Motorcycle antilock braking systems and fatal crash rates: updated results

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Contents

Abstract

Introduction: Antilock braking systems (ABS) prevent wheels from locking during hard braking and have been shown to reduce motorcyclists' crash risk. ABS has proliferated in the United States fleet, and the objective of the current study was to update the effectiveness estimate for ABS with additional years of data and a broader variety of motorcycle types.

Methods: Motorcycle drivers involved in fatal crashes per 10,000 registered vehicle years during 2003–19 were examined for 65 motorcycle models offering ABS as an optional feature. Fatal crash rates for motorcycles with ABS were compared with rates for the same models without it.

Results: ABS was associated with a statistically significant 22% reduction in motorcycle driver fatal crash involvements per 10,000 registered vehicle years.

Conclusion: This finding adds to the growing literature demonstrating the safety benefits of motorcycle ABS.

Keywords: motorcycle ABS, fatal motorcycle crashes, crash avoidance technologies, antilock brakes, motorcycle crashes

Introduction

Under hard braking, motorcycles are less stable than four-wheel vehicles and rely on riders' skills to remain upright and stable. Braking too hard and locking a wheel, especially the front wheel, creates an unstable situation that could lead to a serious fall. Riders' reluctance to apply full braking force, out of concern of wheel lock, may result in braking that is inadequate to avoid or mitigate a crash impact. In-depth analyses of motorcycle crashes, like the MAIDS[1] (Association of European Motorcycle Manufacturers, 2004) and Hurt et al. (1981) studies, had examples of crashes caused by either loss of control due to wheel lock or failure to adequately brake. While proper braking technique is a skill that can be taught, hard-braking events inherently occur during panic situations in which riders are less likely to react appropriately. The Hurt and MAIDS studies found that improper braking was a major precrash factor, and another study found that 43% of braked motorcycles lost stability in crashes (Roll et al., 2009).

Antilock braking systems (ABS) were developed—first for airplanes (Malsen, 2008), then for light vehicles and trucks, and finally for motorcycles—to help vehicle operators avoid wheel lock during hard braking. ABS functions by monitoring wheel speed precisely during braking events and, when wheel lock is imminent, begin a cycle of reducing brake line pressure and increasing it again; this cycle repeats many times per second until the risk of wheel lock is no longer detected. Motorcycles equipped with ABS allow riders to confidently apply larger braking inputs in an emergency without fear of wheel lock, and some newer systems have been coupled with a lean angle sensor and complex algorithms to allow stronger braking inputs while cornering (Lich et al., 2016).

Research consistently has shown benefits of ABS for motorcycle safety. These studies generally fall into one of three categories: test-track evaluations, examinations of in-depth crash information for motorcycles without ABS, and comparisons of crash rates for motorcycles with/without ABS. No one type of study is more important than another, and the state of knowledge on ABS and motorcycle safety is

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[1] Motorcycle Accidents In-Depth Study.

strengthened by consistent findings across all these types of studies. Test-track evaluations have shown that ABS improves braking performance of both novice and experienced riders (Vavryn & Winkelbauer, 2004) and in a variety of situations (Gail et al., 2009; Green, 2006). Braking decelerations were higher and stopping distances were shorter, and typically fewer trials were required to achieve the best result with ABS. Green (2006) noted that riders without substantial experience or skill were able to achieve high levels of braking performance using motorcycles equipped with ABS. A crash reconstruction study (Gwehenberger et al., 2006) found that about half of the investigated crashes were deemed relevant to motorcycle ABS and that between 17 and 38% could have been avoided if the motorcycles had been equipped with ABS. Two more in-depth studies found that ABS has the potential to prevent 38 to 50% of serious motorcycle crashes (Rizzi et al., 2009; Roll et al., 2009).

In terms of studies comparing crash rates of motorcycles with/without ABS, one found that the rate of fatal crashes was about 31% lower for motorcycles with ABS compared with the same motorcycles without ABS (Teoh, 2013). This was similar to an earlier result showing a 37% benefit (Teoh, 2011). ABS has been shown to reduce the rate of collision insurance claims by about 21% (Basch et al., 2015; Highway Loss Data Institute [HLDI], 2009, 2013), with a stronger effect during the first month of the insurance policy (HLDI, 2012). Importantly, Basch et al. (2015) showed that the effect of ABS did not vary by riders' automobile claim rates (a measure of risky driving). Moreover, although the effect was small, riders with higher automobile claim rates were more likely to have ABS on their motorcycle, refuting the notion that the observed benefits of ABS are due simply to safer riders being more likely to purchase the ABS option. Using certain crash types assumed less relevant to ABS as a comparison group, the National Highway Traffic Safety Administration studied motorcycle ABS (NHTSA, 2010), but did not find a statistically significant effect. A similar method was used by Rizzi et al. (2009, 2015) using head-on crashes as the comparison group. The 2009 study estimated ABS to be associated with a 41% reduction in injury crashes and a 54% reduction in fatal crashes. The 2015 study estimated benefits for injury crashes ranging from 24 to 34% in three European countries; severe/fatal crashes were reduced by 34 to 42%. Rizzi et al. (2016b) investigated crashes of ABS and non-ABS motorcycles and found sliding crashes to be far less common among those equipped with ABS, and that none of the ABS-equipped motorcycles' sliding crashes involved braking. This study also estimated a 52% reduction in fatal crashes associated with ABS. Another Rizzi et al. study (2016a) showed that ABS not only reduces the likelihood of crashes but also reduces their average severity.

Over the past decade, all member states of the European Union, Brazil, Japan, Taiwan, Australia, New Zealand, and India have mandated that certain on-road motorcycles be equipped with ABS. Simultaneously, ABS has proliferated in the U.S. motorcycle fleet, both as standard and as optional equipment (Teoh, 2021). While this proliferation has accelerated, ABS is still far from ubiquitous among new motorcycles; it is a standard feature on 56% of 2020 motorcycles registered as of January 1, 2021, available as an option on 26%, and not available for 18% (IIHS analysis of data obtained from IHS Markit). With far greater numbers of ABS-equipped motorcycles on the road, the purpose of this study was to update the results of Teoh (2011, 2013) to include more motorcycle models/types and a larger sample size.

Methods

Data on fatal motorcycle crashes were extracted from the Fatality Analysis Reporting System (FARS), a national census of fatal (death within 30 days) crashes on public roads that is maintained by NHTSA. Exposure data consisted of national motorcycle registration counts obtained from IHS Markit (formerly R. L. Polk and Company). Motorcycle make, model, and model year in both databases were identified by decoding the first 10 digits of the vehicle identification number (VIN) using software developed and maintained by HLDI. ABS availability and motorcycle type were determined using a motorcycle information database maintained by HLDI. Motorcycles with missing or invalid VINs were excluded.

To be included in the study, a motorcycle model was required to have ABS as an option, and the presence of that option must have been discernable in the VIN. For example, many BMW motorcycles had optional ABS before it became standard across their fleet, but whether a given motorcycle had the option could not be determined from the VIN. On the other hand, Honda uses separate VIN codes for the Gold Wing and Gold Wing ABS, so presence of the option is known. This means that motorcycles with ABS are being compared with the same motorcycles without the option, which eliminates the effect of motorcycle type (Teoh & Campbell, 2010) and minimizes other potential confounding factors like usage patterns, socioeconomic status, and other demographic factors. The final study sample included 65 make/model motorcycles, as shown in Table 1, far exceeding (and including) the 13 in Teoh (2013). Some motorcycle models, or model years of specific models, were excluded due to zero registrations of either the ABS or non-ABS version. For each motorcycle model, model years included in the study were identical for ABS and non-ABS versions. There were 10 different types of motorcycles represented in the study sample.

Table 1. Study motorcycles, each with both ABS and non-ABS versions registered for each model year

Make and model	Model years	Motorcycle type
Harley -Davidson Night Rod	2008–2008	Cruiser
Harley-Davidson V-Rod	2008–2008	Cruiser
Honda CB1100	2013–2014	Standard
Honda CB300	2017–2019	Sport
Honda CB500	2013–2018	Dual purpose
Honda CB650	2018–2018	Unclad sport
Honda CBR1000RR	2009–2018	Supersport
Honda CBR250	2012–2013	Sport
Honda CBR300R	2015–2018	Sport
Honda CBR500R	2013–2018	Sport
Honda CBR600RR	2009–2018	Supersport
Honda CBR650	2014–2018	Sport
Honda CRF250	2017–2018	Dual purpose
Honda CTX1300	2014–2014	Touring
Honda CTX700	2014–2016	Cruiser
Honda Forza	2014–2016	Scooter
Honda Fury	2010–2019	Chopper
Honda Gold Wing	2001–2016	Touring
Honda Gold Wing Valkyrie	2014–2015	Cruiser
Honda Grom	2018–2019	Standard
Honda Interceptor	2002–2015	Sport
Honda Interstate	2011–2015	Cruiser
Honda Monkey	2019–2019	Standard
Honda NC700	2012–2017	Dual purpose
Honda NT700V	2010–2010	Sport touring
Honda PCX150	2019–2019	Scooter
Honda Rebel 300	2017–2018	Cruiser
Honda Rebel 500	2017–2018	Cruiser
Honda Reflex	2001–2007	Scooter
Honda ST1100	2001–2002	Sport touring
Honda ST1300	2003–2010	Sport touring
Honda Sabre	2010–2013	Cruiser
Honda Shadow	2013–2018	Cruiser
Honda Silver Wing	2003–2010	Scooter
Honda Stateline	2010–2016	Cruiser
Indian Scout	2016–2019	Cruiser
Kawasaki Concours 14	2008–2010	Sport touring
Kawasaki Ninja 1000	2012–2013	Sport
Kawasaki Ninja 300/400	2013–2019	Sport
Kawasaki Ninja 650	2013–2019	Sport
Kawasaki Ninja ZX–10R	2012–2018	Supersport
Kawasaki Ninja ZX–14R	2013–2014	Sport

Make and model	Model years	Motorcycle type
Kawasaki Ninja ZX-6R	2013–2019	Supersport
Kawasaki Versys-X 300	2017–2019	Dual purpose
Kawasaki Vulcan 1700	2009–2013	Touring
Kawasaki Vulcan S	2015–2019	Cruiser
Kawasaki Z650	2017–2019	Unclad sport
Kawasaki Z900	2017–2018	Unclad sport
Suzuki B-King	2008–2008	Unclad sport
Suzuki Bandit 1250	2007–2009	Standard
Suzuki Burgman 650	2005–2010	Scooter
Suzuki GSX-R1000	2015–2015	Supersport
Suzuki GSX-S1000	2016–2017	Sport
Suzuki SV650/SV650S/Gladius	2007–2018	Unclad sport
Suzuki V-Strom 650	2007–2009	Dual purpose
Triumph Rocket III Touring	2013–2013	Cruiser
Triumph Speed Triple	2011–2012	Unclad sport
Triumph Sprint ST	2006–2010	Sport touring
Triumph Thunderbird	2010–2012	Cruiser
Triumph Tiger	2007–2012	Dual purpose
Victory Cross Roads/Cross Country	2014–2016	Touring
Victory Vision	2009–2010	Touring
Yamaha FJR1300	2004–2005	Sport touring
Yamaha FZ-07	2017–2017	Unclad sport
Yamaha YZF-R3	2017–2019	Sport

Data were analyzed for fatal crashes and registrations occurring during 2003–19. The rate of driver fatal crash involvements per 10,000 registered vehicle years for each motorcycle model, both ABS and non-ABS versions, were computed. If ABS does not affect the risk of fatal motorcycle crashes, then the fatal crash rate for each study motorcycle should not vary by whether or not it has ABS. Under this assumption, an expected count of drivers involved in fatal crashes was computed for each ABS motorcycle model as the product of the fatal crash rate per registered vehicle year for the non-ABS version and the number of registered vehicle years of the ABS version. A rate ratio estimating the effect of ABS was calculated as the sum of the observed number of drivers in fatal crashes for ABS motorcycles (O) divided by the sum of their expected number of drivers in fatal crashes (E). This is also known as the standardized mortality ratio (SMR). It standardizes the exposure distributions of the two study groups to limit possible bias due to, in this study, some motorcycles being more likely to have the ABS option than others. Using formulas derived by Silcocks (1994), a 95% confidence interval for the SMR was computed as (L, U), where:

$$L = \beta 0.025(O, E+1) / [1 - \beta 0.025(O, E+1)] \quad (1)$$

$$U = \beta_{0.975}(O+1, E) / [1- \beta_{0.975}(O+1, E)](2) \quad (2)$$

where $\beta_p(a,b)$ is the $100\times p^{th}$ percentile from the beta distribution with parameters a and b. Furthermore, the SMR was computed for motorcycle types: cruiser/standard, touring, sport touring, sport/unclad sport, supersport, and other.

In addition to the main analyses, data on driver age, speeding behavior, blood alcohol concentration (BAC), helmet use, helmet law type (coded in the state where the crash occurred), number of vehicles in the crash, and crash location (rural vs. urban) were tabulated for ABS and non-ABS cohorts. Missing BAC values were adjusted using multiple imputation results available in FARS (Subramanian, 2002). Also, a simple rate ratio was computed using the sums of driver fatal crash involvements and registered vehicle years to determine whether the effect estimated with the SMR was due to differences in exposure distributions. In a slight departure from Teoh (2013), motorcycles with zero driver fatal crash involvements for both the ABS and non-ABS versions were included in the current study. This does not affect the SMR, as both O and E are equal to zero, but it could affect the simple rate ratio, as the number of registered vehicle years without a fatal crash is informative.

Results

Table 2 presents the study sample and computations for the SMR. As in Teoh (2013), Honda motorcycles comprised the majority of registered vehicle years for both ABS and non-ABS samples, although to a lesser extent and with a broader variety of motorcycle types. The fatal crash rate per 10,000 registered vehicle years was 5.7 for ABS motorcycles, compared with 7.4 for the same motorcycles not equipped with ABS. Motorcycle drivers or passenger were killed in about 96% of these motorcycle driver fatal crash involvements, so reductions in fatal crash rates represent a direct benefit to motorcyclists.

Table 3 presents the SMRs for ABS vs. non-ABS motorcycles overall and by motorcycle type. The overall SMR is 0.776 with a 95% confidence interval of (0.691, 0.870). This represents a statistically significant 22% reduction (computed as [SMR−1] × 100%) in fatal crash risk associated with ABS. The simple rate ratio is 0.775 (5.7 divided by 7.4, but without rounding the numerator or denominator), which is almost identical to the SMR, suggesting that the results are not driven by differences in exposure distributions. ABS was associated with reduced fatal crash risk across all types of motorcycles, although slightly larger effects were observed for cruiser/standard, touring, and sport-touring motorcycles than for sport/unclad sport and supersport motorcycles. Statistical significance varied largely as a function of sample size among the types of motorcycles.

Table 2. Motorcycle fatal crash involvements and registered vehicle years, 2003–19

	Non-ABS			ABS			
Make and model	Observed fatal crash involvements	Registered vehicle years	Rate per 10,000	Observed fatal crash involvements	Registered vehicle years	Rate per 10,000	Expected fatal crash involvements
Harley-Davidson Night Rod	12	28,353	4.2	5	10,466	4.8	4.4
Harley-Davidson V-Rod	1	9,584	1.0	1	2,857	3.5	0.3
Honda CB1100	6	14,701	4.1	0	2,225	0.0	0.9
Honda CB300	2	763	26.2	1	561	17.8	1.5
Honda CB500	18	28,379	6.3	5	7,644	6.5	4.8
Honda CB650	0	192	0.0	0	72	0.0	0.0
Honda CBR1000RR	193	64,910	29.7	16	4,292	37.3	12.8
Honda CBR250	54	66,965	8.1	4	10,774	3.7	8.7
Honda CBR300R	22	16,012	13.7	4	4,358	9.2	6.0
Honda CBR500R	64	37,169	17.2	8	9,161	8.7	15.8
Honda CBR600RR	186	102,329	18.2	7	6,720	10.4	12.2

	Non-ABS			ABS			
Make and model	Observed fatal crash involvements	Registered vehicle years	Rate per 10,000	Observed fatal crash involvements	Registered vehicle years	Rate per 10,000	Expected fatal crash involvements
Honda CBR650	25	10,099	24.8	7	1,969	35.6	4.9
Honda CRF250	2	8,384	2.4	0	898	0.0	0.2
Honda CTX1300	5	2,850	17.5	1	4,175	2.4	7.3
Honda CTX700	6	15,846	3.8	7	18,797	3.7	7.1
Honda Forza	8	9,400	8.5	1	2,357	4.2	2.0
Honda Fury	57	90,703	6.3	1	1,908	5.2	1.2
Honda Gold Wing	577	1,191,153	4.8	120	320,243	3.8	155.3
Honda Gold Wing Valkyrie	3	6,373	4.7	1	400	25.0	0.2
Honda Grom	9	12,304	7.3	1	2,323	4.3	1.7
Honda Interceptor	59	102,529	5.8	16	31,353	5.1	18.0
Honda Interstate	14	16,409	8.5	0	314	0.0	0.3
Honda Monkey	3	461	65.1	0	196	0.0	1.3
Honda NC700	20	28,354	7.1	4	7,857	5.1	5.5
Honda NT700V	0	10,808	0.0	0	1,830	0.0	0.0
Honda PCX150	0	287	0.0	0	57	0.0	0.0
Honda Rebel 300	5	4,463	11.2	1	1,285	7.8	1.4
Honda Rebel 500	8	5,782	13.8	3	1,677	17.9	2.3
Honda Reflex	44	143,762	3.1	5	24,860	2.0	7.6
Honda ST1100	6	14,592	4.1	1	2,973	3.4	1.2
Honda ST1300	34	98,338	3.5	15	43,981	3.4	15.2
Honda Sabre	16	19,577	8.2	0	556	0.0	0.5
Honda Shadow	13	17,219	7.5	0	730	0.0	0.6
Honda Silver Wing	49	103,894	4.7	7	20,195	3.5	9.5
Honda Stateline	7	17,556	4.0	0	1,433	0.0	0.6
Indian Scout	18	17,107	10.5	7	10,136	6.9	10.7
Kawasaki Concours 14	22	36,089	6.1	21	42,086	5.0	25.7
Kawasaki Ninja 1000	14	6,793	20.6	2	3,847	5.2	7.9
Kawasaki Ninja 300/400	96	89,277	10.8	60	57,682	10.4	62.0
Kawasaki Ninja 650	43	32,436	13.3	37	24,475	15.1	32.4
Kawasaki Ninja ZX-10R	75	17,114	43.8	33	8,235	40.1	36.1
Kawasaki Ninja ZX-14R	12	6,521	18.4	10	6,263	16.0	11.5
Kawasaki Ninja ZX-6R	88	29,044	30.3	21	8,565	24.5	26.0
Kawasaki Versys-X 300	0	1,052	0.0	0	1,083	0.0	0.0
Kawasaki Vulcan 1700	13	25,320	5.1	10	14,840	6.7	7.6
Kawasaki Vulcan S	9	10,981	8.2	4	14,181	2.8	11.6
Kawasaki Z650	6	2,030	29.6	1	1,893	5.3	5.6
Kawasaki Z900	5	1,884	26.5	4	1,662	24.1	4.4
Suzuki B-King	3	13,319	2.3	0	534	0.0	0.1
Suzuki Bandit 1250	7	22,581	3.1	2	7,564	2.6	2.3
Suzuki Burgman 650	48	94,599	5.1	10	28,590	3.5	14.5
Suzuki GSX-R1000	14	2,958	47.3	0	147	0.0	0.7
Suzuki GSX-S1000	4	1,637	24.4	3	3,026	9.9	7.4

Make and model	Non-ABS Observed fatal crash involvements	Non-ABS Registered vehicle years	Non-ABS Rate per 10,000	ABS Observed fatal crash involvements	ABS Registered vehicle years	ABS Rate per 10,000	ABS Expected fatal crash involvements
Suzuki SV650/SV650S/Gladius	77	86,717	8.9	4	6,192	6.5	5.5
Suzuki V-Strom 650	20	60,695	3.3	3	11,861	2.5	3.9
Triumph Rocket III Touring	2	1,568	12.8	0	397	0.0	0.5
Triumph Speed Triple	8	3,977	20.1	4	2,807	14.3	5.6
Triumph Sprint ST	7	11,294	6.2	2	10,758	1.9	6.7
Triumph Thunderbird	6	10,262	5.8	5	13,600	3.7	8.0
Triumph Tiger	11	15,612	7.0	10	26,901	3.7	19.0
Victory Cross Roads/Cross Country	5	6,028	8.3	7	10,910	6.4	9.0
Victory Vision	4	12,549	3.2	0	3,826	0.0	1.2
Yamaha FJR1300	24	44,294	5.4	15	43,709	3.4	23.7
Yamaha FZ-07	11	3,523	31.2	2	2,313	8.6	7.2
Yamaha YZF-R3	11	3,249	33.9	9	3,722	24.2	12.6
Total	2,191	2,971,010	7.4	528	923,302	5.7	680.7

Table 3. Standardized mortality ratio for ABS vs. non-ABS motorcycles by type, 2003–19

	Observed fatal crash involvements	Expected fatal crash involvements	SMR	95% CI
Cruiser/standard	37	54.6	0.678	(0.434, 1.047)
Touring	138	180.3	0.765	(0.609, 0.960)
Sport touring	54	72.4	0.745	(0.514, 1.075)
Sport/Unclad sport	176	217.2	0.810	(0.660, 0.993)
Supersport	77	87.7	0.878	(0.638, 1.206)
Other	46	68.3	0.673	(0.453, 0.993)
All study motorcycles	528	680.7	0.776	(0.691, 0.870)

Note: CI = confidence interval. SMR = standardized mortality ratio.

Potential influences of known risk factors on the ABS effect estimate were investigated by comparing the distributions of these factors among ABS and non-ABS study motorcycles, as summarized in Table 4. Driver factor differences between ABS and non-ABS motorcycles were minimal, with the largest difference being speeding (5% for ABS and 9% for non-ABS motorcycles). Speeding was the only difference in the table that was statistically significant. Drivers of ABS-equipped motorcycles were slightly more likely to have been involved in single-vehicle crashes (42% vs. 38%). Differences by helmet law or crash location (rural vs. urban) were minimal. The ABS/non-ABS differences in Table 4 generally were smaller than observed by Teoh (2013). As the current study sample included a broader variety of motorcycle types, the riders in the study sample were now younger, on average, than in Teoh (2013).

Table 4. Driver and crash factors of study motorcycles involved in fatal crashes, 2003–19

	Non-ABS versions		ABS versions	
Driver	N	%	N	%
Age < 30	754	34	171	33
Age 30–39	299	14	74	14
Age 40–49	259	12	76	14
Age 50+	878	40	207	39
Speeding*	202	9	25	5
BAC 0.08+ g/dL	396	18	102	19
Helmeted	1,672	76	419	79
Crash				
Single-vehicle	822	38	220	42
Rural location	931	42	225	43
Universal helmet law	958	44	239	45
Partial helmet law	1,152	53	273	52
No helmet law	81	4	16	3
Total	2,191		528	

* Difference between ABS and non-ABS group was statistically significant at the 0.05 level.

The study sample of motorcycles was compared with all motorcycles in the United States with optional ABS, including those that were not VIN-discernable and did not otherwise fit the study inclusion criteria, as well as to the entire U.S. motorcycle fleet. ABS availability as an option was lower for cruiser/standard and supersport motorcycles, relative to their share in the U.S. fleet.

Table 5. Registered vehicle years of model year 2001+ motorcycles by type, 2003–19

	Motorcycles with ABS available as an option included in study		All motorcycles with ABS available as an option		U.S. fleet	
	N	%	N	%	N	%
Cruiser/standard	303,979	8	1,571,887	16	38,786,663	46
Touring	1,608,179	41	5,103,246	51	15,685,265	19
Sport touring	360,752	9	660,135	7	1,629,860	2
Sport/unclad sport	677,440	17	991,878	10	6,797,536	8
Supersport	244,314	6	299,719	3	8,425,010	10
Other	696,648	18	1,420,833	14	12,766,750	15
Total	3,894,312		10,047,698		84,091,084	

Discussion

The results of the current study reinforce previous findings that ABS is highly effective in reducing motorcyclists' fatal crash risk. The fatal crash rate was 22% lower for ABS-equipped motorcycles than for the same models without ABS. This was somewhat lower than previous estimates in the U.S. of 31% (Teoh, 2013) and 37% (Teoh, 2011). Several factors may contribute to this smaller result including the broader variety of motorcycle types included in the study (in particular, supersport and sport/unclad sport had lower ABS effectiveness estimates), the relatively younger study sample, or that several motorcycle models now offer ABS as a standard feature and were not included in the current study. Estimating the ABS effect using a different study design for motorcycles where it is a standard feature is an interesting avenue for future research. Nevertheless, the robustness of the results reported in the current study, prior crash and insurance claim rate studies, crash reconstruction analyses, and test-track trials underscore the real safety benefits that ABS offers motorcyclists.

ABS, of course, is not the only crash avoidance technology that can benefit motorcyclists. Combined braking systems (CBS), in which input on either the front brake lever or the rear brake pedal activates brakes on both wheels, have been suggested to be beneficial in addition to ABS (Basch, 2015, HLDI, 2013), but often it is difficult to determine the presence or availability of CBS on specific motorcycles. Another motorcycle safety technology that is difficult to identify on specific motorcycles is traction control, which limits throttle input or engine torque when excessive wheel slip is detected during acceleration. Motorcycle stability control (MSC), which combines ABS, CBS, and traction control and optimizes their functionality during cornering with a lean angle sensor, was introduced in 2013 (Lich et al., 2016). This system seems promising, and Gail et al. (2009) predicted a benefit for a conceptual system similar to MSC. It is worth noting that while certain systems on four-wheel vehicles can be adapted to motorcycles relatively straightforwardly (e.g., ABS, traction control), dynamic control methods for single-track vehicles do not follow directly from those of dual-track vehicles (Corno et al., 2015). Automatic emergency braking (AEB), which is becoming virtually standard on passenger vehicles (IIHS, 2016), potentially can be adapted to motorcycles, but its fitment would not be completely straightforward (Lucci et al., 2021; Savino et al., 2013). These motorcycle crash avoidance technologies are reviewed in further detail by Savino et al. (2020). Crash avoidance technology on other vehicles, particularly passenger vehicles, can benefit motorcyclists as well provided the technologies detect motorcycles reliably (Teoh, 2018).

The current study has several limitations, one of which is that optional ABS was studied, and thus the people opting to purchase a safety feature may be more safety conscious than those who do not purchase it. This could bias the ABS rate lower through safer riding practices if those translate into lower fatal crash rates. However, little evidence of this differential was observed in the current study and the only significant difference in driver/crash factors was speeding, with ABS-equipped riders less likely to speed. Also, research by Basch et al. (2015) shows that riders with higher automobile insurance claim rates were more likely to ride motorcycles with ABS.

Another possible limitation is that motorcyclists with ABS would tend to drive more aggressively, as has been purported to occur in passenger vehicles (Grant & Smiley, 1993; Winston et al., 2006). Such a phenomenon would bias the ABS rate higher. Even if riders of ABS-equipped motorcycles were taking more risks, the net effect of ABS is beneficial. Another limitation is that it is possible that there are systematic exposure differences between ABS and non-ABS motorcycles beyond number of registered vehicle years. For instance, someone investing more in their motorcycle may put more miles on it. But without further data on this, it is impossible to predict the magnitude or direction of any such bias. Also, the study design, which compares identical make/model/model year motorcycles, should minimize this sort of bias.

The current study adds to the growing literature demonstrating clear safety benefits of motorcycle ABS. While ABS has proliferated in the U.S. fleet at the same time that many other countries have mandated its use, further expanding the fitment of ABS is a major opportunity for motorcycle safety.

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