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Addressing the Motorcyclist Advisory Council Recommendations:

Synthesis on Roadway Geometry, Pavement Design, and Pavement Construction and Maintenance Practices

U.S. Department of Transportation
Federal Highway Administration

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

Non-binding Contents

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16. Abstract

Roadway geometry, pavement design, and pavement construction and maintenance practices are designed to construct and maintain roadway facilities that provide for motor vehicle travel. Typical practices focus on passenger car or truck needs and may not specifically recognize the special needs of motorcycles. This synthesis highlights the general recent history of motorcycle-specific safety research while also addressing specific road design, pavement design, and construction and maintenance issues related to motorcycles. Significant gaps in design, friction needs, and motorcycle-specific concerns related to roadway and pavement construction and maintenance are identified. The final portion of this report summarizes potential research topics that could be investigated to help improve the safety of both motorcycle travel and all other types of motor vehicle travel 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

4 E's	Engineering, Education, Enforcement, and Emergency Medical Services
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACEM	Association des Constructeurs de Motocycles
ARTBA	American Road and Transportation Builders Association
BPN	British Pendulum Number
BPT	British Pendulum Test
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CFME	Continuous Friction Measurement Equipment
CFR	Code of Federal Regulations
CMF	Crash Modification Factor
COV	Coefficient of Variation
DelDOT	Delaware Department of Transportation
DFT	Dynamic Friction Tester
DOT	Department of Transportation
EU	European Union
FARS	Fatality Analysis Reporting System
FAST	Fixing America's Surface Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FN	Friction Number
GDOT	Georgia Department of Transportation
GES	General Estimates System
HFST	High Friction Surface Treatment
IHE	Institute of Highway Engineers
IRI	International Roughness Index
LF	Longitudinal Friction
MAC	Motorcyclist Advisory Council
MAIDS	Motorcycle Accident In-Depth Study
MCCS	Motorcycle Crash Causation Study
MnDOT	Minnesota Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices for Streets and Highways
NCHRP	National Cooperative Highway Research Program
NHDOT	New Hampshire Department of Transportation
NHTSA	National Highway Traffic Safety Administration
NTPEP	National Technical Product Evaluation Program
NYSDOT	New York State Department of Transportation
NZTA	New Zealand Transport Agency
PC	Point of Curvature
PMM	Pavement Marking Materials
PT	Point of Tangency
SCRIM	Sideways Force Coefficient Routine Investigation Machine
SF	Sideways Friction

SN	Skid Number
SRT	Skid Resistance Tester
TMG	Traffic Monitoring Guide
TRB	Transportation Research Board
TRL	Transport Research Laboratory
TxDOT	Texas Department of Transportation
USDOT	U.S. Department of Transportation
VDOT	Virginia Department of Transportation
VMT	Vehicle Miles Traveled
VTTI	Virginia Tech Transportation Institute
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation

CHAPTER 1. INTRODUCTION

On December 25, 2015, President Obama signed the Fixing America's Surface Transportation (FAST) Act (*Federal Register*, Volume 82, Number 5). This legislation reestablished the Motorcyclist Advisory Council (MAC) and authorized the MAC to address "infrastructure issues of concern to motorcyclists." The MAC met five times between December 2017 and December 2019 and published a recommendations report on February 10, 2020. The recommendations specifically addressed "road design, construction, and maintenance practices" and their influence on motorcycle safety (Sayre et al., 2020).

By necessity, motorcycle safety efforts initiated by motorcycle associations have primarily focused on the motorcycle rider (training and protective equipment) rather than infrastructure engineering aspects. Similarly, State highway safety plans, which are designed to address the "4 E's" of highway safety (i.e., engineering, education, enforcement, and emergency medical services), commonly focus on motorcycle-related education and enforcement issues.

The last three updates to the National Highway Traffic Safety Administration (NHTSA) *Countermeasures That Work* document (in 2013, 2015, and 2018) have been identical in noting that for motorcycles, "Slippery roadway surfaces and markings, surface irregularities and debris, unpaved shoulders, and unforgiving roadway barriers all can be dangerous. These issues are not included in this guide because State Highway Safety Offices have little or no authority or responsibility for them" (Goodwin et al., 2013; Goodwin et al., 2015; Richard et al., 2018). In recognition of the impact of engineering, the latest version of the countermeasure document added a section on engineering and roadway design to the pedestrian and bicycle sections, which notes the following: "However, there is a growing recognition of the importance of road design and the built environment in fostering safer user behaviors" (Richard et al., 2018).

In recognition of the importance of road design and the built environment on motorcycles, this report is focused on the infrastructure roadway engineering components of motorcycle safety. Within this report, the use of the term "motorcycle rider" refers to the person who is operating the vehicle, while "passenger" indicates the person who is sitting on the motorcycle but is not operating the vehicle. Finally, the "motorcyclist" refers to riders and passengers.

MILESTONES IN MOTORCYCLE SAFETY

In 2000, the Transportation Research Board (TRB) Standing Committee on Motorcycles published a document (referred to as the "Millennium paper") describing the current state (in 2000) of motorcycle safety (Bednar et al., 2000). Bednar noted the benefits of education/training and personal protective equipment (e.g., helmets) for motorcycle safety. They also identified the roadway environment as a significant consideration for the next millennium. As part of this document, Bednar et al. specifically recommended action in the areas of design, construction, and maintenance to improve motorcycle safety. Motorcycle fatalities and injuries were near their lowest just prior to 2000 and have doubled since that time (see Figure 1).

Unfortunately, the TRB motorcycle committee was discontinued as part of the most recent TRB reorganization, but the needs noted in Bednar et al. (2000) remain, as evidenced by the 2020 MAC recommendations. This document includes a number of items identified in the Millennium

paper in 2000, such as the specific effects of milled surfaces and joint and crack sealants on motorcycles. The Millennium paper also referenced two major research efforts related to motorcycle safety: the Hurt study (Hurt et al., 1981) and the 2006 European Motorcycle Accident In-Depth Study (MAIDS) sponsored by the Association des Constructeurs de Motocycles (ACEM). Both of these key studies recognized the need for additional efforts in motorcycle safety.

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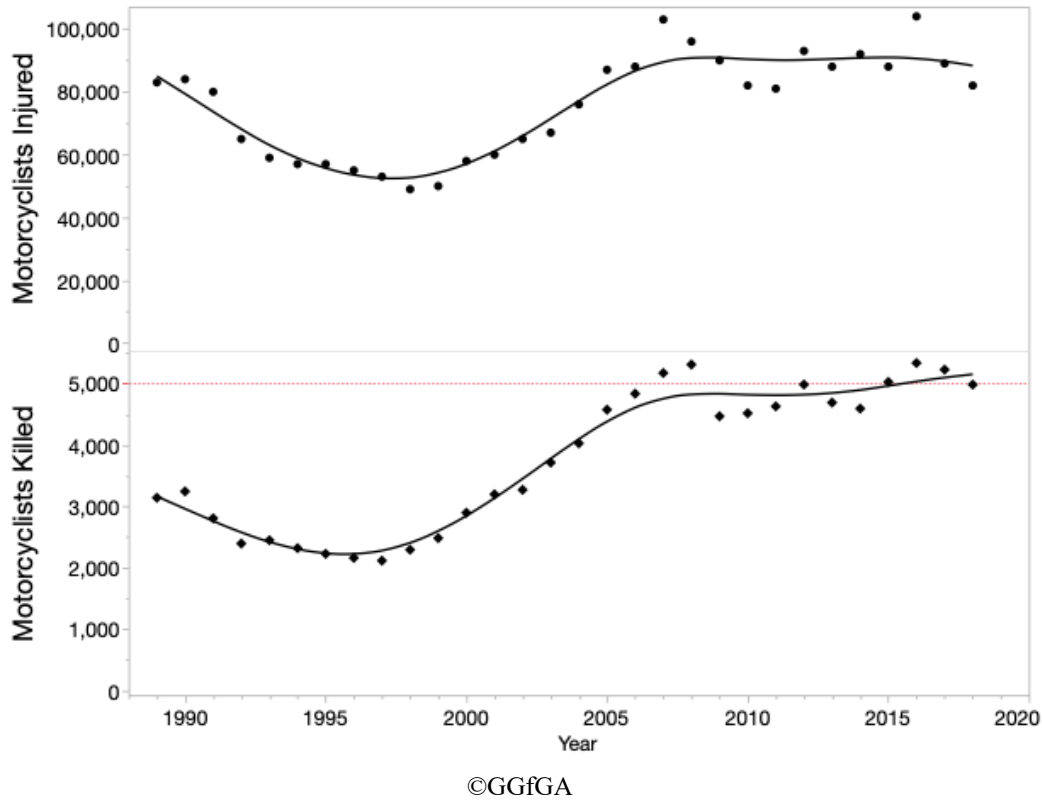
Figure 1. Motorcycle injuries and fatalities 1989–2018 (data from NHTSA, 2021a).

Hurt Study

In the early 1970s, NHTSA sponsored what is considered the first major U.S. motorcycle safety study, the final report for which is entitled *Motorcycle Accident Cause Factors and Identification of Countermeasures* (Hurt et al., 1981). Known as the Hurt study for the lead researcher, Dr. Hugh H. Hurt, the study was performed from 1975 to 1980. The study report referenced the 1973 Second International Congress on Automotive Safety (which had the theme "Motorcycles and Other Recreational Vehicles") as having an impact on the need for motorcycle safety awareness.

The Hurt study had three main objectives:

- Perform in-depth analysis of motorcycle crash causes.
- Look at effectiveness of motorcyclists' safety equipment in use at the time.
- Identify potential countermeasures for motorcycle safety.

The study involved documenting and reconstructing 900 motorcycle-involved crashes. Enhanced data were also gathered for 505 of the 900 sites via interviews of other motorcyclists at the crash sites. The in-depth crashes were compared to data from 3,600 crashes over a 2-year period in Los Angeles, CA. The Hurt study found that over 75 percent of the motorcycle crashes involved other vehicles, and 67 percent were related to an intersection. Oftentimes, it was found that the other vehicle did not see the motorcyclists. Accordingly, the main recommendations for countermeasures focused on training and the need for more conspicuity of the motorcyclist (Hurt et al., 1981). However, the research team did recognize the effect of environmental factors on motorcycle safety, noting in a 1982 presentation that pavement irregularities may not be the main cause of crashes, but they are oftentimes contributory because the motorcyclists must balance their awareness of the pavement with the roadway in general and nearby vehicles (Ouellet, 1982).

Motorcycle Accident In-Depth Study

With input from Dr. Hurt, ACEM initiated the European MAIDS study in 1998, with the results published in 2004. MAIDS involved in-depth analysis of 921 crashes and also addressed exposure by interviewing motorcyclists in similar situations who were not involved in a crash. MAIDS included crashes from Italy (200), Netherlands (200), Spain (121), Germany (250), and France (150). Approximately 80 percent of the crashes involved a collision with another vehicle (ACEM, 2009), similar to the over 75 percent from the Hurt study. Half involved an intersection, somewhat lower than the 67 percent in the Hurt study, but the definition of intersection was noted in the Hurt study as being more liberal than the typical police definition of intersection (Hurt et al., 1981).

At least two additional large-scale, infrastructure-related, motorcycle-centric safety studies have been performed in the United States since the 2000 Bednar et al. study and the original Hurt study and MAIDS. These studies are the Virginia Tech Transportation Institute (VTTI) naturalistic study and the Federal Highway Administration (FHWA) motorcycle crash causation study (MCCS).

VTTI Naturalistic Study

The VTTI naturalistic study included 100 participants in four different locations in the United States and involved 30 crashes and 122 near-crashes. Unlike other crash data studies, most of the crashes (16 of 22) were related to falling over onto the roadway at a slow speed (Williams et al., 2015), but intersections did show a definite impact in near-crash involvement (Williams et al., 2016). Low-speed crashes where the rider impacted the roadway were not found in high numbers in the other studies, and it was noted that these types of crashes are probably not reported to police. This could also be an indication that the roadway affects crashes more than has been indicated in other studies that use crash reports as the primary method of analysis.

## Motorcycle Crash Causation Study

The FHWA MCCS final study report was published in 2019. The study involved 351 motorcycle crashes in Orange County, CA. Approximately 77 percent of the studied crashes involved collisions with other vehicles. Most of the crashes occurred in daylight and in clear weather

conditions. Single-vehicle crashes occurred more frequently on curves than on straight portions, and fatal crashes were associated with tighter curves. There were roadway design issues identified in 6 percent of the crashes and maintenance-related issues in 5 percent (Nazemetz et al., 2019).

Timeline of Motorcycle Safety Activities

A timeline of select motorcycle safety activities is shown in Figure 2, including the aforementioned motorcycle safety studies. Specific results from these activities are discussed in more detail later in this report.

A Guide for Addressing Collisions Involving Motorcycles, National Cooperative Highway Research Program (NCHRP) 500, Vol. 22, was produced as part of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan implementation effort, and it specifically focused on motorcycle safety. It included an implementation objective specifically related to design, construction, and maintenance of roadway facilities (Potts et al., 2008).
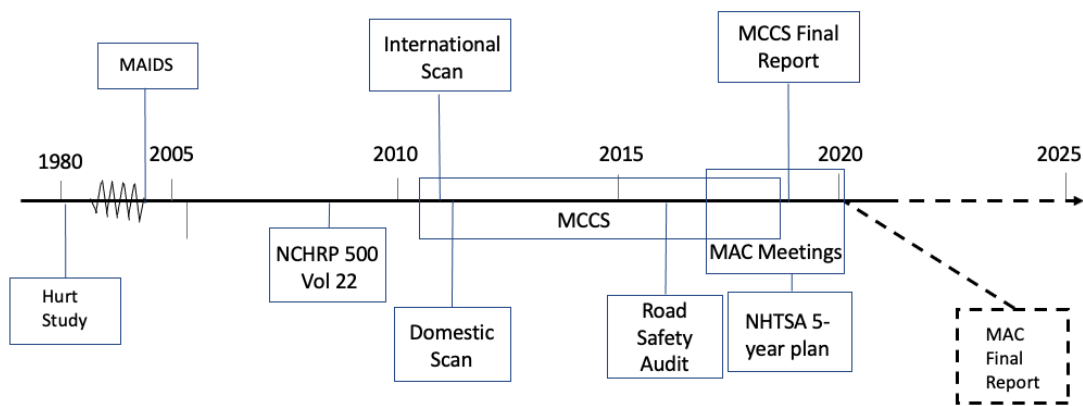
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Figure 2. Timeline of selected motorcycle safety activities from 2011–2021.

After the release of NCHRP 500, Vol. 22, both an international and a domestic fact-finding scan were conducted in conjunction with FHWA. The international scan was completed in September 2010, and the corresponding report, *Infrastructure Countermeasures to Mitigate Motorcycle Crashes in Europe*, was published in 2012 (Nicol et al., 2012). The domestic scan on motorcycle safety was performed in March/April 2011, and its report, *Leading Practices for Motorcyclist Safety*, was published in 2011 (Capers, 2011). Each scan included considerations related to infrastructure.

A road safety audit related to locations with a high frequency of motorcycle crashes was performed at three sites, one on a state route in Washington State, one on a North Carolina state route, and one on a National Park Service highway also located in North Carolina (Nabors et al., 2016). NHTSA's latest 5-year plan for motorcycles published in 2019 reiterated that 1 of the 10

"core objectives for motorcycle safety" originally identified in 1997 included "incorporating motorcyclist safety into the design of roadways" (NHTSA, 2019).

Figure 2 is not an exhaustive listing of motorcycle activities or publications. Since the focus of Figure 2 was on showing the infrastructure-related motorcycle safety highlights in the past 10 years, not shown is the October 2007 action plan by FHWA on reducing motorcycle fatalities, which included a foreword from then Secretary of Transportation Mary Peters describing how she personally broke her collarbone in a motorcycle crash (U.S. Department of Transportation [USDOT], 2007). The 2007 action plan identified the importance of addressing infrastructure as a part of the strategy and recognized the organization of the MAC and the Roadway Safety for Motorcycles brochure (FHWA, 2007) as tools to address infrastructure issues.

MOTORCYCLE-SPECIFIC ISSUES RELATED TO INFRASTRUCTURE (STABILITY AND CONSPICUITY)

To address infrastructure improvements needed to reduce motorcycle crashes, it is essential to identify how motorcycles are different than other vehicles on the road. As one of the researchers working with Dr. Hurt noted, "Passenger vehicles simply do not roll over on their side as soon as some instability develops, but motorcycles often do" (Oeullet, 1982). Motorcycles are inherently unstable since they only have two tires in line to support them, compared to a standard vehicle with four tires. Only having two tires in line also makes the stability of each tire important, so motorcycles are vulnerable to conditions and frictional characteristics of the roadway that would not impact a typical passenger vehicle.

Stability

The main differences, in relation to pavements, between a motorcycle and a typical vehicle are in the number of tires in contact with the pavement and the configuration and type of tires. With only two tires in line, the motorcyclist covers a narrow portion of the roadway width, which also means that the typical two wheel paths that are commonly considered in pavement performance measures based on four-wheel vehicles do not necessarily apply to motorcycles. Therefore, there are different considerations for motorcyclists compared to other vehicle drivers. The United Kingdom's Institute of Highway Engineers (IHE) *Guidelines for Motorcycling* notes the following issues that road designers need to be aware of that are specific to motorcycles (IHE, 2005):

> *For the benefit of non-rider highway designers and traffic engineers, the key differences between motorcycles and other vehicles are set out below:*
>
> - *The consistency of grip between tyres and the road surface is critical to motorcycle stability, particularly when leaning over for cornering, braking or accelerating.*
> - *Most braking effort and all steering control for a motorcycle is through the front tyre which means that riders try to avoid combining braking and steering in order to reduce the likelihood of overwhelming front tyre grip as it deals with conflicting forces. Any change in this grip, and particularly a sudden decrease, can lead to loss of control during the manoeuvre as the front*

wheel slides away. Loss of front tyre grip on a bend almost invariably leads to a crash.

- *All accelerating force is through the small patch of the rear tyre in contact with the road. A sudden reduction in grip (eg because of a surface change midway through a bend) can result in the rear tyre slipping sideways and in loss of control.*
- *Motorcyclists adopt a different line through bends than drivers of twin-track vehicles, traversing the width of the lane in order to maximise grip through minimizing steering inputs. This keeps the machine as upright as possible and maximises forward visibility and safety. Anything that forces riders to choose a less than optimum riding line through a bend increase the risk of loss of control.*

Motorcycles are also typically much smaller and lighter than other vehicles on the road. Motorcycle tires are also smaller and wear differently than typical vehicle tires. Motorcycles use different types of tires for the front and rear wheel, unlike cars, which typically use the same tire for each wheel, thus allowing for the tires to be rotated. Figure 3A and 3B show examples of both motorcycle tires and a car tire for comparison. Figure 3A shows the front tire (the left image) as being less wide than the rear tire (center image) as well as an example of an all-weather motorcycle tire (right image). The all-weather tire has significantly more siping (i.e., grooves) than a regular tire (left and center images). Both the front and rear motorcycle tire are rounded and thinner than a typical car tire (see Figure 3B for an example car tire), and the car tire has a flatter surface and more intricate tread pattern. There are a variety of motorcycle tires; some are defined by motorcycle type or riding experience. There are also motorcycle tires specifically designed for performance as well as those specifically designed to be all-weather (Michelin, n.d.; Dunlop, n.d.).

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A. Typical motorcycle tires.
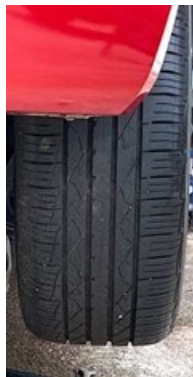
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B. Typical car tire.

Figure 3. Typical motorcycle and car tires.

Conspicuity

Due to their smaller and sleeker nature, motorcycles are also not as conspicuous on the road. Motorcycles can be found in the center, left, or right of a lane since a typical roadway is 10 to 12 ft wide and a typical motorcycle is only 1 to 2 ft wide. A passenger car, on the other hand, will always be near the center if within a lane since a car is typically wider than 6 ft. Motorcycles also only have limited width for placement of headlights compared to other vehicles. Car and truck headlights typically overlap and cover the full width of the front of the vehicle. Conspicuity is an area that has been and continues to be addressed. Motorcycle Safety Awareness Month and many State-sponsored efforts focus on "sharing the road" (NHTSA, 2019) and the need to be aware of motorcycles, like the "Look Twice Save a Life" (used by the Texas Department of Transportation [TxDOT]) and "Start Seeing Motorcyclists!" campaigns (used by the Minnesota Department of Transportation [MnDOT]).

MOTORCYCLE EXPOSURE AND CRASH DATA

The recent trends in motorcycle crashes (fatal and injury crashes) were shown in Figure 1. The figure showed a similar trend over the time period for motorcycle fatalities and injuries. The following sections discuss motorcycle crash trends and the issues with estimating motorcyclist exposure in more detail.

Trend in Motorcycle Fatalities

In 1981 when the Hurt report was published, it noted that there was concern that motorcycles were "the most dangerous form of motor vehicle transport" since they were disproportionately represented in fatal crashes (10 percent of the overall fatal crashes and 1 to 2 percent of the vehicle registrations) and motorcyclist fatalities were approaching 5,000 a year (Hurt et al., 1981). Figure 4 shows that the total number of motorcycle-related fatalities decreased in the 1990s, alongside a reduction in overall vehicle-related fatalities. Although the graphs in Figure 4 are in different scales, it is clear that the trend in overall U.S. fatalities has shown an overall decline over the last 40 years, while motorcycle fatalities have oscillated. The total U.S. vehicle fatalities decreased from a high near 50,000 in the 1990s to under 40,000 in 2019. In contrast, motorcycle fatalities decreased to a low around 1996 and are currently back at the Hurt 1980's levels. Figure 4 shows that motorcycle fatalities increased for 10 straight years in the late 1990s and early 2000s (1996–2008).

Figure 4 also shows an apparent different trend between overall vehicle fatalities and motorcycle fatalities. Figure 1 showed a similar trend for both motorcycle injuries and fatalities over a similar time period to Figure 4. The graphs only use actual count data and do not address exposure.
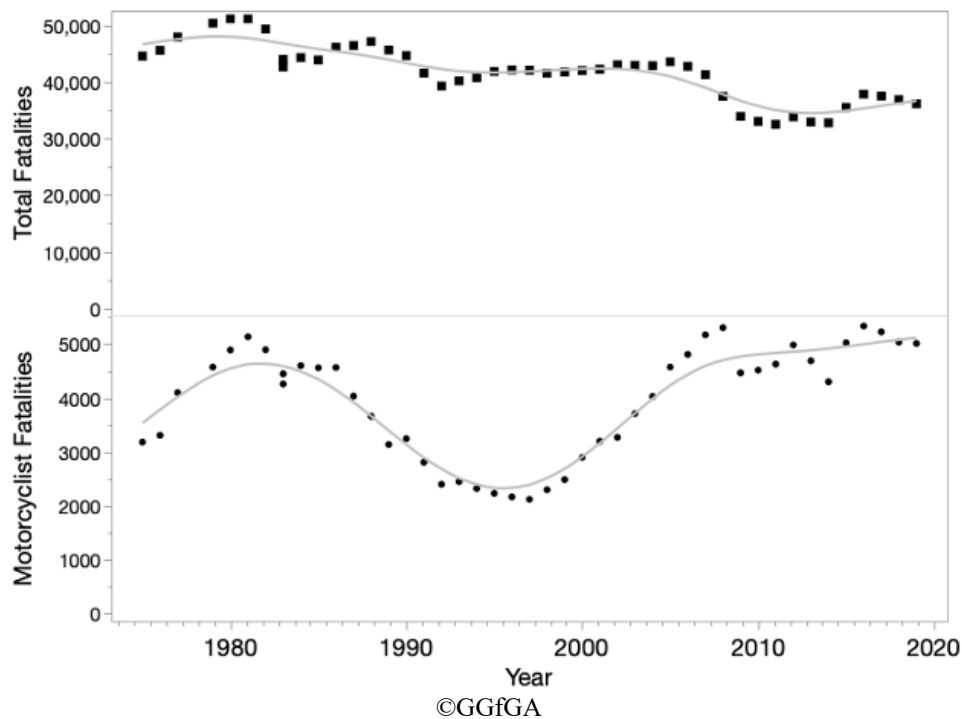

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Figure 4. Comparison of U.S. total fatalities and motorcycle fatalities 1974–2020 (based on data from the Insurance Institute for Highway Safety, 2021).

Motorcycle Vehicle Miles Traveled

Vehicle miles traveled (VMT) is a common component of exposure. An NCHRP study for the AASHTO Committee on Planning identified that motorcycle VMT has been found to be either

undercounted or overcounted based on the technology and approximation methods used. Researchers identified how these inconsistencies varied based on the various ways vehicles can be counted, classified and converted into VMT following the *Traffic Monitoring Guide* (TMG). They also identified that "between 2000 and 2007 motorcycle registrations increased by 64 percent but estimated VMT only increased by 30 percent" (Cambridge Systematics, 2010). Motorcycles are defined as class 1 vehicles in the TMG, which includes 13 different vehicle classes (FHWA, 2016). Because of the small number of motorcycles compared to other vehicles, typical statistical methods used to analyze other vehicles are not always relevant or appropriate to analyze the class 1 vehicles (motorcycles).

An FHWA report examining crash data specifically related to motorcycles noted that some studies that tried to identify motorcycle crash frequency used a surrogate of motorcycle VMT (e.g., registrations) due to lack of VMT data (Lyon et al., 2016). Based on the latest NHTSA motorcycle data fact sheet, this surrogate relationship may be improving, but it is not consistent over time. From the fact sheet, the relationship between registered motorcycles and motorcycle VMT over the past 10 years (2010–2019) shows a very weak correlation ($R^2 = 0.24$), while the correlation is vastly improved when looking at just the last 5 years of data ($R^2 = 0.94$) (NHTSA, 2021b). Accurate motorcycle VMT is needed to appropriately address locations that have a high volume of motorcycles. Accurate VMT is also needed to perform valid statistical analysis related to exposure and risk for motorcyclists.

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 motor vehicle traffic fatalities in the United States are attributed to motorcyclists (NHTSA, 2021b), yet motorcycles make up only 3 percent of registered vehicles and only 0.6 percent of VMT (NHTSA, 2021b). Based on data acquired from the Fatality Analysis Reporting System (FARS) and the General Estimates System, 5,014 motorcyclists were killed in 2019 (NHTSA, 2021b). These statistics demonstrate that motorcyclists have a greater likelihood of being involved in a fatal or serious injury crash compared to occupants of passenger cars. Because a motorcycle is one of the most vulnerable motor vehicles on the road, there is a clear need to conduct targeted research to determine ways to safely accommodate motorcycles and reduce crash severity associated with these vehicles.

The MCCS study conducted by 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, the same overall results have not been realized for motorcyclists. An increase in motorcycle vehicle registrations over the past 20 years may have had an effect on the increased fatalities, and some relative improvement is shown in the data: in 2007, motorcyclists were 37 times more likely to be killed than car occupants per distance traveled (NHTSA, 2008), but based on 2019 data, that number has decreased to 27 times more likely to be killed (NHTSA, 2021b). Looking specifically at the conditions related to motorcycle crashes may provide a direction for more focused future efforts.

A 2002 study that assessed motorcycle crash conditions in Hawaii evaluated the interactions between the motorcycle rider and the temporal and physical conditions that influenced safety performance based on statistical assessment for crash data that extended over the 10-year period of 1986 to1995 (Kim et al., 2002). Kim et al. (2002) further used logistic regression analysis to predict crashes and compare expected crashes to those observed at their study locations. They found approximately 56 percent more injury crashes than expected at curved road locations and just over 53 percent more injury crashes at rural locations.

Many of the locations where crashes involving motorcycles commonly occur are associated with physical road characteristics such as horizontal curves, intersections, or cross-sectional features. The VTTI naturalistic study by Williams et al. (2016) evaluated risk factors that influence motorcyclist crashes. They determined that crash risks associated with horizontal curve locations increase when excessive speeds are observed (by a factor of 45 percent). The same study further observed that motorcyclists traversing a horizontal curve to the right are twice as likely to crash as motorcyclists going straight. Other issues commonly observed at horizontal curve locations include the motorcycle traversing the curve too wide or crossing into the oncoming lane. The same study noted that motorcycle crashes or near-crashes that occur at signalized intersections, uncontrolled intersections, or driveway entrances can be expected to have greater risks than other intersection locations. In addition, the researchers noted that the type of road surface (paved or unpaved) and vertical grade are additional factors that should be considered when assessing potential risk to motorcyclists.

The NHTSA (2021b) Motorcycle Traffic Safety Facts summary for 2019 indicated the following:

> In 2019 there were 2,495 fatal two-vehicle crashes involving a motorcycle and another type of vehicle. In 41 percent (1,034) of these crashes, the other vehicles were turning left while the motorcycles were going straight, passing, or overtaking other vehicles. Both vehicles were going straight in 558 crashes (22%).

CHAPTER-CONCLUDING COMMENTS

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 roadway geometrics, paving, and maintenance features and how the characteristics contribute to the motorcycle crash condition.

CHAPTER 2. ROAD DESIGN FEATURES AND THEIR INFLUENCE ON MOTORCYCLE CRASHES

Chapter 1 identified some of the safety concerns associated with motorcycle crashes, with particular attention to injury level for crashes associated with geometric characteristics and pavement features. The geometric characteristics commonly cited in the literature include horizontal curvature, intersection configuration, cross-sectional characteristics, sight-distance limitations, pavement, and friction characteristics. Chapter 2 expands on these characteristics and how they relate to motorcycle safety.

HORIZONTAL CURVES

Transportation agencies in the United States typically use circular and/or spiral curves at roadway horizontal curve transition locations. Schneider et al. (2010) noted that a motorcyclist adapts to the roadway curvature by reducing speed upon entry to the curve. This speed change is often accompanied by a path correction, where the motorcycle may enter the curve on the outside of a travel lane, shift to the inside of the lane as the vehicle traverses the curve, and then return to the outside of the lane as the vehicle exits the curve. This path correction often occurs at the same time as the motorcycle accelerates for the length of the curve. Drivers of four-wheel vehicles make similar adjustments to their travel path. Some agencies use spiral curves to introduce circular curves in a manner that approximates the natural path of a four-wheel vehicle. A spiral curve has a variable radius, ranging from a radius approaching infinity at the tangent to a radius that matches the horizontal curve at the end of the transition. This use of spiral curves is more common at higher-speed locations.

In addition to the application of spiral curves, horizontal roadway curvature may also be based on circular curve geometry, where the curve, or a combination of curves, has a single radius and begins at a point of curvature (PC) and ends at a point of tangency (PT). Figure 5 depicts four common circular curve configurations: a simple horizontal (circular) curve, broken back curve, compound curve, and reverse curve.
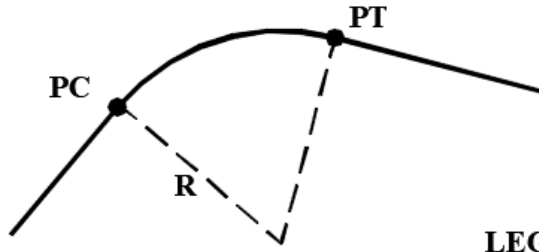
LEGEND

PC = Point of Curvature
PT = Point of Tangency
R = Radius for Circular Curve

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A. Simple horizontal curve.

LEGEND

PC_n = Point of Curvature
PT_n = Point of Tangency
R_n = Radius for Circular Curve
n = Curve Number

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B. Broken back curve.

Figure 5. Circular curve designs for roadways.

C. Compound curve.
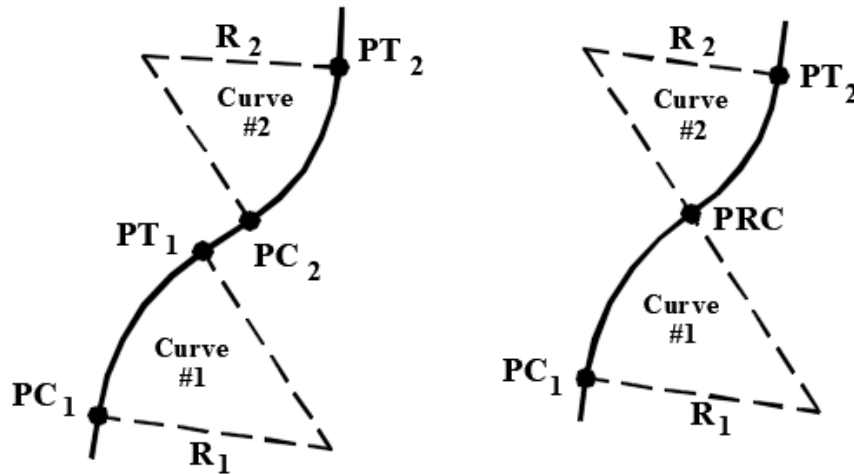
LEGEND

PC_n = Point of Curvature

PT_n = Point of Tangency

PRC = Point of Reverse Curvature

R_n = Radius for Circular Curve

n = Curve Number

D. Reverse curve (with tangent on left, without tangent on right).

Figure 5. Circular curve designs for roadways (continued).

Mackilop (2015) hypothesized that because motorcycle riders approaching horizontal curves focus on the PT for a large percentage of time, the use of a spiral transition from tangent to circular curve (where the spiral has a constantly changing radius) may actually send a message to the rider that the horizontal curvature appears flatter and therefore may seem less severe than it actually is. Mackilop suggested that this anomaly may contribute to a higher number of motorcycle crashes that occur at locations with spiral transitions into horizontal curves. It is notable that the use of spiral transitions for highway design is commonly recommended to replicate how a vehicle may traverse a horizontal curve at higher-speed rural locations (AASHTO, 2018). More research is needed to better understand how spirals influence motorcycle operations.

A 2010 study by Schneider et al. evaluated how various roadway geometric features influenced motorcycle crash severity on rural two-lane roadways in Ohio. From 2004 to 2008, Ohio roadways experienced 950 motorcyclist fatalities, equating to an average of approximately 190 per year. Schneider et al. (2010) specifically observed that motorcycle crashes occurred more frequently at horizontal curve locations. They hypothesized that this observation was likely due to reduced sight distance at these locations as well as characteristics that required the rider to handle the motorcycle more deliberately. They determined that approximately 38 percent of all Ohio motorcyclist fatalities occurred at or near horizontal curves. This number can be compared to approximately 29 percent of the passenger car fatal crashes occurring at horizontal curves during the same 5-year study period. Schneider et al. further determined that the lengths and radii of horizontal curves were two features that significantly influenced motorcycle crash frequency. Based on a trial-and-error analysis, Schneider et al. determined that the influence of the horizontal curvature on crashes extended from approximately 300 ft upstream of the PC to 300 ft downstream of the PT (see Figure 6). Schneider et al. indicated that the curve length, including the additional 300 ft of transition at each end of the curve, represented the roadway section that most influenced crash risk.
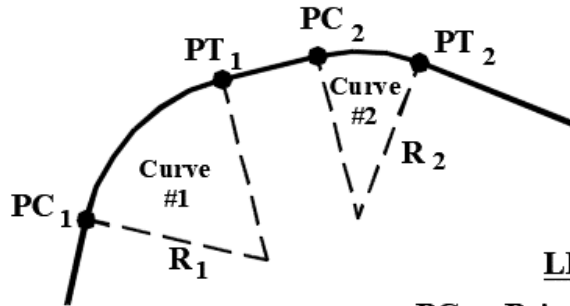

LEGEND

PC = Point of Curvature

PT = Point of Tangency

R = Radius for Circular Curve
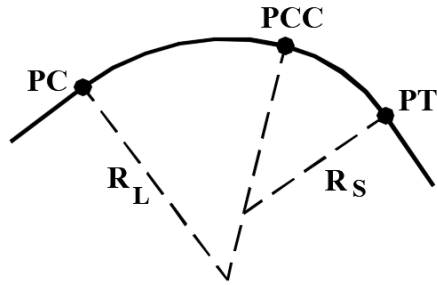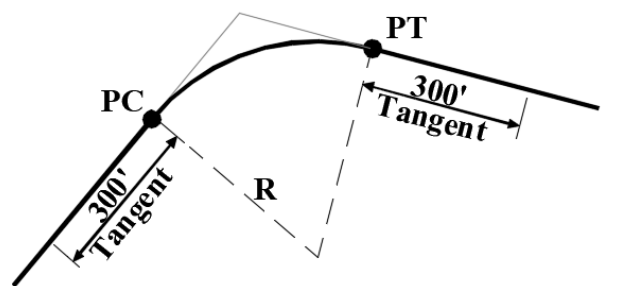
©Texas A&M Transportation Institute

Figure 6. Isolated simple horizontal curve.

An analysis by Geedipally et al. (2011) of Texas motorcycle crashes showed that motorcyclists accounted for 15 percent of all fatalities for the years spanning 2003 to 2008. Examination of

total motorcycle crashes in Texas during the same period revealed that approximately 34 percent of the rural crashes occurred at horizontal curve locations. Geedipally et al. further noted that approximately 9 percent of the motorcycle-related crashes occurred at urban locations. The same study showed that locations with a combination of both horizontal and vertical curves increased the likelihood of fatal crashes. The research team determined that this observation was statistically significant only for urban regions.

Gabauer and Li (2015) analyzed Highway Safety Information System roadway and crash data from 2002 to 2011 for the State of Washington. For their analysis, Gabauer and Li evaluated motorcycle crashes involving roadside barriers at locations with horizontal curvature. Gabauer and Li used a definition consistent with the Schneider et al. (2010) study where the research team defined an isolated curve as a circular curve that began on the tangent at 300 ft before the PC and extended through the curve and onto the second tangent for an additional 300 ft (see Figure 6). Gabauer and Li then developed statistical models that included continuous predictor variables such as horizontal curve radius, annual average daily traffic (AADT), length of horizontal curve, and percent vertical grade. Gabauer and Li also incorporated a "normalized radius" variable they developed by dividing the observed curve radius by the State of Washington design standard recommended minimum radius based on an assumption that the design speed was equivalent to the posted speed limit. Because there could be more than one maximum superelevation value linked to a given radius, Gabauer and Li used the "largest permissible" superelevation. In addition, the researchers considered categorical variables that included the number of lanes, shoulder width, presence of vertical curvature, divided versus undivided cross section, and isolated horizontal curve status (based on the 300 ft before and after threshold previously identified). Based on an analysis of 344 mainline motorcycle-to-barrier crashes (234 occurring in the curved section and 110 occurring in the 300 ft tangent section before or after the curve), Gabauer and Li determined that the strongest crash predictor was the curve radius. Their analysis resulted in the following observations related to horizontal curve radius:

- Horizontal curves where the radii values are less than 500 ft are 40 times more likely to have motorcycle-to-barrier crashes than when the radii are 2,800 ft or greater.
- Horizontal curves with a radius of 820 ft or less can be expected to increase crash frequency by a factor of 10.
- For locations with identical radii, roadways with longer curves, larger AADT values, and isolated curve configurations (i.e., curves not located within 300 ft of another curve end) are stronger candidates for the placement of motorcycle-to-barrier crash countermeasures.

Xin et al. (2017a) examined motorcycle crash history along Florida roadways. They evaluated crash and road characteristic data that extended over an 11-year period (2005 to 2015). The research team determined that even though curved roads accounted for only 6 percent of the number of miles in Florida, 57 percent of single-motorcycle fatal crashes and 36 percent of single-motorcycle severe injury crashes occurred at locations with horizontal curvature. The researchers used the 300-ft transition definition suggested by previous research teams (see Figure 6) to identify isolated candidate curve locations. In cases where the curve transitions overlapped within the 300-ft region before or after the horizontal curve, Xin et al. classified the curve type as a reverse curve if the center points of the curves were on opposite sides of the road, as depicted in Figure 6. Curves that were not identified as reverse curves were then assigned curve types of single curves or compound curves. Based on this data set, the researchers

conducted a statistical analysis for the identified 2,168 single-motorcycle crashes and determined the following relationships:

- When compared with flat curves (radius greater than or equal to 4,000 ft), sharp curves with a radius less than 1,500 ft could be expected to increase the probability of a fatal or serious injury crash by approximately 8 percent. Moderate curves did not have any significant trend.
- Locations with reverse curves were affiliated with an increase of approximately 6 percent in fatal or serious injury crashes.

The same research team also specifically focused an analysis on Florida rural, two-lane, undivided highways (Xin et al., 2017b). The study included 431 motorcycle crashes that were associated with 2,179 rural two-lane highway horizontal curve study locations. Like their previous findings, Xin et al. determined that an increase in curve radius could be expected to be associated with a decrease in the total number of motorcycle crashes. For this study, they specifically found that a radius less than 2,000 ft (resulting in sharper curves) was significantly associated with an increase in the number of motorcycle crashes and that the relationship was logarithmic. The team also developed a crash modification factor (CMF) for the radius, as depicted in Equation 1.

$$CMF_R = \left(\frac{R}{5000}\right)^{-0.208}$$
(Eq. 1)

Where:

R = radius (feet).

Xin et al. (2017b) also observed unexpected findings at reverse curve locations. Xin et al. noted the following: "On 74.8% of roadway segments, the presence of a reverse curve tended to result in a decrease in motorcycle crash frequency."

Xin et al. (2018) extended the Florida-based research by conducting statistical modeling to develop CMFs for single-motorcycle crashes on rural two-lane highways. Based on a database that included 2,444 curved segments with the 300-ft transition on each end (see Figure 6) and 10,164 tangent segments, the researchers compiled study sites that included rural, two-lane, undivided highways with a length of at least 600 ft, homogeneous road characteristics, and no signalized intersections. The researchers matched crash data for the period from 2005 through 2015. This research by Xin et al. yielded the following observations:

- Risk for single-motorcycle crashes decreased as the horizontal curve radius increased. This equated to a motorcyclist having almost five times the risk of a crash on horizontal curves with a radius of 1,500 ft or less compared to risk on a similar road with a straight section. This amount reduced to about two times the risk for moderate curve radii (greater than 1,500 ft but less than or equal to 3,000 ft). For flatter curves with radii greater than 3,000 ft, the risk was 1.88 times that observed for a straight roadway segment. The researchers defined a straight segment as one with a radius greater than 20,000 ft.

- The placement of reverse curves resulted in more crashes than at locations without reverse curvature. This observation reversed the findings from the 2017 study by the same core group of authors. The authors hypothesized that this reversal was due to inclusion of an interaction term in the statistical model that accounted for curve radius as well as curve type.
- Higher speed limit and presence of auxiliary lanes and intersections were all associated with higher crash frequencies. The researchers also determined that paved roads and shoulders were associated with higher speeds and therefore increased the likelihood of crashes. In contrast, they observed that narrower roads tended to be associated with fewer crashes. The researchers hypothesized that this observation may be because narrower roads tend to be lower-performing local roads and more riders on these facilities may be local riders who are familiar with the narrower road.

The final report for a study by Wang et al. (2018) that evaluated motorcycle safety due to negotiation at horizontal curves in Florida provided a comprehensive summary of the Florida work to date, including a final CMF for single-motorcycle crashes at horizontal curves. The study findings confirmed that sharper curves are more often associated with greater risk to the motorcyclist. The resulting CMF is depicted in Equation 2.

$$CMF_R = X$$ (Eq. 2)

Where:

CMF_R = the curve radius (feet) for rural two-lane curves, and
X = applicable values as follows:

3.27 $R \leq 1000$ ft
2.98 1000 ft $< R \leq 2000$ ft
1.82 2000 ft $< R \leq 10{,}000$ ft

In addition, Wang et al. noted the following key findings:

- Speed is a controlling factor for fatal and severe injury crashes.
- Roadside features including trees, barriers, and other fixed objects create added risk at horizontal curve locations.
- Motorcycle riders exhibit safer behavior when they are alerted to riskier situations.

Based on the published literature related to horizontal curvature, a consistent finding is that risk increases as horizontal curvature becomes sharper. This observation similarly applies to motorcycles as well as other vehicles. The type of curve (i.e., simple, reverse, or compound) also appears to strongly influence rider performance.

There are additional roadway features that merit consideration when evaluating motorcycle safety at curved locations. One item that is not fully addressed in the motorcycle safety literature is the presence and influence of superelevation and how that relates to the safety at horizontal curve locations with varying radii thresholds. An additional influential factor at horizontal curve locations is the role that the motorcycle lean angle has on safety performance. A 2018 study by

Rose et al. validated the equations used for motorcycle lean estimates at horizontal curves. This information should be expanded to include how these varying lean angles influence safety performance for varying speed thresholds.

In addition to horizontal curve characteristics, a large number of crashes also occur at intersection locations. The following section identifies some of the intersection-related issues.

INTERSECTIONS

Research has consistently indicated that motorcycle crashes frequently occur at or near intersections. Haque et al. (2008) examined Singapore intersection motorcycle crash data for a 5-year period (from 2001 through 2005). Based on this information, Haque et al. then conducted a study using video of four signalized intersections with the goal of evaluating vehicle exposure and how red-light running contributed to a high number of motorcycle crashes. They observed that when motorcycle riders encountered queues at intersections, they typically weaved back and forth through the queue until they were closer to the actual intersection. In the event the intersection included a dedicated left-turn lane (vehicles in Singapore travel on the left side of the road), riders tended to use the exclusive turn lane as a bypass lane. The research team recommended that construction of wider lanes and exclusive turn lanes should help reduce the number of intersection-related motorcycle crashes.

In 2011, Geedipally et al. studied motorcycle crashes in Texas and determined that riders involved in crashes at or near intersections were 22 percent more likely to have only minor or no injuries compared to crashes at higher-speed locations. The researchers hypothesized that this observation could be due to motorcycle riders reducing their speed as they approached intersections in anticipation of a perceived greater risk at these intersection locations.

Another 2011 study by Muttart et al. used eye-tracking technology to evaluate drivers' glance patterns, with particular attention to their behavior at intersection locations. Of the 32 riders/drivers who participated in the study, the research team acquired eye-tracking data for 23 participants. The research team observed that motorcycle riders glanced more often at the road surface than did drivers. They also observed that as a motorcycle rider executed a left turn in front of oncoming traffic, he or she rarely looked back at the oncoming vehicle once he or she began to execute the turn. Finally, Muttart et al. observed that the motorcycle riders did not stop at the stop bar as often as drivers of cars. Because of this tendency, the motorcycle rider entered the intersection early and had to perform multiple vehicle guidance tasks while also continuing to scan for traffic.

Sager et al. (2014) further noted that the most common intersection-related motorcycle crash occurs when the motorcyclist is approaching an intersection and an oncoming car that is turning left at the intersection fails to observe the approaching motorcycle. To determine how the motorcycle positioning within the lane could potentially influence the conspicuity of the motorcycle, Sager et al. conducted a driving simulator study to investigate the concept generally taught in motorcycle training programs that it is safer for riders to position their vehicles toward the left in their lane (closer to the roadway centerline for a two-lane highway). They further noted that other research has suggested contradictory guidance, with hypotheses that a right-of-lane position might be safer at intersection approach locations (Ouellet, 1990).

To investigate the gap acceptance at intersections, Sager et al. (2014) explored this hypothesis about lane position at an intersection approach by conducting a driving simulator study with 17 undergraduate students. Their simulation runs examined gap acceptance behavior when the approaching vehicle was a passenger car and compared the gap analysis to scenarios when the approaching vehicle was a motorcycle. For the second configuration, the approaching motorcycles were located approximately 1.2 m to the left and to the right of the center of the lane. Sager et al. determined that when faced with an approaching car, the drivers accepted fewer gaps than they did when the approaching vehicle was a motorcycle. In addition, their simulator participants were more likely to turn left in front of a motorcycle positioned in the left-of-lane position than when the motorcycle was in the right-of-lane position. This finding suggested that the right-of-lane position may be safer at intersection approach locations.

CROSS-SECTION DESIGN AND OPERATIONAL CHARACTERISTICS

Shoulders

The presence and condition of shoulders may affect motorcyclist safety. A lack of shoulders offers a motorcyclist no place to take an evasive riding action if necessary (Brown et al., 2015). A stalled motorcyclist on a roadway without a shoulder or with only a narrow shoulder is especially vulnerable to moving traffic on the adjacent lane. A wide shoulder provides an errant motorcyclist recovery space before impacting a fixed roadside object (Potts et al., 2008). Paving currently unpaved shoulders so they can be used for these purposes is a recommended method of assisting in motorcycle recovery and avoidance maneuvers (New Zealand Transport Agency [NZTA], 2017).

Schneider et al. (2010) further determined that shoulder width and AADT were critical factors that influence motorcycle crash frequency. In rural environments, locations with narrow shoulders provide little recovery space for vehicles negotiating a horizontal curve. In fact, Schneider et al. determined that rural roadways with shoulder widths of 6 ft or less will have approximately 52 percent greater likelihood of crashes occurring at horizontal curve locations.

Clear Zones

Providing an area free of roadside hazards is critical to motorcyclists since many motorcycle crashes result in the motorcyclist leaving the road. A study of over 4,500 single-vehicle motorcycle crashes in New South Wales, Australia, found that crashes involving roadside objects accounted for 36 percent of single-vehicle motorcycle crashes and 55 percent of single-vehicle motorcyclist fatalities (Motorcycle Council of New South Wales, 2010).

Clear zone widths in the AASHTO (2011) *Roadside Design Guide* are calculated using a passenger car or truck as the design vehicle. A clear zone for a motorcycle might need to consider a motorcyclist who has been thrown from his or her bike, making it uncertain if the AASHTO clear zone widths are adequate (Haworth et al., 2011). In any case, a wider clear zone is better because it allows a motorcyclist more distance to decelerate before striking a roadside hazard (Brown et al., 2015). Haworth et al. (2011) reported,

> *Motorcycles differ from other vehicles in that they overhang their wheel track by about half a metre on each side and because they lean to change direction, which*

markedly alters the clearance they require when travelling upright (VicRoads, 2001). Failure to account for these characteristics may result in riders colliding with poles or signs or fences that are placed too close to the edge of the pavement.

When objects cannot be located outside the clear zone, agencies have recommended a variety of methods to minimize risk to motorcyclists. These include using flexible or breakaway signs and poles, mounting street signs on light poles rather than on a separate signpost, and using motorcycle-friendly crash barriers (NZTA, 2017; Transport for London, 2017; Nicol et al., 2012).

Signs Related to Motorcyclists

The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) is the U.S. standard for traffic control devices on roads open to public travel. Section 2C.32 of the current edition of the MUTCD (FHWA, 2012) describes signs intended to warn road users of surface conditions that might adversely affect their ability to maintain control of their vehicle. Section 2C.33 states that the SLIPPERY WHEN WET (W8-5), LOOSE GRAVEL (W8-7), or ROUGH ROAD (W8-8) signs may be helpful to motorcyclists if those conditions exist. The GROOVED PAVEMENT (W8-15) sign (alternate legends are TEXTURED PAVEMENT or BRICK PAVEMENT) and the METAL BRIDGE DECK (W8-16) sign may be used to warn motorcyclists of these conditions.

The current MUTCD includes two plaques that relate specifically to motorcycles. W8-15P is a supplemental warning plaque showing a motorcyclist on a motorcycle, used with the GROOVED PAVEMENT (W8-15) or METAL BRIDGE DECK (W8-16) warning signs or the LOOSE GRAVEL (W8-7), GROOVED PAVEMENT (W8-15), METAL BRIDGE DECK (W8-16), or STEEL PLATE AHEAD (W8-24) warning signs in temporary traffic control conditions. R3-11P is a supplemental regulatory plaque with the text MOTORCYCLES ALLOWED and is used to supplement preferential lane signs.

The proposed amendments to the MUTCD (FHWA, 2020a) do not include any new signs specific to motorcycles. They do include new restrictions on the use of word or symbol pavement markings denoting motorcycle use of preferential lanes. This change is proposed because communicating that motorcycles are permitted to use the preferential lane is accomplished through the regulatory supplemental plaque that complements high-occupancy vehicle signing (FHWA, 2020a).

Several States in the United States have a State MUTCD or have adopted a State supplement to the MUTCD. Some have special word message signs for situations where roadway conditions make it necessary to provide road users with additional warning information and where a standard message is not provided in the MUTCD. As an example, the Virginia Department of Transportation (VDOT) supplement to the MUTCD (VDOT, 2011) deleted the METAL BRIDGE DECK (W8-16) sign but includes three additional warning signs that must be supplemented with the W8-15P plaque. These are the STEEL GRID DECK (W8-V1), EXPANSION JOINTS (W8-V2), and OPEN JOINTS ON BRIDGE (W8-V3) warning signs.

The *Virginia Work Area Protection Manual* (VDOT, 2020), the Virginia replacement to Part 6 of the MUTCD, includes the following statements regarding motorcycles that are not part of the MUTCD:

- The need for smooth riding surfaces for motorcyclists should be provided, or advance warning notification given whenever roadways surfaces are disturbed.
- The special needs and control of motorcyclists should also be considered through a temporary traffic control zone.
- Pavement scarring of the roadway exceeding 1/8 inch should be repaired to prevent deterioration of the pavement surface and to provide a smooth surface for motorcyclists.
- Steel plates provide a challenge to motorcyclists when they traverse a steel plate unexpectedly in the roadway.
- The design of the crossover should accommodate all vehicular traffic, including motorcycles, trucks, and buses.

FHWA recently examined the potential for novel signs to be used as motorcycle crash countermeasures. Documented in the report *Novel Highway Signs to Support Infrastructure-Based Motorcycle-Crash Countermeasures* (Weaver et al., 2021), the study found that the sign types that are likely to produce the most tangible impacts on driver behavior are the advance curve warning and limited sight-distance signs. Any new signs, with the exception of signs with word-only messages not otherwise provided for in the MUTCD, may require further human factors research and would require experimentation in accordance with the provisions of the MUTCD prior to any on-road applications.

A domestic scan team supported by NCHRP explored leading practices for motorcyclist safety. The findings were reported by Capers (2011), with the recommendations to:

> *Encourage the National Committee on Uniform Traffic Control Devices to change the MUTCD guideline for motorcycle placard use from 'may' (a suggestion) to 'should' (a recommendation). Ensure that the new motorcycle placard is used in work zones and in other locations that present riding challenges, such as sharp curves and areas of frequent high winds.*

Some States have supplements to the MUTCD (Washington State Department of Transportation [WSDOT], 2021a) or have standard plan details (New Hampshire Department of Transportation [NHDOT], 2018) that require motorcycle-specific signs in certain cases.

The National Committee on Uniform Traffic Control Devices is a private organization that develops recommendations that are submitted to FHWA for consideration when updating the MUTCD. Currently, there is not a representative on the national committee representing motorcyclists. The international scan team suggested that one way for more motorcycle-specific traffic control devices to be adopted is for a representative from a motorcycle advocacy group, such as the American Motorcycle Association, to apply for membership (Nicol et al., 2012).

Lane Filtering/Lane Splitting

Lane splitting occurs when a motorcyclist overtakes another vehicle within the same lane or between lanes. Lane splitting is sometimes called "white-lining" or "stripe-riding" (James, 2020). Lane filtering is a subset of lane splitting. Lane filtering describes a motorcyclist lane splitting under a condition where the surrounding vehicles have either stopped moving or are moving slowly. As an example, a motorcyclist might lane filter through traffic to reach the front of the queue on an arterial where traffic is stopped at a red light. Lane sharing is the situation where two motorcyclists ride in the same lane side-by-side or in a staggered formation.

Laws in the United States and Elsewhere

Laws in the United States related to lane splitting, lane filtering, and lane sharing differ widely among States (James, 2020). While many States do not specifically prohibit any of these riding behaviors, three States specifically allow lane splitting and/or filtering. Lane splitting has never been specifically prohibited by California law (Levi, 2018), but the California vehicle code was amended in 2016 to direct the California Highway Patrol to develop education guidelines for lane splitting. The California Highway Patrol released its lane splitting safety tips in September 2018 (California Highway Patrol, 2018). Utah's lane filtering law went into effect on May 14, 2019. In Utah, motorcyclists may legally filter on a road with a posted speed limit of 45 mph or less, when the road has two or more adjacent traffic lanes in the direction of travel, when the adjacent vehicles are stopped, when the motorcyclist is traveling at 15 mph or slower, and when the movement can be made safely. In Montana, as of October 1, 2021, it will be legal for motorcyclists to filter when the lanes are wide enough to safely do so, the motorcyclist is traveling 20 mph or slower, and the vehicles being passed are either stopped or traveling no faster than 10 mph. Lane splitting is legal in many Asian countries (Levi, 2018) and in parts of Australia (Kurlantzick and Krosner, 2016). In the European Union, Germany is the only country that restricts lane splitting to lane filtering only (Motorcycle Legal Foundation, 2020). In the United Kingdom, lane filtering is taught as part of the compulsory basic training for motorcycle licensing (Salvatore et al., 2011).

Purported Benefits of Lane Splitting

Often-cited benefits of lane splitting are that it allows motorcyclists to avoid being hit from behind when in a stopped or slowed queue (Guderian, 2011); it reduces traffic congestion and, accordingly, fuel consumption and emissions from all vehicles (Yperman, 2011); it helps prevent older air-cooled motorcycles from overheating (Aiello [2008], as cited in Sperley and Pietz [2010]); it allows motorcyclists to save time on their trips (Yperman, 2011); and it provides better visibility for the motorcyclist to proactively maneuver through traffic (Sperley and Pietz, 2010).

Safety Risks

Lane splitting and filtering involve risk. First, lane-splitting motorcyclists are closer to other vehicles than they would be if they were riding in a lane behind another vehicle, giving them less time to react when necessary (Rice et al., 2015). Uneven pavement and raised pavement markers between lanes also pose hazards to lane-splitting motorcyclists (Rice et al., 2015). The United

Kingdom allows lane splitting and has found that the predominant safety issue is that it violates driver expectation; in other words, motor vehicle drivers do not expect motorcycles where they are lane splitting and may inadvertently turn into them (Sexton et al. [2004], Clarke et al. [2004], and Crundall et al. [2008], as cited in Sperley and Pietz [2010]). Motorcyclists responding to a survey on lane splitting in California most frequently mentioned distracted drivers, including those looking at a cell phone or texting, as a serious threat to safety when lane splitting (Ewald and Wasserman, 2014).

Safety Study Findings

The 2009 MAIDS study of powered two-wheeler crashes in five European countries concluded that 0.45 percent of motorcycle crashes involved lane splitting (Sperley and Pietz, 2010) and that motorcyclists were seven times more likely to be hit while stopped compared to crashing while lane splitting (Kurlantzick and Krosner, 2016). Vehicle drivers not expecting motorcyclists to be lane splitting has resulted in a predominance of sideswipe and turn-into-path crashes for lane-sharing-related crashes in the United Kingdom (Sperley and Pietz, 2010).

The Australian Capital Territory of the state of New South Wales, Australia, conducted a 2-year trial of lane filtering from February 2015 through January 2017. During that time, there was no change in the rate of rear-end or lane-change crashes but a significant increase in the number and rate of property-damage-only sideswipe crashes (sideswipe crashes were identified as a proxy for lane-filtering crashes). The conclusion that lane splitting "was a relatively low risk riding activity for motorcyclists under the conditions of the trial" resulted in a change in the laws of New South Wales from prohibiting lane splitting to allowing lane splitting at a speed less than 19 mph (Beanland, 2018).

A 2010 Oregon Department of Transportation (ODOT) literature review concluded that lane-splitting crashes were rare even in areas where lane splitting was legal and widely practiced (Rice and Troszak [2014], as cited in Kurlantzick and Krosner [2016]). In a study of 5,969 motorcyclist crashes in California that occurred from June 2012 through August 2013, motorcyclist injuries were far less severe when the collision-involved motorcyclist was lane splitting than when the collision-involved motorcyclist was not lane splitting (Rice et al., 2015).

Three studies conducted between 2011 and 2015 found that lane-splitting motorcyclists in California were less likely to be involved in a crash than motorcyclists who were not lane splitting (Rice and Troszak [2015], Ouellet [2016], and Guderian [2011], as cited in Kurlantzick and Krosner [2016]). Two of these studies reported that lane-splitting motorcyclists are 43 percent less likely to be involved in a rear-end crash (Rice and Troszak [2015] and Guderian [2011], as cited in Kurlantzick and Krosner [2016]). James (2020) noted that a year after the California Highway Patrol issued its lane splitting safety tips, motorcyclist fatalities were reduced by 30 percent because motorcyclists were less likely to be involved in a rear-end crash.

Studies have suggested that improvements in safety when lane splitting is allowed may be because motorcyclists who lane split are different than motorcyclists who do not. The 2012–2013 California motorcycle crash study (Rice et al., 2015) found that compared with other motorcyclists, lane-splitting motorcyclists were more often riding on weekdays and during commute hours, using better helmets, traveling at lower speeds, less likely to have been using

alcohol, and less likely to have been carrying a passenger. Lane-splitting motorcyclists were much less often injured during their collisions (Rice et al., 2015).

Motor Vehicle Driver Attitudes toward Lane Splitting

A 2014 survey of motor vehicle drivers in California showed that more than 60 percent of respondents somewhat or strongly disapproved of lane splitting, even though it is legal in that State. The most common reason for disapproval was that lane splitting was considered unsafe (Ewald and Wasserman, 2014). The 2-year lane-filtering trial in New South Wales, Australia, found that attitudes toward lane filtering became more positive during the trial, and that most motor vehicle drivers supported lane filtering even though they may not have necessarily believed it improved safety (Beanland, 2018).

Advance Stop Lines

Permitting lane filtering provides the opportunity to create an advance stop line for motorcyclists at signalized intersections, similar to the concept of bike boxes used for bicyclists in the United States. However, the MUTCD currently has no provisions for advance stop lines for motorcyclists, and the concept would require experimentation in accordance with provisions from the MUTCD. Trials of shared (by motorcyclists and bicyclists) advance stop lines in London have been positive (Tilly and Huggins [2003], as cited in Motorcycle Council of New South Wales [2010]), presumably because they allow these users to be visible in front of other traffic and reduce the potential for conflict at intersections. Because a motorcyclist can accelerate more quickly than a car (ACEM, 2006), motorcyclists at the front of the queue can quickly leave the platoon behind them. The ability of motorcyclists to filter to the front of a queue is a significant factor in why motorcycling is the preferred transportation option for many people in London (Transport for London, 2017).

SIGHT DISTANCE

In the United States, AASHTO's (2018) *A Policy on Geometric Design of Highways and Streets* (the "Green Book") is used as a guide for designing roadway facilities with sight distance that is sufficient for a driver to see, react, and stop or maneuver to avoid a collision. The design calculations are based on the characteristics of passenger cars and passenger car drivers, and in the case of intersection sight distance, trucks are also considered. Calculations in the Green Book do not consider the unique characteristics of a motorcycle or motorcyclist in designing facilities that provide adequate sight distance. The sections below describe how the Green Book's calculations might change if a motorcycle were used as the design vehicle.

Stopping Sight Distance

Stopping sight distance is the distance required by a motorist to bring the vehicle to a stop after an object of a specified height becomes visible. The available sight distance on a roadway should exceed the stopping sight distance (AASHTO, 2018). Stopping sight distance is the sum of a motorist's brake reaction distance and braking distance.

The Green Book's calculations for stopping sight distance use the speed, perception-reaction time, and deceleration rate assumed for a passenger car driver. The speed variable is based on the

posted speed limit of the roadway and would not differ between the case of a passenger car driver and a motorcyclist. Additionally, research has shown that most motorcyclists are able to respond to an unexpected object along the roadway in 2.5 seconds or less (Davoodi et al., 2011a), equal to the 2.5-second perception-reaction time assumed by the Green Book for a passenger car driver. However, while motorcycles may be capable of deceleration rates higher than those of passenger cars (assumed in the Green Book to be 11.2 ft/sec^2), even though many newer motorcycles have anti-lock braking systems, some motorcyclists do not brake at their vehicle's full capability, presumably for fear of wheel-locking (Ecker et al., 2001). Also, it could be assumed that a motorcyclist may try to stop for a hazard in the road that is smaller than the 2.0-ft target object assumed by the Green Book, a height that the Green Book considers to be "representative of the smallest object that involves risk to drivers."

Sight Distance on a Crest Vertical Curve

The variables of grade differential, driver eye height, stopping sight distance, and target object height are components of the Green Book's calculations for determining the minimum length of a crest vertical curve. Like speed, grade differential is based on the roadway geometry and would not differ for passenger cars and motorcyclists. Additionally, research has shown that the eye height of a motorcyclist exceeds the 3.5-ft eye height of a passenger car driver assumed by the Green Book (Davoodi et al., 2011b). However, stopping sight distance, as discussed in the section above, may differ for motorcyclists based on their deceleration and braking behavior, and target object height may be less than the 2.0 ft assumed for passenger cars.

Sight Distance on a Sag Vertical Curve

Headlight sight distance is often used as the basis for determining the minimum length of sag vertical curves. The Green Book calculation uses grade differential, which would be identical for passenger cars and motorcyclists because it is based on the road design. The Green Book's assumed headlight height of 2 ft is exceeded by the headlight heights of most motorcycles; for example, Davoodi et al. (2011a) found that 95 percent of motorcycle headlights were higher than 2.6 ft. The Green Book assumes a passenger car headlight tilt of 1 degree upward, while motorcycle headlight tilt is often adjustable by the rider.

Sight Distance on a Horizontal Curve

Components used to determine the available sight distance on a horizontal curve using Green Book calculations would not differ for a passenger car versus a motorcycle because they are based on the geometry of the curve. However, while sight distance on a horizontal curve may be considered adequate for motorists looking downstream along the roadway, motorcyclists on a horizontal curve may fixate on something other than the roadway ahead and "override" their sight distance, meaning they may not be looking far enough down the road to detect and respond to a hazard even if the available sight distance exceeds the motorcycle's stopping sight distance (Smith et al., 2013). The previous section regarding horizontal curves provides additional information regarding this issue. The design of horizontal curves should consider the different road positions that motorcyclists occupy; for instance, in countries that drive on the left, at a horizontal curve to the left, motorcyclists will usually be closer to the center of the road than for curves to the right (Transport for London, 2017).

Passing Sight Distance

The Green Book's calculations for minimum passing sight distance use eye height, speed, deceleration rate, perception-reaction time (to abort a passing maneuver), and vehicle length of the passing driver. Additionally, the speed and height of the opposing vehicle and the length of the vehicle being passed are considered. Defaults for these values in the Green Book are based on passenger cars. When calculating the minimum passing sight distance for a motorcyclist, eye height would be similar (Davoodi et al., 2011a) and speed unchanged because it is based on the posted speed limit of the road. However, no research could be found on the deceleration rate or perception-reaction time specific to a motorcyclist aborting a passing maneuver. Additionally, the passing vehicle length, assumed to be 19 ft for a passenger car in the Green Book, would be substantially less for a motorcycle since most motorcycles are shorter than 8 ft. The minimum passing sight distance calculation also assumes a 12-mph speed difference between the passing passenger car and the vehicle being passed, and a space headway of 1 second between the passing passenger car and the vehicle being passed. Either could be different in the case of a passing motorcyclist, though no research could be found.

Milling et al. (2016) stated that "inadequate overtaking provisions may lead to unsafe overtaking manoeuvres, particularly when the average speed of a vehicle over a length of road is slower than the average speed of a motorcycle. This may be due to repeated and tight horizontal geometry. A motorcyclist sitting behind slower vehicle/vehicles may overtake at non-designated and unsafe locations." Not providing passing zones because the calculations used to mark and sign them are based on calculations of passenger cars and are too conservative for motorcyclists may compel a motorcyclist to attempt a risky maneuver in a zone marked as no-passing.

Intersection Sight Distance

The Green Book uses many of the same components as the calculations above to determine minimum intersection sight distance values for various maneuvers. They include eye height, perception-reaction time, vehicle speed, braking deceleration, gap acceptance behavior, and position from the edge of the road of the approaching driver, as well as the height and speed of the opposing vehicle.

As mentioned above, the 3.5-ft eye height for a passenger car driver is exceeded by a motorcyclist (Davoodi et al., 2011a), and the perception-reaction times for both passenger car drivers and motorcyclists are similar (Davoodi et al., 2011b). Vehicle speed is a factor of the road's posted speed limit and would be the same for either the passenger car or motorcycle scenario. Most motorcycles are capable of deceleration rates higher than those of passenger cars (assumed in the Green Book to be 11.2 ft/sec^2), although motorcyclists often do not brake at their vehicle's full capability for fear of wheel-locking (Ecker et al., 2001). The height and speed of the opposing vehicle would be the same whether the approaching vehicle were a passenger car or a motorcycle.

However, it is assumed that the position of the approaching driver from the edge of the road for a passenger car, assumed in the Green Book as 14.5 ft, would be substantially less for a motorcyclist positioned at the edge of the road due to a motorcycle's shorter length. Also, while

the Green Book lists time gap acceptance for passenger cars, single-unit trucks, and combination trucks, there are no assumptions made for motorcyclists.

A factor applying to all types of sight distance is the comparative small size of motorcycles when they are the "opposing vehicle." Barriers, vegetation, and road signs must be placed in such a manner that they do not hide motorcycles, not even partly, from view (ACEM, 2006).

Motorcyclist Field of Vision

Separate from sight-distance calculations, other views on a motorcyclist's field of vision can be considered. The field of vision for a motorcyclist may be narrower because a motorcyclist leans forward, whereas a passenger car driver leans back. Additionally, the type of helmet worn by a motorcyclist may affect how much can be seen. Open-face helmets have almost no effect on the motorcyclist's field of vision and may provide an even better view than that of the average car driver, while the predominant integral helmet considerably limits what a motorcyclist can see (ACEM, 2006).

Because a motorcyclist's eye height is higher than the eye height of a passenger car driver (Davoodi, 2011a), the motorcyclist often sees a car approaching an intersection before the driver of that vehicle can see the motorcyclist. This may give the motorcyclist a false sense of having been seen (ACEM, 2006).

In studies by de Lapparent (2006) and Pai and Saleh (2007, 2008a, 2008b), riding in darkness without street lighting was related to severe motorcyclist injury. A study by the Norwegian Public Roads Administration found that motorcyclists often experience reduced visibility when wearing glasses, visors, or windshields, which may decrease even further when riding inside tunnels (Vlahogianni et al., 2012).

ROAD SURFACE

Another infrastructure component, also part of the roadway environment, is the road surface. Motorcyclists, and all other vehicles, make contact with the roadway through the road surface. Road surfaces are typically classified by their surface type and as either paved or unpaved. Out of the 4.1 million miles of road in the United States, 71 percent are paved (2.9 million miles) and 1.2 million miles (29 percent) are unpaved (compacted gravel or soil) based on the published 2019 FHWA Table HM-12 (FHWA, 2020b). Paved surfaces are also typically considered either asphalt pavement (sometimes called asphalt concrete, or flexible) or concrete pavement (sometimes called portland cement concrete, or rigid), based on the driving surface layer. In the same FHWA table, concrete pavements are only about 2 percent of the total mileage of paved roads in the United States, but they account for 10 percent of the non-interstate principal arterials and minor arterials, the functional classes identified as having the most (53 percent) motorcycle crashes by NHTSA (2021b), so both asphalt- and concrete-surfaced pavements are discussed here.

Each pavement type has different texture, friction, and responses to loading. General motorcyclist concerns related to pavements include irregular friction or loss of friction, uneven surfaces, and loose material or oil on the surface. A transportation agency's goal in paving a roadway surface is to place a smooth, unblemished pavement; even the Code of Federal

Regulations (CFR) notes that pavements "shall be designed to accommodate current and predicted traffic needs in a safe, durable and cost-effective manner" (23 CFR 626.3). It is the wear of a pavement, from environment, loading, or a combination of both, that causes distresses, unevenness, and irregularities. This wear is inevitable and will be discussed more in the Construction and Maintenance section.

Paved Roads

Typical roadway pavements are composed of aggregates with either liquid asphalt (asphalt pavements) or cement (concrete pavements) as the binder. Paved surfaces—asphalt and concrete—experience different distresses that adversely affect motorcyclists.

Asphalt-Surfaced Pavements

Asphalt pavements can have friction issues due to the materials used. Asphalt pavements can also wear, resulting in raveling, rutting, cracking, and potholes, as shown in Figure 7.

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Figure 7. Distressed asphalt pavement.

Crack Sealing (Tar Snakes or Tar Stripes)

A typical pavement preservation treatment for cracking in asphalt pavements is sealing the cracks using asphalt-based sealers. A recent NCHRP report on best practices for crack treatments describes overbanding as the use of a squeegee to level the filler material at the surface of the crack, effectively increasing the width of the "tar snake." In the NCHRP report, the negative effects of overbanding are considered visual appeal, tracking of the material by vehicle tires, stress on the crack itself, and potential for snowplow damage, but potential loss of friction for motorcycles is not discussed (Decker, 2014). In a study to improve crack seal specifications, overbanding was identified as clearly improving sealant performance (Al-Qadi et al., 2017), but the effect of overbanding on surface friction has not been studied.

Chip Seal

Chip seals (also known as bituminous surface treatments) are a type of asphalt-surfaced road, but instead of mixing the asphalt in a plant and placing it with a paver, the asphalt material and the aggregate are placed directly on the road. Chip seals are constructed by placing a layer of an asphalt-type liquid on the pavement and covering it with a layer of aggregate and then rolling and brooming the surface to seat the aggregate and remove loose aggregate. This can be constructed in one or several layers. A potential concern with chip seals is that if excessive aggregate is placed or the surface is not properly broomed after placement, loose aggregate can be left on the surface. California's version of the MUTCD adds a Section 6F.101(CA) LOOSE GRAVEL sign (W8-7) that should be used on all chip seal projects. The added section also encourages the use of the motorcycle plaque (W8-15P) for motorcycles (California Department of Transportation [Caltrans], 2021). Australia is reportedly considering encouraging the use of specialty equipment for placing chip seals in one operation using a special paver to improve safety and reduce the possibility of loose gravel (Esnouf, 2017).

The final texture of chip seals, which is related to the size of aggregate used, can also be a discomfort to motorcyclists and bicyclists. California studied the effects of chip seal texture on bicycles after receiving complaints from bicycle riders when a chip seal was placed on US 1 north of San Luis Obispo. The study involved bicycle riders and different chip seal textures and found a correlation between (macro) texture of the chip seal and acceptable ride quality. When the macrotexture was too high, it caused discomfort to the bicycle riders. The recommendations included the use of finer aggregates in the chip seal and additional research on the macrotexture of chip seals (Li et al., 2013). Additional research on aggregate size and its influence on motorcycle behavior is warranted.

Concrete-Surfaced Pavements

Pavement Problems

Concrete pavements can have friction issues due to materials used, surface preparation, or surface wear. Concrete pavements can also rut (due to studded tires in winter), buckle (mainly a concern in northern, cold-weather States), or experience popouts. Punchouts are a form of popout found in continuously-reinforced concrete pavements. Concrete pavements can also crack, as shown in Figure 8, or experience faulting (difference in elevation at the joints or cracks), which can affect the smoothness of the ride.

Figure 8. Distressed concrete pavement.

Tined Concrete

Concrete pavements are textured at the time of construction typically by tining the surface transversely or longitudinally before the concrete has set. Longitudinal tining is increasing in use due to noise concerns with transverse tining. The Wisconsin Department of Transportation (WisDOT) performed a data-based crash comparison of transverse-tined concrete and longitudinally tined concrete and found no difference in overall wet- or dry-weather crashes. The longitudinally tined pavement used for comparison was in California. The WisDOT study did not specifically examine motorcycles or motorcycle safety, but researchers noted that California had improved its longitudinal tining practices, specifically in response to motorcycle safety (Drakopoulos and Örnek, 2007). FHWA noted that longitudinal tining, constructed using an even spacing of 19 mm (¾ inch), was shown to be acceptable for motorcycles (FHWA, 2021a).

Unpaved Roads

Loose material is always a concern in unpaved pavements and is well recognized by the motorcycle community. A recent NCHRP synthesis titled *Converting Paved Roads to Unpaved* notes the increasing trend of converting paved roads to gravel roads, identifying at least 27 States that recently allowed or performed this conversion (Fay et al., 2015). This asset management concept is based on risk and funding; if there is not sufficient funding for all roads, then priorities must be set to manage the overall assets. The synthesis report specifically notes that motorcyclists should be considered prior to conversions and identifies one conversion that involved motorcycles in Vermont, noting that even the motorcyclists supported the transition from paved to unpaved. The location, Mill Road near Montpelier, VT, is also a dead-end road, so it mainly affects the residents located on the street. Vermont left the pavement near the intersection, as shown in Figure 9, evidently recognizing the need for extra stability for stopping and turning.

©Google Earth

Figure 9. Google Earth picture of Mill Road, Montpelier, VT.

PAVEMENTS AND FRICTION

Pavement friction is an important component of the stopping ability of all vehicles and is important in overall motorcycle stability. Due to the reduced inherent stability of an inline two-wheeled motorcycle, abrupt changes in friction on a pavement can lead to a motorcyclist losing control even without braking.

Roadway friction is not just a function of the pavement—it is related to how the tire and the pavement interact (somewhat analogous to walking on ice with heavy, treaded boots compared to walking on ice with thin, slick dress shoes). The higher the friction between the tire and pavement, the more friction that is available for vehicle deceleration or stopping or for turning movements. The coefficient of friction (μ) is the friction force between the tire and the pavement (F) divided by the weight on the tire (F_w) and is calculated as shown in Equation 3 (Flintsch et al., 2012).

$$\mu = \frac{F}{F_w} \qquad \text{(Eq. 3)}$$

Based on this equation, for a constant coefficient of friction, the frictional force (F) between the tire and pavement must decrease when the weight (F_w) decreases. However, the coefficient of friction is not really a constant; it varies based on the movement of the tire (from free rolling to fully locked), changing pavement surface, and other factors. Roadway friction involves numerous factors: vehicle and tire parameters (i.e., vehicle speed, braking, turning, and tire type), surface characteristics (materials and texture), and temperature and other environmental factors (AASHTO, 2008).

Surface Characteristics/Texture

Friction related to surface characteristics is affected by the texture of the pavement. Pavement microtexture and macrotexture are terms often related to friction of a pavement. Microtexture is the texture felt (derived from the aggregate particles themselves), and macrotexture is the texture that can be seen and that is most often directly measured (derived from the aggregate shape, size, and any texture added) (Hall et al., 2009). Generally, microtexture is considered related to dry

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friction and macrotexture to wet friction, though there is some overlap (Permanent International Association of Road Congress, 1987). Microtexture in asphalt pavements is influenced by the coarse aggregate used, and microtexture in concrete pavements is influenced by the fine aggregate used. Macrotexture in asphalt pavements is influenced by the size and type of aggregate and the mix design, while macrotexture in concrete pavements is typically a result of surface preparation (i.e., tining or grinding) (Hall et al., 2009).

Friction Testing of Pavements

The coefficient of friction is an empirical value, so friction testing of pavements is dependent on the method of testing. There is no defined gold standard for comparing and relating pavement friction values. Different pavement-friction-based tests have been loosely correlated to wet-weather crashes, and different thresholds of friction values for pavements have been developed in this manner (AASHTO, 2008). Different friction coefficients are related to the test method and conditions under which the friction is measured, with the two most common being longitudinal friction and sideways friction.

A number of test apparatuses exist to test friction. There are methods to test friction that can be performed on a roadway at or near highway speeds, and there are methods that can be performed statically that require closing a lane for testing of a road surface or performed in a laboratory. For network-level evaluations, travel speed (high-speed) testing is the most desirable. The two most common types of travel speed pavement friction testers provide two different types of friction measurements: longitudinal and sideways.

Longitudinal friction (LF)—AASHTO T 242, Standard Method of Test for Frictional Properties of Paved Surfaces Using a Full-Scale Tire (AASHTO, 2020a), is the current AASHTO standard for longitudinal pavement friction. LF friction values are denoted in the standard as friction number (FN) (T 242 is a joint standard with ASTM E274 [they are essentially identical]). LF is currently the most common pavement friction test used in the United States and is typically performed using a device identified as a locked-wheel tester (LWT). LF is primarily spot tested (generally ½ to 1 mi between tests for network-level testing) in the outer wheel path. The test result is speed dependent, and the standard test speed is 40 mph; with this test speed and the challenges of testing with a trailered system, testing on sharp curves and leading up to intersections is not commonly performed. The LWT has two different standard tires that can be used (i.e., ribbed or smooth), but the ribbed tire is currently more prevalent in the United States. The ribbed tire has been associated more with microtexture, whereas the smooth tire has been associated with macrotexture. Differences in the results between the smooth and ribbed tire used for testing have been documented. Researchers have found that the smooth tire can be more affected by the amount of water sprayed on the pavement surface, which could cause it to be less repeatable than the ribbed tire. One study identified a coefficient of variation (COV) of 6 percent to 10.6 percent for the smooth tire compared to a COV of 3.1 percent to 5.5 percent for the ribbed tire run on the same surfaces (Choubane et al., 2006).

Side Force (or Sideways) Friction (SF)—SF is currently the most common pavement friction test used in Europe and is typically performed using continuous friction measurement equipment (CFME), the most common being the Sideways Force Coefficient Routine Investigation Machine (SCRIM®). The AASHTO Committee on Materials and Pavements recently adopted a new

standard, TP 143, Continuous Measurement of Sideway-Force Friction Number for Highway Pavements (AASHTO, 2021), which covers sideways friction testing. SF friction values are denoted in the standard as the sideways FN. The SF standard uses a smooth tire about 3 inches in width, oriented at an angle (typically ~20 degrees) to the direction of travel. It also uses water to wet the pavement in front of the angled tire. It can provide an almost continuous measurement of friction (every 4 inches), and the standard test speed is 40 mph, but it can also be run at lower or higher speeds. More on SF is included in the section on European experience with friction.

The literature often uses skid number or friction number generically to describe the results of SF or LF friction testing; the result may also have a speed associated with it, like SN40 or FN40 to indicate the test was run at 40 mph. Research from the United Kingdom has been performed where SF has been loosely correlated ($r = 0.76$) to LF, when the LF equipment was run at much lower speeds (< 15 mph) than is typically used for normal testing (Roe et al., 1998). Recent efforts in the United States have found a strong correlation between LF and SF when using the locked-wheel tester (for LF) with a ribbed tire at the standard speed and using a SCRIM® at 30 mph (for SF), with the LF value typically 85 percent of the SF value (de León Izeppi et al., 2019). However, in general, the different values (i.e., SN or FN) are somewhat dependent on the testing parameters (e.g., type of equipment, type of tire, test speed, pavement surface) and are not simply interchangeable. Macrotexture is often also recorded using separate laser-based instruments (i.e., 3D line lasers for pavement measurements) when LF or SF measurements are taken to provide a complete picture of pavement friction.

European Experience with Friction

Friction testing began in Britain using a motorcycle. In 1927, the precursor to the British Road Research Laboratory (now the Transport Research Laboratory [TRL]) developed a skid tester using a motorcycle with a sidecar. The sidecar wheel was angled, like the test tire on the SF equipment now, and it was noted that the motorcycle with sidecar was a precursor to the current SCRIM® (Salt, 1977). A recent TRB presentation identified 25 different devices in use to measure friction in Europe, with SF and the SCRIM® being the most prevalent. Comité Européen de Normalisation (CEN) TS 15901-8 is the European standard for SF testing. CEN also identified the most common static test in use in the United Kingdom as the Skid Resistance Tester (SRT) pendulum (known as the British pendulum test, AASHTO T 278 [AASHTO, 2020b], in the United States) (Goubert, 2018). The European Union (EU) project Tyre and Road Surface Optimization for Skid Resistance and Further Effects as well as the Rolling Resistance, Skid Resistance and Noise Emission (ROSANNE) measurement standards for road surfaces were conceived to develop harmonized standards in Europe for surface measurements and management including friction (Scharnigg, 2017). The EU harmonization efforts have had mixed results (de León Izeppi, 2018).

Current U.S. Guidance on Friction

FHWA has two technical advisories related to pavements and friction. T 5040.38 (FHWA, 2021a) encourages agencies to manage friction on their networks by using best practices in pavement management, evaluating wet-weather crash data, and using the data to identify projects to prioritize. FHWA (2021b) notes on its safety website that "70 percent of wet pavement crashes can be prevented or minimized by improved pavement friction" but does not mention dry

pavement crashes and friction. T 5040.36 (FHWA, 2021c) specifically relates to pavement management and describes the components of friction (micro and macrotexture) and recommends surface texture techniques for both asphalt and concrete pavements. As noted previously, the advisory for concrete pavements specifically notes that longitudinal tining spaced evenly at 19 mm has been shown to be acceptable for motorcycles.

Motorcycle Tires versus Car Tires

The differences in tires between motorcycles and cars were described previously. The differences are expected to show distinctions in friction testing and friction demand. A TRL study (Lambourn and Wesley, 2010) noted that there is often an impression that motorcycle tires exhibit better friction capabilities than passenger car tires. This belief implies that roadway friction is not as important for motorcycles since motorcycle tires are designed for better grip. To test this notion, TRL compared three different types of European motorcycle tires (racing, street, and luxury) to a typical European car tire. A LWT device was employed, and the four different tires were used as the test tire and run under both dry and wet conditions. The tests were run at three different speeds and using two different pavement surfaces, a typical dense asphalt surface and a higher macrotexture stone matrix asphalt. The researchers concluded that even though a car tire typically provided the lowest friction value, the trends and resulting friction coefficient values were similar for car and motorcycle tires. The researchers did experience issues with the dry testing, noting that it created considerable wear on the tires compared to the wet testing (Lambourn and Wesley, 2010). The testing was performed only on straight sections; it would be beneficial to see if this type of research could be repeated with a CFME on curves. This research also poses concern about the concept of just using existing equipment without water to test dry friction since it has obvious cost limitations due to test tire wear.

Friction and Road Contamination

TRL also performed a study on friction and road contamination using an LWT with a standard smooth tire and testing in both wet and dry conditions on asphalt and concrete (Lambourn and Viner, 2006). At the regular test speed (40 mph), the friction was too high to record with the LWT when dry. The surfaces were then tested at the regular speed in different conditions: wet, saturated with oil, covered with wet clay, and covered with coarse sand. For comparison, the researchers also used two cars with normal car road tires outfitted with a Skidman measuring system (skid car) that measures the deceleration during braking and turns it into a coefficient of friction. The average skid car values (four tires with tread) and LWT results (using one smooth tire) are shown in Table 1 for asphalt and Table 2 for concrete pavement.

Table 1. Friction results on asphalt pavement.

Asphalt	Dry	Wet	Oil	Wet clay	Coarse sand
LWT (smooth tire)	*	0.68	0.01	0.28	0.52
Skid car (4 tires with tread)	0.78	0.64	0.41	0.48	0.52

*Too high to measure.

Table 2. Friction results on concrete pavement.

| Concrete	Dry	Wet	Oil	Wet clay	Coarse sand
LWT (smooth tire)	*	0.52	0.24	0.38	0.25
Skid car (4 tires with tread)	0.85	0.64	0.44	0.54	0.56

*Too high to measure.

As shown in the tables, the study found that the results from a smooth (LWT) and treaded tire (skid car) were significantly different for the different types of contamination. Even values of almost zero were measured for the smooth tire, while the tire on the car measured much higher values. The researchers also noted that even a small level of contamination reduced the friction value when a smooth test tire was used (Lambourn and Viner, 2006). As noted earlier, an LWT with a smooth tire is more sensitive to macrotexture, which would be affected by pavement surface contamination. This test indicates that while the wet friction was similar for the smooth tire and the car tire, this finding did not correlate to the same friction measurement for different contamination conditions of the pavement. This could be due to the difference in loading on the tires or differences between one tire and four tires coming into contact with the pavement. Potentially, this could mean that motorcycle and car tires could react differently under different conditions of the pavement.

Friction Issues for Motorcycles

As noted earlier, friction testing in the United States is typically performed intermittingly, with a ribbed tire, and in straight sections of the roadway. Motorcycles are more susceptible to small areas of low friction, and their wheels do not always ride in the wheel paths (unlike cars, which primarily are in the wheel paths); therefore; researchers are not truly measuring motorcycle friction by measuring only intermittingly, and only in one wheel path, as is done with the LWT (AASHTO, 2020a).

A recent FHWA report on friction noted that NCHRP Report 37 from 50 years ago revealed that "the lowest friction levels are found on high-speed roads, curves, and approaches to intersections: in short, in locations at which high friction is needed most" (de León Izeppi et al., 2019). These are also the locations where the LWT used in the United States cannot test since it must be operated at a constant speed of 40 mph for testing. Typical friction testing sprays water on the pavement before testing and is also only performed in one wheel path, so it does not truly measure dry friction or variability across the lane. The Federated European Motorcycle Association has recognized these differences and recommended that friction testing be more continuous, involve the complete lane by including 3D laser techniques, and be reported in finer terms (i.e., every 15 ft instead of every 0.1 mi [500 ft]) (Willingers, 2018). There are some ongoing efforts to develop the use of CFME and 3D line lasers in the United States to measure continuous friction (Mergenmeier, 2018). The FHWA friction study (de León Izeppi et al., 2019) used CFME and 3D line lasers to measure friction. The researchers also compared the results of a CFME and an LWT and found that the CFME was able to identify areas of lower friction, even in a curve, that the LWT missed. Figure 10 shows the lower measured friction values in a curved section (shown by the lower values and red color) compared to the beginning and end of the curve, as measured by the CFME (de León Izeppi et al., 2019). The LWT, due to the lower testing frequency and inability to test in curves, did not identify the lower values at all.
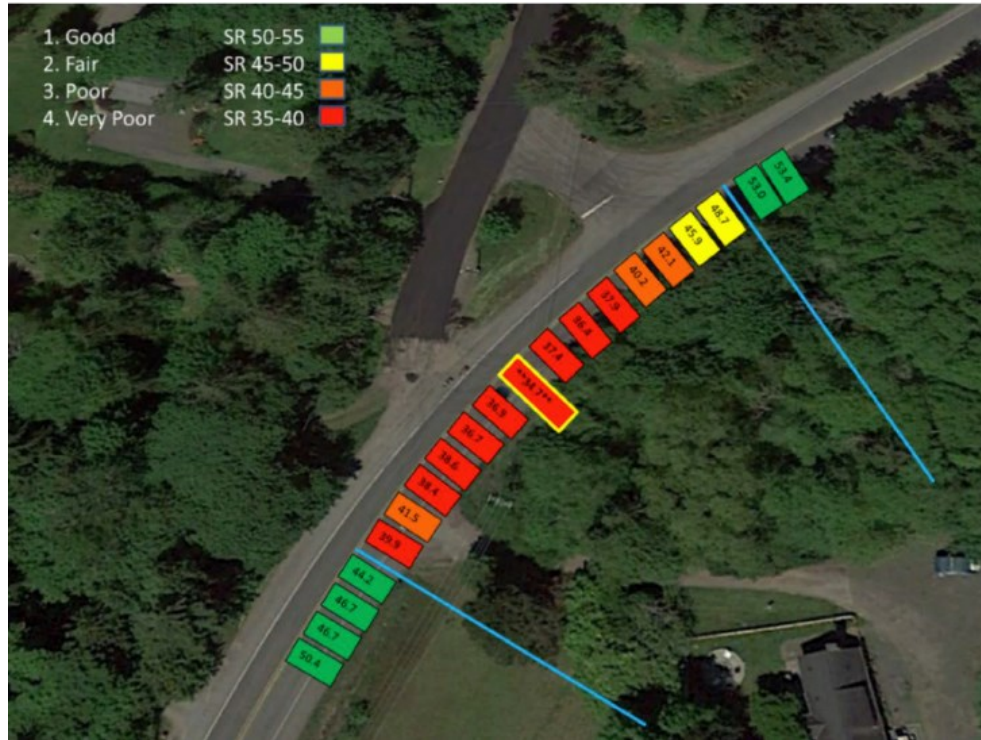
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Figure 10. Friction measurements in a curve.

High Friction Surface Treatment

Recently, the use of high friction surface treatment (HFST) has expanded significantly. HFST is mainly being used for curves with high crash rates but also for intersections and other spot areas. While recent HFST guidance notes that "there are no known negative safety effects for motorcycles" (FHWA, 2017), no research has been found specifically related to HFST and motorcycles in the United States. One study that reported on an HFST installation in an intersection in Kentucky noted that HFST should be beneficial to motorcycles since overall rear-end crashes were reduced (Scopatz et al., 2018). An example of a potential beneficial use of HFST to prevent motorcycle crashes was identified in Rhode Island through personal communication. In 2014, HFST was installed on a section of Tunk Hill Road in Scituate, RI. There were five motorcycle crashes on this road in the 5 years before the HFST installation. In the 7 years since the HFST was installed, there have been no motorcycle crashes (email communication with Sean Raymond, Rhode Island DOT, May 6, 2021). Figure 11 shows the site after HFST installation.

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Figure 11. Rhode Island location after HFST installation.

The European version of HFST is slightly different in materials and usage, and the current UK design manual recommends HFST on approaches to roundabouts, intersections, and pedestrian crossings and for certain curves and gradients (Highways England, 2020). Guidelines in the United Kingdom specifically note that the HFST should terminate on the straight tangents (not in a curve) for optimum motorcycle stability (IHE, 2005). London's *Urban Motorcycle Design Handbook* notes that maintenance of HFST is necessary and that a few small areas of the United Kingdom are moving away from HFST due to the resultant life-cycle costs. Transport for London (2017) noted that the treatment can lose friction over time and can even create rough roads because patches of the HFST material can detach from the roadway if not maintained. FHWA's experience with HFST has shown that issues can be more of a function of specifications that allow poor installation practices or applications applied on poor roads originally (personal communication with Frank Julian, retired FHWA, July 2021). Due to the enhanced friction benefits, HFST should be a benefit to motorcycles if installed and maintained appropriately.

Just like for any other pavement, oil, leaves, or some other deleterious material that partially covers an HFST installation may be more dangerous than the uncovered surface due to the friction differential. In addition, similar to chip seals, if the aggregates are dislodged due to wear, the remaining binder material will provide little to no friction resistance.

Friction and Pavement Markings

Even if the pavement is designed, constructed, and maintained in a manner conducive to good frictional properties, it can be for naught if the pavement markings placed on top of the pavement have vastly different friction characteristics. The effect on a motorcycle is such that the friction differential can be more detrimental than the overall pavement friction.

The international scan performed in 2011 noted that some European agencies had specifications addressing friction differentials due to different pavement types (e.g., HFST) or pavement markings. The report also noted that intersection-related pavement markings in some countries (including Belgium) leave a gap for motorcycles and bicycles (Nicol et al., 2012). The report

included a recommendation of investigating pavement marking materials and techniques that are motorcycle friendly. The current EU standard for pavement marking materials, EN 1436:2018, includes several different skid-resistance classes, S1 to S5, that are differentiated by minimum friction values in terms of SRT (SRT is the European designation for the British pendulum test value; the United States uses the British Pendulum Test (BPT) or British Pendulum Number (BPN) values varying from 45 to 65. The specifications also include an S0 that does not have a friction requirement. In the United Kingdom, the minimum recommended class is S1 (greater than 45 SRT). Class S3 (greater than 55 SRT) is recommended if additional skid resistance is warranted. The specification does note that "in general, high classes of retroreflection and slip/skid resistance cannot be obtained together" (European Committee for Standardization, 2018).

Traditionally, retroreflectivity concerns have driven pavement marking design more than friction. While there are standards and testing for retroreflectivity, the current U.S. guidance from the MUTCD on pavement marking materials and friction simply states, "Consideration should be given to selecting pavement marking materials that will minimize tripping or loss of traction for road users, including pedestrians, bicyclists, and motorcyclists" (FHWA, 2012).

The AASHTO National Technical Product Evaluation Program (NTPEP) Project Work Plan for Pavement Marking Materials (PMM) does include a laboratory friction requirement (British pendulum test, ASTM E303/AASHTO T 274) for tape markings but does not include friction testing for the more frequently used paint or thermoplastic materials (NTPEP, 2019). In addition, it requires the use of the BPT for initial testing for tape but does not address long-term friction durability. The NTPEP Standard Work Plan for Field Evaluation of Pavement Markings Materials (NTPEP, 2019b) and the AASHTO Standard for Thermoplastic Traffic Line Material (AASHTO T 250) do not include any requirements for friction testing. The field evaluation portion of the NTPEP program includes retroreflectivity and a visible durability component, but not friction.

The Florida Department of Transportation's (FDOT's) standard specifications and design manual require a minimum friction value for patterned pavement pedestrian crosswalks (FDOT, 2021). The patterned pavement (Specification Section 523) uses special materials for overlaying decorative crosswalks and is primarily used or requested by local governments. FDOT requires the use of an LWT or a newer static test called the dynamic friction tester (DFT, ASTM E1911) to test the friction of the surface overlay, both as part of installation and regularly afterward, using Florida Test Method FM 5-592. Prior to 2008, Florida used the British pendulum test (BPT) value in the test method but discontinued the use of the BPT in 2007 due to issues found with the test in the field. Florida switched to the DFT to test skid resistance for in-service applications after performing research and finding comparable results for the DFT and the LWT test (Holzschuher et al., 2010).

FDOT also has skid-resistance requirements for preformed thermoplastic (Section 971-6) that requires an initial lab test of 55 BPN for bicycle and pedestrian crosswalk markings and a 35 BPN for other tape-type markings. The Florida specifications for standard hot-placed thermoplastic materials do not have the same friction testing requirements, but they do require the addition of sharp silica sand in bicycle and pedestrian crosswalk markings, which should improve the friction resistance (FDOT, 2019).

Testing of pavement markings in one study in Italy showed average friction values of the pavement markings were found to be on the order of 85 percent of the pavement friction values. Researchers tested 16 different roads and used two different friction measurement techniques. They also applied non-skid aggregates to the pavement markings and found that the friction was improved slightly over non-treated marking materials, but the improvement decreased with wear (Pasetto and Damiano Barbati, 2011).

ODOT has a standard detail related to pavement markings for crosswalks that is designed to avoid the wheel paths. This detail, similar to Figure 12, is also used in roundabouts (Oregon DOT, 2021).
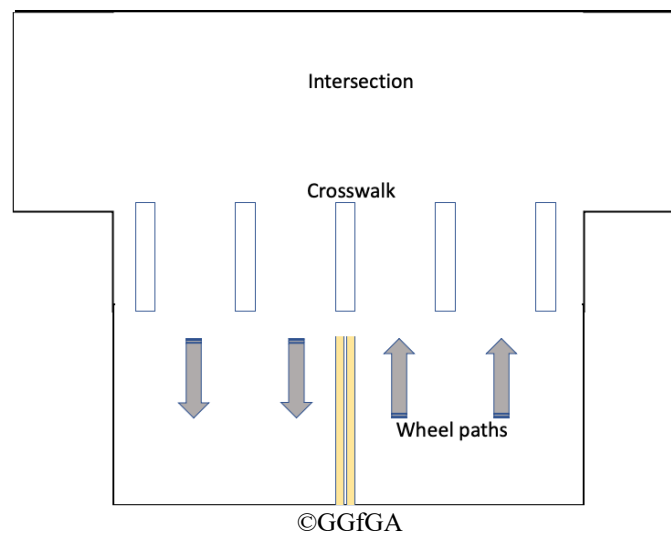

Figure 12. Staggered crosswalk detail.

CHAPTER-CONCLUDING COMMENTS

Prospective Design and Operational Safety Countermeasures

Identifying and deploying design and operational strategies to improve motorcycle safety performance can be challenging and, in many cases, costly. The deployment of any suitable design or operations-based treatments must also balance how other road users may be impacted. The literature review previously identified several prospective countermeasures that can be expected to enhance safety; however, more research is needed before the impact each of these items may have on motorcycle-related safety performance is fully understood.

These potential treatments include the following:

- Increase the radius of a horizontal curve to provide enhanced visibility.
- Increase the length of a horizontal curve.
- Consider including auxiliary lanes (particularly exclusive right-turn lanes) at locations where motorcycle volume is higher.
- Minimize roadside features (trees, barriers, and other fixed objects) and widen clear zones with particular attention to the outside of the curve.

- Widen shoulder widths in a manner consistent with the road purpose (e.g., wider for freeways, narrower for two-lane highways).
- Employ human factors research and experimentation with novel motorcycle warning signs with the potential to reduce crashes, in accordance with the provisions of the MUTCD.
- Maintain smooth driving surfaces.
- Minimize the use of raised pavement markings at locations with frequent lane changes (additional research is needed for snow plowable pavement markings).
- Evaluate the use of advance stop lines for motorcycles at signalized intersections.

Recommendations Related to Pavement Types and Friction

Common practices for maintenance of pavements, including chip seals and crack sealing of asphalt pavements and tining/grinding of concrete pavements, can have an effect on the texture and frictional properties of the pavement. As described earlier, California identified a relationship between ride quality and texture for bicyclists and recommended a limit on the macrotexture for chip seals based on this relationship. More research is needed to identify these types of texture or friction limits as related to different types of surfaces for all two-wheeled vehicles, bicycles, and motorcycles.

Based on the existing research studies, it is clear that the way friction is currently being measured in the United States has its limitations for motorcycles. Motorcycles would benefit from continuous friction measurements provided by CFME, and other technologies, like 3D lasers, that can provide full lane coverage in curves and intersections for friction measurement. A VDOT-led transportation pooled-fund study has activities investigating friction, including CFME and 3D lasers, underway. Using CFME to identify areas for investigation of safety treatments could be beneficial to motorcycle safety. Similarly, specifically looking at all motorcycle-specific crash rates to identify locations for treatment could be more beneficial to motorcyclists than using just wet-weather motorcycle crash rates or overall vehicle wet-weather crash rates.

Recommended friction levels for pavements, as related to type of road, geometry, and special considerations (such as pedestrian crossings), have been proposed in both Europe and the United States (de León Izzeppi, 2018). Motorcycle-specific conditions could also be addressed within this type of framework.

The current *AASHTO Guide for Pavement Friction* does not address friction differentials, or any other motorcycle considerations (AASHTO, 2008), but the current task force revising the manual is considering additional language to specifically address motorcycles (personal communication with John Donahue, May 2021). The proposed language incudes this wording in relation to motorcycles: "Due to the nature of just having two wheels on the pavement, they also are sensitive to smaller areas of low friction or lack of continuous friction longitudinally, especially approaching intersections. Also, due to the way they take curves to maintain stability, they specifically have a need for predictable friction both longitudinally and transversely (across the entire lane, not just in wheelpaths) in curves."

The 2010 domestic scan included a recommendation to develop an NCHRP problem statement for research specifically on pavement markings and friction (Capers, 2011). As noted earlier, the

international scan also highlighted pavement marking friction needs. The guidance for the AASHTO strategic safety plan identified Strategy 11.1 A3 as related to pavement marking and traction for motorcycles (Potts et al., 2008). MnDOT reportedly has a study underway on pavement marking friction and the friction differentials' effect on motorcycles and bicyclists (TRB, 2021). Additional research is needed to address what friction levels should be required for pavement markings and the best method to test the friction. The requirements could be implemented by adding to AASHTO standards for pavement markings and the AASHTO NTPEP requirements for pavement marking materials.

CHAPTER 3. CONSTRUCTION AND MAINTENANCE ISSUES RELATED TO MOTORCYCLES

The 2020 MAC report (Sayre et al., 2020) specifically identified 11 recommendations, 10 of which are highly related to construction and maintenance practices associated with improved motorcycle safety. The 11 topic areas include the following:

- Pothole maintenance.
- Milled surfaces.
- Manhole covers.
- Steel plates.
- Uneven pavement.
- Gravel or debris.
- Traffic barrels.
- Chip seals.
- Joint and crack sealing.
- Pavement markings and friction.
- Traffic actuated signals.

Many of the areas and recommendations could also affect other vehicles in a positive manner. For example, potholes, milled and uneven pavement, and debris on the roadway are a concern for all motorists, but some conditions have more of an impact on motorcycles than other vehicles, like wet grass clipping debris on a roadway. Typical vehicles would not be too affected by this type of debris, but a motorcycle might, especially if the debris is located in a curve. This chapter discusses construction and maintenance practices, with an emphasis on the above recommendation areas and their impact on motorcycles.

## PRIOR STUDY RECOMMENDATIONS RELATED TO CONSTRUCTION AND MAINTENANCE

NCHRP 500, Vol. 22 recommended friction testing for paving marking materials and encouraged keeping the pavement as clean and smooth as possible during construction. The report noted that issues with potholes, pavement rutting, manholes, irregular pavement surfaces, and pavement deteriorations particularly affect motorcycles. The researchers noted that Team Oregon was involved in reviewing new surface treatment options being considered by ODOT and recommended the use of advance warning for uneven pavement conditions while also noting that determining thresholds for exactly what type and level of pavement deterioration constitute unacceptable conditions for motorcycles needs more research (Potts et al., 2008).

The international scan report also recommended increasing use of advance warning signs specifically for motorcyclists. Researchers reported that Norway used a paved apron for gravel driveways to limit gravel going onto the roadway, effectively preventing the need for future maintenance (Nicol et al., 2012). The domestic scan from 2011 similarly encouraged the use of advance warning signs, especially the W8-15P placard with a depiction of an actual motorcycle. Additional recommendations included sharing construction and other hazardous conditions through the internet and addressing the need for friction standards in designing and placing pavements and pavement markings (Capers, 2011). The road safety audit report revealed that

North Carolina has installed paved aprons on gravel driveways and recommended such use to prevent gravel from entering the roadway. The Safety Edge™ was recommended (potentially as a standard construction detail) to reduce run-off-the-road crashes (Nabors et al., 2016).

STANDARD PRACTICES AFFECTING MOTORCYCLES (CONSTRUCTION AND MAINTENANCE PRACTICES)

All State transportation departments regularly contract out construction activities, and some now also contract out maintenance-related activities. A State's standard specifications and specific project plans are how agencies communicate with contractors on what is expected and what is acceptable during construction. While each State has numerous design plans, States typically have only one specification book. A review of the current State DOT standard specifications was conducted to specifically identify if the specifications mention motorcycles. Figure 13 shows the States that specifically mention motorcycles in their standard specifications and in what context they are mentioned. As shown with the darkest shade, most States do not mention motorcycles even once. Some States specifically call out motorcycles in terms of recognizing that they need to be detected by any traffic signal detector loops that are installed. The States noted as "not found" (not fully searchable) in Figure 13 have their standards online in such a format that they were not completely searchable, but motorcycles were not identified in the areas checked. Curiously, of the 40 States that did not mention motorcycles at all, over half of them did include a reference to bicycles.
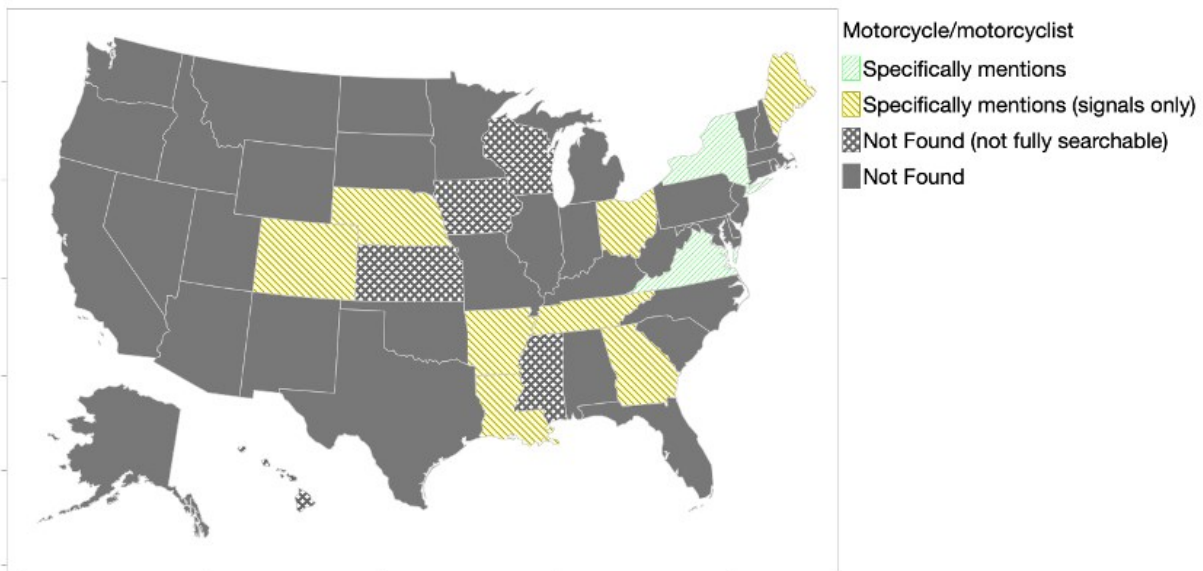
©GGfGA

Figure 13. States that specifically mention motorcycles in their specifications.

Construction contractors can be made more aware of special conditions related to motorcycles if the requirements are included in the specifications. As noted in Figure 13, both Virginia and New York include additional information related to motorcycles in their standard specifications.

Among other motorcycle-specific guidance in VDOT's replacement to Part 6 of the MUTCD, noted in the Signs Related to Motorcycle section earlier, VDOT specifications mention

motorcycles in their standard specifications in regard to removing pavement markings. VDOT requires contractors to make repairs if they cause damage to the pavement that could affect "motorcyclist, bicyclists or other users" in such a way as to make the surface of the road unsafe (VDOT, 2021).

The New York State Department of Transportation (NYSDOT) standard specifications (Section 619) require a portable message sign that warns motorcyclists to use caution if the pavement is milled and open to traffic on roadways with a speed limit greater than 45 mph and restricts the milled surface to be open to traffic for no more than 7 days (NYSDOT, 2021). Milling and milled surfaces is one area where special attention in the standard specifications could benefit motorcycles.

Milled, Ground, or Grooved Surfaces

Asphalt pavements are often milled to remove surface irregularities before repaving as part of normal maintenance practices. The removed material is predominately recycled back into the pavement as recycled asphalt pavement. In its *Recycled Asphalt Pavement Best Practices Manual*, the National Center for Asphalt Technology recognized that milled surfaces could be problematic for motorcycles and noted that some state agencies will check the texture or have a texture depth limit (e.g., ½ inch peak to valley) before opening a milled surface to traffic (West, 2010).

The domestic scan report noted that many States require a milled surface to be "closed to traffic until it is repaved" (Capers, 2011). The current State specifications do not support that claim; the closest found was Florida. Florida specifications note, "Repave all milled surfaces no later than the day after the surface was milled" (FDOT, 2019). Florida does require that a milled surface open to traffic have a smooth longitudinal transition and "a texture that will provide an acceptable riding surface," and the surface is required to be swept with a power broom before opening to traffic (FDOT, 2019). There is definite variety in the requirements for when and how long milled surfaces can be left exposed to vehicular traffic in the different State specifications, and some examples are shown in Table 3.

New Hampshire allows milled surfaces to be left under traffic but also has a work zone traffic control standard that includes signing specifically for motorcycles (MOTORCYCLES USE CAUTION or GROOVED PAVEMENT with motorcycle plaque) (NHDOT, 2018).

Maryland allows traffic to run on a milled surface for up to 10 days, but the specifications also require a control test section be used to measure the macrotexture of the pavement based on the milling equipment used, along with daily checks on the texture. Maryland has a monetary penalty in the specifications if the contractor does not comply with texture limits (Maryland Department of Transportation, 2020).

Table 3. Milling requirements in different State specifications.

State	Milling requirements in specifications	Reference
Alabama	Allows the surface to be open to traffic for 7 days if regular milling is used and 30 days if micro-milling (accuracy to 1/16 inch) is used.	Alabama Department of Transportation, 2018
Colorado	Allows a milled surface to be open for 10 days.	Colorado Department of Transportation (CDOT), 2019
Georgia	Restricts micro-milled surfaces to 5 days as a riding surface (on the interstate) but may allow traveling on milled surfaces for other roadways for up to 30 days.	Georgia Department of Transportation (GDOT), 2021
Kansas	Limits milling to 2 mi in length in front of the paving and requires feathering for joint and manholes if left open to traffic.	Kansas Department of Transportation, 2015

Uneven Pavement

It can be difficult on a multilane facility to not leave a longitudinal joint when paving adjacent lanes. This causes the pavement to be uneven longitudinally. Transverse unevenness can occur due to multiple layers of paving or due to the milling getting too far ahead of the paving. Transverse unevenness also can occur at the approach to bridge ends or where the pavement type changes.

Colorado longitudinal joint requirements are the same as described in the domestic scan report of 2011 (Capers, 2011). Colorado's current 2019 specifications (Section 401.16) dissuade leaving a longitudinal joint but allow a 1.5-inch vertical drop-off if a longitudinal joint is approved by CDOT (2019), and a taper is required if greater than 1.5 inch:

> *Where paving operations are on the present traveled roadway, the Contractor shall arrange paving operations so there will be no exposed longitudinal joints between adjacent travel lanes at the end of a day's run. With the approval of the Engineer, the Contractor may leave an exposed longitudinal joint conforming to the following:*
>
> *(1) When the thickness of the pavement course being placed is 1.5 inches or less a vertical exposed longitudinal joint may be constructed.*
> *(2) When the thickness of the pavement course being placed is greater than 1.5 inches the joint shall be constructed according to one of the following:*
>> *(i) The entire joint shall be tapered 3:1 or flatter. A Taper steeper than 3:1 shall be considered vertical.*

(ii) The top portion of the longitudinal joint may be vertical. The vertical portion shall be a maximum of 1.5 vertical inches. The remainder of the joint, below the vertical portion, shall be tapered 3:1 or flatter.

California restricts vertical longitudinal joints to no greater than 1.8 inch (0.15 ft) and requires a 1-ft-wide taper for any longitudinal joint left thicker than 1.8 inch. California also restricts the length of the longitudinal joint to be the length of a day's paving (Caltrans, 2018).

Georgia requires that a BUMP sign be used if the vertical difference in elevation of a longitudinal joint is ¾ inch or greater with no taper (GDOT, 2017).

The domestic scan also identified Safety Edge™ as a potentially useful measure for motorcyclist safety (Capers, 2011). Safety Edge™ creates a more traversable angle at the longitudinal edge of a pavement instead of a straight vertical edge. Demonstrations have been performed in 20 States (FHWA, 2021c), and many States have added Safety Edge™ requirements to their standard specifications. Some States have also incorporated a notched wedge requirement into their paving operations to replace a vertical edge during construction (WisDOT, 2021).

Maine Department of Transportation (2020) standard specifications allow a contractor to temporarily (less than 7 days) have traffic traverse longitudinal rumble strips but require a RUMBLE STRIP CROSSING sign and a motorcycle plaque.

Utilities/Steel Plates

Utilities are also often overlooked in terms of their impact on vehicles in their construction and maintenance operations. Utility work is included in roadway construction contracts for better coordination purposes. Steel plates are mainly used for utility repairs under the roadway, and they are often placed without any notice or protection, as shown in Figure 14. VDOT performed research looking at approaches for handling steel plates (Cottrell, 2006) and now requires reflective tape to be placed at the corners of the plates, as shown in Figure 15.

Figure 14. Typical steel plate.
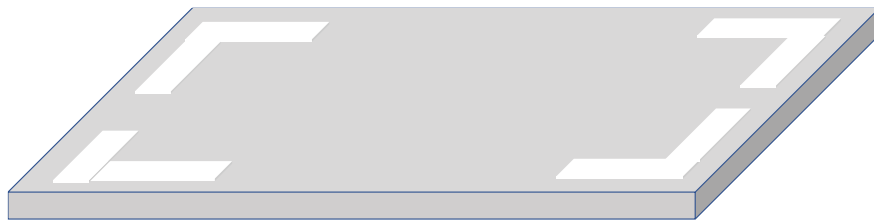
Figure 15. Plate marked with tape.

The Delaware Department of Transportation (DelDOT) has a standard detail for steel plates (DelDOT, 2017) that includes tapering with asphalt and requires a minimum coefficient of friction of 0.35 for the surface of the plate. The standard limits the use of plates on certain roadways, during weekends, and to 4 consecutive days. The Delaware standard specifications also pay for the asphalt that is used in taper (termed temporary roadway material [TRM]) and do not allow the use of steel plates between November 1 and April 1 without approval of DelDOT (2021).

The *City of Atlanta Public Works Right-of-Way Manual* includes an appendix on metal plate requirements that requires plate markings at the edges with reflective tape and a skid-resistance coating for the entire plate. It also requires advance signing (City of Atlanta, 2019).

Both the DelDOT standard detail and the City of Atlanta manual show two different allowable methods of installation for steel plates based on the speed of the roadway. One method includes recessing the steel plate into the pavement such that the surface is flush and is used for roadways with higher speeds. The other method involves steel plates placed on top of the surface with asphalt tapers and is allowed for lower-speed roads. Both methods require that the plates be anchored into the existing pavement with pins or dowels.

Work Zone Traffic Control Specific Guidance and Research

While WSDOT and TxDOT do not mention motorcycles in their specifications, as shown in Figure 13, they do specifically recognize motorcyclists in their work zone traffic control guidelines and work zone training, respectively.

WSDOT's (2021b) *Work Zone Traffic Control Guidelines for Maintenance Operations*, which are referenced by their specifications, have a specific motorcycle signing detail. The signing requirement is actually codified in State law (Washington State Legislature, 2021b). The law states in part:

> *If the construction, repair, or maintenance work includes or uses grooved pavement, abrupt lane edges, steel plates, or gravel or earth surfaces, the construction, repair, or maintenance zone must be posted with signs stating the condition, as required by current law, and in addition, must warn motorcyclists of the potential hazard only if the hazard or condition exists on a paved public highway, county road, street, bridge, or other thoroughfare commonly traveled. For the purposes of this subsection, the department shall adopt by rule a uniform sign or signs for this purpose, including at least the following language, "MOTORCYCLES USE EXTREME CAUTION." (Washington State Legislature, 2021b)*

Failure to comply with the law is a misdemeanor and subject to fines.

TxDOT, as a result of a Strategic Highway Safety initiative, developed a 30-minute online training program entitled "Reducing Risks to Motorcycles in Texas Work Zones" that is available on the workzonesafety.org website.

The American Road and Transportation Builders Association (ARTBA) also has a free beta version of a 1-hour online training program, "Work Zone Safety for Motorcycles and Bicycles," which includes a quiz. ARTBA also provides a guide that specifically addresses motorcycle and bicyclist safety needs around work zones, titled *Guidelines on Motorcycle and Bicycle Work Zone Safety* (ARTBA, 2021). The guide includes eight recommended practices and specific actions agencies can take to address motorcycle safety in the areas of:

- Addressing pavement unevenness.
- Using realistic design speeds in work zones.
- Using advance warning signs specifically for motorcycles.
- Using portable (changeable) message signs as needed for added visibility.
- Addressing steel plates.
- Being cognizant of pavement markings' effect on motorcycles.
- Reviewing agency manuals and contract documents for inclusion of motorcycles.
- Regularly monitoring pavement conditions.

The Ohio Department of Transportation specifically looked at motorcycle crashes in work zones due to the increase in motorcycle fatal crashes between 2006 and 2012 (Schneider et al., 2013). Northern States typically have a shorter motorcycle season than warmer-climate States (Eustace

and Dissanayke, 2016). In Ohio, the warmer season is also when the majority of the construction is performed due to the more favorable weather conditions. The study recognized that the portion of a tire that contacts the pavement is 10 times greater for a typical car compared to a motorcycle. Work zone crashes in lane closures were the most common crash identified, and the location of the crash was in the area of the actual construction work (in contrast to advance warning or transition areas) in the majority of the crashes. As part of the study, researchers also surveyed over 600 riders about their impressions of safety in work zones and hazards of most concern. Grooved pavement was the highest concern (46 percent), followed by uneven lanes (26 percent) and longitudinal joints (20 percent). Similarly, pavement milling was the work activity that was of biggest concern for motorcyclists (41 percent), over paving (24 percent). Seventy-seven of the survey respondents stated that they would prefer to detour around a work zone instead of travel through it, and 20 percent would go over 20 mi to avoid a work zone (Schneider et al., 2013).

The next section summarizes different considerations related to providing advance warning to motorcyclists, potentially to allow them to avoid construction or maintenance work zones or at least be more aware of them.

SIGNING AND ADVANCE WARNING

Advance Warning Signs for Construction and Maintenance Activities

NCHRP 500, Vol. 22 included an objective for motorcycle safety specifically recommending advance warning signs for construction and maintenance activities (Potts et al., 2008). The motorcycle-specific sign additions to the MUTCD noted previously, and the addition of motorcycles to an existing note in the material section (related to friction needs for pedestrians and bicycles), were first added in the 2009 revisions of the MUTCD. These requirements remain either optional (signs) or vague (friction requirement with no associated testing to verify). As noted previously, any new signs, with the exception of signs with word-only messages not otherwise provided for in the MUTCD, may require further human factors research and would require experimentation in accordance with the provisions of the MUTCD prior to any on-road applications.

The 2011 domestic motorcycle scan recommended that motorcycle-specific methods be put in place to allow motorcyclists to report poor pavement conditions (Capers, 2011). Though not necessarily for motorcycles in particular, many of those advance warning capabilities have been established in the last (approximately) 10 years, like 511 and 311.

511 and 311

In the year 2000, the 511 number was established by the Federal Communication Commission to deliver travel information to the public (FHWA Office of Operations, 2021). Since then, State transportation departments have vastly increased the use of this service to warn of construction affecting the roads and to allow the public to report problems. GDOT (n.d.) has a 511 internet site (and cellphone apps) that provides construction information, roadway speed, crash information, live video of the roadway, and views of the overhead variable message signs. Travel routing has also recently been added.

Other States also include the ability to report issues with the roadway through the internet or other phone-based services. Tennessee has a pothole repair website with links to fill out a form or call a maintenance region (Tennessee Department of Transportation, 2021). The Pennsylvania Department of Transportation (2021) encourages calling 1-800-FIX-ROAD to report issues. The Utah Department of Transportation (2021) has an app called ClickN'Fix that users can put on their phone to report issues.

Most of the roadways in the United States are actually owned by local governments. 311 is similar to 511 in that it is used by many large municipalities to allow citizens to report issues, including roadway issues. Atlanta and Los Angeles are just two of the major cities with 311 capabilities (City of Atlanta, n.d.; Los Angeles Bureau of Street Services, n.d.).

Small Business Innovation Research (2021) has a project underway called Bayesian Assessments and Real-Time Rider Alerting and Cueing for Upcoming Danger Avoidance (BARRACUDA) that is designed to be a motorcycle-specific method for reporting issues and route planning to avoid motorcycle-specific dangerous situations on the roadway like areas under construction or with poor pavement condition. This application recognizes that pavement condition is an ongoing maintenance issue, not just related to construction work zones.

PAVEMENT CONDITION

The Hurt study from the 1980s only identified 2 percent of the crashes looked at as being caused by roadway defects. The researchers also noted that the study was done in California, and the results may be different in locations with harsher winters (Hurt et al., 1981). That may be why the MAIDS study, which included in-depth studies of crashes from a more varied geography (France, Germany, Netherlands, Spain, and Italy), found a higher rate of 3.6 percent (ACEM, 2009). In the more recent MCCS, which also used California crashes, the roadway was the primary cause in only one of the MCCS crashes, but it was contributory at a similar level to the Hurt study, at 1.4 percent. Fifteen other crashes in the MCCS noted that there were pavement defects, but they were not a primary or contributing factor, so in total, about 6 percent of the crashes were in areas with pavement defects (Nazemetz et al., 2019).

In an in-depth study of 110 motorcycle crash sites in New Jersey between 2005 and 2008, 2 of the 10 final recommendations involved pavement condition. The study found that 33 percent of the crash sites were located on rough roads (international roughness index [IRI] greater than 170 in/mi), and many of the sites had evidence of debris (sand/gravel) on the road or on the shoulder. Recommendations were made to identify and repair deficient roads and keep roads clear of debris (Mehta et al., 2009). A study related to motorcycle crash data in Puerto Rico considered the effect of pavement condition on motorcycle crashes. Researchers found a significant effect of medium to high severity pavement defects (potholes and patches) on motorcycle crash rates (Medina et al., 2008).

Both the New Jersey and the Puerto Rico studies identified pavement conditions (IRI > 170 and medium to high potholes and patches) that would also be considered detrimental to all other vehicle types. Motorcycles may experience issues at even lower levels of deterioration than other vehicles. While it is not always easy to clearly identify pavement condition effects on a

motorcycle crash, simulation allows for the possibility of quantifying the effects of pavement condition on motorcycle stability, and potentially by inference, future motorcycle crashes.

Simulation Related to Rutting

Researchers have used CarSim® and BikeSim® to evaluate the effect of rutting on both cars and motorcycles (BikeSim® is a computer program that simulates the movement of a motorcycle on a roadway; it is supported by the same company that designed the computer program CarSim®). In a study by D'Amico et al. (2018), motorcycle stability was more strongly affected and at lower rutting values in straight sections as compared to a car. In curved sections, any amount of rutting produced a severe skid effect at low speeds, while the car only experienced a severe skid effect at high speeds. In general, the researchers found that the "simulations showed generally more severe effects of rutting on the stability of the PTW (powered two wheeler or motorcycle)" (D'Amico et al., 2018).

Simulation Related to Raveling/Friction Loss

Bella et al. (2012) used BikeSim® to evaluate friction characteristics of wear/polishing of asphalt for its effect on stability of motorcycles. The stability of a rider was correlated to the effects of friction, roadway geometry, braking action, and motorcycle speed using modeling. For speeds ranging from 65-70 mph there was identified a certain level of friction (0.5 in the simulation software) below which a motorcycle would lose stability and crash. But, it was also identified that motorcycle stability was still affected even at a much higher level of friction (0.7), it just did not result in a crash. The study demonstrated the effect that friction can have on the stability of a motorcycle, even under higher friction values.

CHAPTER-CONCLUDING COMMENTS

While many of the same construction and maintenance considerations for other vehicles (clear signs in work zones, clean and even pavement condition) will also benefit motorcycles, these areas are especially relevant for motorcycles. Specifically mentioning motorcycles in construction and maintenance documents and manuals can assist in promoting awareness of the particular importance of these issues to motorcyclists for contractor and maintenance personnel.

Different agency specifications have very different requirements for measuring, monitoring, and enforcing pavement irregularities like texture and unevenness during construction and maintenance operations. A synthesis that examines the different approaches may provide insight into trends or identify the need for additional research to identify cost-effective, safe, and reasonable rationale for such practices.

While pavement condition may not be identified as a primary factor in motorcycle crash studies, poor pavement condition can divert a motorcyclist's attention from other factors on the roadway, potentially resulting in a crash. As noted in this chapter, existing research using computer simulation shows that motorcycles are much more sensitive to pavement condition compared to other vehicles. Additional research is needed to identify the different effects that pavement distresses have on motorcycles compared to other vehicles. Computer simulation is a positive approach, and more research using simulation would be of benefit, but also some type of field validation will likely be necessary.

Some positive construction and maintenance efforts affecting motorcycles have been identified (i.e., VDOT and NYSDOT standard specifications including motorcycles, TxDOT and ARTBA work zone training, motorcycle-specific messaging) and can be replicated, shared, or used by other agencies. Developing some of these into noteworthy practices would allow for easier dissemination and implementation.

CHAPTER 4. NEXT STEPS AND POSSIBLE FUTURE ACTIVITIES

A significant component associated with many motorcycle crashes may be the interaction between a motorcycle and an infrastructure-based element, such as curves, intersections, the roadway surface, and lane striping. 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.

While poor pavement condition is undesirable for all vehicles, this synthesis showed that conditions that are tolerable for other vehicles, like texture, friction, and even a common pavement distress like rutting, may not be the same for two-wheeled vehicles like motorcycles. Additional research is needed to identify the effect these different conditions have on motorcycles and identify potential countermeasures.

There is no current motorcycle design vehicle. Research is needed to recommend an appropriate design vehicle and in what cases the motorcycle design vehicle should be used. Both the United Kingdom (Transport for London, 2017) and ACEM (2006) have design vehicles in their manuals that could be considered. With a motorcycle design vehicle, other research that could be performed includes:

- Evaluate proper cross slope for motorcycles (consider lateral slope as well as longitudinal transition for rate of change).
- Study the influence lane position has on motorcycle crashes near intersections.
- Address sight-condition considerations specifically for motorcycles and recommend any design adjustments.
- Investigate motorcyclists' lean angle on curved sections to address safety in terms of assessing the relation between speed and curve geometry.

Lane filtering was recently legalized in Utah (in 2019) and will be legal in Montana in October of 2021. Before and after crash data from these States should be studied to determine the type of effect that legalization of this practice may have on safety.

The computer simulation effects noted in the Pavement Condition section show large differences in the effect of pavement condition on motorcycles compared to other vehicles. More research is needed in this area to quantify these differences and identify relevant safety action levels for motorcycles compared to other vehicles.

- Different States have different allowable pavement drop-off heights before a taper is needed; simulation might identify a proper consistent value.
- States have different requirements on milled surfaces; simulation and additional research could provide recommendations for reasonable requirements.
- Friction requirements for pavement markings are limited. Research on friction measurements and friction over time for pavement markings would allow life-cycle analysis of pavement marking friction.

State transportation departments and other roadway agencies need specific guidance on what actions can be taken to make roads safer for motorcycles. NYSDOT has a section in its *Highway Design Manual* specifically related to motorcycles in work zones (NYSDOT, 2020), which ensures that variable message signs required by specifications are included in the contract by the designers. The TxDOT and ARTBA online training noted earlier are also good examples of guidance for maintenance and construction operations. Specific training for highway design engineers related to motorcycles and motorcycle safety is also needed. Making road agencies aware of this training and encouraging the use of the training would be beneficial.

Training for design, construction, and maintenance needs to include specific examples of positive actions that can be taken to improve motorcycle safety. Examples include:

- Develop and use a standard detail for paving aprons on gravel driveways or cross streets.
- Consider appropriate friction requirements for pavements, especially in curves.
- Specify friction requirements for pavement markings or leave openings for motorcyclists in wide transverse pavement markings. Limit the use of large full-lane-width pavement markings, especially in curves.
- Add language to traffic signal specifications requiring that the equipment detect motorcycles.
- Limit bumps, uneven lanes, edge drop-offs, and milled surfaces during construction or maintenance operations or add motorcycle-specific signs to address and warn motorcycles.
- Require contractors and utilities to use steel plates and manholes with textured surfaces and install plates and manholes flush with the pavement or use tapers.
- If budget is limited, prioritize repairs for potholes and surface irregularities in curves.
- Limit overband or add angular sand to crack sealant surfaces.

The additional research noted here could be used to develop an AASHTO highway design handbook for motorcyclists that covers design, construction, and maintenance activities.

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