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Addressing the Motorcyclist Advisory Council Recommendations:

Synthesis on Intelligent Transportation System Applications and Automated Technologies for Motorcyclists

U.S. Department of Transportation
Federal Highway Administration

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

Technical Documentation Page

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16. Abstract Motorcyclists and their specific issues have been largely overlooked in the discussion of connected and automated vehicle technologies and their corresponding applications This synthesis details the general recent history of this technology area related to specific motorcycle safety concerns and reports findings from motorcyclist focus groups and a federal agency listening session. Areas of safety concerns that can potentially be enhanced or mitigated are identified across the various facets of information researched for this synthesis.		
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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)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ABS	Anti-lock Braking System
ACEM	European Association of Motorcycle Manufacturers (Association des Constructeurs de Motocycles)
ADAS	Advanced Driving Assistive System
ADS	Automated Driving System
ARAS	Advanced Rider Assistance System
AV	Automated Vehicle
B2V	Bike to Vehicle
B2X	Bike to Everything
CBS	Combined Braking System
CAV	Connected and Automated Vehicle
C-ITS	Cooperative Intelligent Transportation System
CMC	Connected Motorcycle Consortium
ConVeX	Connected Vehicle to Everything of Tomorrow
C-V2X	Cellular Vehicle to Everything
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPS	Global Positioning System
IIHS	Insurance Institute for Highway Safety
ITS	Intelligent Transportation System
M2V	Motorcycle to Vehicle
M2X	Motorcycle to Everything
MAC	Motorcyclist Advisory Council
MAIDS	Motorcycle Accident In-Depth Study
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
SAE	Society of Automotive Engineers
SEE	Search, Evaluate, and Execute
TTI	Texas A&M Transportation Institute
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2M	Vehicle to Motorcycle
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
VMT	Vehicle Miles Traveled
WHO	World Health Organization

CHAPTER 1: INTRODUCTION

The Motorcycle Advisory Council (MAC) was reestablished by the United States Department of Transportation (USDOT) Office of the Secretary of Transportation as part of the Fixing America's Surface Transportation Act, Section 1426. The purpose of MAC is to improve motorcyclist safety by providing the Federal Highway Administration (FHWA) with recommendations involving infrastructure-based countermeasures. In 2020, MAC provided its recommendations report to the former USDOT Secretary of Transportation Elaine L. Chao (Sayre et al., 2020). A recommendation from that report entails examining the use of intelligent transportation system (ITS) technology (e.g., connected vehicles, automated vehicles, and communications) to enhance motorcyclist safety.

This report is part of a series of reports related to motorcycle-specific safety issues, all of which are available on FHWA's motorcycle safety website (https://safety.fhwa.dot.gov/motorcycles/). The first report focuses on roadside safety hardware and barriers in relation to motorcycles and motorcyclists (Silvestri-Dobrovolny et al., 2021). The second report covers the current state of the practice related to roadway geometrics, maintenance practices, and pavement design and their impact on motorcyclists (Geary et al., 2021). This current report, which focused on ITS technology and applications, in the third in the series. The final report focused on noteworthy practices that can be employed by practitioners. Advanced systems have considerable potential to reduce motorcyclist fatalities and injuries if motorcycles are included in design requirements. Any ITS technology must be developed with motorcycles as a specific vehicle class and must address motorcycles with specific written policies, guidelines, and procedures to ensure that the unique operational behaviors and vehicle characteristics of motorcycles are taken into account during development, testing, and deployment of ITS technology. The purpose of this document is to continue the expansion and documentation of research relating to motorcyclist safety with a specific focus on ITS technologies. Motorcycles are a class of vehicles that have been largely left out relative to many of the ITS technologies, especially advancements such as connectivity and autonomy. Documenting current practices relating to implementing these developments within the motorcycle community and industry will further advance research and identify potential opportunities for integration.

TERMINOLOGY

The USDOT ITS Joint Program Office recognizes connected vehicle (CV) and automation-related technologies as the future of transportation in its online ITS ePrimer (USDOT, 2021). The ITS ePrimer defines ITS as "an engineering discipline that encompasses the research, planning, design, integration, and deployment of systems and applications to manage traffic and transit, improve safety, provide environmental benefits, and maximize the efficiency of surface transportation systems." ITS encompasses a wide range of technologies, from advanced traffic management systems (e.g., traffic incident response and coordinated signal timing) managed by transportation management centers, to active parking management and smart city applications. Some of the emerging technologies recognized in the ITS arena are unmanned aerial systems, artificial intelligence, and connected and automated vehicles (CAVs) (USDOT, 2021).

Connected vehicle and automated vehicle technology either assist the driver or transfer the driving task to the technology. It should be recognized that a vehicle can be connected but not automated, and automated but not connected, and different types of connectivity and levels of automation exist. Moreover, the terminology has changed since the inception of these concepts, thereby confusing matters further. While the language describing connectivity is continually evolving, terms like vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to network (V2N), and vehicle to everything (V2X) are still used. Due to continuing rapid changes in this arena, the following section defines and clarifies the terminology used in this document, including V2V, V2I, V2N, and V2X.

Connected Vehicle Technology

CV technology refers to vehicles capable of communicating with other vehicles and/or the road's infrastructure to provide the motorist (or motorist's vehicle) with accurate information in real time. According to USDOT (n.d.), CVs have the potential to decrease the number of vehicle crashes, reduce traffic and travel time, and in turn, reduce fuel consumption and emissions. There are several trial deployments currently across the United States demonstrating the wide variety of safety applications connectivity offers. However, most research conducted in this arena has only been specific to four-wheel vehicles.

Connectivity can be between vehicles (V2V), between vehicles and infrastructure (V2I), or between vehicles and other devices (V2X). The exchanges of data and information can result in increased system performance. CV technology supports a variety of information, warning, and assistance services that can aid in decision-making to reduce congestion and improve safety. In Europe, the term cooperative intelligent transportation system (C-ITS) is more commonly used instead of CV (European Telecommunications Standards Institute, 2022).

Automated Vehicle Technology

Automated vehicle (AV) technology employs hardware and software capable of automatically performing driving tasks for the driver and is described by the level of automation and the vehicle. The Society of Automotive Engineers (SAE) International J3016 standard is widely used in the AV arena and defines six levels of driving automation (0 = no automation, 1 = driver assistance, 2 = partial automation, 3 = conditional automation, 4 = high automation, and 5 = full driving automation) (SAE International, 2021).

Automated Driving Systems

The SAE standard defines automated driving systems (ADSs) specifically as the hardware and software that are collectively capable of performing to Level 3, 4, or 5.

Advanced Driver Assistance Systems

The SAE standard recognizes advanced driver assistance system (ADAS) as a term in common use but notes that it is "too broad and imprecise" to be used in the standard. For the purposes of this document, ADASs are advanced safety features integrated into a vehicle's design that assist a driver with various driving and parking tasks and are considered Level 1 and 2 features by the SAE J3016 standard. These features do not replace the driver but are meant to support and help with tasks such as blind-spot monitoring or rear cross-traffic alerts. They can automate and/or enhance vehicle systems to improve driving performance and safety, reduce the workload on the driver, and avoid potential crashes. In some instances, an ADAS provides information to a driver, and some functions are automated in more advanced systems.

The terminology used for ADASs can also be confusing. AAA, J.D. Power, the National Safety Council, and *Consumer Reports* have jointly published a document with recommended common terminology for ADASs (including terms like adaptive cruise control, lane-keeping assistance, blind-spot warning, and forward collision control) in an attempt to reduce confusion, especially for consumers (see https://advocacy.consumerreports.org/wp-content/uploads/2019/11/CR-ADAS-Common-Naming-One-pager.pdf).

Advanced Rider Assistance Systems

Advanced rider assistance systems (ARASs) are not recognized in the SAE standard, but they are defined in this document as systems capable of helping a motorcyclist with riding tasks through a variety of applications and methods. The term advanced rider assistance system was coined in 2010 by the European SAFERIDER project (Dodge & Halladay, 2008; Bekiaris et al., 2009; Lumiaho, 2012). ARAS denotes equipment that supports and assists the operator of a powered two-wheeler and/or reduces the stress and strain for a motorcyclist (Kuschefski et al., 2011). In essence, ARASs are ADASs specific to motorcycles and motorcyclists. The assistance an ARAS provides can potentially help motorcyclists overcome human capability limitations in terms of cognitive ability or skill. Examples of ARASs include anti-lock braking systems, combined braking systems, blind-spot assist, adaptive headlights, curve warning systems, lane-keep assist, and so forth.

Automated Vehicle Technology and Connectivity

ADAS technology can be supported by connectivity. For example, forward collision warning systems can be supported via vehicle-based sensors or connectivity, or both. This is similar for motorcycles and ARAS technology. However, connectivity presents challenges when implemented on a motorcycle. The ultimate outcome of this integration for passenger vehicles is expected to someday lead to fully automated driving, SAE Level 5, which does not require a human driver. Since motorcycles are fundamentally different than passenger cars and motorcyclists often ride for pleasure, not just for basic transportation, it is somewhat difficult to envision an SAE Level 5 fully automated motorcycle without some human component. As recently as this past year, it was recognized that “mixing automation with humans is much more difficult than designing for a wholly automated environment. The AV industry faces several human factors challenges concerning humans who are not in the vehicle—drivers of other vehicles, motorcyclists, bicyclists, and pedestrians” (Hart, 2021). Currently, bicyclists and pedestrians are prohibited from interstate facilities due to safety and mobility concerns. Motorcycles, on the other hand, are quite capable of maneuvering in the vehicle stream. However, the concept of a fully automated interstate of the future introduces questions pertaining to the visibility of motorcycles (or other vehicles) without up-to-date technology that can mitigate such challenges. While one solution would be a prohibition of motorcycles from the future interstate, the practicality of such a declaration would be suspect. What must be done is to address the detection, design, and mobility challenges with motorcycles that will enable them to continue to interact with the vehicle stream. This is the primary reason motorcyclists need to be specifically considered in the future of connected and automated applications.

UNDERSTANDING THE NEED

The World Health Organization (WHO) stipulates that injury among motorcyclists is a global health problem, with nearly 300,000 annual deaths worldwide (WHO, 2015; Savino et al., 2020). Despite this fact, motorcycles are a class of vehicles that have been generally excluded from safety advancements, like infrastructure-based countermeasures, and other technological developments, such as CV technologies. Since passenger vehicle drivers make up 97 percent of registered vehicles in the United States, it is reasonable that past research about connectivity and other assistive vehicle systems has mostly focused on serving this group.

Nevertheless, although motorcycles make up the remaining 3 percent of registered vehicles, motorcycle fatalities are overrepresented and account for nearly 14 percent of all traffic deaths in the United States (National Highway Traffic Safety Administration [NHTSA], 2021). In addition, in 2019, USDOT reported a rate of 25.47 motorcyclist fatalities per 100 million vehicle miles traveled (VMT), while passenger vehicles totaled a rate of 0.89 passenger car deaths per 100 million VMT (NHTSA, 2021). These data strongly suggest that significant opportunities exist to improve overall transportation safety by addressing this vulnerable road user group. Initiatives such Road to Zero, managed by the National Safety Council, seek to end roadway deaths, including motorcyclists, through accelerating the advancement of technology in vehicles and infrastructure (National Safety Council, 2022). CV and ARAS advancements can help prevent motorcycle crashes since these applications can enhance motorcyclists' and drivers' attention and perception of their surroundings, including each other's presence on the roadway (Flanigan et al., 2018).

CV technologies have the potential to make the unseen motorcyclist "seen" by other drivers. In a study conducted by the European Association of Motorcycle Manufacturers (ACEM), research personnel found that 51 percent of motorcycle crashes were caused by perception and decision failures of another vehicle driver (ACEM, 2009). Similarly, FHWA found that nearly 43 percent of motorcycle crashes were caused by an attention failure, distraction, or stress of the other vehicle driver (Nazemetz et al., 2019).

ARAS technologies also have the potential to contribute to reducing motorcycle crashes. The same ACEM study noted above showed that 37 percent of motorcycle crashes were caused by the motorcyclist. Among these accidents, nearly 73 percent were due to a perception failure, while 19 percent were caused by a decision failure of the motorcyclist (ACEM, 2009). Similarly, FHWA found that motorcyclists' inattention contributed to 32 percent of crashes (Nazemetz et al., 2019). Although assistive driving systems have reduced crash rates in four-wheeled vehicles, significant design differences exist between motorcycles and passenger vehicles. Motorcycles cannot adopt ADAS features without special consideration and research. For instance, compared to passenger vehicles, motorcycles are less stable, less visible, and smaller in general. Because motorcycles possess less stability than a passenger vehicle, hard braking may cause the wheels to lock, increasing the motorcyclist's chance of falling. Additionally, any small changes in the environment, or motorcyclist's attention, can exacerbate instability. Integrating connectivity or systems like ADASs must involve consideration of these factors and assurance that systems promote safety rather than risk. Designers will have to confirm that systems that may control the motorcycle's speed or direction will not cause instability with sudden movements. Furthermore, designers may also have to consider sensor and camera placement carefully for CV applications.

Since motorcycles can sit lower than passenger vehicles, research must investigate if it will interfere with detection accuracy. These concerns are just a few examples of the many special design considerations that are necessary for incorporation of assistive systems in motorcycles.

Despite the potential benefits these advanced solutions offer, motorcycles have been considered in discussions of connectivity, but due to the challenges with the V2V rule and Federal Communications Commission (FCC) action that has contributed to uncertainty regarding spectrum activities, various motorcycle activities were not completed. The National Transportation Safety Board (NTSB) recognized the potential benefit of CV technologies (e.g., V2V and V2I) and enhanced braking and stability control (i.e., ARASs) for motorcyclist safety but also noted that motorcycles are not currently being fully designed into the CV systems, and the ARASs need to be more widely available (NTSB, 2018).

Research and industry leaders have expressed that this discrepancy is partly due to the design challenges associated with motorcycles, like their inherent instability and ability to lean. These issues have not been fully researched, and how advanced countermeasures can be integrated is unknown. Other challenges include developing user and vehicle requirements that satisfy users and yield acceptance among the community. Additionally, motorcycles are subject to the same roadway design parameters of larger vehicles, which have seen significant technical innovations that are not well represented and/or utilized in the motorcycle arena. Specifically, motorcycles are not considered a design vehicle for any safety design. USDOT's automated vehicle 2.0 through 4.0 activity reports (USDOT, 2017, 2018, 2020) recognize motorcycles and motorcyclists but do not provide any specific plans related to automated and/or connected motorcycles.

Motorcycle-specific automated and/or connectivity plans have yet to be developed, and research examining the interaction between equipped vehicles and non-equipped motorcycles is very limited. Research is also limited on user acceptance and integration of multiple assistive systems, and there is a general lack of data about ARAS effectiveness on roadway safety, especially for newer ARASs. Given the current uncertainty with the connectivity technology and spectrum, it is difficult to determine aspects of a research program that would benefit from these challenges being addressed with light vehicles.

RESEARCH OBJECTIVES

Given the disproportionality between passenger vehicle and motorcycle traffic-related death rates, it is essential to research new methods to increase motorcycle safety. Technology innovations such as connectivity (CVs) or assistive vehicle systems for motorcycles (ARASs) have not advanced as rapidly as passenger vehicles and, in many instances, have been mostly excluded from these discussions altogether. Research examining CVs and ARASs is warranted to improve safety for this vulnerable road user group. This synthesis addresses the gap in research and knowledge by reviewing the current state of practice of motorcycle connectivity and other assistive motorcycle devices, synthesizing what key stakeholders see on the horizon, and outlining future research.

Specific research goals of this project were to:

- Understand the current state of practice of ARASs and CVs for motorcycles.
- Understand the current state of knowledge of ARASs and CVs among motorcyclists, original equipment manufacturers (OEMs), and key federal agencies.
- Identify challenges and research gaps and provide recommendations for future research paths.

This report presents findings relating to motorcycle connectivity and other assistive system research. It discusses the methodology for the research; documents feedback from crucial stakeholders like motorcyclists, OEMs, and key federal agencies; and synthesizes the findings and provides recommendations for additional research.

CHAPTER 2: LITERATURE REVIEW

LITERATURE SEARCH

Since the primary research goal of this project was to understand the current state of practice and knowledge of motorcycle connectivity (CVs) and ARASs, it was essential to conduct a well-rounded literature review to fully capture the breadth of technology and associated benefits that may support motorcyclist safety. Because motorcycles have been mostly omitted from these research areas, it was important to perform two separate searches relating to CVs and ARASs. The first search focused on academic research publications, while the second focused on topical publications in the motorcycle arena. Topical publications were considered non-scholarly content written for the general public. These publications were inclusive to motorcycle forums, technical and nontechnical magazines, newspaper articles, and websites.

Like any tight-knit community, the motorcycle community has its own vernacular. The familiarization phase of the literature review was essential to the project team to ensure the appropriate use of keywords and phrases since that input would determine the literature search output. Choosing these keywords was challenging for several reasons. The language used between manufacturers was often not consistent, most likely due to branding and marketing purposes. Some manufacturers and researchers applied terms (e.g., ADAS) typically used for passenger vehicles to motorcycles, while others did not, instead using ARAS. There were also instances where key phrases were used interchangeably or meant something different depending on the source. For instance, connectivity is often used interchangeably with autonomy, even though as noted earlier, these terms are separate concepts.

Project team members developed a comprehensive list of terms. Table 1 outlines the search terms and phrases that were used in the literature review. The search yielded nearly 60 academic and topical articles relating to motorcycle connectivity or ARASs. Findings from these articles were used to identify challenges, discover research gaps, and inform future research avenues. A summary of these findings is presented in later sections of this report.

Table 1. Keywords and phrases for literature review.

Search	Keywords and Phrases
Common phrases to use in conjunction with primary searches	Motorcycle, Powered Two-Wheeler, Powersport Vehicle, Motorbike, Scooter, Moped
Connectivity	Connected Vehicles, Connected Motorcycle, CAV, Vehicle-to-Vehicle Communications, Vehicle-to-Infrastructure Communications, Dedicated Short-Range Communications (DSRC), Intelligent Transportation Systems (ITS), C-ITS, Cooperative Intelligent Transport Systems, Automated Control, Connected Helmet, V2I, V2V, Bike to Vehicle (B2V), Bike to Everything (B2X), Vehicle to Motorcycle (V2M), Motorcycle to Vehicle (M2V), Motorcycle to Everything (M2X), Riderless, Autonomous
ARASs	Advanced Rider Assistance System (ARAS), Advanced Driver Assistance System + Motorcycle, Adaptive, Warning, Information, Autonomous, Automated, Active, Passive, Warning, Braking, Accelerating, Lane, Adaptive Cruise Control, Active Cruise Control, Blind Spot, Collision Two-Wheeled Vehicle

LITERATURE REVIEW RESULTS

Motorcycle Risk and Crash Causation

Motorcyclists face more severe consequences for much more minor errors than do drivers of passenger vehicles. Advanced countermeasures like connectivity and ARASs may help the motorcyclist maintain a higher margin of safety given the environmental and cognitive stressors motorcyclists face. For instance, environmental factors such as light, vibrations, noise, and climate can affect motorcycles far more significantly than a passenger vehicle since motorcycles are less stable and do not possess as much traction. Thus, there is a greater burden for operation on the motorcyclist. In one study (Kuschefski et al., 2011), researchers asked participants to compare their motorcycle to their car and evaluate different sensory strains. Over 200 responses showed that motorcyclists experience more strain by a factor of at least 1.7 times for every sensory input, such as smell, light, vibrations, noise, climate, and comfort. Results also found that change in climate affected motorcyclists by a factor of 4.6 compared to when in their passenger vehicles.

Considering the overload of sensory inputs, physical stamina and strength, and minimal margin of error that must be maintained while riding, it is understandable why motorcycle crash rates are overrepresented. Common precrash scenarios identified in the literature include limited time for motorcyclists to take any evasive action (Penumaka, 2014), inadequate braking (Sporner & Kramlich, 2001; Rizzi et al., 2009), scan errors (ACEM, 2009), low saliency (Hurt et al., 1981), and loss of control (Penumaka et al., 2014). Furthermore, an in-depth study of motorcycle-related accidents was conducted in partnership with ACEM and the European Commission. The study entailed examining accidents from 1999–2000 and included five sampling locations in France, Germany, Netherlands, Spain, and Italy, thus creating the Motorcycle Accidents In-Depth Study (MAIDS) database. Results found that nearly 88 percent of motorcycle crashes had been identified as an operator error by either the motorcyclist or driver (ACEM, 2009). Findings showed that these specific errors were classified as either perception, comprehension, decision, and/or reaction failures (ACEM, 2009). Perception errors were classified as ones in which a motorcyclist or driver failed to detect dangerous conditions altogether. Comprehension errors involved perceiving a dangerous situation, but not comprehending the danger associated with the situation. Decision failures included the operator making the incorrect decision to avoid a dangerous roadway scenario. Finally, a reaction failure included the operator failing to react to a dangerous condition.

Other studies analyzed the European MAIDS database to understand the causation factors leading to these human errors (Penumaka et al., 2014). Results showed that motorcyclists typically made perception and execution failures, while passenger vehicle drivers primarily made perception and comprehension failures. Furthermore, of the execution errors, specifically braking maneuvers, made by motorcyclists, the analysis revealed that in 41.1 percent of accidents examined, hard braking resulted in wheel locking. It was also noted that researchers found a difference in braking patterns between novice and experienced riders. In 76.5 percent of cases, weak braking was typically due to either rider panic or lack of skills to perform maximum braking (Penumaka et al., 2014). Research also identified other common crash factors for motorcycles, such as limited time for motorcyclists to take evasive action. Studies have shown that brake reaction times are slightly lower for motorcyclists than for passenger vehicle drivers.

However, this result is most likely due to the operator's proximity to a brake pedal versus a lever on motorcycles (Dinges & Durisek, 2019). Penumaka et al. (2014) also noted that many of these crashes occurred at a traffic intersection, which is a finding supported by other work (Savino et al., 2020). Specifically, the most common intersection crashes were sideswipe crashes occurring as the vehicle turned right or left (Savino et al., 2020).

ADASs and CVs That Can Benefit Motorcyclists

ADAS and CV technologies in other vehicles can ultimately improve motorcyclist safety. Due to known conspicuity issues, motorcycles have an innate propensity to benefit from the ability to communicate with other vehicles or to be automatically detected by other vehicles.

The Insurance Institute for Highway Safety (IIHS) looked at three ADASs (lane-keeping assistance, blind-spot warning, and forward collision warning) in relation to the benefit they could provide for motorcycles (Teoh, 2017). Using national transportation crash data from 2011–2015, IIHS analyzed the potential impact of these technologies on motorcycle safety and estimated that the technologies could potentially eliminate 8,000 two-vehicle crashes per year involving motorcycles. Of course, these benefits are dependent on the technologies recognizing a motorcycle. A 2014 AAA study found that the systems that were offered at that time detected motorcycles on average 26 percent later than typical full-size sedans were recognized (AAA, 2014).

ARASs in Use

Advanced technologies may help motorcyclists overcome unavoidable environmental factors, perception and attention issues, and other factors, such as experience level, that might hinder them. Unlike connective applications that are currently more relevant solely on the infrastructure side (e.g., connected signal systems), ARASs are in public use and are becoming more common. Motorcycle OEMs and designers are still relatively behind in adopting advanced safety features in general, but there have been some recent advances in ARASs. For example, anti-lock braking systems for motorcycles have been in use long enough for research studies to have been performed on their safety, but only recently have motorcycle designers and manufacturers started to include adaptive cruise control in their design. Touted as one of the most advanced motorcycles on the market, the Ducati 2021 Multistrada V4 is the first of its kind to possess both front and rear radar and offers adaptive cruise control, blind-spot detection, traction control, and Bluetooth and Wi-Fi capability (Rais, 2020). Other industry leaders, like Bosch and Honda, have also submitted patents for steering assist and collision warning systems, respectively.

The literature review identified various ARASs. Below is a list of ARAS features that emerged from the team's review (Beanland et al., 2013; Basch et al., 2015; Rizzi, Kullgren et al., 2015; Rizzi, Strandroth et al., 2015; Savino et al., 2020).

- **Anti-lock Braking System (ABS)**—Advanced braking system that prevents wheels from locking when braking, especially on wet or slippery road surfaces.
- **Combined Braking System (CBS)**—Autonomous braking system in which the application of one brake control will activate both front and rear brakes.

- **Autonomous Emergency Braking**—Autonomous braking system that in an emergency ensures maximum braking power is applied.
- **Active Cruise Control**—A system that relieves motorcyclists from having to manually adjust to the speed of the vehicle they are following when cruise control is set.
- **Traction Control**—An autonomous system that intervenes and limits power to maintain traction to the wheels if a slip is detected, especially on loose or slippery road surfaces.
- **Stability Control**—An autonomous system that intervenes and limits power to the wheels if the possibility of instability is detected.
- **Blind-Spot Assist**—A system that uses cameras and other sensors to detect and provide a visual warning of vehicles traveling in the blind spot or alongside the motorcyclist.
- **Adaptive Headlights**—Headlights that will adapt in real time to illuminate dark space left or right of the motorcycle while cornering.
- **Forward Collision Warning System**—A system that warns the motorcyclist of an impending collision by detecting stopped or slowly moving vehicles ahead.
- **Curve Warning System**—A warning system used to alert motorcyclists they are approaching a curve too fast.
- **eCall**—A system that uses a cell phone network connection to contact dispatch to send help if a crash is detected.
- **Lane-Keep Assist**—An alert that warns motorcyclists if they drift out of their respective lane.
- **Global Positioning System (GPS) Navigation**—A system that provides someone's current location, travel route, and general traffic information.
- **Tire Pressure Monitoring System (TPMS)**—A system that informs motorcyclists if their tires have too much or too little air pressure.

Several studies showcasing the benefits of ABSs for motorcyclists were identified. The ABS for motorcycles is similar to the ABS used for cars, which controls and cycles the braking to prevent locking the brakes. The CBS is specific to motorcycles in that it has different controls for front and rear brakes, but the CBS activates both brakes. A motorcycle may have ABS, CBS, or both. An NHTSA study of six different types of ARAS-equipped motorcycles (some equipped with CBS and some with ABS) compared to non-equipped motorcycles found improved stopping distance could be attained with either CBS or ABS technology (Green, 2006). ABS-equipped motorcycles have also been the focus of crash safety studies. Using fatal crash data from 2003–2011, IIHS-supported research found a statistically significant difference in crash rates for motorcycles with ABS (3.8) compared to motorcycles without ABS (5.2) (rate is per 10,000 registered vehicles). This finding constituted a 31 percent lower fatal crash rate for ABS-equipped motorcycles (Teoh, 2013, 2021a). ABS use on motorcycles has increased from 0.2 percent in 2002 to 16.1 percent in 2021 (Teoh, 2021b).

The literature review identified industry manufacturers Honda, Bosch, Ducati Motor, BMW, Suzuki, Garmin, and Yamaha as leading the development of ARASs. OEMs have been advancing and implementing ARAS technologies to remove strain from motorcyclists and reduce the risk of injury. Research has suggested that ARASs could reduce crashes by upward of 40 percent (Füssl et al., 2012). There are also many different types of assistance ARASs can provide. For instance, researchers have denoted the difference in ARASs by whether they are active or passive. An active system will provide user support by using crash avoidance technologies, such as blind-spot detection, lane-keep assist, parking assist, and so forth, to hopefully prevent a crash from occurring. Passive systems, on the other hand, are meant to reduce the effects of a crash once it has occurred (i.e., airbags, seatbelts, whiplash protection, etc.) (Bayly et al., 2006). Passive systems, except for potentially as related to riders' apparel, are not relevant for motorcyclists. For this report, the project team denoted the difference in assistance an ARAS provides by the system's purpose and level of autonomy, like what was described by Kuschefski et al. (2011) and is explained below. The taxonomy provided included the following (some of the above ARASs are noted as examples):

- **Comfort Assisting Systems**—These systems reduce strain on motorcyclists in terms of ergonomics and environmental conditions. Posture comfort is provided through systems such as adjustable seats, handlebars, and levers. Other comfort systems meant to combat severe environmental conditions, light, or vibration include adaptive cornering lights, heated grips, or motorcycle fairing used to reduce air drag.
- **Informing Systems**—Information systems provide information to motorcyclists to help them prepare and optimize their decision-making. These systems provide information relating to the motorcyclist's location, upcoming traffic, or motorcycle information (e.g., fuel gauge, GPS, etc.).
- **Warning Systems**—Unlike informing systems, warning systems will only signal or warn the motorcyclist in specific, risky scenarios. These warnings may emerge if a motorcycle is experiencing issues or dangerous roadway conditions are up ahead. However, the information provided by both warning and informing systems may be ignored by the motorcyclist and do not necessarily invoke action (e.g., collision warning system, curve warning system).
- **Assisting Systems**—Assisting systems indicate that a riding error has occurred. Motorcyclists may receive this information visually, audibly, or haptically (e.g., lane-keep assist, etc.).
- **Partly/Fully Autonomous Systems**—Partly (e.g., adaptive cruise control) and/or fully (e.g., ABS) autonomous systems are systems that can maneuver the motorcycle's direction and speed. The system has the capability to intervene with the driving task, but partly autonomous systems still require the driver's attention to monitor the roadway and system.

Based on the leading causes of motorcycle crashes discussed previously, ARASs could potentially increase motorcyclist safety by providing improved reaction times to critical scenarios and increased roadway visibility. However, acceptance of these systems has been a major topic of contention identified throughout both the literature review and motorcyclist focus groups. If primary users do not accept this technology, it will not be utilized, and the safety benefits of ARASs may not be realized.

Research in this field has shown that acceptability depends on the type of assistance an ARAS provides. Füssl et al. (2012) found from a literature review, focus group interviews, and online surveys that acceptability will be higher for systems that are primarily used in emergency situations. Acceptability was highest for systems that displayed high reliability and did not interfere with the riding task, such as anti-lock braking systems, lane-keep assist, adaptive cruise control, and intelligent speed assistance (Montanari et al., 2011; Füssl et al., 2012; Beanland et al., 2013). Beanland et al. (2013) also found that acceptability will depend on how well known the system is, like ABS. Motorcyclists also expressed worry that these systems would increase the cost of motorcycles and make riding an impractical mode of transportation (Füssl et al., 2012; Beanland et al., 2013). However, even if the cost of these systems were reasonable, researchers indicated a worry on behalf of their focus group participants that if motorcyclists become too dependent on technology, they will not develop important skills to ride safely (Montanari et al., 2011; Füssl et al., 2012; Beanland et al., 2013). Instead, motorcyclists believed that research should focus on motorcycle safety training and educational outreach for both motorcyclists and passenger vehicle drivers to improve safety. However, it is important to note that user acceptance may be low in the beginning stages of newer technology and change over time. For example, the motorcycle community displayed low acceptance in the early adoption stages of ABS. Still, over time, motorcyclists have come to view ABS as a major consideration in purchasing a motorcycle. In a study conducted by Nordqvist and Gregersen (2011), 82 percent of riders reported that they would choose an ABS-equipped motorcycle.

CV Applications

Unlike with ARASs, not as many advancements relating to CV applications or automated features for motorcycles have been made in recent years. While it is known that research and development activities are taking place, these activities have been proprietary. Although four-wheeled vehicle applications have and will continue to progress, especially as safety deployments operate and continue to be planned across the United States, motorcycles can benefit to some extent from the application of advanced technology. Integrating connectivity, however, will enhance current ARASs. Some studies have estimated major positive impacts from incoming vehicle information and intersection safety connectivity applications (Silla et al., 2018).

ARASs currently rely on one source of information—the use of on-vehicle sensors and technology. Providing more information through connectivity can increase safety by increasing awareness time and optimizing the system and motorcyclist's decision-making abilities. Although one limitation of connectivity is the dependence on a good GPS signal, which can be degraded by various obstacles in the environment such as trees or roadway structures, connectivity can increase the ability to sense the environment even when the driver or motorcyclist's visual line of sight is obstructed (Anaya et al., 2017). Figure 1 illustrates an expanded vehicle environment in which information from infrastructure (V2I) and/or other vehicle signals (V2V) help the system and motorcyclists operate in a more robust roadway information environment. As described in the figure, informational inputs are received by the ARAS, which then informs either a particular system component of a motorcycle or a rider to perform an evasive action.

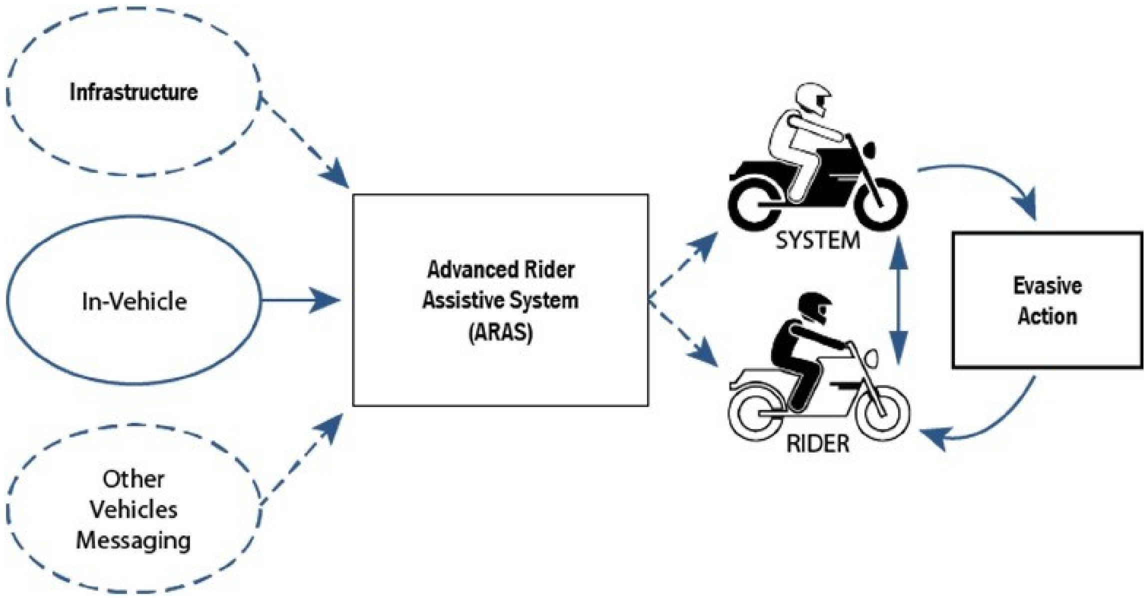

Figure 1. Relationship between CV applications and ARAS.

The literature review showed that while research in the CV applications and ARAS motorcycle field is limited, several emerging projects, stakeholders, and challenges are noteworthy. Key U.S. involvement includes:

- Motorcyclist Advisory Council to the Federal Highway Administration.
- NHTSA Motorcycle Safety Program.
- USDOT ITS Joint Program Office.

A USDOT-sponsored study on motorcycle safety and ITS applications identified the need for funding for motorcycle safety research in the United States and noted that most of the research related to ITS applications and motorcycles was being performed outside the United States (Flanigan et al., 2018). The following section discusses some of these efforts.

European Initiatives

In the literature review for this project, European activities involving ACEM and the Federated European Motorcycle Association were identified in support of advancing motorcycle connectivity. The Connected Motorcycle Consortium (CMC) is a group of manufacturers, suppliers, and researchers based in Germany working together to advance CV applications in motorcycles. The group has produced significant work in this field, such as various specifications and other guidelines to achieve motorcycle connectivity. CMC has also developed performance standards for connected application requirements for such systems. The standards and requirements related to system, activation, real-time, reliability, and compatibility requirements are documented in its *Basic Specification Evaluation Report*, version 1 (CMC, 2020). These documents and guidelines appear to be the first of their kind.

CMC developed multiple use cases for motorcycle connectivity (Table 2). Each use case describes when motorcyclists might be most vulnerable if they lack even the smallest piece of traffic information. Examples of these use cases are separated into categories of seeing or warning the motorcyclist and motorcyclist comfort.

Table 2. CMC use cases.

Aimed at Driver (Seeing)	Aimed at Motorcyclist (Warning)
Motorcycle Approach Indication	Emergency Electronic Brake Light
Motorcycle Approach Warning	Traffic Jam Warning
Intersection Movement Assist	Adverse Weather Warning
Left Turn Assist	Approaching Emergency Vehicle Warning
Forward Collision Warning	Slow or Stationary Vehicle Warning
Do Not Pass Warning	Broken Down Vehicle Warning
	Lane-Change/Blind-Spot Warning
	Road Works Warning
	Aimed at Motorcyclist (Comfort)
	In-Vehicle Signage
	Green Light Optimal Speed Advisory

CMC has also developed a set of performance standards that include (CMC, 2020, p. 85):

a) Percentage of successfully avoided collisions: this is the number of collisions that didn’t happen . . . for which a warning is given compared with the total number of collisions that occurred . . . when there was no intervention by the algorithm.
b) Percentage of too-late detected collisions: this is the ratio between the number of collisions occurred . . . for which a warning is given, and the total number of collisions occurred . . . when there is no intervention by the algorithm.
c) Percentage of not-detected collisions: this is the ratio between collisions occurred . . . for which no warning is given and the total number of collisions occurred . . . when there is no intervention by the algorithm.
d) Percentage of true positives: this is given by the ratio between the number of detected collisions (avoided or not) and the total number of collisions that occurred . . . when there is no intervention by the algorithm. The number of detected collisions is the sum of the successfully avoid collisions plus the too-late detected collisions (represented by a and b in this list).
e) Percentage of false positives: this is defined as the percentage of non-dangerous situations for which a warning is given.
f) Percentage of false negatives: this is equivalent to the percentage of not-detected collisions (c).
g) Percentage of true negatives: this is defined as the complementary of the percentage false positives.

Much of the current work relating to motorcycle connectivity has involved identifying the potential benefits CV applications can offer to improve motorcyclist safety. While the number of deployments and demonstrations has been limited, some significant efforts have been identified in Europe. Industry leaders like Honda, BMW, and Ducati have made announcements regarding V2M technology deployments. Using DSRC, in 2013, Honda demonstrated motorcycle connectivity in the development of its V2M system. Honda’s V2M system can alert a driver if a motorcycle is nearby (Japan Products, 2013).

In 2016, news emerged that BMW was making similar efforts. In BMW's Connected Ride System, motorcyclists, by using a smartphone connection, can receive crucial roadway information. Examples of this information include road weather warnings, obstacle detection, camera-based collision warnings, adaptive headlights, and intersection assistance, which alerts motorcyclists if the signal is about to change (BMW Press, 2016). At the 2019 Consumer Electronics Show, Ducati rolled out a Multistrada 1260 motorcycle that, along with Audi and Ford passenger vehicles, was equipped with cellular vehicle-to-everything (C-V2X) technology to demonstrate how C-V2X can be used to negotiate the right of way at a four-way, non-signalized intersection (McMahon, 2019). FCC is currently developing requirements for multiple communications technology, and there is an ongoing cooperation between governmental agencies to examine aspects of safety, latency, and performance.

Companies have also exhibited V2V and vehicle-to-pedestrian (V2P) safety scenarios, such as in the first American demonstration of the Connected Vehicle to Everything of Tomorrow (ConVeX) project. ConVeX is a collaboration between Ducati, Audi AG, Ericsson, and several other institutes and companies funded by the German Federal Ministry of Transport and Digital Infrastructure whose purpose is to develop a testbed for field tests of C-V2X applications to validate performance and feasibility (ConVeX Consortium, 2021). In the project, the V2V case featured the intersection movement assist scenario, which addressed angle collisions at intersections, while the V2P scenario exhibited how V2X can protect road users such as pedestrians and bicyclists. The use case scenarios included studying the interoperability between equipped vehicles and motorcycles. Moreover, in 2018, the ConVeX group demonstrated connectivity between motorcycles, vehicles, and infrastructure. They demonstrated scenarios such as intersection collision and across traffic turn collision risk warnings. Triumph and Bosch have also released cellular and Bluetooth accessible devices for motorcycle connectivity purposes.

ARAS and CV Challenges

A discussion guide by Sandt and Owens (2017) identified key areas related to pedestrians and bicyclists, and some of these areas could also be considered in relation to motorcycles. They include:

- **Detection:** As noted earlier, existing technology can be slower to identify motorcycles than cars.
- **V2X Basics/Connectivity:** Achieving connectivity will require special design considerations and research to obtain reliable signaling and communication. For example, motorcycles sit lower than vehicles, possess a small surface area, and can lean. They also have smaller frames upon which to mount any antennas. These factors, among others, will affect signaling and communication.

The project team also noted other gaps in knowledge and work after completing the literature review. These research areas did not emerge in literature, but the project team believes these topics warrant further investigation to continue the integration of connectivity in motorcycles and the advancement of other safety features. These areas include:

- **Warning Intervention Mode and Timing**—Motorcyclists need to maintain high situational awareness and attention while riding. The slightest change in motorcycle stability can easily cause a motorcyclist to fall since motorcycles are inherently unstable. Warnings must be carefully designed to not distract the motorcyclist's attention for too long. Alerts being too frequent may be too distractive and persuade motorcyclists to ignore system alerts altogether. Warning modes should also be carefully considered and minimize the time needed for the motorcyclist to interpret them.
- **Motorcycle Connectivity Advancement versus Passenger Vehicle Advancement**—Further analysis is needed to determine how to achieve maximized safety for motorcyclists. It is unclear whether achieving motorcycle connectivity will be as beneficial for motorcyclist safety as fully developed vehicle connectivity. Preliminary challenges with motorcycle connectivity, like warning intervention mode and timing, and motorcyclist acceptance may signal that ITS technology may not be suitable for motorcycles. Comparative research and performance modeling should determine which technological avenues will optimize safety for motorcyclists.

CHAPTER 3: STAKEHOLDER FEEDBACK

In addition to a literature review, the project team recognized that feedback from stakeholders such as motorcyclists, OEMs, and certain federal agencies was essential to performing robust research. Focus groups generate discussion beneficial to topics that require collective views and supplemental meaning to facts, especially in comparison to surveys or an independent literature review (Morgan, 1996).

Given motorcycle connectivity is a relatively new area of research, observing discussions among stakeholders provides context to the challenges slowing its progression and identifies research priorities. To gather this feedback, two focus groups were conducted with motorcyclists, and a listening session was held with personnel from FHWA and NHTSA. Agency staff from the federal agencies specialized in a variety of research fields, including connectivity and automation infrastructure research, motorcycle safety, human behavior, and human factors. A better understanding of the similarities and differences in each group's opinions, goals, and perspectives can identify crucial next steps in research and development.

MOTORCYCLIST FOCUS GROUP

Focus Group Methodology

A crucial step in addressing the motorcycle safety gap is to gather current knowledge and recommendations from actual motorcyclists and potential users of upcoming technology. Adoption and full implementation of motorcycle connectivity and other systems like ARASs will depend on acceptance by the motorcycle community. To address this crucial step, the project team hosted via Microsoft Teams two virtual focus groups with motorcyclists to further understand their opinions about what may influence their choice to utilize an ARAS and/or connectivity or not. The project team specifically recruited motorcyclists from the Texas Motorcycle Safety Coalition. The coalition represents a broad range of experience and includes instructors, educators, and enthusiasts. The project team screened each participant using a screener survey to get a mix of experience, age, race, and gender. The screener survey included questions about demographic information, riding experience, role in the motorcycle community (i.e., motorcycle instructor, motorcyclist, industry member, etc.), and familiarity with automated or connected vehicles. Participants were required to be at least 18 years of age and familiar with at least 30 percent of ARAS terms. The screener survey asked respondents to indicate their familiarity with ARAS terminology but did not define the terms for the potential participants. This step was done later in the context of the actual focus group to assess if there were discrepancies in the participants' real and perceived knowledge. Terms used in the screener included:

- Anti-lock Braking System.
- Stability Control.
- Combined Braking System.
- Active Cruise Control.
- Lane-Keep Assist.
- Collision Warning System.
- Curve Warning System.

- Traction Control.
- Autonomous Emergency Braking.
- eCall.
- Blind-Spot Assist.
- Adaptive Headlights.
- Cruise Control.
- Tire Pressure Control.
- GPS Navigation.

Participants were compensated for their time.

Eight to 12 participants were invited to each focus group. The discussion lasted approximately 90 minutes and was led by a Texas A&M Transportation Institute (TTI) moderator. Another researcher from TTI served as a notetaker, and the session was recorded but not transcribed. During the focus groups, the TTI moderator discussed several subjects designed to inform the research goals, including:

- General state of knowledge and opinions regarding upcoming technology.
- Motorcyclist trust and acceptability.
- Current motorcyclist strategies to avoid crashes.
- Safety needs of motorcyclists and what they desire to see in future motorcycle technology.

A group exercise was also implemented during the discussion to gauge the group's familiarity with connectivity, autonomy, and ARASs. First, participants were given a short, 2-minute quiz to quantify their familiarity with various ARASs. Participants were also asked verbally if they were familiar with either CVs or AVs. Once verbal and written responses were collected from the group, the TTI moderator presented a PowerPoint reviewing the definition of CVs, AVs, and various ARASs and an illustration describing the relationship between CVs and ARASs.

Focus Group Results

Participant Overview

Two focus groups consisting of seven and nine motorcyclists, respectively, were hosted in August 2021. Nearly 88 percent of participants identified as male, with a median age of 55 plus years. All participants in each group had many years of riding experience. In the first focus group, nearly 86 percent of participants had over 10 years' riding experience, while in the second focus group, 78 percent had over 10 years' riding experience. The remaining participants in both groups had a minimum of 6 years of riding experience.

Figure 2 details the frequency of the type of riding the participants in the focus groups did. A leisure motorcyclist was defined as someone who used their bike on the weekend and/or after work in their free time. Meanwhile, the regular motorcyclist had other options for transportation besides their motorcycle. These motorcyclists rode regularly but would opt out of riding if the weather were bad or if they did not want to ride that day. Finally, a motorcyclist who rode every day despite road conditions and used their bike as their primary mode of transportation was considered a primary motorcyclist.

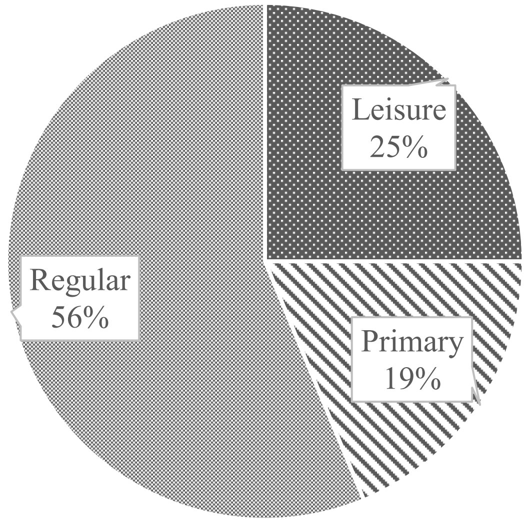

Figure 2. Participant current riding frequency.

Everyone who participated considered themselves a motorcyclist. Half of the total participants had worked as either a motorcycle instructor and/or educator. One participant had experience in manufacturing and sales, and another participant had experience in repair work. Each participant was familiar with a wide variety of ARASs, and 81 percent and 75 percent had previously heard of AVs and CVs, respectively.

Safe Riding Practices

Similar reports between both focus groups were made on how to ride safely. Multiple participants (including some of the motorcycle instructors) often referred to the motorcycle training they had received to obtain their license when discussing safe riding. For example, many discussed “all the gear, all the time” and using the search, evaluate, and execute (SEE) system while riding. One motorcycle instructor described the SEE system as a method for motorcyclists to assess current roadway conditions for risk, maintain high situational awareness, and better prioritize riding tasks. Even if motorcyclists were not familiar with this acronym, almost every participant stated or described the importance of riding defensively and to always have alternative options to avoid danger (an “out”). The participants in each group considered it crucial to have high situational awareness to be a good motorcyclist, but to be a great and safe motorcyclist, it is important to always have strong predictability skills.

Motorcyclists reported many common mistakes and general safety concerns for the community. Participants reported that often motorcyclists can become complacent, too comfortable, and even overly confident in some scenarios. To avoid this false sense of security, motorcyclists should always assume the worst. As one participant stated, motorcyclists should “ride as if they are invisible” and never ride beyond their comfort and/or skill level. In fact, some personal crashes discussed were due to overconfidence, and many did not improve their riding skills until they received official training. Participants commented that novice motorcyclists are most likely to have these issues due to lack of training and will take bigger risks, such as high-speed lane splitting. A major safety problem identified was unlicensed, untrained motorcyclists on shared roadways. According to one of the motorcycle instructors, nearly 30,000 motorcyclists ride unlicensed in Texas. Furthermore, educational outreach is difficult, and it is often hard to convince motorcyclists, especially those who are complacent, that they might need additional training. Other motorcyclists affirmed that it was difficult for them to take the steps to receive additional training for some official licensing, but they acknowledged that advanced courses can and had improved their skill set tremendously.

Thoughts on Connectivity and ARASs

A difference in tone and attitude regarding the utilization of motorcycle connectivity and advancing ARASs existed between the two focus groups. The first group was not as accepting of advanced motorcycle technology as the second group but saw the benefits of upcoming technology to improve motorcycle safety. In contrast, the second group had some concerns, but most of their feedback was generally positive. However, despite the difference in attitude, very similar motorcycle connectivity and ARAS concerns and benefits were still discussed among the two focus groups. As shown in Table 3, the focus groups identified several concerns and potential benefits related to ARASs.

Table 3. ARAS concerns and benefits.

Concerns	Potential Benefits
• Overreliance on Technology. • Warning Display Distraction. • Motorcyclist Interaction with Autonomous Features. • User Acceptance.	• System Reaction Times. • Improvement of Novice Motorcyclist Confidence. • Preventive Measure.

As many of the focus group participants related, part of being a great motorcyclist is maintaining high situational awareness and predicting future events. Integrating technology that inherently enhances situational awareness may prevent motorcyclists from naturally developing fundamental situational awareness skills and cause deskilling. A few participants mentioned that a motorcyclist being too unfamiliar with riding an unequipped motorcycle might put them at a higher risk of injury. Participants feared that if motorcyclists became too reliant on assistive technology, they would not be prepared for situations when assistive technology was unavailable or malfunctioned. Similar findings were found in previous studies using motorcycle rider focus groups (Montanari et al., 2011; Füssl et al., 2012; Beanland et al., 2013). Additionally, group members expressed concern that technological advancements would increase the cost of the motorcycle and make it an unreasonable mode of transportation. Focus groups conducted by Füssl et al. (2012) and Beanland et al. (2013) also received the same feedback from their participants regarding cost increases.

Others focus group members were worried that even if motorcycles were able to receive warnings, these warnings would be distracting, especially at high speeds. Unlike vehicles, motorcycles are less forgiving. Because motorcycles only have two wheels and are not as stable, motorcyclists are more sensitive to any system or environmental change and have a slim margin of error. Because of the lack of stability—and as a result, increased sensitivity—motorcyclists face higher risks and even more significant consequences for smaller errors in comparison to a passenger vehicle. These same concerns led both groups to be against active systems and bikes with autonomous features. Multiple participants expressed concern that if a system were to noticeably take over the stability, direction, and/or speed of the motorcycle, the motorcyclist might have an adverse physical reaction, putting them at risk for dropping their bike. Motorcyclists believe that if the community is to accept these systems, the system must not produce any jerky movements.

Participants worried that any hard system actions might cause motorcyclists to believe they are losing stability and negatively react, thereby increasing their chance of falling. The first focus group, however, mentioned that these features should still be integrated with passenger vehicles and can help improve motorcycle safety as a result. Implementing these advanced features will help motorcycles become more visible to drivers. Focus group participants described four-wheeled vehicle drivers as always being distracted. One focus group member even described four-wheeled vehicle drivers as typically inattentive due to texting, eating, or other tasks that do not involve driving. Another participant also observed that four-wheeled drivers typically do not expect motorcyclists on the road. Active systems in four-wheeled vehicles would benefit drivers, especially at times when they lack vigilance, and since a passenger vehicle has higher traction, drivers will not have to fear losing stability if the system takes over automatically.

Although many had concerns for motorcycle connectivity and ARASs, participants on average agreed that these systems can improve safety if their concerns were addressed. The first group believed that some systems may be more effective than others, while the second group was more accepting of all systems on the stipulation of system flexibility. In other words, it would primarily depend on the context and the specific motorcyclist's goals. One example given was ABS may provide the motorcyclist improved safety on highways, but if the motorcyclist were off-road, ABS would not be helpful. Participants agreed that having the option to turn these features off and on at their convenience might help increase user acceptance if similar scenarios emerge. Additionally, it would help give novice motorcyclists more confidence and experience since they would have the ability to gradually learn how to ride a bike without safety features at their own pace.

Some motorcyclists indicated that some ARASs would provide them more confidence while riding. They were still adamant that motorcyclists should always be extremely aware and familiar with their equipment but recognized sometimes situations emerge that are unavoidable even when the motorcyclist has done everything correctly. These situations include braking for unforeseen objects in the roadway or roadway surfaces that are more slippery than anticipated. The second group even discussed that these systems might be able to respond faster than the actual motorcyclist to a high-risk scenario, especially if something unexpected emerges.

The first focus group also discussed concerns for how motorcycles would convey ARAS and C-ITS alerts to motorcyclists. They recognized ARAS and ITS applications could be useful in unexpected scenarios but feared the system warning mode might be too distracting and increase the motorcyclist's risk of injury. Due to the small surface area of a motorcycle, one participant mentioned they could only receive warnings on their bike's small display or in a heads-up display within their helmet. They said that taking a motorcyclist's attention off the roadway, even if only briefly, and especially at high speeds, may put the motorcyclist in danger. They also expressed concern that the time needed to interpret the alert on the display may be distracting to the motorcyclist and infringe on safety. The same participant mentioned that passenger vehicles might be more forgiving to drivers who briefly take their eyes off the road. However, for motorcyclists, doing so could prove fatal.

Other Recommendations from the Focus Groups

At the conclusion of the focus group session, motorcyclists were asked if they had other safety concerns that did not emerge in the earlier discussion. The list below presents issues mentioned by participants that could benefit from motorcycle connectivity.

- **Roadway Maintenance in Construction Zones**—Both focus groups discussed roadway maintenance in construction zones as a significant safety problem for motorcyclists. They explained that motorcyclists often struggle to identify loose gravel in the road unless a warning sign is available. Participants also explained they fear approaching loose gravel, knowingly or unknowingly, because it can increase their crash risk since loose gravel may cause their motorcycle to lose traction with the road's surface. Participants urged that construction workers be more diligent about cleaning the roadways to avoid these problems altogether. Other roadway conditions resulting from construction were also noted, such as uneven lanes. If the motorcyclist must change lanes, the unevenness may cause difficulty if the difference between the lanes is substantial.
- **Barrier Design**—A few participants mentioned their fear of specific barrier designs found on roadways. They believed current guardrails are not designed for motorcyclists, especially if they were to crash. One participant even mentioned a fear of decapitation if they were to hit a cable barrier. The group recommended safer barrier designs be explored to prevent further injury or damage if a motorcyclist were to crash.
- **Lane Splitting and Filtering**—The second focus group discussed the legalization of lane filtering and lane splitting to avoid motorcycle crashes. Lane splitting refers to a motorcyclist traveling between lanes of traffic, while lane filtering is a similar situation occurring only at a stopped, signalized intersection, which then allows the motorcyclist to bypass the queue of vehicles. If motorcyclists are filtering, they will ride between vehicles to the front of the intersection to avoid a rear-end collision. Several participants agreed that lane splitting should be made legal. However, one participant agreed more with the legalization of lane filtering rather than lane splitting because they felt lane splitting would be abused too often. The participant acknowledged that other motorcyclists might also abuse lane filtering, which is why the member speculated it had not been made legal in many states. Participants did agree that if both are used appropriately, safety will increase.
- **Unlicensed Riders and Training**—A major topic initiated by participants in the first focus group was the number of unlicensed motorcyclists in Texas and the lack of training. According to one participant, also a former motorcycle instructor, there are nearly 30,000 unlicensed riders in Texas. The high number of unlicensed riders, as the group discussed, may be due to the ease of purchasing a motorcycle when a license is not required. Furthermore, the same participant mentioned that one could often spot motorcycle riders who have not received proper training. Other participants reported that

those who received a three-wheel training course somehow obtained a full M class license rather than a restricted license and believe incorrect licensing is a major problem.

Many of the concerns mentioned from the focus group sessions are consistent with MAC recommendations. Reports have been produced discussing and addressing these issues and their impact on motorcyclists, including roadside safety hardware and barriers (Silvestri-Dobrovolny et al., 2021), roadway geometrics, maintenance practices, and pavement design (Geary et al., 2021). Further information is available for review on FHWA's motorcycle safety website (https://safety.fhwa.dot.gov/motorcycles/). While these issues may not seem related to motorcycle connectivity, they can all be impacted by the adoption of C-ITS technologies for motorcycles, which can increase motorcyclists' awareness of their surroundings. Motorcyclists can receive advance warnings of construction obstacles and barrier areas; technology can alert motorcyclists and drivers in the event of lane splitting or filtering; and the effective and proper use of technology can be addressed in all required training.

LISTENING SESSION WITH FHWA AND NHTSA STAFF

To better understand the direction and development of federal policy and research related to motorcycle connectivity, a listening session was convened with federal agency staff. The listening session included representatives from FHWA and NHTSA who are currently working on initiatives designed to advance C-ITS and ARAS safety applications for motorcycles. The listening session sought to gain insight into specific activities at the federal level and gather information from state departments of transportation about policy goals and directions and identified research areas. The listening session supported the research objectives by allowing the project team to learn firsthand about the initiatives undertaken in this research area and how they may support policy goals as well as the potential gaps when considered in context with the findings from the motorcyclist focus groups.

Listening Session Methodology

Working with FHWA staff, the project team compiled a list of people working in applicable research fields of motorcycle connectivity and safety to participate in the listening session. Applicable research fields included research into connectivity and automation infrastructure, motorcycle safety, human behavior, and human factors. The session, which lasted approximately 90 minutes, began with the moderator providing background information about the project and the purpose of the research. The intent of the session was to learn what initiatives each department of each agency was undertaking regarding C-ITS for motorcycle safety. Further, the project team was interested in what the participants identified as the challenges in addressing motorcycle safety and the current research gaps. The project team identified broad questions to ask the group, but the group was encouraged to talk among themselves and let the discussion related to research needs and policy questions develop organically.

Listening Session Findings

Listening Session Summary

The listening session with federal agencies validated the earlier literature review findings of a major gap in research regarding motorcycle connectivity and other advanced applications to improve motorcycle safety. Participants acknowledged that there are not currently any research efforts, to their knowledge, aimed at investigating and assessing the technology necessary to achieve motorcycle connectivity and/or automation. Instead, this research arena has focused only on four-wheeled vehicles thus far. Participants speculated that delays in advancing research and policy initiatives may be due to ongoing debates and discussions over which wireless communication, DSRC versus LTE-CV2X, will be utilized to achieve connectivity. Motorcycle manufacturers may be hesitant to invest in this technology until these decisions are made. As one participant phrased the problem, the connectivity among passenger vehicles must be addressed and established first, and then motorcycles will be an add-on feature.

Although motorcycles have not been the primary focus in discussions or research of connectivity and/or autonomy, many participants stated that there have instead been research initiatives focusing on motorcycle interactions with equipped, automated, or connected passenger vehicles. One participant mentioned that NTSB has even recommended that equipped vehicles should not only be capable of detecting other vehicles but also able to specify vehicle or user type (motorcycle, pedestrian, bicyclists, etc.). Furthermore, according to NTSB, this level of accuracy in detection systems should be incorporated as part of the performance standards of future connected passenger vehicles. Federal agency stakeholders in the listening session also expressed the general concern the infrastructure needed for passenger vehicle connectivity and roadway adaptions will potentially increase motorcyclists' risk of a crash or injury.

The group of participants agreed that motorcycles would benefit from connectivity. A few examples were given during the discussion, such as that motorcyclists are not always the best at anticipating a curve correctly and will make a mistake in their lean angle or speed. Additionally, motorcyclists lack saliency, or noticeability. Drivers often do not anticipate motorcyclists, and the size of motorcycles makes them harder to see. Furthermore, some listening session participants expressed the opinion that motorcyclists wearing dark clothing may increase the likelihood of not being seen by another vehicle. By integrating motorcycle connectivity, these issues may be avoided altogether and improve safety, but there are other technical issues to consider first.

Identified Research Gaps and Challenges

Difficult design decisions will have to be made to achieve motorcycle connectivity, like antenna or sensor placement. Helmet laws vary among states and not all motorcyclists wear helmets, so it has been recommended to place the antenna on the bike. However, even if the antenna is placed on the motorcycle, the motorcyclist or passenger might cause interference. Designers and manufacturers will have to consider these types of problems in future prototypes, as well as the number of sensors needed and placement since motorcycles sit lower than passenger vehicles. Participants suggested that Honda, as a major industry leader, may serve at the forefront of motorcycle connectivity. The group was unaware of any connected or automated vehicle deployments focused on motorcycle safety or interactions.

Future Research Areas

At the end of this discussion, the TTI moderator asked all participants to share their first research priority on motorcycle connectivity. The list below is presented in descending order, from the most often mentioned research topic to the least.

- **Equipped Vehicle and Driver Detection of Motorcycles and Accuracy**—Many participants agreed that understanding the ability of current machine vision systems and passenger vehicle drivers to detect motorcycles accurately is of utmost importance. Understanding the perception limits of the sensors or connectivity provides researchers with a better grasp of how ADASs may assist drivers with motorcycle-related interactions and how an ADS that replaces a human driver may perceive motorcycles and navigate safely. Assessing current machine vision systems will guide design and further performance standards for any connected and/or automated system and other features like ADASs and ADSs to improve interactions between vulnerable road users, not just motorcyclists.
- **User Acceptance**—A major concern expressed during the listening session was whether motorcyclists may oppose connectivity altogether. Some participants suggested, based on past project experience, that motorcycle connectivity may go against motorcyclists' ultimate goals as owners of motorcycles. Motorcyclist concerns such as cost, design aesthetics, and increased visibility may deter them from utilizing these features. Research in this field must establish if there will be market acceptance.
- **Warning Displays**—More research needs to be conducted on how motorcyclists receive warnings or signals. These messages can indicate pavement conditions, upcoming construction zones, traffic, traffic light status, nearby vehicles, and so forth. However, it is important to assess how to provide motorcyclists with the most accurate information to increase their safety without taking their attention away from the roadway. Developing a better understanding of this issue will be a major step in achieving motorcycle connectivity.
- **Performance Standards**—There is a gap in research as to how automated and connected vehicles operate in a heterogenous mix of vehicles. Performance standards for advanced vehicles should focus on the interaction between the various types of vehicles, including motorcycles, and include the necessary design and technical requirements that ensure all road users' safety, especially in detection accuracy.
- **Motorcyclist Trust**—Motorcyclists will not use assistive technology, even if it decreases the risk of crash or injury, if they do not trust the system. Trust is essential, especially during times the motorcyclist needs extra assistance. These situations may include the system providing motorcyclists with crucial safety information they cannot obtain on their own or taking over specific riding tasks if a motorcyclist is experiencing a dangerously high workload. On the other hand, motorcyclists may be too trusting and become overdependent on systems to perform specific tasks. Studying motorcyclist trust will give insight into how to calibrate system capability to better guide design. If this relationship is miscalibrated, motorcyclists may not responsibly use the assistive technology.

CHAPTER 4: CONCLUSIONS

This report identified the challenges and opportunities for CV and ARAS technologies within the motorcycle community. A major objective of implementing additional technology on motorcycles is to improve their safety. Motorcyclists can suffer greatly increased consequences from issues of stability, pavement conditions, and other challenges to the riding environment. Some of the ARAS technologies, like ABS, have already demonstrated safety benefits. Although not universally desired by riders, technology has the capability to reduce these consequences and provide for a safer riding experience. As recognized in the literature (Flanigan et al., 2018), technology can be used to both improve safety and enhance the rider's experience. By focusing on both aspects, the motorcycle community may be more prone to acceptance of the new technologies.

THE MOTORCYCLE SAFETY BUBBLE

A concept that illustrates the layers of safety within the motorcyclist environment is shown in Figure 3. At the core of the safety environment is the motorcyclist wearing personal protective equipment, a foundational requirement taught in all motorcycle classes. Next, the ARAS features discussed previously can add an additional layer of safety. ARAS features are essentially self-contained within the vehicle and do not rely on external inputs from other vehicles or infrastructure. OEMs are continuing to offer advances in this area even though not all motorcyclists view them as a positive.

The next level of safety can be provided by establishing a connected environment in which the motorcycle can communicate with other vehicles. Information could be sent and received as part of the next generation of vehicle connectivity that is envisioned for the future. The final layer of the safety environment can be thought of as the vehicle-to-infrastructure link, in which roadway devices communicate information to the driver and the vehicle systems. Overall, the V2V components are in their infancy stage within the motorcycle arena and are only slightly more developed in passenger vehicles.

Evaluation of the effectiveness of each defense separately and in combination should be studied further. Literature review results indicate that the integration between combinations of these defenses and their impact on overall motorcyclist safety have not yet been studied.

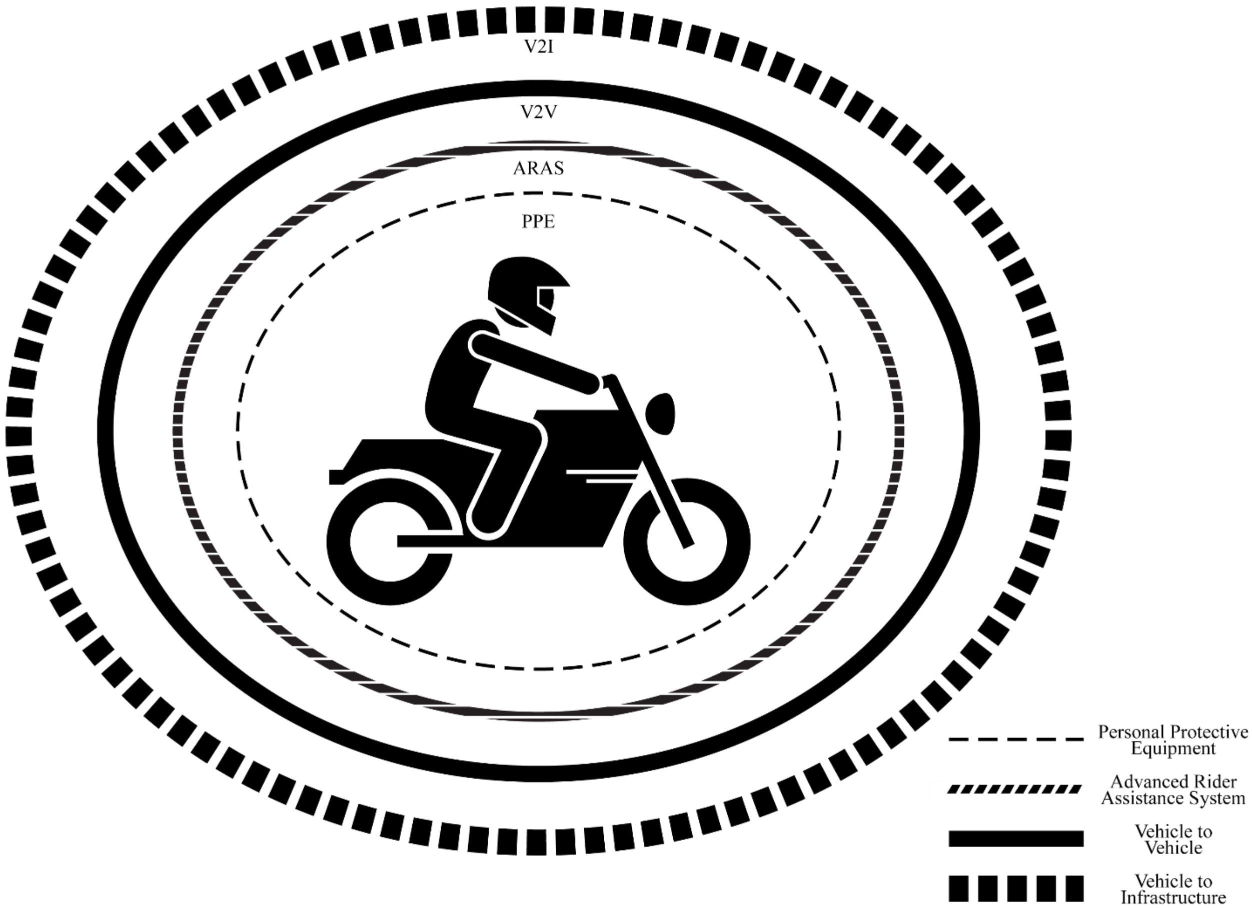

Figure 3. Motorcycle safety bubble.

ITS TECHNOLOGY APPLICATIONS FROM PRIOR RESEARCH

Research findings from previous tasks in this project were reviewed to determine where CV applications can be utilized to enhance motorcyclists' safety. The information to make this assessment developed from the project team's literature review, focus groups, and listening sessions. Following is a summary of the issues that can potentially be addressed through CV applications:

- **Motorcycle VMT Uncertainty and Data**—Accurate data are essential to advance research to enhance motorcycle safety performance. However, estimating motorcycle VMT is currently challenging since there is not a uniform estimation method among states (Transportation Research Board, 2007). Furthermore, research is needed to determine which methods are more or less accurate compared to others. CV technologies could potentially address this need if a reporting of the vehicle type were associated with the connectivity information exchanged with the infrastructure. This measure would require assumptions related to market penetration since not all motorcycles will be equipped with these technologies at the onset. However, by addressing this gap and collecting more accurate motorcycle VMT, designers and researchers could better prioritize the development of CV applications by the level of applicability to increase motorcycle safety.

- **Sight Distance**—ITS applications and ARASs can be designed to help increase the saliency of motorcyclists and improve their visibility of the roadway and roadway elements. Motorcyclists' field of view can be narrower compared to an automobile driver. For example, CV applications may enhance motorcyclists' visibility of obstacles in the roadway.
- **Pavement Conditions**—According to FHWA (2020), nearly 29 percent of roadways (1.2 million miles) are unpaved. Given that motorcycles are less stable and do not possess as much traction as passenger vehicles, unpaved roadways may be a safety concern. Other pavement conditions—such as slick surfaces, level of deterioration, and irregular surfaces—also pose risks to motorcyclists and can exacerbate instability. Unfortunately, these changes in roadway conditions may not be recognized by motorcyclists in time to take evasive action. CV applications may provide warnings to the motorcyclist in time to avoid these unsafe conditions while riding, but further research is needed in this field.
- **Construction Zones and Maintenance**—Like pavement conditions, construction zones can be very unsafe and increase the risk for motorcyclists, and warnings beforehand might prevent injury and damage. Often, pavement irregularities in terms of road texture, unevenness, and loose gravel exist on the roadway in construction areas. Focus groups with motorcyclists also revealed these situations were a significant concern since, without signage, motorcyclists were unable to tell if there was loose gravel in the road.
- **Lane Splitting and Filtering**—Lane splitting allows a motorcyclist to move between lanes of slow moving traffic while lane filtering allows a motorcyclist to move between lanes of stopped traffic to get to the front of the traffic queue. Both lane splitting and filtering serve as a preventive safety measure to help the motorcyclist avoid a rear-end collision whenever traffic is stopped or slowed down. Currently, laws vary widely between states. For some, both splitting and filtering are illegal, while in other states, both are legal. A significant concern for either action is that motorcyclists will abuse the ability to lane split or filter, and in turn, increase their and other drivers' crash risk. However, studies have shown that motorcyclists are, in fact, seven times more likely to be hit while stopped than when lane splitting (Kurlantzick & Krosner, 2016). ITS applications may mitigate the likelihood of a crash caused by lane splitting or filtering by notifying nearby drivers that a motorcycle is approaching. Warnings can also serve to notify motorcyclists of vehicles attempting to change lanes to avoid a collision as well.
- **Level and Type of Pavement Deterioration (i.e., Deterioration Thresholds) That Is Detrimental to Motorcycle Safety**—Communicating information about pavement condition is thought to be useful only if it occurs before being encountered. This capability requires a detailed and oft-repeated inventory of pavement conditions at a highly sophisticated level of mapping. Additionally, conditions such as construction that can impact pavement markings as well as pavement surfaces have to be reported in conjunction with the pavement condition, all of which would be reported via V2I communications. The level of information and infrastructure required to affect this alert to motorcyclists across a national road network would be tremendously expensive.
- **Effect of Surface Condition as a Contributing Factor in Motorcycle Safety**—Similar to the previous item, notifying motorcyclists of surface conditions other than pavement condition might be useful but is currently challenging to achieve on a large scale. Surface

conditions include pavement conditions, weather (snow, rain, ice), and even other surface conditions, such as debris, rocks, or slick surfaces from spilled materials such as oil. No current sensors that detect the full array of these conditions in real time currently exist. Additionally, the density of infrastructure required to detect such conditions on an uninterrupted roadway basis would be considerable and costly.

SUMMARY OF ITS TECHNOLOGIES

Table 4 summarizes the safety areas identified through the course of this research that may be solved or partially mitigated through ITS technologies and applications. This cross-tabulation is useful because it illustrates that the two most identified areas of concern are motorcyclist acceptance and the methods for alerting motorcyclists. Both concerns were identified in nearly all of the sectors of research. These findings thus indicate where the top needs for further research and development are within the ARAS and CV research areas for motorcycles.

Table 4. Summary of identified areas to include in motorcycle CV research and development.

Area of Concern	Area of Mention			
	Prior Tasks	Literature Review	Focus Groups	Listening Session
Motorcyclist Acceptance	X	X	X	X
Warning Intervention Displays, Modes, and Timing		X	X	X
Performance Evaluation of ARASs and CVs		X		X
Design		X		X
Motorcycle Connectivity Advancement vs. Passenger Vehicle Advancement		X	X	
Vehicle Stability			X	
System Reaction Times			X	
Warning Display Distraction		X	X	
Improvement of Novice Motorcyclist Confidence			X	
Motorcyclist Interaction with Autonomous Features			X	X
Equipped Vehicle and Driver Detection of Motorcycles			X	X
Performance Standards		X		X
Motorcycle VMT	X	X		
Sight Distance	X			X
Pavement Conditions	X		X	
Constructions Zones and Maintenance	X		X	
Lane Splitting and Filtering	X		X	
Pavement and Roadway Surface Conditions	X		X	

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