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Contents

From the Editor

Firstly I would like to take this opportunity to thank Tony Foster for dusting off his Editor's hat and coming out of retirement to assist with the last edition of Impact. Tony's help has been very much appreciated.

I have recently been in discussions with Victor Craig of the National Association of Professional Accident Reconstruction Specialists (NAPARS), and the Editor of the associations Accident Reconstruction Journal. We have each expressed interest in articles published by the other, and the two bodies have agreed a share of material to try and bridge the occasional divide that there is between the UK and the USA.

This edition features an article by Dr Gemma Briggs of The Open University, who is a Senior Lecturer in Psychology. Her work centres around distracted driving, and the effects of phone use, including hands-free, on driving ability. She is keen to work with the institute and its members - particularly Police Collision Investigators - to further her work in this area. Equally she is more than happy to offer advice to investigators in this regard. Consequently, Gemma is presenting a series of webinars, starting on 15th September, in which she will be discussing her work (see advert on page 5).

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Braking Capabilities of Motorcyclists - An Update

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Introduction

This article reviews published studies related to the deceleration that motorcyclists can produce by braking. Several concepts are important to consider while interpreting these studies. First, there is a difference between the braking capabilities of a motorcycle and the deceleration an average rider can achieve on that motorcycle. Most riders will not be capable of fully utilizing the braking capabilities of their motorcycle. Second, it is important to note that many of these studies were conducted with riders who were not confronted with actual emergency situations. Instead, they were conducted on test tracks, roads without hazards, or parking lots. This means that these studies capture what riders are capable of under ideal circumstances. When confronted with actual emergencies, many riders may not achieve the decelerations that riders in these studies did.

An important point is made by Ayres and *Kubose* [1], who noted that *"it has long been understood that faster responses tend to be less accurate…there is no single value that can be said to represent the reaction time of even one person for one task, without considering the accuracy of task performance."* This is relevant to the braking deceleration achieved by motorcyclists because "*a driver would tend to respond quickly although perhaps not very accurately when a collision is imminent, but would take a more careful approach (accurate, appropriate) with more time available."* Thus, *"one should not expect…that drivers will efficiently use all time available to make an optimum avoidance maneuver…it is unreasonable to expect optimal response timing and maneuver performance by drivers faced with emergencies."*

It is also important to state that riding experience does not necessarily equate to the ability to achieve higher decelerations during emergency braking. When we speak of riding experience, it is important to ask: experienced at what? Even riders who have ridden many miles are not frequently confronted with the need to brake in an emergency fashion, and so, even experience riders may not be experienced at emergency braking. Experience does not necessarily equate to skill, and skill in one area may not equate to skill in another area. On the other hand, the data does appear to show that antilock brakes (particularly with linked or integrated braking systems) help riders achieve higher levels of deceleration more consistently, and much of this benefit (at least the consistency part) is likely to carry over to emergency braking in the face of actual emergencies.

A Review of the Studies

Tolhurst and McKnight tested and compared five methods of braking in a straight line and three methods of braking in a curve [2]. For all eight methods, the rider applied the front brake to the maximum extent possible without locking the wheel. For the straight-line braking tests, which were run from a nominal speed of 40 mph, the method of rear wheel braking varied as follows: no rear wheel braking, light rear wheel braking, locked rear wheel braking, pumping of the rear brake, and heavy rear wheel braking just below the level necessary to lock the wheel. For the tests related to braking in a curve, which were run from a nominal speed of 30 mph, the method of rear wheel braking varied as follows: no rear wheel braking while keeping the motorcycle leaned, heavy rear wheel braking while keeping the motorcycle leaned, and heavy rear wheel braking while righting the motorcycle.

This study utilized three expert riders

operating three different motorcycles – a Yamaha FJ1100 (a sport touring motorcycle), a Yamaha 550 Vision (a standard motorcycle), and a Suzuki GS 550 (a standard motorcycle). For the straight-line braking, adding the heavy rear wheel braking to the front wheel braking (below the level necessary to lock the wheel) produced the highest deceleration and the shortest stopping distance. The lowest deceleration and longest stopping distances resulted when only the front brake was applied. This study did not examine rear wheel only braking. For braking in a curve, the highest deceleration and shortest stopping distances were achieved by righting the motorcycle while applying heavy braking to both brakes (without locking the wheels). The lowest deceleration and longest stopping distances were generated by continuing to lean in the curve and not applying any rear brake.

*Tolhurst and McKn*ight noted that there were *"highly significant differences among the three [riders]…[these] differences are more easily attributed to differences in the design of motorcycle, particularly the tire 'footprint,' than to the skill of the riders."* These authors only reported a single average stopping distance for each braking method, and so their article does not enable deeper analysis of motorcycle-to-motorcycle or rider-to-rider differences. These authors also noted that *"applying both brakes just short of lock-up can demand a high degree of braking skill. Less proficient riders might find one of the alternative methods to be more effective for them."* Given that this study utilized expert riders, the decelerations reported are unlikely to be achieved by the average rider.

Prem conducted *"emergency straight-path braking"* tests with 59 volunteer riders. He used the Motorcycle Operator Skill Test (MOST) to provide a quantitative assessment of the riders' skill level [3, 4]. The MOST takes the riders through a series of tasks designed to test their steering and braking performance. The braking maneuver from this test required the riders to brake aggressively to a stop from a speed of 32 kph (20 mph). A red signal light was activated to indicate to the riders when they should begin braking. The motorcycle used by the volunteers, a Honda CB400T, was instrumented to record the rider's front and rear brake-lever force inputs and motorcycle speed.

Prem analyzed differences in braking technique between skilled and less-skilled riders. He found that skilled riders applied higher levels of front brake force than the less -skilled riders. Less-skilled riders preferred the use of the rear brake. The skilled riders also modulated the level of front and rear wheel braking to maintain optimum braking as weight shifted towards the front of the motorcycle during heavy braking. The less-skilled riders maintained a generally constant level of pedal pressure independent of the weight shift. More skilled riders also exhibited shorter braking reaction times, though it should be kept in mind that this reaction was to an illuminating light that the riders knew would illuminate, not to an actual emergency situation.

Fries, Smith, and Cronrath performed testing with five different motorcycles to determine the deceleration of the motorcycles when the rider employed the rear brake only and when a combination of front and rear braking was employed [5]. They tested a 1968 Harley-Davidson FLH (a touring motorcycle), a 1978 BMW R90 (a standard), a 1982 Honda XR500R (a dirt bike), a 1972 Honda SL350 (a standard), and a 1972 Honda SL125S (a standard). Each motorcycle was tested at nominal speeds of 20, 30, and 40 mph (32.2, 48.3, and 64.4 kph) on worn asphalt. The experience level of the riders was not reported in the study. Overall, the deceleration from rear only braking was less than when heavy front braking was also used. The range of deceleration for rear only braking was 0.31 to 0.52g. The range of decelerations when heavy front wheel braking was also employed was between 0.54 and 0.88g.

These authors observed that *"when faced with an emergency stopping situation, or avoidance situation, a motorcycle [rider] has the decision of whether to stop using the rear brake only, front and rear brakes combined, or by laying the motorcycle down. There are several common misconceptions about motorcycles. One is that they will stop faster if they are laid down on their side…When a motorcycle is stopped by laying it on its side there is a delay in implementing the deceleration…The test results show that laying a motorcycle over and rear wheel braking have very similar deceleration factors. However, when laying a motorcycle over there is an impact and risk of injury when the motorcycle hits the pavement. Also, all control is lost. If the motorcycle is kept upright, it is possible to reduce braking and steer. Front and rear wheel braking provides the best deceleration factors. Our testing also demonstrates that even during hard braking with front and rear brakes, the experienced driver consistently maintained a straight path without causing the motorcycle to fall."*

On the other hand, it should be acknowledged that the riders in this study were not confronted with an actual emergency, and thus, had a different level of urgency than that which riders in real crash scenarios might be confronted. In some crash situations, riders will not be able to avoid a collision regardless of the deceleration they are able to achieve. In these situations, it is not unusual for riders to unintentionally lay the motorcycle down by over-braking the front brake.

Hunter reported acceleration and braking tests conducted by the Washington State Patrol on a dry, level roadway with a 1983 and a 1985 Kawasaki 1000 police motorcycle [6]. For deceleration tests with rear braking only, Hunter reported decelerations between 0.35 and 0.36g. For deceleration tests with front braking only, *Hunter* reported decelerations between 0.64 and 0.74g. For deceleration tests with heavy front and rear braking, Hunter reported decelerations between 0.63 and 0.96g. For the rapid acceleration tests, *Hunter* reported accelerations between 0.48 and 0.73g. He did not specify the experience level of the riders who conducted these tests, although he indicates that they both worked for the Washington State Patrol (presumably they were experienced motor officers). In the discussion, this paper observes that *"overall operator skill has a great influence on the deceleration ability of the motorcycle."*

Hugemann and Lange conducted 74 instrumented braking tests with 18 different riders, 15 of whom were riding their own motorcycle [7]. Motorcycle types were not specified. The riders had varying levels of experience (less than 12,500 miles and up to 80,000 miles) and were instructed to brake from 50 kph (31 mph) to a standstill *"within the shortest possible distance."* The tests were conducted on dry asphalt. Riders characterized as *"skilled"* exhibited mean decelerations between 0.70 and 0.81g. Riders characterized as *"novice"* exhibited decelerations between 0.44 and 0.52g. Individual test results were not reported in this article.

Bartlett reported testing with four motorcycles – a Harley-Davidson FXRT, a Yamaha FZ600, a Suzuki Katana 750, and a Kawasaki EX650 [8]. For tests that utilized only the rear brake, the maximum decelerations between these four motorcycles varied between 0.38 and 0.46g. For tests that utilized only the front brake, the maximum decelerations varied between 0.88 and 0.89g. *Bartlett* reported testing with combined front and rear braking for the Harley-Davidson. This produced a maximum deceleration of 0.96g. In this testing, the Yamaha brake pads were deteriorated, resulting in metal-to-metal contact. The maximum deceleration produced with the Yamaha with these deteriorated brake pads was 0.75g. The experience and skill levels of the test rider was not reported in this study.

Ecker and his colleagues [9] conducted a study comprised of approximately 600 tests performed by more than 300 riders of varying levels of experience (novice to 40+ years) operating an instrumented Honda CB500. Most of the riders were participants in motorcycle safety courses. As the riders were operating the Honda around a training facility, the test coordinator would trigger a red light mounted to the instrument cluster, signaling the rider to *"make a full stop emergency braking maneuver."* The authors noted that *"the test persons were aware of the imminent signal to start the maneuver. However, the test coordinator could vary the instant of triggering the maneuver via remote control within several seconds so that there was some uncertainty involved for the test persons."* These tests were conducted on dry asphalt from a speed of approximately 60 km/h (37 mph). The average deceleration for all 600 runs was 0.63g with a standard deviation of 0.12g. One conclusion of this study was that *"a correlation between experience and deceleration is hardly recognizable, especially for more than 1 year of riding experience."* Another conclusion was that half of the tested individuals utilized 56% or less of the deceleration that could be achieved with the motorcycle.

Vavryn [10] examined the influence of rider experience level and the effectiveness of antilock braking systems (ABS). He reported the results of 800 tests performed with 181 subjects on two different motorcycles. The riders were asked to "come to a complete stop as soon as possible without falling off the vehicle." Initial speeds were either 50 or 60 kph (31 or 37 mph). The subjects performed two tests on their own motorcycle and then two runs on a motorcycle equipped with ABS. One of the ABS-equipped motorcycles was a standard-style BMW and the other was a scooter equipped with linked ABS. The average deceleration for experienced motorcyclists on their own motorcycle was 0.67g (SD = 0.14g). When riding the motorcycles equipped with ABS, that number jumped up to 0.80g (SD = 0.11g). Eighty five percent of the subjects exhibited improved braking with the ABS-equipped motorcycle and the novice riders achieved almost equal braking decelerations to the experienced riders when operating the ABS-equipped motorcycles. Vavryn also noted that *"the deceleration the novice drivers achieved with ABS almost equals the experienced drivers' deceleration. All of the novices improved their deceleration with ABS."* Without ABS, the novice riders achieved an average deceleration of 0.57g.

Bartlett, Baxter, and Robar reported hundreds of brake tests from reconstruction classes conducted at the Institute of Police Technology and Management (IPTM) from between 1987 and 2006 [11]. These tests were conducted at various locations around the country with 112 different motorcycles and riders. They were conducted on dry asphalt or concrete. Initial speeds in the tests were nominally 20, 30, and 40 mph (32.2, 48.3, and 64.4 kph). The riders in these tests were typically motorcycle unit officers or instructors from a police agency. Thus, this study was of experienced riders operating in parking lots. The data in this study included 275 rear brake only tests, 239 front brake only tests, and 221 tests with combined front and rear braking. This data yielded the conclusion that the decelerations were normally distributed with a mean and standard deviation for the rear only braking of 0.37g ± 0.06g, with front only braking of 0.60g ± 0.16g, and with combined front and rear wheel braking of 0.74g ± 0.15g.

Bartlett and Greear [12] presented brake test data from students in a motorcycle training program (Skills Training Advantage for Riders from the State of Idaho) with three skill levels – Basic I, Basic II, and Experienced. The authors noted that *"the Basic I program is for riders who are new to motorcycling, with virtually no experience, and is conducted on STAR training motorcycles. These bikes are typically 250cc or smaller, with front disc and rear drum brakes. The Basic II program is for riders who are returning to motorcycling or those who have* *ridden on dirt, but not on the street, i.e., riders with some experience but not much on street cycles. These riders also use the program's training motorcycles. The Experienced program is for riders who have been riding for more than one year and is conducted using the riders' own motorcycles."*

The culmination of each program was a riding skills test, which included a stopping test conducted in a parking lot. Riders were instructed to approach the stopping area at a steady speed between 15 and 20 mph (24.1 and 32.2 kph). Once in the stopping area, they were to stop the motorcycle as quickly as they could with maximum braking. Bartlett reported the results of 288 tests, close to 100 tests for each experience level. The results of these tests *"were almost indistinguishable"* for the three skill levels. The Basic I group produced decelerations with a mean and standard deviation of 0.60g ± 0.16g, the Basic II group produced decelerations of 0.64g ± 0.14g, and the Experienced group produced decelerations of 0.61g ± 0.14g. When the experience levels were combined into one dataset, the decelerations were 0.62g ± 0.15g. In this study, no information was reported about the front-to-back braking split used by each rider or about the braking systems on the motorcycles for the tests where the students use their own motorcycles. The summary of braking data included below assumes that the riders in this study generally used both brakes and that the motorcycles did not have antilock brakes.

Dunn [13] reported brake test data and tire mark characteristics for three motorcycles – a 1995 BMW R1100RS (sport-touring with antilock brakes), a 2003 Buell XB9R (sport), and a 2005 Harley-Davidson XL 1200 Sportster Custom (cruising/touring). They tested three different braking strategies – best effort front braking only, best effort rear braking only, and best effort front and rear combined braking. Initial speeds for the tests were nominally 25, 45, and 60 mph (40.2, 72.4, and 96.6 kph) and most of the tests were conducted on a flat, dry asphalt surface. One set of tests was conducted on wet asphalt with the BMW, a motorcycle equipped with antilock brakes. The riders used in this study varied in years of experience, from 2 years to 35 years. Nothing was reported regarding the annual mileage covered by the riders.

For the BMW, the rear-braking-only strategy produced decelerations between 0.364 and 0.416g. The front-braking-only strategy produced decelerations between 0.671 and 0.828g. The combined front and rear braking strategy produced decelerations between 0.642 and 0.842g. For all three strategies, the decelerations increased with increasing speed. On the wet asphalt surface, the BMW produced decelerations with both brakes between 0.637 and 0.827g. For the Buell, the rear-braking-only strategy produced decelerations between 0.345 and 0.380g. The front-braking-only strategy produced decelerations between 0.548 and 0.709g. The combined front and rear braking strategy produced decelerations between 0.612 and 0.708g. Again, for all three strategies, the decelerations increased with increasing speed. For the Harley-Davidson, the rear-braking-only strategy produced a deceleration of 0.386 (this strategy was only tested at 45 mph). The front-braking-only strategy produced a deceleration of 0.518g (this strategy was only tested at 45 mph). The combined front and rear braking strategy (tested at 45 and 60 mph) produced decelerations between 0.658 and 0.674g.

Dunn found that *"at the extreme, the rear tire of the Buell lifted off the ground in some tests." Frank* [14] noted that *"pitch-over events are common in motorcycle accidents and can be caused by impact to the front wheel and occasionally by hard brake application... Provided there is sufficient tire/road friction, at the limit of the braking capacity of the motorcycle the weight on the rear tire is zero. Though not inevitable, this is the point at which the motorcycle can pitch-over." Frank* conducted 18 sled tests to evaluate the trajectory and velocity of riders and passengers on motorcycles that pitched over due to braking. This testing used target decelerations of 1.0, 1.15, and 1.3g. Target speeds for the testing were 20, 30, and 33.5 mph (32.2, 48.3, and 53.9 kph). The lowest braking deceleration that produced a pitch-over in *Frank's* testing was 1.0g with a test speed of 30.2 mph (48.6 kph).

Fatzinger, Landerville, Bonsall, and Simacek [15] reported a study of motorcycle deceleration for sport motorcycles during over-braking of the front wheel. Testing was conducted with the following motorcycles: a 2002 Kawasaki ZRX1200R, a 2006 Yamaha YZF-R6, and a 2013 Ninja EX300. Thirteen tests were completed, with initial speeds ranging from 50 to 60 mph. All three motorcycles had independently actuated front and rear brakes without antilock brakes. Testing was conducted on a flat asphalt surface. Brake pressure was applied to the front brake lever or the rear brake pedal with elastic straps. Electronically controlled valves installed in each brake line prevented this pressure from being applied to the calipers until the motorcycle was up to speed. Of the 13 tests, 3 were performed with a 6 ft, 1 in and 175 lb dummy on the motorcycle. In some of the tests, rear wheel braking was applied in addition to the front braking, and in some of the tests, no rear braking was applied. Front wheel lockup was achieved in 9 of the tests.

Fatzinger et al reported that the deceleration achieved by the motorcycle with front wheel lockup depended on the lean angle of the motorcycle at the beginning of the braking. They reported that the average deceleration when the initial lean was approximately 2 degrees or less was in the range of 0.69 and 0.8g. The average deceleration when the initial lean was around 3 or 4 degrees was between 0.51 and 0.67g. The average deceleration when the initial lean angle was between 8 and 9 degrees was 0.32 to 0.39g. When the front wheel braking resulted in a pitch-over, the deceleration was in the range of 0.8 to 0.86g. Rear brake application did not significantly increase the deceleration of the motorcycles when front wheel lock had been achieved. Also, there were *"no significant differences noted in the peak and average decelerations between the tests"* with and without the dummies.

Peck, Deyerl, and Rose examined the effect of tire pressure on the deceleration achieved with full application of the rear brake only [16]. This testing utilized a 2003 Suzuki GSF1200 equipped with Michelin Pilot Road radial tires. The tests were run from a nominal speed of 30 mph (48.3 kph) – three tests with the rear tire at 40 psi and three tests with the rear tire at 20 psi. The front tire was inflated to the manufacturer recommended tire pressure of 36 psi for all tests. These authors documented the size of the tire contact patch by using a rear swingarm stand to suspend the rear tire above a piece of brown paper, putting paint on the tire, and then lowering the tire onto the paper. The size of the rear tire contact patch was 46% larger at 20 psi than at 40 psi and the average deceleration was 5% greater at 20 psi than at 40 psi. For the tests at 40 psi, the three tests yielded the following decelerations (g): 0.324, 0.321, and 0.327 (average = 0.324). For the tests at 20 psi, the three tests yielded the following decelerations (g): 0.341, 0.339, and 0.338 (average = 0.339). These findings related to the influence of tire pressure are consistent with results reported by others for passenger cars [17, 18].

Table 1 summarizes the decelerations from the studies reviewed here. These decelerations can potentially be applied for calculating a motorcycle's speed loss due to maximal braking by the operator or for assessing a motorcyclist's ability to avoid a crash. The reconstructionist will need to consider conditions relevant to each particular crash. For example, what evidence is there related to the braking strategy rider utilized (rear only, front only, or front and rear combined)?

Study	Best Effort Braking Decelerations on Dry Roadway (g)			
	Rear Brake Only (No ABS)	Front Brake Only (No ABS)	Front and Rear Combined (No ABS)	Front and Rear with ABS
Tolhurst and McKnight [5] (expert riders)		0.77	0.97	
Fries, Smith, and Cronrath [8]	0.31 to 0.52		0.54 to 0.88	
Hunter [9] (experienced riders)	0.35 to 0.36	0.64 to 0.74	0.63 to 0.96	
Hugemann and Lange [10]				
Bartlett [11]	0.38 to 0.46	0.88 to 0.89	0.96	
Ecker [12] (mixed experience levels)			0.63 ± 0.12	
Vavryn [13]			0.67 ± 0.14	0.80 ± 0.11
Bartlett, Baxter, Robar [14] (motor officers)	0.37 ± 0.06	0.60 ± 0.16	0.74 ± 0.15	
Bartlett and Greear [15] (students)			0.62 ± 0.15	
Dunn, et al [16]	0.345 to 0.386	0.518 to 0.709	0.612 to 0.708	0.642 to 0.842
Fatzinger, et al [18]		0.69 to 0.80		
Peck and Deyerl [19]	0.321 to 0.341			
Summary (min to max)	0.31 to 0.52	0.52 to 0.89	0.54 to 0.96	0.64 to 0.842

Table 1 – Summary of braking decelerations from various studies (dry pavement)

Studies for Motorcycles with Integrated and Antilock Brakes (ABS)

This section reviews additional studies that focused on motorcycle braking systems equipped with integrated front and rear brakes or antilock brakes. These studies provided illustrative results of the influence of these systems, but these systems vary in how various manufacturers implement them. Reconstructionists can refer to the owner's manual for specific motorcycles for information specific to individual motorcycles. Individual motorcycles can also be tested.

Mortimer examined the effectiveness of integrated brakes on a motorcycle without ABS [19]. His testing utilized a 1979 Yamaha XS-400 with standard brakes as the original equipment and a 1982 Yamaha XS-1100 with integrated brakes as the original equipment. Mortimer modified both motorcycles so that they could be operated in either a standard braking mode or an integrated braking mode. The integrated mode on the XS-400 could only be operated with the right-side rear brake foot pedal. On the XS-1100, the integrated braking would be activated with either the right-side foot pedal or hand lever. Five experienced riders were used. Tests were run from a nominal speed of 25 mph (40.3 kph), and the riders attempted to stop the motorcycle in as short a distance as possible. Each rider performed testing on each motorcycle, and they made five stops in each test condition. The tests were run with the hand brake only, the foot brake only, and then both.

Mortimer noted that *"the stopping distances were directly measured at the point where the motorcycle came to a stop in terms of the distance from the cones marking the entrance to the braking course. The stopping distance was translated into the mean deceleration during the stop, assuming an initial speed of 40.3 km/h."* This manner of measuring the stopping distance and deceleration is prone to error since there is no way to know, in any given instance, if the riders began braking at the cone or to know that the rider started braking from a speed of precisely 40.3 kph (25 mph). *Mortimer* found the greatest benefit from integrated brakes for the condition of braking with the foot pedal only. He noted that *"use of the foot brake alone of the XS-400 motorcycle produced a 72% greater mean deceleration in the integrated than the separated mode. Similarly, use of the foot brake of the XS-1100 motorcycle in the integrated mode produced a 50% increase in mean deceleration compared with the separated mode…In addition, when both brakes were used on the larger motorcycle there were significant and consistent increases in deceleration obtained on both the dry and wet pavements in the integrated mode* *compared with the separated mode, but the increments were not as large as those found for the operation of the foot brake alone."*

As mentioned in the prior section, *Vavryn* [10] examined the effectiveness of ABS, reporting the results of 800 tests performed with 181 subjects on two different motorcycles. The riders were asked to *"come to a complete stop as soon as possible without falling off the vehicle."* Initial speeds were either 50 or 60 kph (31 or 37 mph), and the subjects performed two tests on their own motorcycle, and then two runs on a motorcycle equipped with ABS. One of the ABS bikes was a standard BMW, while the other was a scooter equipped with linked ABS. The average braking deceleration for motorcyclists on their own motorcycle was 0.67g (SD = 0.14g). However, when riding the motorcycles equipped with ABS, that number jumped up to 0.80g (SD = 0.11g). Eighty five percent of the subjects exhibited improved braking with the ABS-equipped motorcycle and the novice riders achieved almost equal braking decelerations to the experienced riders when operating the ABS-equipped motorcycles.

Green reported a test program conducted by NHTSA, in cooperation with Transport Canada (TC), *"to assess the effectiveness of anti-lock braking systems (ABS) and combined braking systems (CBS) on motorcycles"* [20]. Six motorcycles were tested on both dry and wet asphalt – a 2002 Honda VFR 800 with ABS and CBS, a 2002 BMW F650 with ABS, a 2002 BMW R 1150R with ABS and CBS, a 2002 BMW R 1150R without ABS or CBS, a 2004 Yamaha FJR1300 with ABS, and a 2004 Yamaha FJR1300 without ABS. Green observed that, with ABS, *"the stopping distances were very consistent from one run to another."* Without ABS, *"the stopping distances were less consistent because the rider while modulating the brake force, had to deal with many additional variables at the same time…Test results from non-ABS were noticeably more sensitive to rider performance variability."* On average, ABS reduced the stopping distances by approximately 5%.

Anderson, Baxter, and Robar [21] reported deceleration testing of motorcycles with the following different braking systems: standard brakes (1990 Harley Davidson Road King FLHTPI), integrated brakes without ABS (1986 Yamaha Venture Royale XVZ13), independent ABS brakes (1999 BMW R1100RPT), integrated ABS brakes, and linked brakes (2003 Honda VFR800 Interceptor). The authors tested each of these systems on an asphalt surface (automobile 0.83) with application of the rear pedal only, the front lever only, and with both levers applied. The initial speed for the tests was approximately 56 kph. All the tests utilized the same operator with many years of riding experience. The authors noted that *"there was no wheel lockup or skidding during any of the tests runs."*

Table 2 summarizes the results of the testing for each braking system. The values in this table are primarily of use for showing the comparison between the different braking systems. This study used only a single experienced rider and the variability in decelerations from test-to-test was not reported. Thus, the values in this table should not be blindly applied to a reconstruction, without consideration of how a typical rider would perform with each system. In addition, the authors noted that *"this testing only analyzed motorcycle braking during the period of maximum, and near-constant, deceleration. Operator reaction time and brake system lag time were not addressed in this study, although such investigation may be worthwhile as extensions of the work presented in this paper. The systems that utilize linkages to actuate both front and rear brakes, such as the integrated and linked brakes of the BMW and Honda motorcycles herein, may have lag times and mechanical behavior that affects the resultant onset of deceleration."* The trend in these values is, however, consistent with the benefits that would be expected from the various braking systems.

Average Deceleration (g)					
	Standard	Integrated	ABS	Integrated ABS	Linked
Pedal Only	0.42	0.58	0.40	0.98	0.62
Hand Lever Only	0.65	0.74	0.89	0.92	0.86
Both Levers	0.71	0.88	0.93	1.00	0.93

Table 2 – Summary of average braking decelerations for various systems [21]

	Rear Brake Only	Front Brake Only	Front and Rear Combined
ABS Off	0.37	0.79	0.79
Race Mode ABS	0.40	0.80	0.80
Sport Mode ABS	0.38	0.76	0.72

Table 3 – Average decelerations reported by Dinges and Hoover [21]

Anderson, Baxter, and Robar concluded that *"motorcycle braking systems that actuate both front and rear brakes with the application of only one control lever produce more effective braking than independent front and rear brakes on a standard system. When combined with anti-lock control the benefits of the combined system are increased. Perhaps more importantly, however, is that the motorcycle is also more stable during the braking maneuver. The increased stability along with the simplified brake application combine to reduce the load on the operator during the stressful moment of hard braking to avoid a crash. The operator does not have to concentrate on modulating pressure between two separate controls and simultaneously keep the motorcycle stable and prevent the wheels from locking, as the system performs these functions and permits the operator to focus on avoiding the crash."*

Dinges and Hoover [22] reported a series of maximal braking tests on a dry, asphalt surface with and without the antilock brakes active on a 2011 BMW S1000RR (a super sport motorcycle). This motorcycle was tested in three modes related to the ABS – sport mode, race mode, and ABS disabled. The BMW was equipped with partially integrated braking when the ABS was active. When the ABS was deactivated, the integral braking was also deactivated. These authors reported a coefficient of friction for the test surface of 0.7, measured using a Ford Expedition with the ABS disabled. Their testing yielded 420 braking runs, with target speeds ranging from 40 to 60 mph. *Table 3* lists the average decelerations reported by Dinges and Hoover for each mode with three braking conditions – rear brake only, front brake only, and front and rear braking combined. In addition to these decelerations, Dinges and Hoover reported hydraulic pressure build times, noting that "the average time it takes to build pressure in the front brake system is between 0.2 and 0.3 seconds…The rear brake system is similar, but a range of 0.2 to 0.4 seconds is shown from the data."

Avoidance Analysis

Crash reconstructionists are frequently asked to determine how a crash could have been avoided. This analysis will typically require an assumption about the level of deceleration a motorcyclist should have been able to achieve. Based on the data summarized in *Table 1*, motorcyclists would typically be able to achieve a deceleration of 0.5g and above on a dry road by utilizing only their front brakes (with a conventional motorcycle braking system). By utilizing both brakes, most motorcyclists will be able to achieve a deceleration of 0.6g and above on a dry road (again, with a conventional motorcycle braking system). With antilock brakes, particularly if there is integration between the front and rear brakes, motorcyclists are likely to achieve higher decelerations with greater consistency than they would have with a motorcycle with a conventional braking system.

That said, the level of deceleration that can be achieved during a specific emergency must consider conditions present that may have affected a rider's ability to achieve these expected levels. External factors such as roadway conditions, other traffic, the presence of cargo or passengers, or what the specific avoidance decision a rider makes may need to be considered when assigning an expected braking level to a specific crash scenario. Also, studies have shown that drivers and riders do not necessarily utilize their full deceleration capabilities when trying to avoid a crash [23, 24].

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