Collaborative Sciences Center for ROAD SAFETY

FINAL REPORT

A Safe Systems approach to motorcycle safety

May 31, 2023

Eric Dumbaugh
Henrick J. Haule
Jonathan Stiles
Florida Atlantic University

Asad Khattak
University of Tennessee, Knoxville

U.S. DOT Disclaimer

Acknowledgment of Sponsorship

This project was supported by the Collaborative Sciences Center for Road Safety, www.roadsafety.unc.edu, a U.S. Department of Transportation National University Transportation Center promoting safety.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CSCRS-R40		

4. Title and Subtitle: A Safe Systems approach to motorcycle safety	**5. Report Date** May 31, 2023
	6. Performing Organization Code
7. Author(s) Eric Dumbaugh, Ph.D. ORCID: 0000-0002-5254-9711 Henrick Haule, Ph.D. ORCID: 0000-0003-0455-4134 Jonathan Stiles, Ph.D. ORCID: 0000-0001-7613-1814 Asad Khattak, Ph.D. ORCID: 0000-0002-0790-7794	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Florida Atlantic University 777 Glades Road Boca Raton, FL, 33431	**10. Work Unit No.**
	11. Contract or Grant No. Collaborative Sciences Center for Road Safety (Grant: 69A3551747113)
12. Sponsoring Agency Name and Address University Transportation Centers Program Office of the Assistant Secretary for Research and Technology U.S. Department of Transportation 1200 New Jersey Avenue, SE, Washington, DC 20590-0001	**13. Type of Report and Period Covered** Final report (May 2021 – September 2022)
	14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This study examines motorcycle safety from a Safe Systems perspective. The report is divided into two sections. The first section is a synthetic review of the literature that seeks to understand motorcycle safety from within the four dimensions that comprise a Safe System. The second section examines motorcycle crash data to uncover patterns in those involved in the crashes, locations, and times of the crashes.

17. Key Words	18. Distribution Statement
Motorcycle, Safe Systems	No restrictions. This document is available through the Collaborative Sciences Center for Road Safety (roadsafety.unc.edu), Chapel Hill,NC

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	64	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Introduction

In 2017, motorcyclists in the United States were about 27 times more likely to be killed per vehicle-mile-traveled compared to passenger car occupants (NHTSA, 2019). Over the past few decades, there has been a multitude of research articles published regarding motorcycle safety, and globally, motorcycles are the fastest growing mode of transportation (de Rome et al., 2011). This trend is even more prominent in low- and middle-income countries, where powered two-wheelers (PTWs) are a standard transportation option for motor vehicles.

Like other vulnerable road users (i.e., pedestrians and bicyclists), the safety of PTWs could be improved by the Safe System approach. The Safe System approach is a comprehensive approach to road safety. It works through multiple layers of protection to prevent crashes, and fatalities or serious injuries in crashes that do occur (ITF, 2016; U.S.DOT, 2022). The approach's four main principles are:

1. People make mistakes that lead to road crashes.
2. The human body has a known and limited ability to tolerate crash forces.
3. System designers share responsibility with road users for crash prevention.
4. All elements of the system should be strengthened to multiply their effects.

A Safe System approach posits that life and health should not be compromised to meet mobility demands. The Safe System approach to motorcycle safety works to reduce the injury risk to an acceptable level by improving the four cornerstones of the system: roadways, speeds, vehicles, and people (Bambach & Mitchell, 2015). The core principle of the Safe System is acknowledging that road users are prone to mistakes and inappropriate decisions, but the system should minimize errors or accommodate the errors such that road users are not exposed to crash forces that will lead to death or serious injuries (OECD/ITF, 2015).

One of the distinguishing characteristics of the Safe System approach is its focus on ensuring the safety of a roadway's most vulnerable users. In mixed traffic environments, this often results in an express concern for the safety of pedestrians and cyclists. However, there is limited information available regarding motorcyclists, even though they are also a vulnerable population. Motorcycle safety is particularly challenging, since motorcyclists have vulnerabilities that are similar to pedestrians and bicyclists, but travel at the speeds of motorists. As a result, attempts to address motorcycle safety may require solutions that differ from those aimed at enhancing the safety of pedestrians and bicyclists.

This study seeks to understand the application of Safe Systems principles to motorcycle safety. It does so using a two-tiered approach. The first is a comprehensive review of the literature focused on four areas of the Safe Systems approach: Safe Users, Safe Vehicles, Safe Speeds, and Safe Roads. It then proceeds to examine the nature of motorcycle crashes in southeast Florida, including the characteristics of individuals involved in motorcycle crashes, the nature of the crashes in which they are involved, as well as the characteristics of the environments in which these crashes are most likely to occur. It concludes with a comprehensive discussion of the application of Safe Systems principles to motorcycle safety.

Part I: Synthetic Literature Review

To better understand how a Safe System framework may relate to motorcycle safety, this report reviews the motorcycle safety literature in the four domains of the Safe Systems approach: Safe Users, Safe Vehicles, Safe Speeds, and Safe Roads. A systematic search of the key terms was performed on the following databases: Google Scholar, Transport Research International Documentation (TRID) Online, and SCOPUS. Articles and reports that were published before 2022 were considered in the study. Six sets of search keywords were used to find literature related to Safe Users, Safe Vehicles, Safe Speeds, Safe Roads, and the Safe System approach. The search keywords relating to motorcycle Safe Users were "motorcyclists", "attitudes", "violations", "behavior", "experience", and variations of these keywords. This resulted in 51 documents (articles and reports) being identified for closer inspection. The search keywords relating to Safe Vehicles included "motorcycle", "type", "engine", "technology", "brakes", "headlight", "helmet", and their variations. This resulted in 68 articles identified for a closer inspection. The search keywords relating to Safe Speeds were "motorcycle", "speed", and "speed limit". About 18 documents were identified for closer inspection. The search keywords relating to Safe Roads were "motorcycle", "crashes", "injuries", "road", and "built environment". It resulted in 50 documents identified for closer inspection relating to Safe Roads. The search keywords relating to the Safe System approach were "motorcycle", "crashes", and "safe system", which led to collection of 9 documents. In total, 156 articles and reports were the center of our analysis.

Safe Users

The characteristics of road users, and their corresponding behaviors, can have a substantial effect on the incidence of traffic-related death and injury. For the purposes of this review, these are centered on four organizing concepts: attitudes and behaviors, helmet use, age and experience, alcohol and drug use, and pillion passengers. Each is detailed in the sections below.

Behaviors and Attitudes

Behaviors found to contribute to motorcycle crash risk include: speeding, riding while unlicensed, riding motorcycles that are too powerful for the rider's abilities or environmental conditions, running red lights, riding on the wrong side of the road, using a mobile phone while riding, riding on sidewalks, overtaking recklessly, riding too fast for conditions, riding while intoxicated, riding without helmets or protective clothing, riding poorly maintained motorcycles, riding with too little headway, and riding modified motorcycles (Haque & Chin, 2010; Lee et al., 2018; Lin & Kraus, 2009; Simpson et al., 2015; Truong et al., 2018). Other risky behaviors include failing to use a turn signal, stopping beyond the stop line, carrying more than two passengers, traveling without a headlight at night, riding in the wrong direction, riding in improper lanes, and overloading (Joewono & Susilo, 2017; Nguyen-Phuoc et al., 2020; Oluwadiya et al., 2009; Wang et al., 2012). Traffic violations increase the likelihood of fatal or severe injury crashes (Kitali et al., 2020).

Speeding violations have a significant role in the occurrence and outcome of motorcycle crashes. Unsafe speeds, measured by the number of motorcyclists cited for unsafe speed, were among the factors leading to severe injuries in single- and multi-vehicle motorcycle crashes (Savolainen & Mannering, 2007). Most motorcyclists lack consideration for speed when crossing intersections, and they run red lights, which then leads them to crash into pedestrians and bicyclists (de Vasconcellos, 2013). Lee et al. (2018) noted that high-speed operations lead to stop sign and traffic signal violations.

Other factors influencing motorcycle and moped traffic violations include roadway attributes, traffic conditions, and weather (Joewono et al., 2015; Joewono & Susilo, 2017; Wang et al., 2012), with higher outdoor temperatures leading to an increased incidence of traffic violations—this behavior is attributed to motorcyclists' desire to reach destinations faster in warmer conditions (Joewono et al., 2015).

Motorcyclists' attitudes can have a profound effect on their operating behaviors (Joewono & Susilo, 2017). These attitudes may emerge from the perceived advantages of operating a motorcycle, including ability to travel at higher speeds, ability to bypass congestion, ease of parking, and sense of freedom and independence (Hagen et al., 2016; Njå & Nesvåg, 2007). It was also revealed that there is a positive correlation between past and forecasted risk-taking behaviors (Dhami & García-Retamero, 2012).

Attitudes about motorcycling appear to vary notably by age. Younger riders have been found to be at increased risk due to a greater propensity for behaviors such as using mobile phones while riding, reckless overtaking, and riding on sidewalks (de Gruyter et al., 2017; Truong et al., 2020). Riders under age 30 are far more likely to ride sport or supersport motorcycles than older adults, with 61% of motorcyclists under age 30 reporting use of such motorcycles, compared to only 6% motorcyclists over age 50 (Lee et al., 2018). Correspondingly, younger riders have also been found to be more likely to exceed speed limits than older motorcyclists, with reasons for excessive speeds including avoiding lateness, sensation seeking, enjoying going faster, and reducing travel time (Dhami & García-Retamero, 2012).

While older motorcyclists may be less likely to speed than younger motorcyclists, they nonetheless adopt riskier behaviors with regard to helmet use, with 96% of motorcyclists under the age of 30 reporting helmet use as either very important or fairly important, compared to 70% of motorcyclists aged 50 and older (Lee et al., 2018). Such behaviors regarding risk may be influenced by participation in specific social groups related to motorcycles. Motorcyclists 50 and older are more than twice as likely to belong to a motorcycle riding group than riders in any other age range (Lee et al., 2018).

Helmet Use

The benefits of wearing helmets in reducing the severity of crashes have been well documented in the existing literature. Despite the benefits, most motorcyclists and pillion passengers in developing countries do not wear or fasten helmets (Li et al., 2008; Nnadi et al., 2015; Wu and Loo, 2016). Zimmerman et al. (2015) observed that even after providing the motorcyclists with free protective gear, the percentage of motorcyclists wearing a helmet at the time of injurious crashes did not significantly change. It was not made clear if the lower percentage was due to riders not wearing helmets or helmets being ineffective. Also, it is worth noting that the study did not specify the type of injuries, which could clearly show the benefits for injuries influenced by helmet use, such as head and neck injuries.

Helmet use is lower among young males than other cohorts, and rates of usage are lower during evenings and weekends, as well as trips occurring on secondary streets (Li et al., 2008). Young respondents indicated comfort as the main reason for not wearing a helmet (Dhami & García-Retamero, 2012). Germeni et al. (2009) noted that perceived barriers to helmet use among young motorcyclists include low perceived efficacy of helmets, peer pressure, lack of appropriate information on helmet use, high helmet cost, vision or hearing disturbance while driving, and beauty or style. Motorcyclists were less likely to wear a helmet because they either felt it looked unfashionable, were in a hurry, were dressed up to go out, or were traveling short distances and at night (Brijs et al., 2014). While the use of helmets was lower among child pillion passengers, an increase in the use of helmets among drivers increased the likelihood of the child pillion passengers wearing helmets (Tosi et al., 2021).

It is clear from the literature that safety is not a motivation for most motorcyclists to wear helmets. For example, in a study conducted by Li et al. (2008), only one-fifth of participants wore a helmet for preventative purposes, and three-quarters wore a helmet to cope with police. Similarly, adolescents not complying with helmet legislation perceived avoiding a legal penalty as a more important benefit of helmet use than safety (Germeni et al., 2009).

Age and Experience

Motorcyclists' age and riding experience play a critical role in motorcycle safety. Age affects the motorcyclist's perception and ability to assess risk, thus influencing riding behaviors (Islam, 2021). Studies showed that younger motorcyclists (up to age 30) are more likely than mature motorcyclists to engage in speeding (Dhami & García-Retamero, 2012; Lee et al., 2018; Lin & Kraus, 2009). As an exception, Dubois et al. (2020) found that drivers older than 70 years on 1,500 cubic centimeter (cc) motorcycles were more likely to be speeding, weaving, and riding erratically than younger drivers on equivalent cc motorcycles. Joewono and Susilo (2017) found that young motorcyclists had slightly more involvement in violations (especially related to road rules) than mature participants. It was implied that mature motorcyclists consider cause-and-effect relationships regarding violations more than young motorcyclists. Evidently, the traveling speed of older motorcyclists when involved in a crash is more likely to be lower than for younger motorcyclists (Stutts et al., 2004).

The youngest and oldest motorcyclists had the greatest risk of being involved in a crash (Moskal et al., 2012). An increase in the age of the at-fault rider was associated with a more than 50 percent increase in the probability of a vehicle colliding with a motorcycle (Haque & Chin, 2010). Conversely, most fatalities in collisions of motorcycles into roadside safety barriers involved young men (Jama et al., 2011). Also, Stutts et al. (2004) showed that older drivers were less likely to be in run-off-road collisions.

Motorcyclists' age is also associated with crash outcomes. Compared to younger motorcyclists, older riders were more likely to sustain fatal or severe injuries when involved in a crash (Shaheed & Gkritza, 2014; Vajari et al., 2020; Wali et al., 2019; Yen et al., 2001). Wang et al. (2021) associated younger riders with decreased probabilities of severe injuries to the pillion passenger. Nguyen et al. (2021) found that the likelihood of severe injuries increased when the age of the motorcyclist involved as the first party in a crash increased. However, there was variation in severity outcomes within the cohort of older riders. Jou et al. (2012) indicated that the fatality rate increased sharply for motorcyclists aged 60 to 70 years but declined for motorcyclists aged more than 70 years. Although older riders suffered severe injuries, it is still unclear if the age-related frailties are the sole explanation for this observation (Stutts et al., 2004).

Furthermore, the rider's experience affects motorcycle safety. Inexperienced motorcyclists (less than 3 years of experience) were one of the major factors in motorcycle crashes (Jimenez et al., 2015). An increase in the number of years a rider held a license reduced the likelihood of being involved in a crash (Moskal et al., 2012). Hosking et al. (2010) indicated that hazard response times decreased as experience increased from inexperienced riders/drivers to inexperienced riders/experienced drivers to experienced riders/drivers. It was suggested that experienced drivers' criterion or threshold for judging an object or event as hazardous helped them to quickly recognize objects in the environment that are potential threats (Wallis & Horswill, 2007). Conversely, Crundall et al. (2013) found that experienced riders had slower response times to hazards than novice riders. It was suggested that experience could degrade hazard perception, especially for riders who are more prone to traffic violations. Crundall et al. (2012) posited that experienced riders use a visual search strategy that prioritizes progression on the road more than hazard perception. It is also possible that slow response times in experienced riders are due to age-related changes in driving reactions (Crundall et al., 2013).

Alcohol and Drug Use

Consumption of alcohol two hours before riding has been found to be associated with hazardous driving behaviors, including speeding, using a mobile phone while riding, and failing to use a helmet (Heydari et al., 2016). Consequently, the percentage of at-fault motorcyclists is higher in the alcohol-positive injured riders than in alcohol-free injured riders (Carvalho et al., 2016). Postmortem results of motorcyclists showed that individuals with positive alcohol/drug tests in the toxicology report were more likely to be at fault for a crash (Sarmiento et al., 2020). Moreover, Moskal et al. (2012) revealed that the risk of being involved in a crash was higher for motorcycle and moped riders with an illegal blood alcohol concentration (BAC) level.

Riding under the influence of alcohol, depressants, or multiple drugs was associated with a significant increase in the likelihood of motorcyclists sustaining severe injuries (Chang et al., 2019a; Rahman et al., 2021; Wali et al., 2019; Wu et al., 2018). Compared to non-drinkers, riders with a BAC ≥ 0.05% were significantly associated with fatal crashes (Jou et al., 2012). Alcohol impairment increases the likelihood of fatal crashes on rural and urban roadways alike (Islam & Brown, 2017). In terms of crash type, single-vehicle motorcycle crashes involving riders under the influence of drugs, medication, or alcohol were more likely to result in fatal or severe injury outcomes (Shaheed & Gkritza, 2014; Wankie et al., 2021). Most fatalities in collisions involving motorcycles and roadside objects involved riding with a BAC level above the legal limit (Jama et al., 2011). Moreover, the crash-involvement likelihood of impaired drivers according to age showed an inverted U-shaped distribution. It increased from the early ages and peaked at middle age (around 37 years) and started declining after 40 years (Kim et al., 2000). However, motorcyclists in their twenties comprised the most impaired riders involved in crashes (Kim et al., 2000).

Pillion Passengers

The presence of a pillion passenger was associated with a decreased risk of motorcyclists being involved in a crash, though it was also associated with an increase in crash risk for moped riders (Moskal et al., 2012). It was suggested that while motorcyclists are more cautious when they have a passenger, pillion passengers are often illegal, and the presence of a pillion passenger on a moped is indicative of a rider who is willing to undertake higher-risk behavior. Other studies investigated the association between pillion passengers and the severity of crashes. Jou et al. (2012) showed that the presence of pillion passengers was associated with a lower risk of fatal crashes. Chang et al. (2019a) concluded that, in general, pillion passengers influenced riders into driving cautiously, reducing the severity of crashes. By investigating the attributes of pillion passengers, Wang et al. (2021) showed that vulnerable passengers (e.g., children and elders) reduced the likelihood of riders sustaining severe injuries. Conversely, vulnerable passengers were found to increase the risk of pillion passengers sustaining severe injuries (Wang et al., 2021). The effect of pillion passengers varied depending on whether the motorcyclist was the first or second party in the crash. The presence of pillion passengers on a motorcycle involved as the second party in a crash increased the likelihood of severe injuries, while motorcyclists involved as the first party in a crash were more likely to be severe when riding without a passenger (Nguyen et al., 2021).

Safe Vehicles

The Safe System approach considers the role of Safe Vehicles in reducing road trauma, asserting that well-designed vehicles can decrease the risk of severe injuries and death by either reducing or absorbing some crash forces or preventing them entirely (Towards Zero Foundation, 2020). The Safe Vehicles component includes designs and features that make motorcycles safer or less safe. Studies evaluated motorcycle and motor-vehicle features influencing safety, such as motorcycle types, engine size, braking systems, airbags, fuel tanks, and crash-avoidance systems.

Motorcycle Type and Engine Size

Overall motorcycle design features, such as size, weight, and peak acceleration, vary across categories and manufacturers (Rizzi, 2016). Previous studies associated the frequency and severity of motorcycle crashes with the motorcycle type and engine size. Figure 1 shows eight street-legal motorcycles according to the classification system developed by the Insurance Institute for Highway Safety (IIHS) and Highway Loss Data Institute (HLDI). It is important to note that the effects of motorcycle types are not consistent between studies due to variations in the categorization of motorcycle types. For example, Teoh and Campbell (2010) and Wu et al. (2018) classified motorcycles into ten and eight types, respectively.

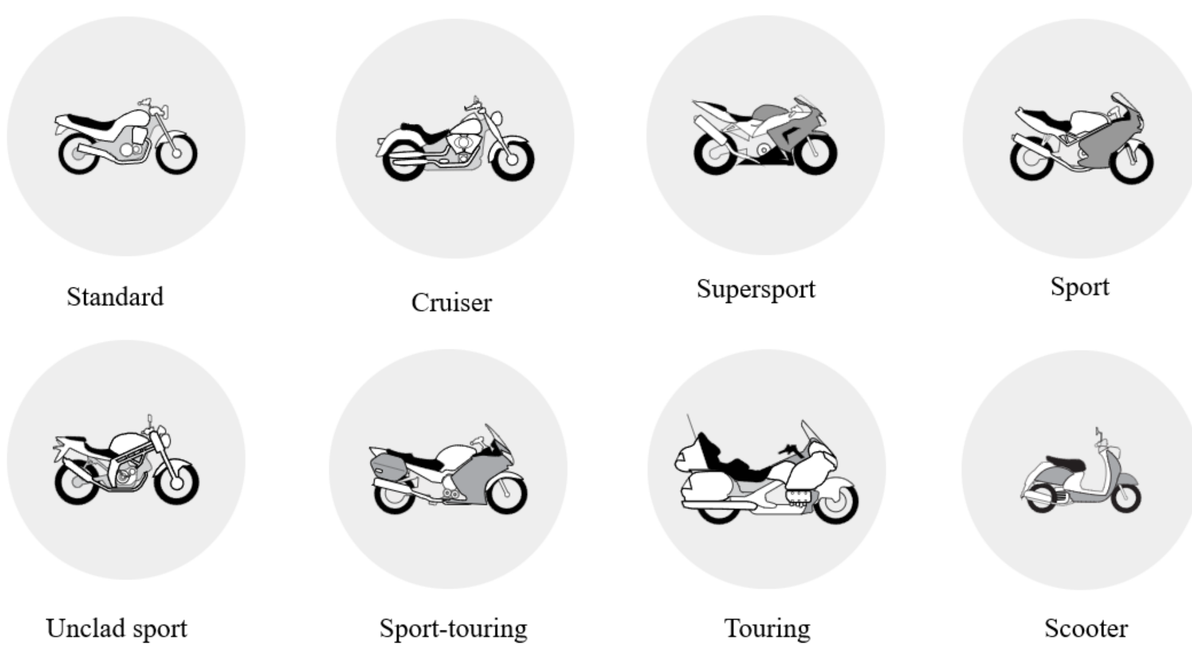


Figure 1. Types of street-legal motorcycles (IIHS-HLDI, 2021)

Wu et al. (2018) found that the roadsters, sports bikes, dual-purpose sports bikes, and off-road bikes had a greater risk of loss-of-control crashes than basic and touring bikes. Also, the off-road bikes had the highest risk of loss-of-control crashes than all other motorcycles. Table 1 summarizes the crash risk factors according to the motorcycle type. Wu et al. (2018) attributed the findings to the rider behavior of the off-road bikes. Although the study observed that riders younger than 35 years preferred roadsters and sports bikes while riders 55 years and older preferred basic and touring bikes, age could not explain the effect of motorcycle type on loss-of-control crashes.

Harrison and Christie (2005) found that trail and dual-use bikes were associated with higher crash risk. It was suggested that the high risk of trail bikes is associated with limited opportunities for riders to acquire safety-related skills, hazards in the off-road environment, low friction of the riding surface, and instability of the motorcycles (i.e., due to high center of gravity and difference in tire tread/profile). Teoh and Campbell (2010) found that motorcyclists' death rates for supersport bikes were four times higher than for cruiser and standard bikes. Sport touring bikes had the lowest rider death rate, which was approximately 15% lower than that for cruiser and standard bikes. Moreover, compared to riders of other types of bikes, many fatally injured supersport bikes' riders were more likely to have been speeding and worn a helmet but less likely to have been impaired. Teoh and Campbell (2010) could not evaluate the effect of age due to a lack of appropriate exposure data.

Table 1. Crash risk factors according to motorcycle type

Motorcycle type	Risk factors	Reference
Basic/Standard	Riding without helmets	Teoh and Campbell (2010)
Roadsters	*	*
Sports bikes	*	*
Dual-purpose sports bikes	*	*
Off-road bikes	Rider behavior, lack of safety-related skills, motorcycle instability, hazards in the off-road environment	Wu et al. (2018); Harrison and Christie (2005)
Touring bikes	Riding without helmets	Teoh and Campbell (2010)
Supersport bikes	Speeding	Teoh and Campbell (2010)
Cruiser	*	*

Note: *Lack of information on the risk factors, hence areas with potential for future research

The effects of motorcycle engine size on the risk of motorcycle crashes are uncertain. A literature survey of old studies by van Honk et al. (1997) indicated that research using data from crash databases, questionnaires, and interviews showed an insignificant relationship between engine size and motorcycle crashes. Also, studies that used data collected before and after imposing restrictions on engine size for novice riders were inconclusive. It was suggested that results from research using the before-and-after method could only be meaningful when the change in the crash rate has stabilized several years after the introduction of engine size restrictions (van Honk et al., 1997).

On the other hand, relatively newer studies have shown a relationship between engine size and the frequency or severity of motorcycle crashes. Yen et al. (2001) analyzed high-performance-small-motorcycles (HPSM), defined as PTW that cannot be classified as scooters, weighing less than 220 pounds, and aerodynamically designed to travel faster than 60 mph. It was found that HPSMs with ≥150cc were more likely to be associated with a higher risk of fatalities. Teoh and Campbell (2010) found that a 100cc increase in engine displacement was associated with higher fatality rates for all motorcycle types except sport-touring bikes. Jou et al. (2012) indicated that heavy motorcycles (>550cc) were more likely to be involved in fatal crashes as compared to light motorcycles (50 – 250cc). Surprisingly, the moped (< 50cc) and large motorcycles (250 – 550cc) had similar fatality risks. These results were attributed to heavy motorcycles being restricted from urban motorcycle lanes. DGT (2007) found that 750 – 1,000cc motorcycles had the highest fatality rate, followed by 500 – 749cc motorcycles.

Langley et al. (2000) found that all motorcycle capacities > 250cc increased the risk of a crash compared to motorcycles with engine capacity ≤ 250cc, except those with engine capacity of 251 – 449cc. Moreover, it was indicated that the crash risk did not increase with the increasing motorcycle capacity when treated as a continuous variable. Similarly, Quddus et al. (2002) showed that injury and damage severities of motorcycle crashes increased with an increase in motorcycle engine capacity. Conversely, Harrison and Christie (2005) found that crash rates were inversely related to engine size, with the highest rate associated with motorcycles with engine capacities of 251 – 500cc.

It is worth noting that even though engine power (i.e., peak horsepower output) is correlated with engine displacement, high-performance motorcycles tend to have smaller engines designed to produce high horsepower (Teoh & Campbell, 2010). Therefore, engine displacement is not an optimal representation of motorcycle performance because low engine displacement, in some cases, may be associated with high power output and a high power-to-weight ratio. Mattsson and Summala (2010) showed that the fatality risk per the number of registered motorcycles and distance ridden increases with the power and power-to-weight ratio of the motorcycles. It was, however, not clear if the observation made was due to the habit of riders of powerful bikes or the characteristics of the bikes. High speeds associated with fatal accidents were predominantly among bikes with a higher end of power and power-to-weight spectrum independent of the rider's age. It was also made clear that motorcycles with high power-to-weight ratios are made to be ridden fast and accelerated quickly, a temptation that is unavoidable by many riders irrespective of age and experience. Mattsson and Summala (2010) concluded that higher fatality risk might be associated with high-performance motorcycles ridden by riders who select the most powerful motorcycles and ride dangerously whatever the performance restrictions.

Braking Systems

Antilock braking systems (ABS) were introduced to improve stability by maintaining wheel rotation during hard braking (Rizzi et al., 2016). The ABS increases braking stability and prevents the rider from falling to the ground. This technology is essential, considering motorcycles provide little protection against injuries in upright crashes and none in sliding crashes (DaCoTA, 2012). Several studies evaluated the impact of the ABS on motorcycle safety. It was found that ABS prevented crashes, increased stability, and changed the phases following critical conditions, making crashes occur predictably (Rizzi, 2016). The ABS were estimated to reduce motorcycle involvement in injury and fatal crashes by 38% and 48%, respectively (Rizzi et al., 2009). In crashes involving ABS-equipped motorcycles, motorcyclists experienced less severe injuries (Vavryn & Winkelbauer, 2004). Vavryn and Winkelbauer (2004) estimated that 31% of intersection crashes could have been avoided if motorcyclists had used ABS-equipped motorcycles. Although it was observed that ABS reduced emergency care visits by 47%, leg injuries were reduced while head-on crashes were not influenced by the ABS (Rizzi, 2016; Rizzi et al., 2015, 2009).

With the advancement in technology, researchers have started evaluating the performance of new braking systems, such as motorcycle autonomous emergency braking (MAEB). Promising results indicate that the autonomous braking systems might have similar positive effects as those observed in passenger vehicles. Lucci et al. (2021) investigated the performance of MAEB during pre-crash lateral avoidance maneuvers (Lucci et al., 2021). Autonomous emergency braking involves automatic braking force application for crash avoidance or reduction of impact speed before the crash.

Field tests indicated that speed reductions due to MAEB during lane changes were similar to those during straight-line conditions. It was also concluded that riders could manage the MAEB application with decelerations up to 0.3 g in straight line conditions and during an avoidance maneuver. Savino et al. (2014)

examined the effectiveness of MAEB using simulation of crash scenarios where MAEB might have been applicable. It was indicated that MAEB could reduce impact speed over 6 mph depending on the crash type and the rider's pre-impact braking behavior.

Despite its potential benefits, the primary concern of MAEB is rider stability. Symeonidis et al. (2012) performed experiments in a laboratory that simulated autonomous and manual braking conditions. It was revealed that autonomous braking at low deceleration is not expected to cause significant instabilities compared to manual braking. Despite the potential for advanced braking systems to reduce motorcycle fatalities, further research is needed before their implementation.

Helmets

Most studies on motorcycle safety gear focused on helmets. Research has shown that motorcycle crash victims not wearing helmets are more likely to suffer severe injuries than helmeted riders (Rahman et al., 2021; Reardon et al., 2017; Schneider & Savolainen, 2011; Shaheed & Gkritza, 2014). Helmets decrease the risk of fatal injuries by protecting the head of the motorcyclist (Kim et al., 2015). Helmets effectively reduced severe and fatal injuries in both single-vehicle and multi-vehicle crashes (Schneider & Savolainen, 2011). The helmet's impact was more pronounced in single-vehicle crashes than in multi-vehicle crashes (Schneider & Savolainen, 2011). In addition to providing physical protection, wearing a helmet may also serve as an indicator of a motorcyclist with good riding habits and skills (Chang et al., 2016).

Motorcyclists were less likely to suffer a head injury, facial injury, or high-severity facial fracture if wearing a helmet at the time of a crash (Lin & Kraus, 2009). Riders wearing helmets were less likely to develop speech problems following a multi-vehicle crash, but helmet use was not associated with a significant reduction in locomotion or feeding difficulties (Crompton et al., 2010). The mechanism of helmets in reducing the likelihood of speech problems stems from helmets preventing severe head injuries. Helmets did not affect locomotion because they were associated with extremity injuries rather than neurological issues from traumatic brain injury. However, it was not clear why helmets did not significantly impact the functional outcome of feeding. Wearing a helmet reduced the risk of fatal injuries, although head injuries were still possible even with them on (Crompton et al., 2010; Nnadi et al., 2015; Zimmerman et al., 2015).

Most non-helmeted motorcyclists who suffered a crash fatality died from head injuries (Solagberu et al., 2006). Brandt et al. (2002) found that failure to wear a helmet significantly increased the incidence of head injuries while helmet use decreased the mean cost of hospitalization. Helmets reduced the likelihood of head and neck injuries in a crash, leading to a reduced probability of death due to head and neck injuries (Keng, 2005). Not wearing a helmet increased the possibility of incapacitating injuries in rural motorcycle crashes and the probabilities of both fatal and incapacitating injuries on urban roadways (Islam & Brown, 2017). However, it is worth noting that some study areas do not have laws mandating helmets (e.g., Ohio), hence motorcyclists involved in crashes may be recorded wearing helmets that do not meet standards (Schneider & Savolainen, 2011), which might lead to underestimating the benefits of helmets in motorcycle crashes.

In addition to the general effect of helmets on motorcyclists' safety, specific helmet attributes may influence the severity of injuries in a motorcycle crash. The type of helmet, which includes full face, open face, and half helmets, affects the severity outcome of a motorcycle crash. Figure 2 shows the most common motorcyclist helmet types, and Table 2 summarizes findings on the effects of the type of helmet worn by motorcyclists involved in crashes.

(a) Full-face helmet (b) Half-coverage helmet (c) Open-face helmet

Figure 2. Common types of helmets (Motorcycle Legal Foundation, 2021; Tabary et al., 2021)

Erhardt et al. (2016) revealed that helmet type was highly associated with a head injury but not a neck injury. Compared to full-face helmets, open-face and half-coverage helmets were associated with a 69% and 91% higher likelihood of head injuries, respectively. Also, helmets not compliant with the United States Department of Transportation (U.S. DOT), named “novelty helmets”, were 178% more likely to be associated with head injuries than full-face helmets. Hitosugi et al. (2004) indicated that motorcyclists wearing open-face helmets were more likely to have sustained severe head and neck injuries than motorcyclists wearing full-face helmets. It was also shown that full-face helmets decreased the incidence of brain contusions. Similarly, Brewer et al. (2013) revealed that the proportions of facial and skull fractures in admitted riders wearing full-face helmets were lower than in admitted riders wearing other helmets. Lam et al. (2015) found that riders wearing partial coverage and open-face helmets were 65% and 91% less likely than riders without helmets to be associated with cervical spine injuries (CSI) in motorcyclists with head injuries. It was suggested that the helmet design, which includes smooth surface and hard lining of padding materials, is the reason for the effect. O’Connor (2005) further suggested that there is no significant difference between the odds of CSI among motorcyclists with full-face and open-face helmets.

Yu et al. (2011) found that the half-coverage helmets provided the least protection from head injuries of the three helmets. Better performance of full-face helmets was associated with the coverage of the whole head and the presence of the chin bar and a visor. It was also revealed that loosely fastened helmets increased the risk of head and brain injuries by reducing the helmet’s effectiveness in preventing head injuries. Unfortunately, many motorcycle users (riders and pillion passengers) in developing countries have a habit of wearing unfastened or loosely fastened helmets just to show compliance with helmet-use laws (Li et al., 2008). Ramli and Oxley (2016) concluded that helmet fixation is more effective than helmet type when considering protecting motorcyclists. Additionally, in Tennessee, Khattak et al (2023) found that incorrect use of DOT-approved helmets was less protective against severe injury compared to correct helmet use.

Table 2. Summary of the effects of helmet type on motorcyclists involved in crashes

Helmet type	Study area	Safety effects	Reference
+69-Full-face	Taiwan	In motorcyclists with head injuries, patients with open-face helmets were 91% less likely than patients without helmets to be associated with cervical spine injuries (CSI)	Lam et al. (2015)
	Maryland	Facial fractures were present in 7% of patients wearing full-face helmets and in 27% of patients wearing other helmets	Brewer et al. (2013)
		Skull fractures were present in 1% of patients wearing full-face helmets and in 8% of patients wearing other helmets	

	Australia	No difference between the odds of CSI among motorcyclists with full-face helmets and with open-face helmets	O'Connor (2005)
Half-coverage	California	Patients with half-coverage helmets were 91% more likely than patients with full-face helmets to be associated with head injuries	Erhardt et al. (2016)
Open-face	California	Patients with half-coverage helmets were 69% more likely than patients with full-face helmets to be associated with head injuries	Erhardt et al. (2016)
	Japan	Patients with open-face helmets were more likely to sustain severe head and neck injuries than patients with full-face helmets	Hitosugi et al. (2004)
Novelty[a]	California	Patients with novelty helmets were 178% more likely than patients with full-face helmets to be associated with head injuries	Erhardt et al. (2016)
Partial coverage[b]	Taiwan	In motorcyclists with head injuries, patients with partial coverage helmets were 65% less likely than patients without helmets to be associated with CSI	Lam et al. (2015)

Note: [a] Helmets that are noncompliant with US DOT safety standards, [b] In the cited study, partial coverage included all other helmets that were not full-face helmets

Protective Clothing

Protective clothing includes gloves, boots, long-sleeved jackets, pants, or one-piece suits made of leather or other fabric with high abrasion and tear resistance (de Rome, 2006). Like helmets, protective clothing helps reduce the severity of injuries suffered by motorcyclists involved in crashes. De Rome et al. (2011) found that the risk of motorcyclists to be admitted to a hospital if they wore a motorcycle jacket, motorcycle pants, or motorcycle gloves at the time of the crash were reduced by 21%, 51%, and 59%, respectively. Additionally, motorcyclists wearing clothing fitted with body armor, which is a high-density foam shield for absorbing and distributing the force of direct impacts to exposed areas, were significantly less likely to sustain injuries to the protected areas than those wearing non-motorcycle clothing.

There are limits to the extent protective clothing can reduce injuries, especially in high-impact crashes. Lin and Kraus (2009) suggested that wearing protective clothing could only reduce the risk of soft tissue injury. Wu et al. (2019) indicated that protective clothing reduces the severity of abrasions and lacerations but does not significantly affect fractures, dislocations, or sprains. Giustini et al. (2014) suggested using a back protector device (e.g., hard shell back protector devices or jackets with airbags) to reduce the number of injuries to the spinal column. Comparing different protective clothing materials, Meredith et al. (2015) found that riders wearing heavy cotton and fleecy cotton knit sustained significantly more abrasion injuries than riders who wore other materials.

Despite the benefits of protective clothing, multiple studies found that most motorcyclists in developing countries did not wear protective clothing (Li et al., 2008; Nnadi et al., 2015; Wu & Loo, 2016). While many riders wear helmets, they neglect other body areas (de Rome et al., 2011). Sumner et al. (2014) observed few motorcyclists wearing protective clothing even after being provided it for free. Comfort could be one of the reasons discouraging motorcyclists from wearing protective clothing. De Rome (2019) found that thermally inefficient motorcycle protective clothing in hot conditions affects riding performance and safety. Future research could focus on manufacturing protective clothing that will attract motorcyclists' daily use. In addition, education campaigns should support wearing protective clothing in the same manner helmet use is promoted.

Airbags, Fuel Tank, and Headlights

Motorcycle elements that could affect a rider's safety include airbags, fuel tanks, and headlights. Airbags can reduce the severity of injuries sustained by motorcyclists when involved in a crash. Specifically, airbags reduce injuries in frontal collisions by absorbing the motorcyclist's kinetic energy and decreasing the motorcyclist's separation velocity from the motorcycle in the forward direction (Kuroe et al., 2005). Researchers have tested several airbag configurations and technologies on motorcycles. Kuroe et al. (2005) found that using an airbag mounted on a large touring motorcycle can reduce fatal and severe injuries to the riders. Kanbe et al. (2007) showed that an airbag installed at the front end of the rider seat of the scooter-type model restrained the rider and effectively reduced injuries. Aikyo et al. (2015) proposed a motorcycle airbag system that uses the vehicle structure of an opposing vehicle in a crash to provide the reaction structure for the airbag and demonstrated its effectiveness in reducing rider's head and chest injuries.

Fuel tanks can contribute to the severity of motorcyclists' injuries involved in crashes, with contact with the fuel tank in a crash being the most common cause of pelvic injuries to motorcyclists (Meredith et al., 2016). In addition, the most common types of pelvic injury to the riders who contacted the fuel tank were fractures and external injuries (Meredith et al., 2016). Hurt et al. (1981) indicated that most groin injuries caused by contact with fuel tanks occurred in frontal crashes, and their severity increased with speed. Moreover, the fuel tank had a significant contribution to the severity of pelvic injuries due to its wedge shape or the shape of its accessories (de Peretti et al., 1994). Wobrock et al. (2006) indicated that the pelvic force, which can lead to pelvis injuries, increased as the fuel tank angle increased. Ouellet and Hurt (1981) concluded that fuel tanks whose shape rose smoothly from seat level minimized groin injuries while tanks that rose steeply in front of the seat increased injury. It is important to note that it is nearly impossible to completely ascertain the assigned contact source (i.e., fuel tank) during a crash due to the possibility of multiple contacts (Meredith et al., 2016). Also, complete kinematics of the rider and injury outcome should be considered because a fuel tank may provide some restraint and reduce the severity of injuries to other body regions (Meredith et al., 2016).

Headlights influence the risk of motorcyclists being involved in crashes. The use of headlights can help drivers more accurately estimate the speed and time to impact of an approaching motorcycle (Cavallo et al., 2021; Pai, 2011). Pai (2011) suggested that the type of headlight influences motorcycles being detected sooner at greater distances. Several studies assessed the headlight configuration that could improve motorcycle safety. Cavallo et al. (2021) found that a vertical yellow-white light arrangement (i.e., one central white light, plus one yellow light on the helmet and two yellow lights on the fork) had more safety benefits than standard headlight configurations (i.e., white central light). Incorporating a tri-headlight configuration on the standard motorcycle frame improved the accuracy of motor-vehicle driver's approach speed judgment as light levels reduced (Gould et al., 2012a, 2012b). Cavallo et al. (2021) concluded that motorcycle safety could be improved by headlight design that draws attention to the vertical dimension of motorcycles. Analysis considering the car's daytime running lamp (DRL) environment showed that a single-central-yellow headlight configuration and a central-and-helmet white headlight configuration had better motorcycle-detection performance than the standard configuration (Pinto et al., 2014). It was critical to consider the car-DRL environment because it reduced motorcycle conspicuity due to the competing light patterns generated by DRL in conditions where motorcycles are at greater distances (Cavallo & Pinto, 2012).

Vehicle Technologies

While crash-avoidance and detection technologies have the potential to improve the safety of motorcyclists, few studies managed to explore applications of vehicle technologies in improving motorcycle safety. Teoh (2017) evaluated motorcycle crashes that would have benefited from three crash-avoidance technologies on vehicles: frontal crash prevention, lane maintenance, and blind-spot detection. It was concluded that, although expanding the capabilities of vehicle crash-avoidance systems has the potential to improve motorcycle safety, its effects are only in the minority of motorcycle crashes, hence the need for other countermeasures (Teoh, 2017). Savino et al. (2015) showed that although AEB in cars has the potential to avoid motorcycle-to-vehicle crashes, it is dependent on the initial position of the vehicle. Sui et al. (2021) and Cao et al. (2019) demonstrated that AEBs in cars could be an effective crash avoidance system for two-wheelers after virtually testing AEBs on real-world crash scenarios.

Similarly, Naranjo et al. (2017) developed, tested, and showed the system's functionality that could produce warnings to the driver in situations of motorcycle movement in blind spots, overtaking, and in sharp bends with low visibility. Fernández et al. (2013) developed a vision-based motorcycle and car detection system in the blind spot area using a single camera installed on the side mirror. It was verified that the system could warn drivers about the presence of a vehicle in the blind spots, including information about the type of the vehicle (Fernández et al., 2013). Despite a few researchers' attempts, more efforts have been directed towards introducing technologies to improve vehicle-to-vehicle or vehicle-to-pedestrian interactions with less attention to vehicle-to-motorcycle interactions.

Safe Speeds

The Safe System approach encourages vehicle speeds that ensure that a system's most vulnerable users are not injured or killed in a crash event. Most of the studies on the relationship between speed and motorcycle safety have focused on posted speed limits, which are reliant on a motorcyclists' compliance with traffic regulations for their success, rather than on strategies to mandate lower operating speeds through design. Spatial analysis by Jiang et al. (2020) found hotspots of fatal motorcycle crashes in areas with a speed limit of 50-70 mph. The risk of loss-of-control motorcycle crashes was higher on roadways with a speed limit > 30 mph (D. Wu et al., 2018). Gabauer (2016) found that more single-vehicle motorcycle crashes involving longitudinal barrier impact occurred on segments with high posted speed limits than multi-vehicle and other single-vehicle crashes. Halbersberg and Lerner (2019) indicated that high posted speed limits increased the likelihood of fatal crashes involving young motorcyclists (18 – 24 years).

Walton et al. (2013) revealed that motorcycle-to-vehicle crashes occurred more frequently than vehicle-to-vehicle crashes at three-legged intersections in 60 mph speed zones. Likewise, Li et al. (2009) found that on roads with speed limits 40–60 mph, the ratio of fatalities to motorcyclists involved in crashes was 5% higher than the ratio of fatalities to motor-vehicle occupants in crashes. It was suggested by Murphy and Morris (2020) that most motorcycle-vehicle crashes could have been avoided if the faster-moving party had been traveling at the speed limit. Higher speed limits may encourage motorcyclists to ride at high speed, making it difficult for a turning-vehicle driver to detect the presence of an approaching motorcycle or determine its speed, hence unable to react with a swerving maneuver (Pai and Saleh, 2008).

Many studies emphasized how the risk of severe outcomes in motorcycle crashes increased as the posted speed limits of the crash location increased (Dadashova et al., 2021; Farid & Ksaibati, 2021; Lee et al., 2018; Li et al., 2009). However, the results are inconsistent due to the variations in speed limit categories and crash types. Savolainen and Mannering (2007) indicated that roads with speed limits > 50 mph were associated with a higher likelihood of fatal crashes in multi-vehicle motorcycle crashes. Similarly, Shaheed et al. (2013) found that motorcycle-vehicle crashes on roads with a speed limit ≥ 55 mph were more likely to result in severe injuries. Waseem et al. (2019) found that roads with a posted speed limit ≥40 mph were associated with severe injuries. Farid and Ksaibati (2021) found that high posted speed limits increased the odds of severe single- and multi-vehicle motorcycle crashes. Dadashova et al. (2021) found that higher speed limits were associated with more severe motorcycle roadway-departure crashes involving a roadside fixed object. Blackman and Haworth (2013) showed that severe motorcycle, moped, and larger scooters crashes were associated with zones having a posted speed limit >50 mph, >55 mph, and 45 mph, respectively. Wang et al. (2021) indicated that roadways with a design speed > 30 mph (which was determined by considering the typical design speed for the class of roadway where a crash occurred) increased the likelihood of severe injuries to the motorcycle rider and the pillion passengers. While analyzing motorcyclists involved in crashes according to age, Lee et al. (2018) revealed that motorcyclists aged ≥ 30 years were more likely to suffer severe injuries on roadways with a posted speed limit ≥ 55mph.

Effects of the speed limit on the crash severity of motorcycle crashes are attributed to the dissipation of kinetic energy during the collision (Geedipally et al., 2011). It is also suggested that severe crashes are more likely on roadways with higher speed limits because drivers have more difficulty controlling vehicles and less time to brake in an emergency (Jiang et al., 2020). Waseem et al. (2019) proposed lowering posted speed limits on roadway segments with higher motorcycle proportion as one of the measures to reduce the severity of motorcycle crashes. Also, policies that could forbid motorcycles from entering roads with high posted speed limits could reduce the severity of motorcycle crashes in the hotspots (Jiang et al., 2020). Other methods of regulating speeds that could be implemented include road narrowing, rumble strips, speed humps, and automatic speed enforcement (Li et al., 2009).

Safe Roads

The Safe System approach recognizes the crucial role road infrastructure has in reducing the frequency and severity of crashes, with improved features providing safety outcomes that are essential for long-term and sustainable trauma reduction (Towards Zero Foundation, 2020). One aspect of improving motorcycle safety involves evaluating the role of several roadway factors on crash occurrence and severity. This section summarizes the findings of previous studies that analyzed the effect of roadway attributes on the occurrence and severity of motorcycle crashes.

Intersections

Intersections have proven to be a dominant street design element affecting the safety of motorcyclists (Lee et al., 2018; Li et al., 2009; Reardon et al., 2017). Table 3 summarizes the findings of previous studies on the effect of intersections on the frequency and severity of motorcycle crashes. Shin et al. (2019) showed that crashes involving motorcycle couriers occurred at intersections more than non-intersection locations. This observation was associated with a higher rate of violations by motorcycle couriers at intersections than other road locations. The effect of intersections on the occurrence of motorcycle crashes varies with the intersection characteristics. For example, right-angled crashes involving a not-at-fault motorcyclist were more likely to occur at three-legged intersections than four-legged intersections (Haque & Chin, 2010). Haque and Chin (2010) attributed this observation to the higher probability of red-light runners at three-legged intersections than four-legged intersections.

It was also indicated that the presence of a red-light camera decreased the likelihood of right-angled crashes with a not-at-fault motorcyclist at intersections (Haque & Chin, 2010). Walton et al. (2013) associated uncontrolled intersections with most motorcycle-car crashes. It was suggested that the driver's expectation of motorcycles being at the uncontrolled intersections was the contributing factor for the motorcycle-car crashes. Manan et al. (2013) indicated that the number of access points per mile increases the number of motorcycle fatalities per mile on primary roads. It was explained that more access points per mile increase conflicts between motorcycles and access roads' vehicles that tend to disregard motorcycles' right-of-way.

Table 3. Summary of the effects of intersections on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Korea	All	All	Most crashes involving motorcycle couriers occurred at intersections	Shin et al. (2019)
	Singapore	MV	All	Right-angled crashes were more likely at three- than four-legged intersections	Haque and Chin (2010)
	Malaysia	All	Primary roads	More access points per mile increased the number of fatal crashes	Manan et al. (2013)
	New Zealand	MV	Arterial, collector, and access	Higher likelihood of crashes at uncontrolled intersections than at intersections with Stop or Yield signs	Walton et al. (2013)
	Singapore	MV	All	Red-light cameras reduced crashes involving a not-at-fault motorcyclist	Haque and Chin (2010)

Effect	Study area	Crash type	Road type	Findings	Reference
Severity	Taiwan	All	All	Intersections increased the risk of fatalities to motorcyclists more than motor-vehicle occupants	Li et al. (2009)
	Dhaka, Bangladesh	All	All	Lower likelihood of fatal crashes at intersections than non-intersection locations	Rahman et al. (2021)
	Dar es Salaam, Tanzania	All	Arterial, collector and access	Higher likelihood of minor injury crashes at intersections than non-intersection locations *	Salum et al. (2019)
	Bali, Indonesia	All	Arterial	Intersections increased the likelihood of minor injuries in crashes involving male riders*	Wedagama (2009)
	Texas, USA	All	All	Higher likelihood of slight or no-injury crashes at intersections than non-intersections	Geedipally et al. (2011)
	Alabama, USA	All	All	Higher likelihood of possible or no-injury crashes at intersections than non-intersections	Islam and Brown (2017)
	Ohio, USA	SV	All	Intersection crashes more likely to be possible or no-injury crashes than non-intersections	Maistros et al. (2014)
	Wyoming, USA	SV	All	Higher likelihood of no-injury, possible injury, or non-incapacitating injury crashes at intersections than non-intersections	Farid and Ksaibati (2021)
	Ghana	All	Unspecified	Higher likelihood of fatal injuries at intersections than non-intersections	Wahab and Jiang (2019)
	Victoria, Australia	All	All	Higher likelihood of fatal crashes at three-legged than four-legged intersections, at stop or yield than signalized intersections, at uncontrolled than signalized intersections, and at roundabouts than signalized intersections	Vajari et al. (2020)
	Ohio, USA	SV	All	Alcohol-impaired motorcyclists were more likely to be in severe crashes at three-legged intersections	Maistros et al. (2014)
	USA	SV	All	Interchange locations increased the severity of motorcycle crashes with fixed objects	Bambach et al. (2011)
	Sweden	All	All	Roundabouts reduced fatal crashes in urban areas except those involving high speeds	Trafikverket (2010)

Note: MV means multiple vehicles; SV means single vehicle; *Minor injury are all other injuries that are not fatal

Intersections and their attributes influence the severity of motorcycle crashes. The risk of fatal crashes at intersections is relatively higher for motorcycle riders than motor-vehicle occupants (Li et al., 2009). However, previous research showed conflicting results regarding the intersections' influence on the severity of motorcycle crashes. Rahman et al. (2021), Salum et al. (2019), and Maistros et al. (2014) found that crashes at intersections were associated with minor injuries. Also, crashes involving young male motorcyclists were less severe at intersections (Wedagama, 2009). Islam and Brown (2017) and Geedipally et al. (2011)

indicated that intersections were associated with slight- or no-injury crashes in urban and rural areas, respectively. Considering the crash type, Farid and Ksaibati (2020) found that single-vehicle motorcycle crashes were less severe at intersections than midblock locations. It was suggested that motorcycle crashes at intersections led to slight or no injuries because of lower speeds maintained by the riders at or near the intersections than midblock locations (Geedipally et al., 2011).

Conversely, Wahab and Jiang (2019) indicated severe crashes were more likely to occur at intersections. However, factors attributing to this observation were not clear. Vajari et al. (2020) revealed that the likelihood of fatal crashes increased at three-legged intersections, at stop or yield intersections, and in uncontrolled intersections. Alcohol-impaired motorcyclists were more likely to sustain severe injuries when involved in a single-vehicle crash at three-legged intersections (Maistros et al., 2014). This finding was supported by Pai (2009). Interchange locations increased the severity of motorcycle crashes with fixed objects (Bambach et al., 2011). Although Traffikverket (2010) suggested that converting intersections to roundabouts in urban areas reduced fatal crashes, Vajari et al. (2020) associated roundabouts with an increased likelihood of fatal crashes. Even though it is not clear how roundabouts could increase the severity of motorcycle crashes, Daniels et al. (2008) showed that roundabouts have a negative safety effect on bicyclists.

Horizontal and Vertical Curves

Table 4 summarizes the findings of previous studies on the effect of horizontal and vertical curves on the frequency and severity of motorcycle crashes. Flask and Schneider (2013) found that townships with more horizontal curves were associated with higher single-vehicle motorcycle crash rates. It was suggested that areas with challenging and curvy roads are favored destinations of riders because motorcycle riding is mostly done for recreation purposes. Most crashes on horizontal curves were single-vehicle motorcycle crashes and those involving loss of control (Kim et al., 2002; Trafikverket, 2010; D. Wu et al., 2018). Conversely, the percentage of motorcycle-animal crashes that took place on straight rural roads was higher than the percentage of non-animal crashes on the same sections (Bramati et al., 2012). It was indicated that motorcycle-animal collisions mainly occurred in ideal driving conditions where riders were surprised by the animal's roadway encroachment.

Table 4. Summary of the effects of roadway alignment on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Sweden	SV	All	Majority of SV crashes occurred on curves	Trafikverket (2010)
	Ohio, USA	SV	All	Townships with more horizontal curves were associated with higher SV crash rates	Flask and Schneider (2013)
	France	SV	All	Riding in curves was associated with higher risk of loss-of-control motorcycle crashes than riding in straight sections	Wu et al. (2018)
	North Dakota, USA	SV	All	Percentage of motorcycle-animal crashes was higher than the percentage of non-animal crashes on straight sections	Bramati et al. (2012)
	Florida, USA	All	Undivided rural 2-lane	Increase in the curve radius was associated with decreased frequency of motorcycle crashes; increase in curve length was associated	Xin et al. (2017)

Effect	Study area	Crash type	Road type	Findings	Reference
				with increased frequency of motorcycle crashes	
	New Jersey, USA	All	All	Short curve radius was associated with an increase in the frequency of motorcycle crashes	Daniello et al. (2010)
	Washington and Ohio, USA	SV	Arterial	Short curve radius was associated with increased likelihood of motorcycle-to-barrier crashes	Gabauer (2016);
	Ohio, USA	SV	Rural 2-lane highways	Short curve radius was associated with an increase in the frequency of SV motorcycle crashes; an increase in curve length was associated with increased frequency of SV motorcycle crashes	Schneider et al. (2010)
	Florida, USA	All	Undivided rural 2-lane	Fewer intersections per mile in a horizontal curve and reverse curves were associated with reduction in the frequency of motorcycle crashes	Xin et al. (2017)
	Ohio, USA	SV	All	More SV motorcycles crashes occurred in townships with steeper grades	Flask and Schneider (2013)
	Florida, USA	All	Undivided rural 2-lane	Presence of vertical grade was associated with an increase in the frequency of motorcycle crashes	Xin et al. (2017)
	Washington and Ohio, USA	SV	Arterial	Steeper grades (> 3%) were associated with increased likelihood of motorcycle-to-barrier crashes	Gabauer (2016)
	Ohio, USA	SV	All	Townships with more vertical curves were associated with fewer SV motorcycle crashes	Flask and Schneider (2013)
Severity	Alabama, USA	All	All	Horizontal curves on urban roadways were associated with an increase in the probability of fatal injuries in crashes involving an at-fault motorcyclist	Islam and Brown (2017)
	Queensland, Australia	All	All	Curved roadways were associated with an increase in the likelihood of severe injuries in motorcycle crashes	Blackman and Haworth (2013)
	Louisiana, USA	All	All	Curved roadways were associated with an increase in the likelihood of fatal injuries in crashes involving an at-fault motorcycle rider	Das et al. (2018)

Effect	Study area	Crash type	Road type	Findings	Reference
	Wyoming, USA	SV	All	Curved roadways were associated with an increased likelihood of fatal and incapacitating injuries in single-vehicle motorcycle crashes	Farid and Ksaibati (2021)
	Hawaii, USA	SV	All	Curved roadways were associated with more fatal and incapacitating injuries than expected	Kim et al. (2002)
	Florida, USA	All	All	Curved roadways were associated with an increased level of crash injury severity across all motorcyclists' age groups	Lee et al. (2018)
	Dar es Salaam, Tanzania	All	Arterial, collector, and access	Curved roadways were associated with an increased likelihood of fatal injuries	Salum et al. (2019)
	USA	All	All	Curved roadways were associated with an increased likelihood of fatal and incapacitating injuries	Wu et al. (2018b)
	Malaysia		All	Most motorcycle fatalities occurred on straight road sections	Manan and Várhelyi (2012)
	Dhaka, Bangladesh	All	All	Curved roadways were associated with a decrease in the likelihood of fatal injuries	Rahman et al. (2021)
	Ghana	All	All	Curved and inclined sections of roadways were associated with an decreased probability of fatal injuries	Wahab and Jiang (2019)
	Texas, USA	SV	All	Vertical curves have a stronger influence on crash severity than horizontal curves	Dadashova et al. (2021)
	Alabama, USA	All	All	Level grade on tangent on urban roads was associated with a reduced probability of incapacitating injuries	Islam and Brown (2017)
	Texas, USA	All	All	Level grade on horizontal curves was associated with an increase in the likelihood of fatal injuries	Geedipally et al. (2011)
	USA	SV	All	Non-level road profiles were associated with an increase in the likelihood of fatal injuries	Bambach et al. (2011)
	Texas, USA	SV	All	Segments with grade were associated more with fatal and incapacitating injuries crashes	Dadashova et al. (2021)

Note: SV means single vehicle

While most studies associated horizontal curves with an elevated risk of severe crashes (Blackman & Haworth, 2013; Das et al., 2018; Farid & Ksaibati, 2021; Islam & Brown, 2017; Kim et al., 2002; Lee et al., 2018; K. F. Wu et al., 2018), few studies indicated that curved roadways were associated with less severe crashes (Manan & Várhelyi, 2012; Rahman et al., 2021; Wahab & Jiang, 2019). Rahman et al. (2021) attributed the occurrence of severe crashes on straight segments to speeding and lack of concentration when driving on straight road sections.

Other studies evaluated the effect of horizontal curves' attributes, such as curve radius and length. Short curve radius was associated with an increase in the frequency of motorcycle crashes, possibly because it exacerbates risk factors, such as poor sight distance and speed variation (Daniello et al., 2010; Gabauer, 2016; Schneider & Savolainen, 2011; Xin et al., 2017). Curves with smaller radii are more demanding from a riding perspective, with increased difficulty transitioning into and out of a curve (Schneider et al., 2010; Xin et al., 2017). Increasing the curve length was associated with an increased likelihood of motorcycle crashes (Schneider et al., 2010; Xin et al., 2017). This result was attributed to higher design speeds on longer curve lengths that motorcyclists could not handle (Schneider et al., 2010). Conversely, high crash risk on longer curves could be attributed to riders' behavior when on curves considering that longer curves commonly have larger radii, making them less challenging to motorcyclists (Schneider et al., 2010). Reverse curves were associated with a decrease in the frequency of motorcycle crashes, while horizontal curves with a high number of intersections per mile were associated with an increase in motorcycle crashes (Xin et al., 2017). It was suggested that motorcyclists become more alert and take safety-oriented measures to compensate for the difficulty of riding in reverse curves (Xin et al., 2017).

Vertical curves and their attributes affected the safety of motorcyclists. Locations with more vertical curves were associated with a lower frequency of single-vehicle motorcycle crashes (Flask & Schneider, 2013). However, steeper grades increased the likelihood of crash occurrence (Flask & Schneider, 2013; Xin et al., 2017). Xin et al. (2017) suggested that a combination of horizontal curves and vertical grades could decrease sight distance, increasing the complexity of riding maneuvers. Crashes involving motorcycle and road barriers were more likely on sections with a grade excess of 3% (Gabauer, 2016). Vertical curves had more significant effects on the severity of crashes than horizontal curves (Dadashova et al., 2021). Segments with grade were associated with a higher risk of severe crashes than segments with no grade (Bambach et al., 2011; Dadashova et al., 2021). While level grade on tangent reduced the severity of crashes in urban roads (Islam & Brown, 2017), level grade on horizontal curves increased the likelihood of fatal crashes (Geedipally et al., 2011).

Road Type

Various attributes define the road type, including the number of lanes, type of traffic flow (interrupted or uninterrupted), median type, and road function (access, collector, or mobility). Therefore, road types in previous studies varied based on the classification criteria in the study area. Table 5 summarizes the findings of previous studies on the effect of road type on the frequency and severity of motorcycle crashes. There is little research on the relationship between road type and the frequency of motorcycle crashes, and the information that is available is mixed. Flask et al. (2014) showed that roadways with six or more lanes and divided highways experience lower multi-vehicle motorcycle crash rates, with the author stating that this is because more lanes provide more opportunities for motorcyclists and drivers to change lanes to avoid collisions. Several studies explored the effect of road type on the severity of motorcycle crashes (Das et al., 2018; Haque & Chin, 2010; Li et al., 2009; Rezapour et al., 2020; Salum et al., 2019; Schneider & Savolainen, 2011; Vajari et al., 2020). Two-lane roadways were associated with an increased likelihood of fatal, incapacitating, and non-incapacitating injuries from single-vehicle and non-intersection-related multi-vehicle crashes (Schneider & Savolainen, 2011). Although roads with ≥4 lanes were associated with an increased likelihood of fatal and incapacitating injury crashes (Rezapour et al., 2020), the likelihood of fatal crashes was higher on 2-lane highways than 4-lane highways (Naqvi & Tiwari, 2017). Rezapour et al. (2020) attributed higher severity of crashes on roads with ≥2 lanes in both directions with an increased exposure due to higher traffic volume (i.e., annual average daily traffic). Naqvi and Tiwari (2017) associated a higher probability of severe crashes on 2-lane highways with the absence of raised medians. Das et al. (2018) indicated that at-fault motorcyclists sustained more severe injuries when involved in crashes that occurred on two-way roadways with no physical separation than two-way roadways with physical separation, one-way roads, and two-way roads with physical barriers.

The roadway functional classification influenced the severity of motorcycle crashes. Interstates were associated with higher likelihood of fatal and incapacitating injuries in motorcycle crashes than other road classes (Wu et al., 2018). This finding was attributed to higher operating speeds despite the higher design standards adopted on the interstate network. Li et al. (2009) indicated that the proportion of fatal crashes on local roads (collector and access roads) was higher for motorcyclists than motor-vehicle occupants. It was suggested that higher risk on local roads was associated with low engineering standards and traffic management (e.g., less lighting, markings, traffic signs, traffic signals, and enforcement) that might be inadequate for motorcyclists. Albalate and Fernández-Villadangos (2010) found that the risk of severe PTW crashes was higher on interurban roads (ring roads) than on urban roads. For crashes involving at-fault motorcyclists, Nguyen et al. (2021) found that the risk of severe injuries was higher in crashes that occurred on national roads than on rural roads. Both Albalate and Fernández-Villadangos (2010) and Nguyen et al. (2021) associated higher severity of crashes with higher operating speeds on interurban and national roads. Manan and Várhelyi (2012) indicated that primary or arterial roads were associated with a higher risk of fatal crashes. This observation was attributed to intrinsically dangerous features on primary roads, such as trees, open culverts, access to rural houses, and narrow road barriers. Rahman et al. (2021) found that fatal crashes were more likely to occur on highways than city or feeder roads. Similarly, Salum et al. (2019) found that crashes were more likely to be fatal when they occurred on collectors than access roads. Results from Rahman et al. (2021) and Salum et al. (2019) could be attributed to relatively lower speed restraints on highways and collectors than city/feeder roads and access roads, respectively.

Area Type and Land Use

Table 6 summarizes the findings of previous studies on the effect of area type and land use on the frequency and severity of motorcycle crashes. Area types, commonly categorized into rural and urban areas, could influence the occurrence of motorcycle crashes. Previous research revealed conflicting results on the effects of area type based on the type of crashes. Kim et al. (2000) and Kim et al. (2002) found that alcohol-impaired and single-vehicle motorcycle crashes were more likely to occur in rural than urban areas. It was suggested that alcohol-impaired motorcycle crashes be treated as a subset of single-vehicle motorcycle crashes. Also, it was indicated that single-vehicle motorcycle crashes are affected by the effects of alcohol, speeding, and risky actions and the influences of environmental and roadway factors such as those found at rural locations. Conversely, several studies (da Silva, 2020; Flask & Schneider, 2013; Harrison & Christie, 2005) found that urban locations and their peripheries increased the likelihood of motorcycle crashes in general, those involving a single vehicle, and those involving commercial motorcycle couriers. Flask and Schneider (2013) attributed this observation to the presence of more destinations and residents in urban areas, increasing the potential for single-vehicle motorcycle crashes. It was also suggested that the results were influenced by underreporting of single-vehicle motorcycle crashes, especially in rural areas due to low injury severities, unlicensed riders, and minimum presence of police and witnesses.

The likelihood of motorcycle riders and pillion passengers sustaining severe injuries was higher when a crash occurred in rural than urban areas (Barzegar et al., 2020; Jiang et al., 2020; Kashani et al., 2014; Kim et al., 2002; Li et al., 2009; Manan & Várhelyi, 2012; Shaheed et al., 2013; Shaheed & Gkritza, 2014). A higher risk of severe crashes in rural areas could be attributed to a lack of strict monitoring of motorcyclist behaviors, such as speeding and alcohol consumption in rural areas (Vajari et al., 2020). On the other hand, urban areas elevated the risk of motorcyclists' injuries compared to motor-vehicle occupants (Keall & Newstead, 2012). Dadashova et al. (2021) found that urban areas were associated with a higher likelihood of severe crashes than rural areas. Geedipally et al. (2011) attributed a higher likelihood of fatal single-vehicle motorcycle crashes in urban than rural areas to the collision with roadside fixed objects. Conversely, Wahab and Jiang (2019) found that rural areas were associated with a higher likelihood of fatal injuries in motorcycle crashes than urban locations. It is possible that higher speeds on roadways in rural areas influence the severity of motorcycle crashes.

Table 5. Summary of the effects of road type on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Ohio, USA	MV	Principal and minor arterials	Segments with ≥6 lanes experienced lower crash rates; divided highways were associated with a reduction in the frequency of motorcycle-vehicle crashes	Flask et al. (2014)
Severity	Ohio, USA	All	All	2-lane roadways were associated with an increased likelihood of fatal, incapacitating, and non-incapacitating injuries from single-vehicle and non-intersection-related multi-vehicle crashes	Schneider and Savolainen (2011)
	Wyoming, USA	All	All	Roads with ≥4 lanes were associated with an increased likelihood of fatal and incapacitating injuries in motorcycle crashes	Rezapour et al. (2020)
	India	All	National highways	Risk of fatal crashes was higher on 2-lane than 4-lane highways	Naqvi and Tiwari (2017)
	Louisiana, USA	All	All	Severity increases when there is no physical separation between two-way roadways	Das et al. (2018)
	USA	All	All	Interstates were associated with a higher likelihood of fatal and incapacitating injuries in motorcycle crashes than other road classes	Wu et al. (2018b)
	Taiwan	All	All	Higher risk of motorcyclists' fatalities than motor-vehicle occupants on local roads	Li et al. (2009)
	Hanoi, Vietnam	All	All	Higher risk of severe injuries on national roads than rural roads in crashes involving at-fault motorcyclists	Nguyen et al. (2021)
	Barcelona, Spain	All	All	Higher risk of fatal PTW crashes on interurban roads (ring roads) than urban roads	Albalate and Fernández-Villadangos (2010)
	Malaysia	All	All	Higher risk of fatal crashes on primary or arterial roads	Manan and Várhelyi (2012)
	Dhaka, Bangladesh	All	All	Higher risk of fatal crashes on highways than city or feeder roads	Rahman et al. (2021)
	Dar es Salaam, Tanzania	All	Arterial, collector, and access	Higher risk of fatal crashes on collector than access roads	Salum et al. (2019)

Note: MV means multiple vehicles

Investigation of the effects of land use on motorcycle safety is rare. However, a few studies found a relationship between land use and the frequency and severity of motorcycle crashes. Kim et al. (2002) found that motorcycle crashes were clustered in areas where people live and work. Not surprisingly, it was indicated that these locations are considered activity generators consisting of most riders' trips. Das et al. (2018) found that residential areas reduced the likelihood of motorcycle users' likelihood of severe injuries and attributed this finding to lower speed limits in residential neighborhoods. Kashani et al. (2014) revealed that the fatality risk of pillion passengers is higher in recreational, agricultural, and nonresidential land uses of urban areas. Islam and Brown (2017) found that motorcycle-at-fault crashes in areas with land use that is not residential, commercial, or industrial in urban locations were associated with an increase in the likelihood of incapacitating injuries. Conversely, Manan and Várhelyi (2012) found a higher risk of motorcycle fatalities in residential areas than in areas with other land uses. However, it was not explained how the residential areas increased the risk of motorcycle fatalities.

Table 6. Summary of the effects of area type and land-use on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Hawaii, USA	SV	All	Higher likelihood of SV motorcycle crashes in rural locations	Kim et al. (2002)
	Hawaii, USA	All	All	Higher likelihood of alcohol-related motorcycle crashes in rural locations	Kim et al. (2000)
	New South Wales, Australia	All	All	The motorcycle crash rate was highest in the metropolitan area	Harrison and Christie (2005)
	Sao Paulo, Brazil	All	All	Majority of crashes involving motorcycle couriers occur in the urban peripheries	da Silva (2020)
	Ohio, USA	SV	All	Urban locations experienced an increased occurrence of motorcycle crashes	Flask and Schneider (2013)
Severity	Iowa, USA	MV	All	Urban locations were associated with an increased likelihood of non-incapacitating injuries in motorcycle crashes	Shaheed et al. (2013)
	Iran	All	All	Most fatal motorcycle crashes occur outside cities	Barzegar et al. (2020)
	Iran	All	All	Likelihood of fatal injuries to pillion passengers was higher in crashes that occurred in rural areas	Kashani et al. (2014)
	Malaysia	All	All	Highest number of motorcycle fatalities occur in rural areas	Manan and Várhelyi (2012)
	Iowa, USA	SV	All	Higher severity of motorcycle crashes occur in rural than urban roads	Shaheed and Gkritza (2014)
	New Zealand	All	All	Urban areas increased the risk of motorcyclists' injuries than drivers	Keall and Newstead (2012)
	Texas, USA	SV	All	Higher severity of motorcycle crashes occur in urban than rural locations	Dadashova et al. (2021)
	Ghana	All	All	Probability of fatal motorcycle crashes higher in rural than urban settlements	Wahab and Jiang (2019)
	Louisiana, USA	All	All	Residential areas were associated with minor injury crashes	Das et al. (2018)
	Iran	All	All	Risk of pillion passenger fatalities was high in recreational, agricultural, and non-residential land uses of urban areas	Kashani et al. (2014)
	Alabama, USA	All	All	Areas with land use that is not residential, commercial, or industrial in urban locations were associated with an increased likelihood of incapacitating injuries in motorcycle-at-fault crashes	Islam and Brown (2017)
	Malaysia	All	All	Highest number of fatal motorcycle crashes occur in residential areas	Manan and Várhelyi (2012)

Note: SV means single vehicle; MV means multiple vehicles

Roadside Objects

Most motorcyclists' fatalities are due to single-vehicle crashes involving collisions with an object in the road environment (Trafikverket, 2010). The most common roadside objects struck by motorcycles are trees, fences, safety barriers, drainage infrastructure, and streetlights or traffic poles (Milling et al. 2016). The risk of fatal crashes was higher in single-vehicle motorcycle crashes when a collision involved guardrails, posts, and trees (Bambach et al., 2011; Schneider & Savolainen, 2011).

The effect of road barriers deserved specific attention in the previous studies. A collision with guardrails was more likely to result in a fatality than possible injuries (Dadashova et al., 2021). The effect of road barriers on the outcome of crashes varies with the barrier type. Berg (2005) indicated a higher risk of injuries when motorcyclists collided with wire rope or concrete barriers than with conventional steel systems. The concrete barriers were associated with a risk of riders being deflected into oncoming traffic and did not dissipate as much kinetic energy as compared to systems made of steel. However, Jama et al. (2011) found that steel W-beam guardrails on horizontal curves were predominantly involved in motorcycle fatalities.

Road Surface Conditions

Road surface conditions can affect the safety of motorcyclists, although, like much else in the motorcycle literature, the results appear to be uncertain. Conflicting results were found in studies that analyzed the effect of road surface conditions on motorcycle crashes. Table 7 summarizes the findings of previous studies on the effect of road surface conditions on the frequency and severity of motorcycle crashes. Xin et al. (2017) found that good road surface conditions on horizontal curves increased the likelihood of crash occurrence. Also, Vajari et al. (2020) observed that paved roads were more likely to be associated with fatal crashes than unpaved roads. Both Xin et al. (2017) and Vajari et al. (2020) attributed this finding to risk-compensation behavior, where motorcyclists engage in risky behavior when they realize the pavement is good and are careful when using poor or unpaved roads.

Conversely, Kim et al. (2002) and Shin et al. (2019) found that road defects and uneven road surfaces increased the frequency of motorcycle crashes. Motorcycle crash rates were higher on asphalt-paved than concrete-paved segments (Flask et al., 2014). It was only suggested that the type of pavement on a roadway could affect vehicular dynamics during a collision. Wankie et al. (2021) indicated that unpaved, muddy, and pothole-ridden roads increased the severity of single-vehicle motorcycle crashes. Wankie et al. (2021) attributed the finding with odds of crashes during rainy conditions, use of worn tires on muddy roads, and excessive speeding to make up for lost time due to poor roadway conditions. Therefore Milling et al. (2016), suggested that improving road surface conditions could reduce the severity and frequency of motorcycle crashes.

Table 7. Summary of the effects of road surface conditions on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Hawaii, USA	Single vehicle	All	Road defects increased the frequency of single-vehicle motorcycle crashes	Kim et al. (2002)
	Korea	All	All	Uneven road surfaces increased the crash frequency	Shin et al. (2019)
	Florida, USA	All	Undivided rural 2-lane	Better pavement conditions on horizontal curves increased crash occurrence	Xin et al. (2017)
Severity	Ohio, USA	Multiple vehicles	Principal and minor arterials	Lower crash rates on concrete- than asphalt-paved segments	Flask et al. (2014)
	Bamenda, Cameroon	Single vehicle	All	Road defects (i.e., unpaved, pothole-ridden, and muddy) increased the severity of single-vehicle crashes involving motorcycle couriers	Wankie et al. (2021)
	Victoria, Australia	All	All	Unpaved roadways were associated with a lower risk of fatal crashes	Vajari et al. (2020)

Lane and Shoulder Width

Studies have shown that lane and shoulder width significantly affect the severity and occurrence of motorcycle crashes. Table 8 summarizes the findings of previous studies on the effect of lane and shoulder width on the frequency and severity of motorcycle crashes. Urban roads wider than 20 feet were associated with an increased likelihood of motorcycle crashes (Jimenez et al., 2015). The higher likelihood of motorcycle crashes was attributed to the influence of wider roads to incite speeding and risky overtaking maneuvers (Jimenez et al., 2015). Conversely, Flask et al. (2014) found that narrow lanes increased the frequency of multi-vehicle motorcycle crashes. It was suggested that narrower lanes might not provide enough space for a motorcycle or motor vehicle to perform evasive crash maneuvers. On the other hand, wider lanes reduced the severity of roadway-departure motorcycle crashes involving fixed objects (Dadashova et al., 2021).

Narrow shoulders increased the frequency of motorcycle crashes with other motor vehicles (Flask et al., 2014). Also, narrower shoulders (< 6 ft) along horizontal curves on rural 2-lane highways increased the frequency of single-vehicle motorcycle crashes (Schneider et al., 2010). Similar to the effect of narrow lanes, narrower shoulders were associated with insufficient space for a motor vehicle or motorcycle to avoid a dangerous situation that could lead to a crash (Flask et al., 2014). In addition, narrower shoulders could also increase the risk of collisions with guardrails and other roadside objects (Schneider et al., 2010). In terms of crash severity, wider shoulders were associated with a higher likelihood of fatalities and serious injuries (Dadashova et al., 2021).

Table 8. Summary of the effects of lane and shoulder width on motorcycle crashes

Effect	Study area	Crash type	Road type	Findings	Reference
Frequency	Ohio, USA	Single vehicle	Arterial and collector	Narrow shoulders (< 6ft) increased the frequency of single-vehicle motorcycle crashes	Schneider et al. (2010)
	Ohio, USA	Multiple vehicles	Principal and minor arterials	Narrow shoulders increased the frequency of motorcycle-vehicle crashes	Flask et al. (2014)
	Bogota, Colombia	All	All	Urban roads wider than 20 feet increased the likelihood of motorcycle crashes	Jimenez et al. (2015)
	Ohio, USA	Multiple vehicles	Principal and minor arterials	Narrow lanes increased the frequency of motorcycle-vehicle crashes	Flask et al. (2014)
Severity	Texas, USA	Single vehicle	All	Wider lanes were associated with minor injury crashes	Dadashova et al. (2021)
	Texas, USA	Single vehicle	All	Wider shoulders were associated with severe injury crashes	Dadashova et al. (2021)

Summary

This review has shown that numerous studies have evaluated the relationship between motorcycle safety and many of the individual elements that comprise the Safe Systems approach: Safe Users, Safe Vehicles, Safe Speeds, and Safe Roads. The user attributes analyzed include riding violations, helmet use, age and experience, alcohol and drug use, and pillion passengers. The vehicle attributes and technologies analyzed include motorcycle type, engine type, braking systems, crash bars, airbags, fuel tanks, and headlights. In addition, studies considered the effect of speed limits on the occurrence and severity of motorcycle crashes. Finally, the roadway elements that influence motorcycle safety include but are not limited to intersections, road alignment, road type, area type, land use, roadside objects, road surface condition, and lane and shoulder width. Some literature has also shown efforts to improve motorcycle safety by promoting campaigns that focus on changing motorcyclists' behavior, including promoting helmets use and educating motorcyclists on the effects of drunk driving.

The Safe System approach aims to reduce the injury risk of motorcycle crashes by focusing on all major parts of the system: roadways, speeds, vehicles, and people. There is guidance on the Safe System approach targeting motor vehicles, pedestrians, and bicyclists. However, efforts on the Safe System approach on motorcycles are scant. Motorcycles provide a far greater challenge to the Safe System approach due to the combination of the user's vulnerability and high operational speeds. This article summarized efforts to develop a Safe System approach focusing on motorcycles. It also provided a review of efforts to improve motorcycle safety by focusing on individual elements of Safe Systems.

Few previous efforts attempted to address motorcycle safety using the Safe System approach. These efforts involved identifying causes of or proposing solutions to motorcycle crashes and trauma by concomitantly considering the four pillars of the Safe System approach. Austroads (2018) categorized the Safe System approaches and treatments according to their influence on the likelihood and severity of motorcycle crashes. The proposed measures include separating motorcycles from motor vehicles, freeing the roadside areas from hazards that can trip upright motorcyclists, having consistent road feature design and delineation for routes, using motorcycle-friendly barrier systems, using flexible signposts, and using speed enforcement and enforcing other regulations.

In Spain, a Safe System approach to motorcycle crashes that comprised 36 measures was proposed to reduce motorcycle crashes (DGT, 2007). The 36 measures were summarized into the following categories: improving riders' training, reducing high-accident-rate scenarios, fighting risky driving, and mitigating measures to reduce the harmfulness of crashes. Similarly, Transport Scotland (2016) attempted to apply a Safe System approach to motorcycle crashes using measures that focused on issues, such as inappropriate placement of white lines or ironworks, the foreshortened lengths of anti-skid surfacing in braking zones, and off-road hazards (Transport Scotland, 2016). Trafikverket (2010) outlined a strategy using a Safe System approach that can help reduce the number of motorcycle fatalities in Sweden by half and reduce the number of seriously injured by 40% between 2010 and 2020. The strategy identified areas with the greatest possibilities for instituting measures that can achieve these goals. The areas of prioritization in improving motorcycle safety included: increasing the number of motorcycles with antilock braking systems (ABS), increasing the number of motorcyclists who ride within the speed limit, increasing focus and alertness, making safer roads and streets, and reducing extreme behavior of motorcycles.

Few studies evaluated the effect of the Safe System approach on motorcycle crashes. Bambach et al. (2015) applied the Safe System approach to motorcycle crashes in Australia and the United States. The study was focused on motorcycle crashes with fixed objects, including roadside barriers (e.g., concrete barriers and steel W-beam barriers), trees, utility poles, and posts. The study analyzed one variable from each element of the Safe Systems, including the presence of roadside barriers (Safe Roads), motorcyclists wearing a helmet (Safe Vehicle), the crash was speed-related (Safe Speeds), and a crash was alcohol-related (Safe Users). The study evaluated crashes where a motorcyclist was killed, hospitalized, or seriously injured. The risk was first analyzed by considering the variables concomitantly. Results showed the difference between two extreme groups (no barrier, no helmet, speeding, and alcohol-related versus barrier, helmet, not speeding, and not alcohol-related). The differences in the risk of crash injuries were apparent when the factors were considered together than when considered independently. The Safe System approach reduced rates of crashes involving a killed, hospitalized, or seriously injured motorcyclist in the United States and Australia.

Chang et al. (2019b) identified scenarios that combine the human, vehicle, roadway, and environmental factors causing severe motorcycle crashes. The study found two extreme scenarios leading to motorcycle crashes with fatal or severe injuries. The first scenario involved a motorcycle getting hit on the weekend by a heavy-vehicle driver without a license, driving a substandard vehicle, speeding, changing lanes illegally, or driving in the wrong direction. The second scenario involved a motorcycle getting hit on a weekday by a heavy-vehicle driver aged 18-34 or 45-54, who was driving without a license, in a substandard vehicle, speeding, changing lanes illegally or driving in the wrong direction (Chang et al., 2019b). In addition to education and enforcement measures to reduce riding violations, the study suggested separating motorcyclists from motor vehicles by implementing motorcycle-exclusive lanes.

Gaps in the literature include the role of the environmental factors (e.g., weather and time of day) in a Safe Systems perspective. Understanding the interaction of environmental factors and other elements of the Safe Systems will help improve motorcycle safety. In addition, recent motor vehicle studies have also introduced a component to Safe Systems called Post-Crash Response, which should be considered when developing a Safe Systems framework for motorcycle crashes (World Health Organization, 2016). Efforts in this element of Safe Systems can consist of measures such as detection technologies that alert emergency responders and police on crashes, especially single-vehicle motorcycle crashes in rural areas.

Part II: Examining Motorcycle Crash Incidence in Southeast Florida

The second section of this study examines motorcycle crashes in Southeast Florida, which includes Miami-Dade, Broward, and Palm Beach Counties. Crash data were collected in the South Florida area for the 2015-2017 period. During this time period, 6,624 PTW riders were involved in crashes, with 481 crashes involving motorcycles that had pillion passengers. Approximately 90% (5,962) of the riders involved in a crash were Florida residents, while 4% (265) of the PTW riders resided in other states, and residential information for the remaining 6% (397) of riders was missing. The risk of PTW riders' involvement in crashes varies with their demographic characteristics, such as age and gender. This section discusses the distribution of crashes according to the sex and age of riders, stratified by the time of day, day of the week, drug or alcohol suspicion, and crash type.

Sex and Age

Motorcycle crashes predominantly involved male riders, 88% of all riders. Only 426 motorcyclists involved in crashes were female, 6% of the total. Also, 6% of the riders involved in crashes lacked information regarding their sex. Some of these motorcyclists were involved in hit-and-run crashes, so no personal information was available in the crash reports. Table 9 indicates that for males and females alike, most riders were involved in crashes between 3:00 pm and 6:00 pm.

Table 9. Motorcyclists involved in crashes, by sex and time of day

	Time of Day									
Gender	Midnight to 3 am	3 to 6 am	6 to 9 am	9 am to Noon	Noon to 3 pm	3 to 6 pm	6 to 9 pm	9 pm to Midnight	Total	Pct
Female	15	7	36	70	82	95	84	37	426	6%
Male	331	153	530	657	932	1,286	1,162	762	5,813	88%
Unknown	22	21	32	37	61	87	78	47	385	6%
Total	368	181	598	764	1,075	1,468	1,324	846	6,624	100%
Pct	6%	3%	9%	12%	16%	22%	20%	13%	100%	

Age is slightly associated with the type of crashes motorcyclists are involved in, such as non-collisions, striking fixed objects, or colliding with another vehicle. Table 10 shows the distribution of crash types according to age group. In general, most riders are involved in collisions with other vehicles. Higher percentages of riders aged 56-65 years and 66-75 years were involved in non-collisions. These non-collisions include overturning and falling or jumping from a motorcycle. This is contrary to the expectation that younger drivers' percentages for these types of crashes would be higher, considering their tendency to drive at speeds that are too fast for the conditions. However, this observation corroborates Dubois et al. (2020) that older drivers >70 years on 1,500 cc motorcycles were more likely to be speeding, weaving, and riding erratically than younger drivers on equivalent cc motorcycles. It could be that senior riders involved in these crashes are the ones using high-powered motorcycles. It was previously established that riders of these types of motorcycles are more susceptible to traffic violations. Results indicated that the percentage of riders under 16 years in collisions with fixed objects is significantly higher than all other age groups. Regardless of the type of crash, specific measures, in terms of education and policies, should be introduced to ensure individuals under the legal driving age do not get behind the wheel.

Table 10. Number and percentage of motorcyclists involved in a crash, by age and type of crash

	Crash type		
Age group	Non-collision	Fixed object	MV: In motion
<16	1 (4%)	4 (15%)	19 (70%)
16-19	33 (10%)	24 (7%)	268 (80%)
20-25	176 (12%)	99 (7%)	1,186 (79%)
26-35	175 (10%)	115 (7%)	1,358 (80%)
36-45	111 (12%)	62 (7%)	736 (80%)
46-55	113 (12%)	60 (6%)	754 (79%)
56-65	78 (15%)	39 (7%)	401 (75%)
66-75	25 (15%)	11 (7%)	122 (73%)
> 75	5 (11%)	4 (9%)	37 (79%)
Total	717 (12%)	418 (7%)	4,881 (79%)

Table 11 summarizes the age of PTW riders involved in all crashes according to the time of the crash. 451 riders with missing age were not considered. The largest share of riders in PTW crashes were between 20-35 years old, with the largest share of crashes occurring in the afternoon and early evening.

Table 11. PTW riders in all crashes, by time of day and age

	Time of day									
Age group	Midnight to 3 am	3 to 6 am	6 to 9 am	9 am to Noon	Noon to 3 pm	3 to 6 pm	6 to 9 pm	9 pm to Midnight	Total	Perc.
<16	0	0	0	2	8	10	6	1	27	0%
16-19	23	5	25	40	50	82	61	51	337	5%
20-25	109	32	109	150	219	319	327	228	1,493	24%
26-35	107	57	170	180	263	336	352	234	1,699	28%
36-45	46	30	97	114	124	208	186	118	923	15%
46-55	41	24	92	122	175	221	177	97	949	15%
56-65	17	10	50	68	108	137	98	44	532	9%
66-75	1	1	16	32	43	37	22	14	166	3%
>75	0	1	2	12	12	10	9	1	47	1%
Total	344	160	561	720	1,002	1,360	1,238	788	6,173	100%
Perc.	6%	3%	9%	12%	16%	22%	20%	13%	100%	

Role of Alcohol in Motorcycle Crashes

Alcohol is considered one of the factors influencing the risk of PTW crashes. Table 12 shows the distribution of riders suspected to be under the influence of alcohol or drugs when involved in a crash according to time of day and their age. 116 motorcyclists involved in collisions were suspected to be under the influence of drugs or alcohol, 2% of the total. Most riders suspected to be intoxicated when involved in crashes were 26 - 35 years old and most of these crashes occurred between 9 pm and 3 am.

Table 12. Number and percentage of motorcyclists involved in a collision suspected of being under the influence of drugs or alcohol, by age and time of day

	Time of day								
Age group	Midnight to 3 am	3 to 6 am	6 to 9 am	9 am to Noon	Noon to 3 pm	3 to 6 pm	6 to 9 pm	9 pm to Midnight	Total
< 16	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
16-19	2 (9%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
20-25	8 (7%)	0 (0%)	0 (0%)	1 (1%)	1 (0%)	1 (0%)	6 (2%)	4 (2%)	21 (1%)
26-35	9 (8%)	4 (7%)	2 (1%)	1 (1%)	3 (1%)	2 (1%)	6 (2%)	10 (4%)	37 (2%)
36-45	3 (7%)	2 (7%)	0 (0%)	5 (4%)	0 (0%)	1 (0%)	4 (2%)	7 (6%)	22 (2%)
46-55	3 (7%)	0 (0%)	2 (2%)	1 (1%)	1 (1%)	7 (3%)	5 (3%)	4 (4%)	23 (2%)
56-65	0 (0%)	0 (0%)	1 (2%)	0 (0%)	0 (0%)	4 (3%)	2 (2%)	2 (5%)	9 (2%)
66-75	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (3%)	0 (0%)	1 (7%)	2 (1%)
> 75	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total	25 (7%)	6 (4%)	5 (1%)	8 (1%)	5 (0%)	16 (1%)	23 (2%)	28 (4%)	116 (2%)

Location of PTW Crashes

This section discusses the attributes of PTW crash locations according to road classification. About 2,742 out of 6,519 crashes lacked road class information. To address this issue, GIS was used to plot the spatial coordinates of these crashes, allowing 2,181 out of 2,742 crashes to be assigned to a road. 532 crashes could not be correctly assigned and are omitted from consideration. Figure 3 shows the distribution of crashes according to the road classification. As shown in Figure 3, most motorcycle crashes occurred on arterial roads, while comparatively few occurred on interstates or expressways.

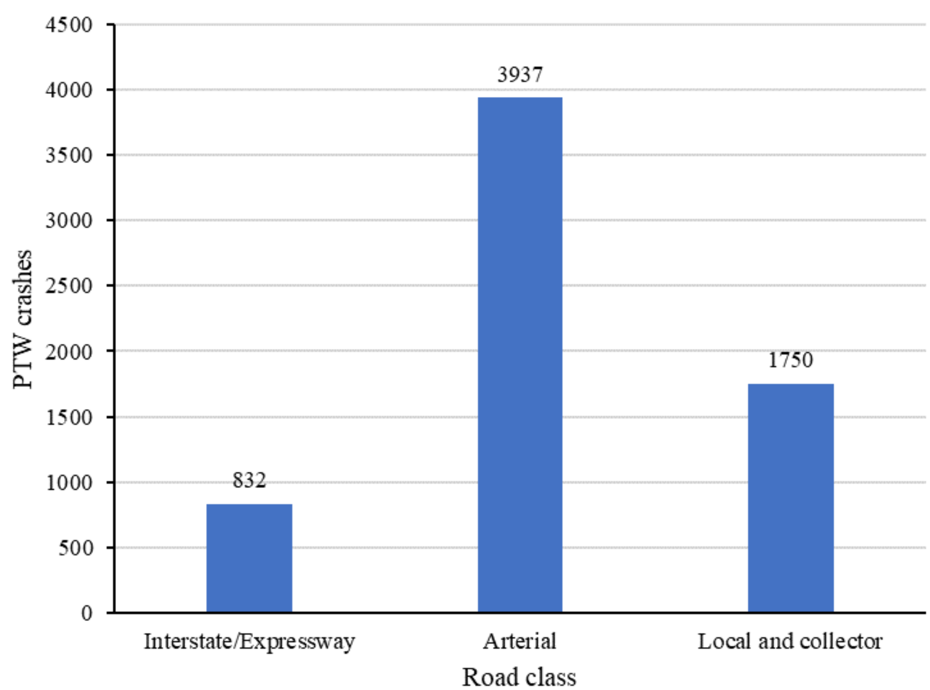


Figure 3. Distribution of PTW crashes according to the road classification

Non-Freeway Roadways

A total of 5,155 out of 6,519 PTW crashes occurred on non-freeways (i.e., arterial, local, and collector roads), or 79% of all crashes. Figure 4 shows the distribution of PTW crashes on arterials according to the crash location. About 71 crashes were recorded to have occurred on acceleration/deceleration lanes; entrance/exit ramps were not considered in the analysis. The crash location "other" included railway crossings, crossover-related, shared-use or trails, and locations not coded. 96 crashes were categorized into the "other" group. Most crashes (70%) occurred at non-intersection locations. A further investigation revealed that many crashes that occurred near or at driveways and alley accesses were included in the non-intersection crashes. Figure 5 provides extracts from crash reports showing an example of cases where motorcycle crashes occurred near driveways and were categorized as non-intersection locations.

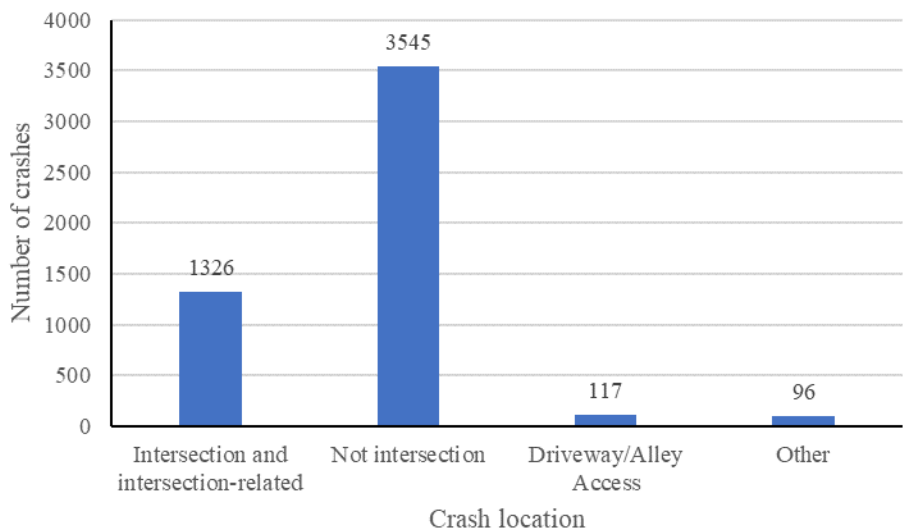


Figure 4. Distribution of PTW crashes on non-freeways according to crash location

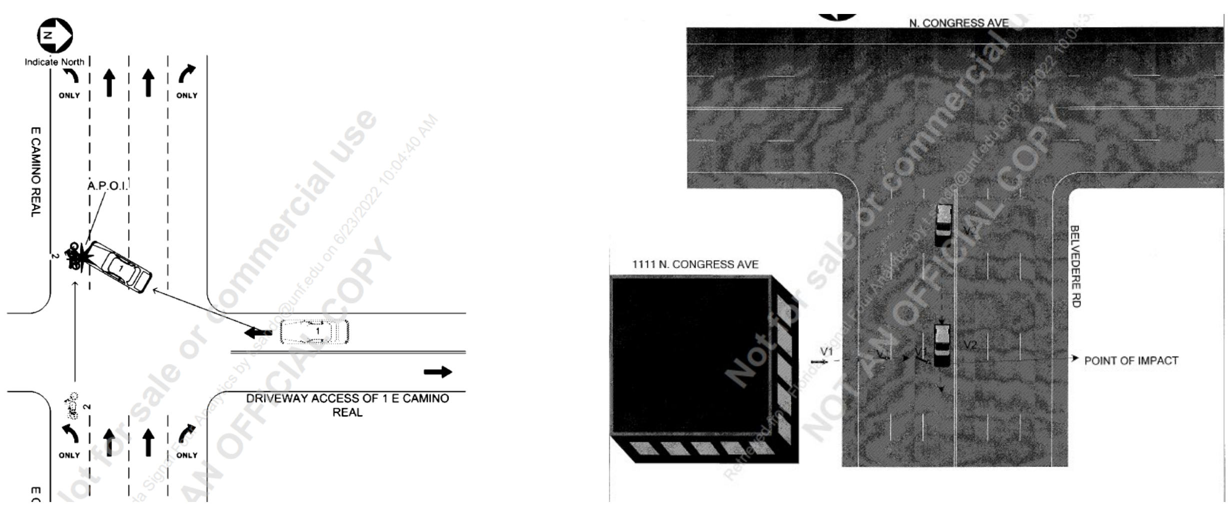


Figure 5. Examples of crashes occurring near driveways categorized as non-intersection crashes

An examination of the data revealed that a large number of angle collisions were reported as having occurred at non-intersection locations. As angle crashes tend to occur at driveways and intersections, we reviewed the police accident reports to determine whether an intersection was present, discovering that 549 crashes initially recorded to have occurred at non-intersection locations were re-classified to driveways or alley accesses. Figure 6 shows the new distribution of PTW crashes on non-freeways according to the crash location. Although the number of crashes at non-intersection locations fell, it is expected that some crashes that occurred near driveways could still be categorized as occurring at non-intersection locations. Efforts to ensure the right coding for motorcycle crash locations, especially driveways and alley accesses, could greatly help improve motorcycle safety. It has previously been found that the number of access points per mile increases the number of motorcycle fatalities per mile (Manan et al. 2013).

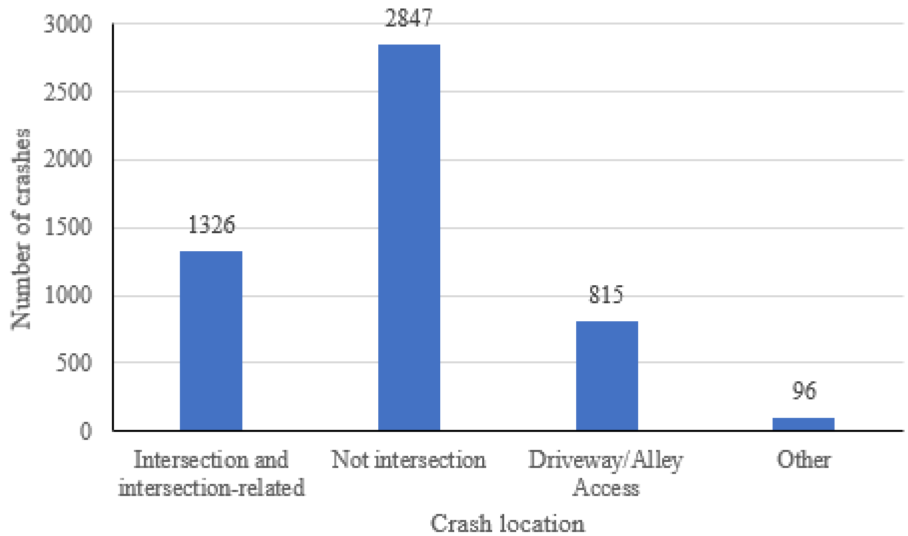


Figure 6. Distribution of PTW crashes on non-freeways, according to crash location after re-classification of non-intersection locations

Non-Intersection Locations

A total of 2,847 PTW crashes occurred at non-intersection locations on non-freeways. Figure 7 shows the distribution of PTW crashes at non-intersection locations according to the crash type. 77% of the crashes involved motorcycles colliding with other vehicles in motion. Non-collision crashes, which include overturning, and falling or jumping from a motorcycle, were the second most common crash type.

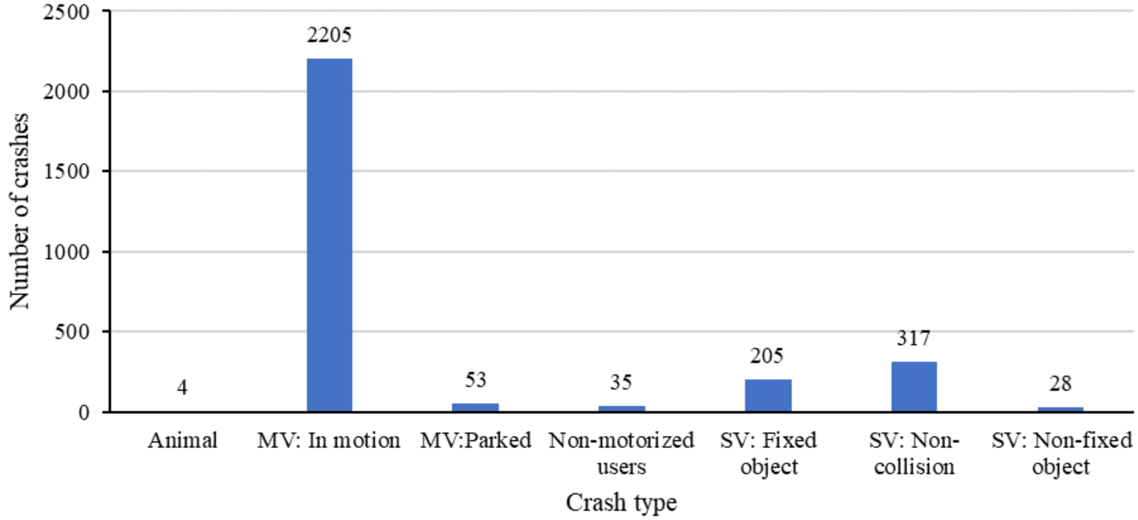


Figure 7. Distribution of PTW crashes at non-intersection locations according to crash type

Multiple-Vehicle Crashes at Non-Intersection Locations

Of multiple vehicle crashes involving a motorcyclist, the majority involved a rear-end collision, followed by other and sideswipe collisions (Figure 8). Considering that most non-intersection crashes were rear-end collisions, Table 13 shows their distribution according to the age of motorcyclist. Like the general trend of all motorcycle crashes, most rear-end crashes involved riders aged 26-35 years old.

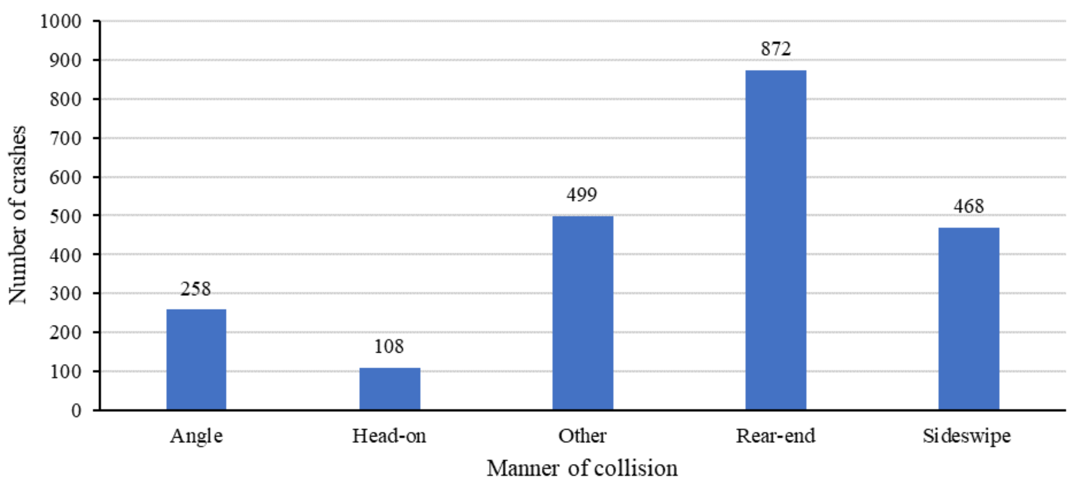


Figure 8. Distribution of non-intersection motorcycle multi-vehicle crashes, according to manner of collision

Table 13. Number and percentage of rear-end crashes at non-intersection locations, according to age of motorcyclist and severity of crash

Age	Fatal and incapacitating injury	Non-incapacitating and possible injury	No injury	Total
<16	0 (0%)	0 (0%)	0 (0%)	0 (0%)
16-19	3 (1%)	30 (9%)	10 (3%)	43 (13%)
20-25	26 (2%)	85 (6%)	50 (3%)	162 (11%)
26-35	37 (2%)	125 (7%)	58 (3%)	221 (13%)

36-45	19 (2%)	55 (6%)	50 (5%)	124 (13%)
46-55	19 (2%)	64 (7%)	59 (6%)	142 (15%)
56-65	14 (3%)	37 (7%)	28 (5%)	79 (15%)
66-75	8 (5%)	13 (8%)	6 (4%)	27 (16%)
> 75	0 (0%)	7 (15%)	2 (4%)	9 (19%)
Total	126 (2%)	416 (7%)	263 (4%)	807 (13%)

A total of 468 motorcycle crashes at non-intersection locations were sideswipes. Table 14 shows the distribution of sideswipe crashes according to the movement of vehicles involved. It is indicated that most sideswipes involved a motorcyclist going straight ahead and a driver changing lanes. This observation could be attributed to the low conspicuity of motorcyclists, because drivers cannot see motorcycles before changing lanes or they fail to judge motorcyclists' speed before executing the lane-changing maneuver. While the issue of drivers failing to see motorcyclists when making left or right turns at intersections could be solved by better traffic control systems, such as protected left turns, the failure to see motorcyclists at non-intersection locations may all be avoided by better vehicle technology. Technologies that warn drivers about motorcycle movement in blind spots or overtaking could help improve motorcycle safety.

Table 14. Distribution of sideswipe crashes, according to the motorcyclist’s and driver’s movement

	Driver’s movement													
Motorcyclist’ s movement	Changing lanes	Entering traffic lane	Leaving traffic lane	Making U-turn	Overtaking	Parked	Slowing	Stopped in traffic	Straight ahead	Turning left	Turning right	Unknown	Total	Pct
Changing lanes	7	0	0	0	0	0	1	4	40	1	2	0	55	13%
Leaving traffic lane	0	0	0	0	0	1	0	0	1	1	0	0	3	1%
Negotiating a curve	0	0	0	0	0	0	0	0	1	0	0	0	1	0%
Overtaking	3	0	0	1	0	1	2	4	9	6	6		32	7%
Slowing	0	0	0	0	0	0	1	1	0	0	0	1	3	1%
Stopped in traffic	0	0	0	0	1	0	1	0	7	1	0	0	10	2%
Straight ahead	100	7	1	8	3	5	1	12	68	25	22	27	279	65%
Turning left	1	0	0	0	0	0	0	1	2	8	1	0	13	3%
Turning right	1	0	0	0	1	0	0	3	5	1	5	1	17	4%
Unknown	2	0	0	0	0	0	1	1	3	2	1	5	15	4%
Total	114	7	1	9	5	7	7	26	136	45	37	34	428	100%
Pct	27%	2%	0%	2%	1%	2%	2%	6%	32%	11%	9%	8%	100%	

Single-Vehicle Crashes

As shown in Figure 7, 550 crashes were single-vehicle crashes, which involved a motorcyclist colliding with a fixed object or spilling the motorcycle (non-collisions). Figure 9 shows the distribution of the movement of PTW riders when involved in single-vehicle crashes at non-intersection locations on non-freeways. Most riders were involved in single-vehicle crashes while moving straight ahead. The second most common rider’s movement in SV crashes at non-intersection locations was negotiating a curve, which highlights the known issue with motorcyclists riding on horizontal curves. Table 15 shows the distribution of motorcycle single-vehicle crashes at non-intersection locations according to the age of motorcyclist and time of day. Most single-vehicle crashes involved riders aged 20-25 years. Motorcyclists aged 26-35 were the second most involved in single-vehicle crashes. Considering that the traveling speed of older motorcyclists involved in crashes is more likely to be lower than younger motorcyclists (Stutts et al., 2004), younger riders' involvement in single-vehicle crashes could be associated with their driving speeds. It was indicated that most single-vehicle crashes occurred between 3:00 pm and 6:00 pm. However, for riders aged 20-25 years, most single-vehicle crashes occurred between 9:00 pm and midnight.

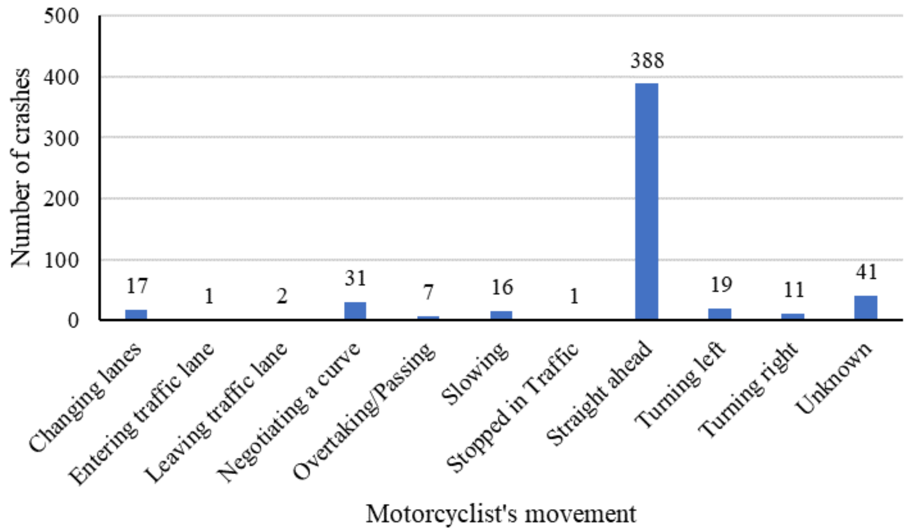


Figure 9. Distribution of rider's movement in PTW crashes involving a single vehicle at non-intersection locations on non-freeways

Table 15. Distribution of motorcycle single-vehicle crashes at non-intersection locations on non-freeways, according to motorcyclist age and time of day

	Time of day									
Age group	Midnight-3 am	3 - 6 am	6 - 9 am	9 am - Noon	Noon - 3 pm	3 - 6 pm	6 – 9 pm	9 pm - Midnight	Total	Pct
<16	0	0	0	0	0	0	0	0	0	0%
16-19	3	1	0	4	5	6	3	5	27	5%
20-25	13	7	10	14	17	24	23	29	137	26%
26-35	9	9	13	20	21	20	19	20	131	25%
36-45	10	3	6	9	8	10	16	12	74	14%
46-55	6	4	6	13	10	23	12	14	88	16%
56-65	2	1	3	8	12	16	10	6	58	11%
66-75	0	0	1	4	5	2	1	3	16	3%
> 76	0	0	0	0	0	1	2	0	3	1%
Total	43	25	39	72	78	102	86	89	534	100%
Pct	8%	5%	7%	13%	15%	19%	16%	17%	100%	

Intersections and Driveways

A total of 2,141 PTW crashes occurred at intersections, near intersections, and at driveways or alley accesses. Figure 10 shows the distribution of intersection, intersection-related, driveway, or alley access PTW crashes according to the crash type. 91% of the crashes involved collisions with other vehicles in motion. Non-collision crashes, which include overturning and falling or jumping from the motorcycle, were the second most common crash type. 47 crashes involved collisions with fixed objects.

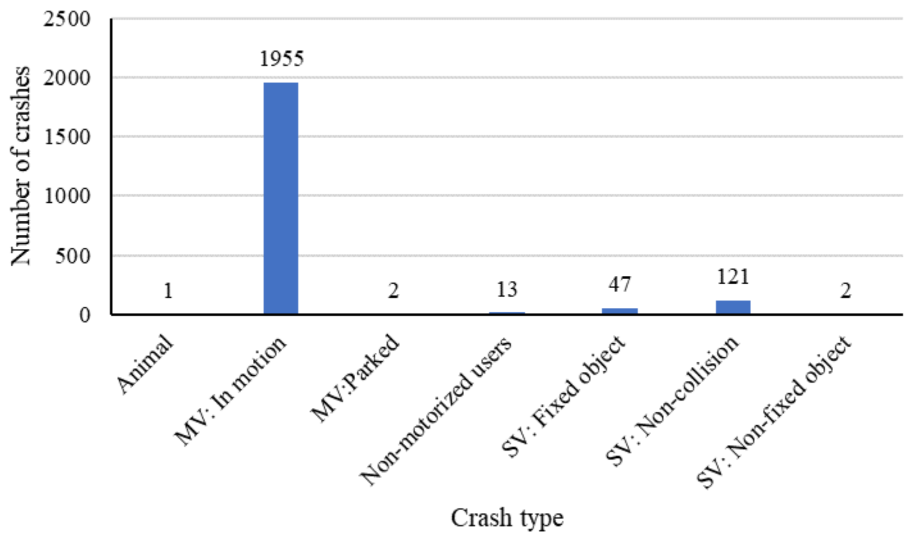


Figure 10. Distribution of intersection, intersection-related, and driveway/alley access PTW crashes, according to crash type

Multi-Vehicle Crashes at Intersections

Figure 11 shows the distribution of 1,955 multi-vehicle crashes at intersection locations according to the manner of collision. Nearly three-fourths were angle crashes. Table 16 is a matrix showing the movement of motorcycles and the vehicles they collided with in crashes at intersections. Most crashes involved a collision between motorcyclists attempting to travel straight through an intersection colliding with a vehicle attempting to turn left. This finding strongly suggests that the turning vehicle failed to see the oncoming motorcyclist. The second most common movements involved in crashes were both PTW and motor vehicles going straight ahead, movements resulting in the rear-end and sideswipe collisions shown in Figure 11.

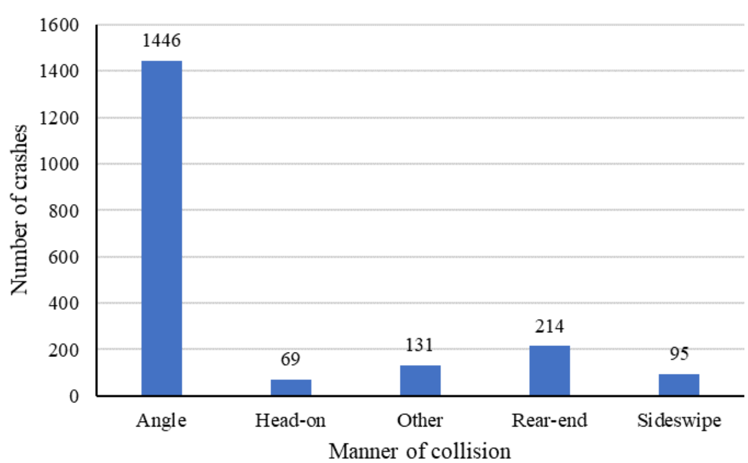


Figure 11. Distribution of intersection, intersection-related, and driveway/alley access PTW crashes involving multiple vehicles on non-freeways, according to the manner of collision

Table 16. Matrix of movement of motorcyclists and drivers in crashes at intersections and driveways

	Driver's movement														
Motorcyclist's movement	Backing	Changing lanes	Entering traffic lane	Leaving traffic lane	Making U-turn	Negotiating a curve	Overtaking	Parked	Slowing	Stopped in traffic	Straight ahead	Turning left	Turning right	Unknown	Total	Pct
Backing	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0%
Changing lanes	0	0	0	0	0	0	0	0	1	2	4	3	2	2	14	1%
Leaving traffic lane	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0%
Making U-turn	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	0%
Negotiating a curve	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2	0%
Overtaking	0	0	0	0	0	0	0	0	0	2	3	32	5	1	43	2%
Slowing	1	0	0	0	0	1	2	0	0	4	4	1	0	1	16	1%
Stopped in traffic	6	1	1	0	0	0	0	0	8	1	35	7	1	1	61	3%
Straight ahead	0	32	8	1	30	0	0	1	8	42	355	860	124	44	1,505	81%
Turning left	0	0	0	0	3	0	1	0	0	1	87	20	5	12	129	7%
Turning right	0	1	0	0	0	0	0	1	1	6	18	6	15	9	57	3%
Unknown	0	0	0	0	3	0	0	1	0	2	1	12	5	11	35	2%
Total	7	34	9	1	36	1	3	3	20	61	511	942	157	82	1,867	100%
Pct	0%	2%	0%	0%	2%	0%	0%	0%	1%	3%	27%	50%	8%	4%	100%	

Considering that most crashes involved a vehicle turning left in front of a motorcycle, as illustrated in Figure 13, we sought to understand the role of intersection control on left-turn crashes. As shown in Figure 12, the majority occurred at uncontrolled locations.

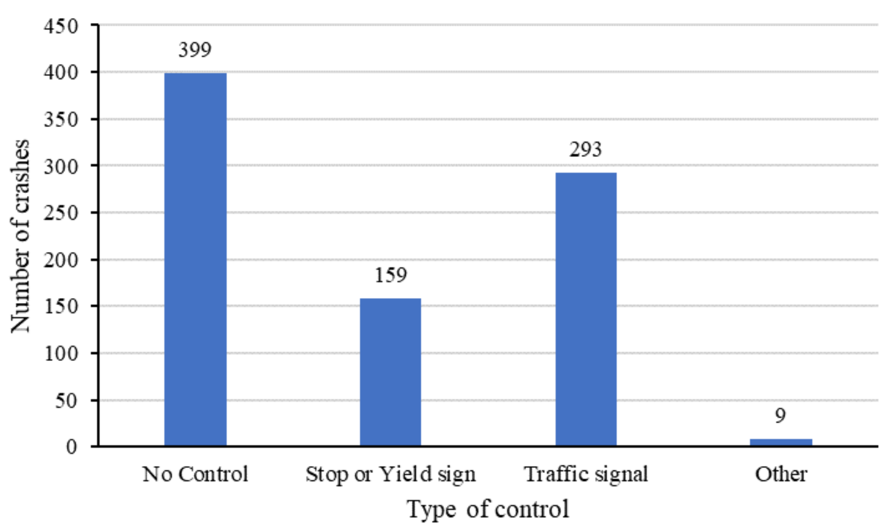


Figure 12. Type of traffic control in front of left-turning vehicles in crashes involving motorcyclists going straight ahead

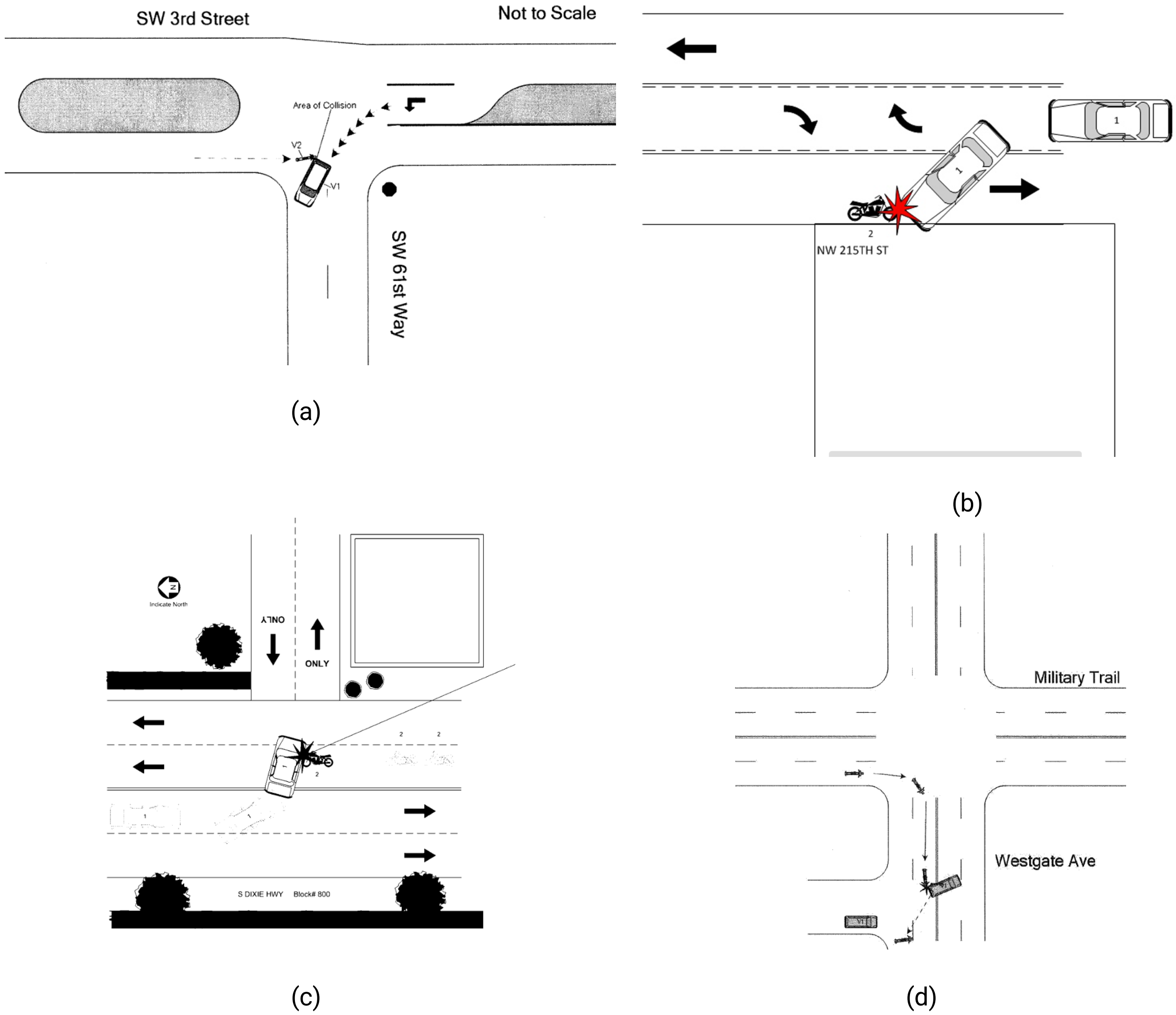


Figure 13. Examples of crashes involving drivers turning left and motorcyclists going straight ahead when there is no traffic control in front of the left-turning vehicle

Single-Vehicle Crashes at Intersections

Only 8% of intersection, intersection-related, and driveway/alley access PTW crashes involved a single vehicle. Figure 14 shows the distribution of the movement of PTW riders in single-vehicle crashes. 107 out of 168 crashes involved motorcyclists going straight ahead. Narratives of police crash reports revealed that most of these crashes occurred in motorcyclists' last-minute attempt to avoid colliding with motor vehicles at intersections. As indicated in the figure, some single-vehicle crashes occurred when motorcyclists turned right or left. A review of the crash reports indicated that some of these crashes involved loss of control of the motorcycle due to making a turn at high speeds.

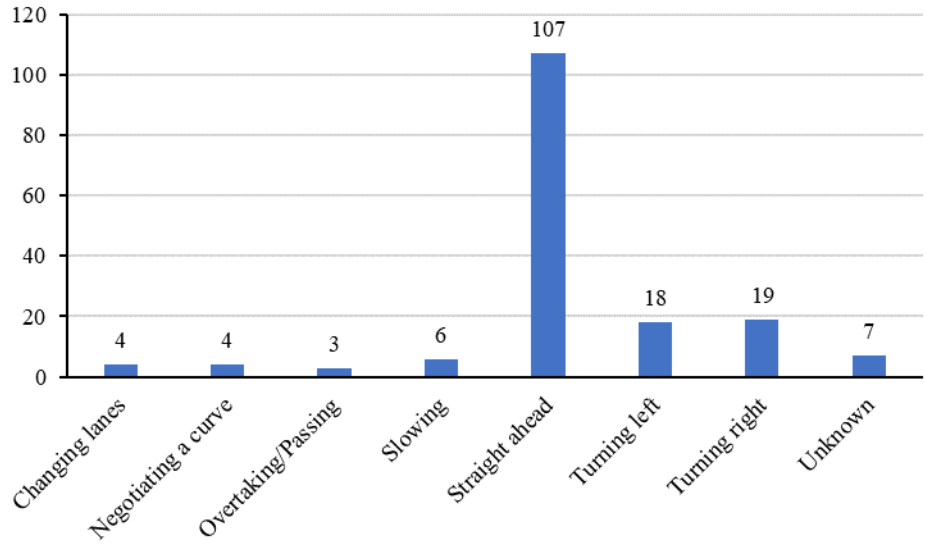


Figure 14. Movement of motorcyclists in single-vehicle crashes at intersections and driveways

Freeways

There were 832 PTW crashes that occurred on freeways, 13% of the total. Of these, 88% occurred along the mainline, with the remainder occurring at entrance and exit ramps. Figure 15 shows the distribution of PTW crashes on the mainline and ramps according to crash type. While the highest percentage of PTW crashes on the freeway mainline involved collisions with other vehicles, the highest percentage of crashes on the ramps were single-vehicle crashes, indicating that motorcyclists may have special difficulties maintaining control at these locations, which often include significant curvature.

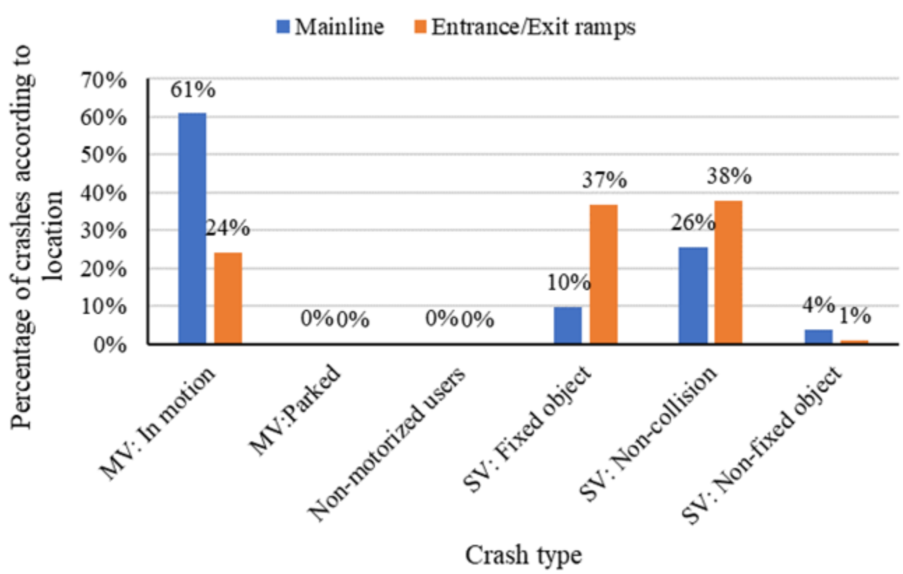
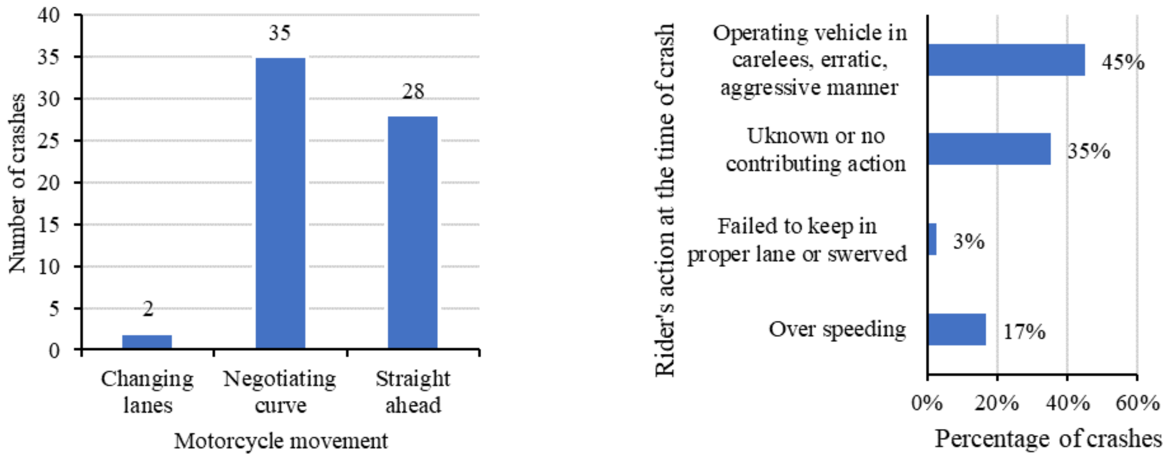


Figure 15. Distribution of PTW crashes on freeways, according to the crash type

Entrance and Exit Ramps

Most of the PTW crashes on the entrance and exit ramps were single-vehicle crashes. This could suggest the issue of motorcyclists losing control, especially when speeding on ramps (see Figure 16a) The other major movement in PTW crashes involving a single vehicle on the entrance and exit ramps going straight ahead. Moreover, Figure 16b indicated that in most of the single-vehicle crashes on exit and entrance ramps, motorcyclists rode in an erratic and careless manner. Designs that could reduce the speed of vehicles when entering ramps could help mitigate these types of crashes and improve motorcyclists' safety.



(a) Motorcyclist's movement

(b) Motorcyclist's action

Figure 16. Distribution of PTW crashes on exit and entrance ramps, according to motorcyclist's movement and action during a crash

Mainline

Multiple-Vehicle Crashes

As indicated in Figure 15, 61% (413 crashes) of PTW crashes on the freeway mainline involved collisions with another vehicle. Figure 17 shows the distribution of PTW crashes involving multiple vehicles on the freeway mainline according to the manner of collision. As expected, most of the crashes were rear-end collisions and sideswipes. Figure 18 shows motorcyclists' and drivers' movements in PTW crashes on the freeway mainline. Most crashes involved both motorcyclists and drivers going straight ahead, hence the rear-end crashes. PTW riders going straight ahead and drivers changing lanes are the second most common movements associated with crashes on the mainline. The other major movements involved riders changing lanes while drivers were going straight ahead and riders going straight ahead while drivers were slowing or stopping in traffic. These movements could also be associated with rear-end crashes.

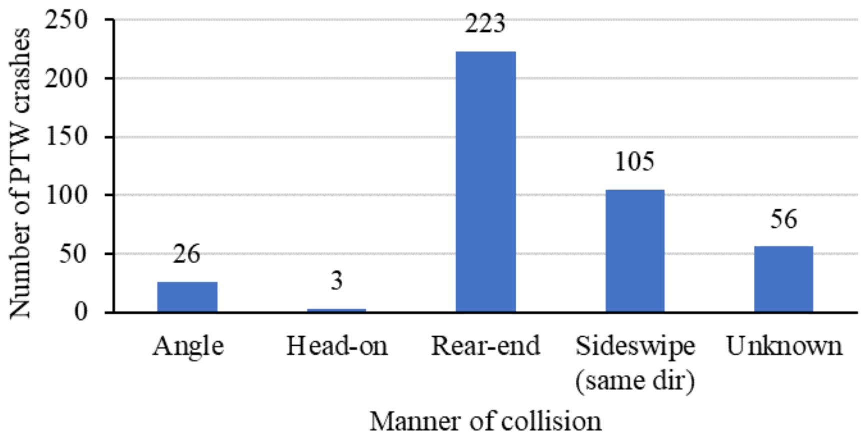


Figure 17. Distribution of PTW crashes involving multiple vehicles on the freeway mainline, according to the manner of collision

	Driver's movement													
Motorcyclist's movement	Backing	Changing lanes	Entering traffic lane	Leaving traffic lane	Negotiating a curve	Parked	Slowing	Stopped in traffic	Straight ahead	Turning left	Turning right	Unknown	Total	Pct
Changing lanes	0	10	0	0	0	1	3	2	41	1	0	2	60	15%
Entering traffic lane	0	0	0	0	0	0	0	0	1	0	0	0	1	0%
Leaving traffic lane	0	0	0	0	0	0	0	0	1	0	0	0	1	0%
Negotiating a curve	0	1	0	0	1	0	0	0	1	0	0	1	4	1%
Overtaking/Passing	0	0	0	1	0	0	1	1	4	0	0	0	7	2%
Slowing	0	0	0	0	0	0	2	1	10	0	0	1	14	4%
Stopped in traffic	0	1	0	0	0	0	0	1	4	0	0	1	7	2%
Straight ahead	1	61	1	1	0	1	33	19	141	4	1	29	292	74%
Turning left	0	0	0	0	0	0	0	0	0	1	0	0	1	0%
Unknown	0	0	0	0	0	0	1	0	4	0	0	1	6	2%
Total	1	73	1	2	1	2	40	24	207	6	1	35	393	100%
Pct	0%	19%	0%	1%	0%	1%	10%	6%	53%	2%	0%	9%	100%	

Figure 18. Matrix of motorcyclist's and driver's movements in PTW crashes involving multiple vehicles on freeway mainline

Single-Vehicle Crashes

Among freeway mainline PTW crashes, 259 were single-vehicle, 39% of the total. Figure 19 shows the distribution of the movements of PTW riders when involved in a single-vehicle crash. Most riders were involved in crashes while moving straight ahead. The other significant movements in PTW crashes involving a single vehicle were negotiating a curve and changing lanes. These movements were associated with 34 single-vehicle crashes on the freeway mainline.

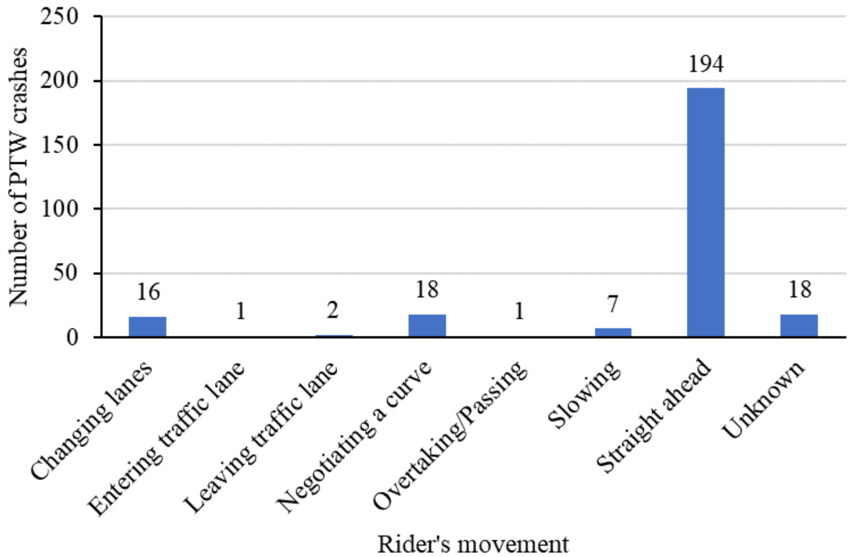


Figure 19. Distribution of PTW rider's movement in SV crashes on the freeway mainline

Crash Risk Factors in Urban Environments

The characteristics of the built environment have been consistently found to influence the incidence of crashes involving pedestrians, bicyclists, and motorists alike. In particular, multi-lane arterial thoroughfares and auto-oriented land uses such as strip commercial development, big box stores, and fast food restaurants have been found to result in dramatic increases in crashes, deaths, and injuries (Dumbaugh and Rae, 2010, Dumbaugh and Li, 2011; Saha, Dumbaugh, and Merlin, 2020), with these land uses resulting in substantially higher rates of crashes than one would expect from traffic volumes alone (Dumbaugh, Saha, and Merlin, 2020) To date, most of the literature on motorcyclist safety has focused on motorcyclist behaviors or the use of protective equipment. There has been surprisingly little examination into how the built environment may influence motorcyclist crashes, particularly in urban environments.

To fill this gap in the literature, this study examines the incidence of motorcycle crashes in Southeast Florida, consisting of Miami-Dade, Broward, and Palm Beach Counties. This study uses 3 years of data (2015-2017) for the analysis. Data on motorcyclists involved in collisions were obtained from the Florida State Safety Office and combined with geospatial references obtained through the Signal Four Analytics web portal. This crash database was then combined with census data and information on land use and street characteristics obtained from Florida Geographic Data Library. Parcel-level land use information was captured by counting those uses located within the block group boundaries. Streets and intersections proved a more complicated matter, as block group boundaries are often delimited by the presence of major streets. Nonetheless, the hazards posed by such facilities affect both adjacent block groups. To address streets located along block group boundaries, we ran a 200-foot buffer around each block group and assigned the streets located within the buffer to each adjacent block group. The result is a geospatial database of motorcyclist crashes occurring at the block group level, and which includes information on the area's demographic characteristics, transportation network characteristics, and land use composition. Crashes were assigned to the block group level.

Dependent Variables

The dependent variable for this analysis is the sum of total, KAB, and fatal crashes occurring at the block group level. Fatal crashes are crashes that resulted in the death of the motorcyclist, while KAB crashes are crashes that resulted in a motorcyclist death or incapacitating injury. As shown in Table 17, below, there was a great deal of variation in crash incidence across the block groups, with the typical block group experiencing

3 motorcycle crashes during the 3-year study period, about half of which resulted in death or incapacitating injury. The variance for these crashes was greater than the mean, indicating the negative binomial regression may be appropriately used to model these data.

Table 17: Descriptive statistics for motorcycle crashes at the block group level

	N	Min.	Max.	Mean	Std. Dev.	Variance
Total	3,410	0	47	3.09	4.340	18.837
KAB	3,410	0	29	1.54	2.319	5.378
Fatal	3,410	0	6	.11	.377	.142

Independent Variables

Crashes were modeled as a function of the characteristics of the block group's street and street network, as well as a function of the land uses contained within it. Each of these variables is described below, followed by descriptive statistics for these variables, included in Table 18.

Street and Network Characteristics

While streets classified as "arterials" are a known risk factor for pedestrians, bicyclists, and motorists alike, it is important to observe that it is not the classification of a street as an arterial thoroughfare that results in crash risk, but instead the design attributes typically associated with this street class, which include higher traffic volumes, multiple travel lanes, and higher operating speeds (Dumbaugh and Rae, 2009; Dumbaugh and Li, 2011; Dumbaugh et. al., 2013; Dumbaugh et. al., 2020). Because of the high correlation between number of lanes and annual average daily traffic, we were only able to include one of these variables in our models. As such, we believed number of lanes was the more relevant measure for motorcyclists, as more lanes not only allow for greater traffic volumes, but also provide additional opportunities for motorcycle filtering, which we believed to be a major risk factor.

We believed each of these characteristics would have different effects on motorcyclist crashes, and thus modeled annual average daily traffic, vehicles speeds, and the number of lanes as separate variables.

- % of streets with speed limits of 25 mph or less. This captures the presence of lower-speed street networks, which would be expected to result in fewer deaths and injuries, and which might conceivably also reduce total crashes by increasing stopping sight distance and allowing for greater preparedness on the part of motorists and motorcyclists alike.
- Miles of streets with 5 or more lanes. This variable is the sum of the miles of streets that have 5 or more lanes within a block group.
- Intersection density. More intersections create more conflict points and thus more opportunities for collisions to occur. This is the count of intersections in a block group, divided by block group acreage.

Land Use Characteristics

The location and configuration of land uses determine the origins and destinations of travel, as can create conditions that make crashes more, or less, likely to occur. Retail and commercial uses, in particular, have been identified as a potential risk factor, particularly when they take an auto-oriented form that includes driveways and unprotected ingress and egress. The data contained in the Florida Geographic Data Library allow these uses to be disaggregated into a finer level of detail to ascertain whether different types of commercial and retail uses are associated with different levels of risk. The following variables were analyzed:

- Population (thousands). This is the count of total persons residing in the block group. The total population was then divided by 1,000 to ease the interpretation of the model coefficients.

- # of groceries
- # of shopping centers
- # of restaurants
- # of gas stations
- # of bars and nightclubs
- # of hotels

Table 18: Descriptive statistics for independent variables

	Min.	Max.	Mean	Std. Dev.
Population (000s)	0	15.4	1.76	1.06
Miles of 5-or-more-lane roads	0	9.87	0.45	0.74
# intersections	0	119	12.20	17.17
% of streets 25 mph or less	0	1	0.02	0.11
# groceries	0	3	0.07	0.30
# shopping centers	0	30	0.32	1.31
# restaurants	0	24	0.70	1.51
# gas stations	0	9	0.46	0.82
# bars and nightclubs	0	6	0.07	0.35
# hotels	0	174	0.46	3.82

Model Results

The results of the models for total, KAB, and fatal motorcycle crashes are presented below. In addition to reporting coefficients and their significance levels we have also included interval rate ratios to ease in the interpretation of the findings.

Total Motorcycle Crashes

As shown in Table 19, motorcycle crashes increase with population, with each additional 1,000 residents in a block group being associated with a 6% increase in motorcycle crashes. Each mile of 5-or-more-lane street is associated with a 22% increase in motorcycle crashes, and each intersection is associated 1% increase in additional crashes. The presence of a lower-speed street network seemed to have a much stronger effect on motorcycle crashes, with a 1% increase in the percentage of streets with speeds of 25 mph or less being associated with a 55% reduction in motorcycle crashes. Of the land use variables, groceries and bars had the strongest relationship with motorcycle crashes, with each grocery associated with a 23% increase in expected motorcycle crashes, and each bar associated with a 20% increase. All of the remaining land use variables were positively and significantly related to motorcycle crashes except for the presence of commercial shopping centers, which had a positive coefficient, but which was not associated at conventional levels of statistical significance.

Table 19: Model for Total Motorcycle Crashes

	Coef.	Std. Err.	z	p	IRR
Population (000s)	0.055	0.017	3.15	0.002	1.057
Miles of 5-or-more-lane streets	0.198	0.025	7.90	0.000	1.218
# intersections	0.014	0.001	12.40	0.000	1.014
% of streets 25 mph or less	-0.663	0.197	-3.36	0.001	0.515
# groceries	0.205	0.057	3.62	0.000	1.227
# shopping centers	0.009	0.016	0.57	0.567	
# restaurants	0.088	0.013	6.54	0.000	1.092
# gas stations	0.152	0.024	6.42	0.000	1.164
# bars and nightclubs	0.179	0.050	3.62	0.000	1.197
# hotels	0.073	0.009	8.03	0.000	1.076
Constant	0.501	0.042	11.86	0.000	

KAB Motorcycle Crashes

Table 20 presents the model for motorcycle crashes resulting in the death or serious injury of the motorcyclist. The model results are roughly the same as that for total crashes, undoubtedly a result of the fact that most motorcycle crashes result in a death or serious injury.

Table 20: Model for KAB Motorcycle Crashes

	Coef.	Std. Err.	z	p	IRR
Population (000s)	0.057	0.020	2.89	0.004	1.059
Miles of 5-or-more-lane streets	0.260	0.028	9.33	0.000	1.297
# intersections	0.013	0.001	10.63	0.000	1.013
% of streets 25 mph or less	-0.366	0.221	-1.65	0.099	0.694
# groceries	0.148	0.064	2.31	0.021	1.160
# shopping centers	-0.011	0.019	-0.57	0.569	
# restaurants	0.068	0.015	4.62	0.000	1.070
# gas stations	0.169	0.026	6.47	0.000	1.184
# bars and nightclubs	0.153	0.054	2.85	0.004	1.166
# hotels	0.044	0.009	4.94	0.000	1.045
Constant	-0.176	0.048	-3.68	0.000	

Fatal Motorcycle Crashes

Table 21 presents the model for fatal motorcycle crashes. All of the variables entered the model with signs consistent with the models shown in Table 10 and Table 11, though not all of the variables entered the models at statistically significant levels. This is almost certainly a result of the relative infrequency of fatal crashes, forcing the model to rely on fewer observations. Nonetheless, the variables with the most profound impact on fatal crashes proved to be population, the mileage of 5-or-more-lane streets, with each additional mile of such streets associated with a 37% increase in expected motorcycle fatalities. Each additional intersection as associated with a 1.3% increase in motorcycle fatalities, while each percentage increase in streets with speeds of 25 mph or less was associated with a 0.95% decrease in motorcycle fatalities, a relationship that is almost perfectly elastic.

Table 21: Model for Fatal Motorcycle Crashes

	Coef.	Std. Err.	z	p	IRR
Population (000s)	0.136	0.046	2.94	0.003	1.146
Miles of 5-or-more-lane streets	0.320	0.057	5.60	0.000	1.377
# intersections	0.013	0.003	4.89	0.000	1.013
% of streets 25 mph or less	-3.022	1.350	-2.24	0.025	0.049
# groceries	0.158	0.158	1.00	0.319	
# shopping centers	0.000	0.041	0.01	0.994	
# restaurants	0.012	0.035	0.35	0.729	
# gas stations	0.124	0.062	1.99	0.047	1.132
# bars and nightclubs	0.065	0.132	0.49	0.624	
# hotels	0.000	0.015	0.01	0.989	
Constant	-2.829	0.123	-22.92	0.000	

Discussion

The model results highlight the role that vehicle speeds and traffic conflicts play on motorcycle crashes in urban environments. The presence of 5-or-more-lane streets, which allow motorcyclists to travel at higher speeds by filtering through traffic congestion, are associated with increases in total and KAB crashes, but especially notable increases in fatal crashes (see Table 22). This indicates that not only are motorcycle crashes more likely to occur on these facilities, but the crashes that do occur are more likely to be severe. The exact opposite effect can be seen for the presence of lower speed street networks. Here, the relationship between speed and fatalities is almost perfectly elastic, with each 1% increase in the percentage of streets with posted speed limits of 25 mph or less associated with a 0.95% reduction in motorcycle fatalities.

Table 22: Incident rate ratios for total, KAB, and fatal motorcycle crashes

	Total	KAB	Fatal
Population (000s)	1.057	1.059	1.146
Miles of 5-or-more-lane streets	1.218	1.297	1.377
# intersections	1.014	1.013	1.013
% of streets 25 mph or less	0.515	0.694	0.049
# groceries	1.227	1.160	
# shopping centers			
# restaurants	1.092	1.070	
# gas stations	1.164	1.184	1.132
# bars and nightclubs	1.197	1.166	
# hotels	1.076	1.045	

Traffic conflicts also appear to play a role in motorcycle crashes. Each additional intersection was associated with a 1.3% increase in total, KAB, and fatal motorcycle crashes. Other than shopping centers, all of the land uses examined in this study were associated with increases in motorcycle crashes, with gas stations and bars being especially problematic. In the case of the former, this is almost certainly because these uses tend to congregate at arterial intersections, increasing the number of traffic conflicts in locations that are already problematic. We were surprised that the presence of shopping centers did not prove to be meaningfully related to motorcycle crashes. This land use tends to be the most problematic for pedestrians and motorists, largely as a result of traffic conflicts created at driveways, particularly within this study area. It is unclear whether this is attributable to the traffic conflicts at these locations not being problematic for motorcyclists (which is unlikely), or whether motorcyclists tend to avoid locations with concentrations of these uses. Given that motorcycles lack cargo space for transporting goods, we strongly suspect that the latter is the case, particularly given the recreational nature of most motorcycle travel in the United States. This interpretation seems to be confirmed by the hazards posed by bars, restaurants, and hotels. These uses tend to concentrate together, particularly in areas with a great deal of tourist activity, and which likely serve as major trip ends for recreational motorcycle travel. Nonetheless, future research is needed to confirm this hypothesis.

Findings

Despite accounting for less than 1% of all vehicle miles traveled, motorcyclists account for 14% of the traffic fatalities that occur on roads in the United States each year (National Safety Council, 2022), with the fatality rate of motorcyclists per vehicle-mile traveled (VMT) roughly 28 times that of passenger car occupants (NHTSA, 2022). While motorcyclist safety efforts often focus on motorcyclist behavior such as helmet use or compliance with traffic laws, the move to a Safe Systems approach to road safety encourages safety professionals to further consider the underlying factors that may contribute to crash risk. Most of the existing research has focused on whether or not a motorcyclist crash resulted in a death or injury, rather than on the factors that may make such crashes more or less likely to occur. While useful for understanding the factors that may exacerbate severity, these studies do not explain why motorcyclists are more likely to be involved in a collision at certain locations (e.g., intersections) in the first place. Previous studies also provided glimpses on the use of motorcycle and vehicle technology in reducing the risk of motorcycle crashes.

This study sought to understand the characteristics of PTW crashes, specifically who is involved, where crashes occur, and how they occur. The South Florida region, comprising Miami-Dade, Broward, and Palm Beach County, served as the focus of this analysis. Crash data were obtained from the Crash Analysis Reporting System (CARS) database maintained by the Florida Department of Transportation (FDOT) for the 2015 to 2017 period. The collected data had 6,525 crashes involving motorcycles, equivalent to 2% of all 403,677 crashes. 832 of the crashes occurred on freeways, while 5,159 occurred at non-freeway locations. Findings from the analysis of these data, along with attendant recommendations for safety practices based on the review of the literature, are shared below across the four domains of the Safe Systems approach: Safe Users, Safe Vehicles, Safe Speeds, and Safe Roads.

Safe Users

Safe Users refers to the characteristics of road users and their behaviors. In this analysis, it was observed that most motorcyclists involved in crashes were male. Among female motorcyclists involved in crashes, there were no distinct characteristics in terms of time of day for crashes or otherwise. Data also revealed that most PTW crashes involved motorcyclists in the age group 20-35 years. It is considered that this group has the most motorcycle riders, but also that this subset of users is more prone to engage in risky riding behaviors. Motorcyclists aged 56-65 and 66-75 years were overrepresented in non-collision crashes, including overturning, jumping, or falling from the motorcycle. This suggests that older adults may have difficulty in controlling their motorcycles.

Most motorcycle crashes occurred from 3:00 pm to 6:00 pm, though motorcyclists aged 20-35 years tend to have more crashes between 6:00 PM and 9:00 PM. In light of findings regarding motorcycle users and the times of day and characteristics of their crashes, we recommend firstly strengthening motor vehicle driver education to make drivers more aware and watchful of low profile, low visibility motorcyclists. This is because it was observed that one third of non-intersection motorcycle crashes were either angle or sideswipe crashes, and that for most of these the motorcycle was driving straight. Additionally, nearly all intersection crashes were angle type crashes, suggesting a large safety problem with drivers effectively seeing motorcyclists while making turns.

Secondly, we recommend that states consider strengthening education requirements for motorcycle licensing. For example, Florida, the state that was studied for this report, already requires completion of a Motorcycle Safety Foundation (MSF) certified course. We recommend that such a course contain additional content, either through state addendums or through the modifications of the standard course template. For all users, including the most predominant group of those 20 to 35 years of age, we encourage strengthening education on what constitutes risky riding behavior, even where such behavior is not in violation of the law. The combination of complex high-speed arterial roads with afternoon rush hour congestion may present a reasonable risk for protected and steady automobile users, but for recreational motorcycle users riding at the same time the risk is much higher. Additionally, the specific challenges for older riders of riding powerful bikes should be addressed.

Safe Vehicles

Safe Vehicles refers to the characteristics of vehicles, such as the protections they offer to users, as well as any dangers they pose. Automobile users have benefitted greatly over the years from a raft of innovations towards preventing crashes and protecting them in the event of crashes, including improvements to braking systems, restraints, and airbags. Motorcycle users have benefited from some innovations, notably antilock braking, but less from advances in user protection. However, because the form of protection most widely available for motorcycles is not built-in to vehicles, recreational motorcycle users often do so as a choice. The most commonly available motorcycle airbag is a vest that must be worn by the rider. Most riders opt to not invest in and wear such vests. Automobile drivers by contrast make no such choice about whether to be protected by an airbag for a given trip since it is required to be built into the vehicle itself. Our literature review showed promising research in the area of built-in motorcycle airbags, however very few motorcycle models currently have such built-in airbags. Based on the literature review of this report, we recommend that research continue in the area of built-in motorcycle airbags, as well as the possibility for their being Federally required in new models when they have been shown to be reliable and effective. Only then would motorcycle users even begin to approach the levels of protections afforded to most automobile users. More recently, advances in digital driver assist technologies have also helped automobile users to avoid crashes altogether, through sensing and informing users of hazards, or automatically taking protective action such as autonomous emergency braking. Our literature review showed that research is being conducted in applying these to motorcycles.

In practice, some new vehicle advances supportive of motorcycle safety are now reaching the marketplace, and findings from this analysis demonstrate how they could be most effective. Blind spot detection is now available from some motorcycle makers, such as BMW's side view assist technology (BMW Motorrad, 2015). However, since this analysis found that most sideswipe crashes were caused by cars changing lanes, the most potentially impactful technological advances are in blind spot detection systems for cars and trucks to better detect motorcyclists and other PTWs. To that end, Honda introduced in 2021 a system called Sensing 360 which is more effective at sensing smaller vehicles such as motorcycles. Additionally, Honda also recently made advances in developing a self-balancing rider assist system (Honda Motor Co., Ltd., 2021). This is also especially welcome, since findings showed that for single vehicle crashes, motorcyclists were mostly traveling straight ahead, suggesting that balance could be a problem for some riders, especially at higher speeds or for older riders on over-powered models. For vulnerable age groups (e.g., senior motorcyclists) and specific crash types, new technologies, especially the detection of motorcyclists in blind spots and forward collision warning systems, could play a role in reducing the number of rear-end crashes. In all of these areas of vehicle technologies, Federal and state governments should consider the best ways to support the widespread adoption of such systems.

Safe Speeds

Most crashes in the dataset did not define any specific contributing action by motorcyclists, and thus only a very small minority of users involved in crashes were identified as engaging in the act of speeding. However, the notion of Safe Speeds within the Safe Systems framework posits that system speed limits should be set at levels that consider the protection of more vulnerable roads users, of which motorcycles are one category. That higher speed limits should be considered a major problem for motorcycle safety is supported by our findings regarding road class and directions of travel for both multi-vehicle and single vehicle crashes. This is because it was observed that the majority of motorcycle crashes occurred on arterial class roads, which is the highest speed non-freeway road class. Furthermore, the analysis of multi-vehicle crashes showed that rear end crashes were the most common type of crash for motorcyclists, which likely results from difficulties with motorcyclists or drivers slowing down from high speeds on such roads, compounded in the latter case by some drivers not noticing lower profile motorcyclists. Additionally, in the subset of sideswipe crashes, motorcyclists were most often going straight ahead, and in that case, drivers were most likely changing lanes or turning, suggesting that drivers may have difficulty judging motorcyclists' speed while they themselves are traveling at high speeds on arterial class roads. Finally, regarding single vehicle crashes, the analysis showed that motorcyclists were again mostly going straight ahead, suggesting that some riders may lose control at high speeds on arterials roads, and also that some riders appeared to lose control on curves, likely while riding at higher speeds.

These findings on the role of speed in motorcycle crashes highlight the danger of a transportation system that relies primarily on high-speed arterial roads to provide access to the needs of daily life, by pointing to their role in crashes involving vulnerable motorcycle users whose visibility to other users is less, and whose steadiness may be more influenced by high speeds. Given such vulnerability, this analysis provides additional reasons for the lowering of speed limits on urban and suburban arterial roadways as well as engaging in traffic calming measures such as narrowing roadways. Furthermore, findings also point to specific locations that should be targeted for reductions, such as horizontal curves and ramps, where speed limits can be lowered and emphasized with signage to reduce the high incidence of motorcycle crashes in such locations. The models developed for this study highlight the role of speed. Each mile of multi-lane street, which allow for motorcycle filtering and thus higher speeds, was associated with a 30% increase in KAB crashes and a 38% increase in fatal crashes. The presence of lower-speed street networks, however, were associated with significant reductions in motorcycles crashed. Each percentage increase of streets with posted speed limits of 25 mph or less was associated with a 0.3% reduction in KAB motorcycle crashes, and a 0.95% reduction in fatal motorcycle crashes.

Safe Roads

Motorcycle crashes predominantly occurred on arterial class roads, followed by local and collector roads. In addition to the hazards posed by higher speeds discussed above, arterial roads also tend to be higher traffic, which in the study area of South Florida is often related to adjacent retail development, such as gas stations and fast food restaurants, creating traffic conflicts and the associated increase in crashes and injuries. Nonetheless, over half of the crashes on non-freeways (56%) occurred at non-intersection locations, although investigation revealed that some of these occurred near or at driveways or alley access. Among crashes that occurred at intersections, near intersections, or driveways, half involved drivers turning left. A large proportion of this subset (46%) occurred at uncontrolled locations, including driveways, two-way left-turn lanes, median crossover, or left-turn bays. However, the number of crashes in locations with stop or yield signs were lower than the number at traffic signals, indicating an issue with traffic signal plans that allow for permitted left turns, especially on larger arterial or collector road types. Protected left turns at signalized intersections could help improve motorcycle safety, by decreasing conflicts that were observed to be a major cause of motorcycle angle crashes. Thus, in terms of improving the safety of roads, future work on motorcycle safety could target improving the signal systems to reduce the conflicts between vehicles and motorcyclists, especially on left turns. In light of these findings, a more comprehensive approach to ensuring safe roadways is through rethinking driveway access management in relation to local land uses to ensure the safety of all vulnerable road users including motorcyclists, cyclists, and pedestrians, through the incorporation of design countermeasures that mitigate right of way crashes.

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Collaborative Sciences Center for
ROAD SAFETY

730 Martin Luther King Jr. Blvd.
Suite 300
Chapel Hill, NC 27599-3430
info@roadsafety.unc.edu

www.roadsafety.unc.edu