers, guardrails).	Available roadside crash data can be used to determine the barrier types most commonly used and resulting in fatal/serious injuries with motorcycle impacts.
MPS Evaluation Criteria	It will be informative to have an evaluation criteria which: 1) Tests barrier strength, which could be longitudinal rail strength in the case of a guardrails. 2) Judges interaction between an ATD and the barrier impacted (e.g., snagging or tearing of ATD while impacting barriers). 3) Evaluates the ATD behavior by maintaining biomechanical limits for the safety of rider (e.g., limits on HIC, neck forces and moments, chest deflection, and thorax injuries).	Potential resources can be current standards or practices used to evaluate ATD crash tests. Available standards and criteria can be referred to determine the ATD biomechanical limits.

Considerations for a Sliding Impact Configuration

The sliding impact configuration has been primarily addressed by European standards and protocols for testing and evaluation of roadside barriers to improve crash outcomes for motorcyclists. Standards (e.g., EN1317-8) are used by many of the roadside barrier manufacturers to evaluate their systems for installation on a roadside. It will be important to develop sliding impact configuration standards in the U.S. to evaluate those roadside barrier systems deployed in the U.S. A sliding impact can occur in an actual crash after the rider is ejected from the motorcycle some distance before impacting a barrier and slides across the surface into a barrier element. Since a sliding configuration has been addressed by existing motorcycle standards in Europe and elsewhere, data and suggestions from those efforts can facilitate the development of U.S. standard and protocols.

FINITE ELEMENT ANALYSIS AND SIMULATION

The development and testing of roadside safety barriers as countermeasures to improve motorcyclist safety has expanded beyond crash testing and ISPEs. Finite Element (FE) analysis and simulation consists of computer modeling (e.g., simulation) of physical objects using finite element method. This approach can be used to determine how physical objects, such as a collision between a motorcycle and a roadside safety barrier, and is now an important resource for researchers. FE is a relatively inexpensive and minimally time consuming compared to traditional crash testing or ISPE approaches. FE also has the benefit of being able to examine a wide variety of barriers and employ accepted crash testing standards and protocols. Another advantage is that FE can be used to design MPS that address both sliding and upright impacting motorcyclists. Further, FE can be helpful to determine risk associated with occupants from an impact such as the risk for a rider (or ATD) due to barrier impact. The trajectory of the rider (ATD) in the simulations can be judged which can facilitate an understanding of the behavior of motorcyclist in actual crashes.

Although FE and simulation are relatively new areas of study, several studies have been conducted using computer simulations as a tool to perform FE motorcycle barrier crash tests with variety of impact configurations. A few of these studies are discussed below to illustrate the efforts and usefulness of FE simulations in crash testing industry.

Schulz et al. (2016) (see also Schulz, 2017) developed an FE model of a motorcycle (Kawasaki Ninja 500 R) (see Figure 20) through a reverse engineering technique in which each part of the motorcycle was disassembled, scanned into a three dimensional computer model, and was then validated using FE for initial robustness. The model was then used in a project by Dobrovolny et al. (2019) to conduct motorcycle barrier crash simulations. The model was used to conduct an upright impact crash test simulation with a retrofitted guardrail system which was then followed by a full scale crash test. Similarly De Franco (2016) conducted a study to design a motorcycle-friendly roadside safety barrier. One of the phases of that study addressed the performance of the FE motorcycle model and also performed numerical validation crash tests using LS DYNA.

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Figure 20. Finite Element Computer Model Developed by Schulz et al. (2016).

Similarly Mongiardini et al. (2017) conducted a study to develop a Finite Element (FE) computer model of a motorcycle with the purpose being to develop a model to investigate upright motorcycle impact characteristics when impacting different types of roadside safety barriers. The FE model of Suzuki GSX-650F sport-touring was developed and simulations were performed using an ATD. Their model showed good correlation when validated by comparing the simulation results with experimental test results.

A study by Dobrovolny et al. (2019) focused on the development of a concrete containment barrier to address the upright motorcycle containment problem associated with concrete barriers. For this study, FE simulations were conducted using LS DYNA to perform several upright motorcycle-barrier crash tests. FE simulation results exhibited acceptable performance which suggested the containment barrier option among multiple other options for full scale crash testing would be beneficial. The containment and redirection abilities of the barrier were judged based on the upright motorcycle-barrier simulations. Similarly, Berg et al. (2005) conducted full scale crash tests and upright FE simulations using simulation software (i.e., MADYMO by Siemens Digital Industry). A full scale crash test was employed to validate a motorcycle barrier model which was then used to understand impact characteristics with a concrete barrier and wire rope barrier at different impact speeds. Their results indicated that the injury risk was high for motorcyclists when impacting a concrete barrier or wire rope barriers. Ptak et al. (2019) used LS DYNA for FE simulations with a MADYMO ATD model to determine motorcycle injury risks due to barrier impact. Motorcycle, helmet, and barrier models were represented by LS DYNA while the 50^{th} percentile Hybrid III dummy was modeled through MADYMO. Upright impact simulations were conducted with an energy absorbing motorcycle barrier. Although the results indicated less effective energy absorption with a barrier, their work indicated the utility of simulation for saving costs and resources compared to an actual crash test.

A paper by Atahan et al. (2018) discusses results obtained after performing motorcycle simulations and full scale crash tests with a continuous MPS. The MPS was evaluated with LS DYNA simulation first and then full scale crash tests were performed to determine crashworthiness of the MPS. The test was performed per EN 1317-8 specifications. A sliding ATD configuration was used to conduct the simulations and results showed acceptable results.

Following the simulations, the full scale crash test results indicate that the MPS was able to satisfy crashworthiness criteria with minimal injury risk to motorcyclist.

At the field of FE continues to develop, it is anticipated that most initial roadside barrier testing will be conducted in simulation first to determine the optimal design and then only conduct a real world crash test to validate the results. This approach will allow for a relatively quick and iterative design approach.

CONCLUSION

The purpose of roadside barrier systems is to reduce the rate injurious and fatal crashes by controlling and mitigating crash forces. While barrier systems have been designed and proven to be beneficial for motor vehicles they do not currently address the problems associated with motorcycle crashes. For example, while a guardrail can mitigate the effects of a motor vehicle crash quite successfully, the same barrier system is associated with motorcyclists sliding along the top of the barrier and also with hitting their head on the discrete posts behind the beam that support the barrier. These crash characteristics can lead to serious upper body and head injuries. In essence, existing barrier designs may be beneficial for errant vehicles but not for motorcyclists.

The synthesis of research presented in this report concludes that motorcyclists are more vulnerable than errant vehicles of motor vehicles and that motorcyclists are more likely to be severely injured when they crash into a barrier system. This research indicates that the body position of a motorcyclists and the type of barrier can significantly influence crash characteristics. In particular, concrete barrier systems were more likely to be associated with motorcyclists vaulting over the system in contrast to a guardrail which was more likely to be associated with motorcyclists sliding into the barrier system. The synthesis also found that helmet use does not guarantee a risk free impact between motorcyclists and barriers largely due to the fact that a motorcyclists' helmeted head may still strike a discrete post. Discrete posts (and other elements such as beams) pose challenges in other ways including motorcyclists striking them as they slide under a guardrail or in some instances causing a rider to vault over the barrier and strike a post.

Addressing the challenges associated with barrier systems is critical for reducing the rate of injurious and fatal motorcyclist crashes. This synthesis summarized several new barriers and retrofit systems currently used or under development that are specifically intended to improve motorcyclist safety in addition to retaining the existing benefit for motor vehicles. These systems included a top rail that allows a motorcyclist to slide along the top of a barrier without the risk of striking a discrete post, a lower rub rail that prevents a motorcyclist from impacting a discrete post under the main guardrail, and a chain fence system with offset support posts that redirects a motorcyclist and prevents that from striking a support post. While no barrier system is 100 percent effective at eliminating motorcyclists' injuries and fatalities and these new designs may prompt an array of secondary issues, they are widely seen as offering a significant benefit to motorcyclists in the event of a crash involving a barrier. Research and installation efforts by the California, North Carolina, and Texas DOTs offer a glimpse into the efficacy of MPS barrier systems; however, it is noted that their research results are a first step in the longer journey of improving outcomes for motorcyclists when involved in barrier crashes.

The synthesis summarized research gaps that should be addressed to improve motorcycle-barrier crash safety. These gaps and research needs include:

- Developing standards or protocols to test an upright motorcycle impact configuration.
- Develop standards for evaluating barriers for sliding test configurations.

- Develop guidelines for addressing proper testing for retrofit barriers (use, adopt, modify European standards).
- Develop IPSE testing guidance and protocols to support DOTs efforts to evaluate the efficacy of barrier systems.
- Develop placement guidance for installation at locations which are critical to motorcyclist safety.
- Develop a largescale motorcycle crash database.

Finally, it is critical to understand the crash characteristics and injury outcomes when a motorcyclist impacts a roadside barrier so that barrier designs can be improved and so that practitioners are able to make sound judgements regarding their installation. Currently, there are no U.S. standards in place to guide testing efforts. The final portion of this report summarized testing parameters to be considered for both upright and sliding impacts into barriers that should be investigated during the planning, development, and research of testing standards in the U.S.

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