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Towards a Safe System Approach to Prevent Health Loss among Motorcyclists

The Importance of Motorcycle Stability as a Condition for Integrated Safety

MATTEO RIZZI

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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MATTEO RIZZI
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Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 7721000

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MATTEO RIZZI
Division of Vehicle Safety, Department of Applied Mechanics
Chalmers University of Technology

ABSTRACT

Health loss among motorcyclists is a global road safety problem for which innovative countermeasures are needed. While the traditional motorcycle safety approach has focused on protective gear and rider education, the Safe System approach adopted in Sweden and other countries implies that the road, the vehicle and the road user, in conjunction with a safe speed limit, should interact to create a safe road transport system. Motorcycles are intrinsically unstable vehicles and the most likely consequence of instability is the rider becoming separated from the motorcycle. In this case, the only countermeasures to avoid health loss are the rider's protective gear, or a forgiving road infrastructure.

The overall aim of this thesis is to understand the chain of events leading to crashes involving motorcycles with Antilock Braking Systems (ABS), compared to similar motorcycles without ABS. This resulted in five studies based on real-life crash data from Sweden, Norway, Spain and Italy. The integrated chain of events was used as a theoretical framework: the chain of events leading to a crash is no longer seen in separate blocks; rather it is a process in which one factor in the early phases of the chain can affect the following ones, thus creating conditions for other countermeasures to be effective.

The findings indicated that Motorcycle ABS reduced emergency care visits by 47%. The severity of the crashes that did occur was lower, which reduced the overall risk of sustaining impairing injuries, although leg injuries were not addressed to the same extent. It was also found that almost 90% of fatal crashes with ABS were upright. This result suggests that leg injuries can be addressed by motorcycle design. An example with a specific design (i.e. boxer-twin engine) was analysed, showing that leg injuries were reduced by approximately 50%. Finally, it was found that the overall reduction of injury crashes with ABS ranged from 24% in Italy to 29% in Spain and 34% in Sweden. Essentially, it is suggested that Motorcycle ABS prevent crashes from occurring in the first place, and they also increase stability and change the phases following critical situations, making crashes that do occur more predictable. Therefore, improving motorcycle stability with ABS can create the conditions for making other safety systems more effective, motorcycle crashworthiness, for instance. It is also shown that these findings are feasible in different riding conditions and environments.

This thesis can be considered a first step towards a Safe System approach for motorcycles. A more stable, ABS-fitted motorcycle provides the foundation for developing further countermeasures based on ABS. However, further research is needed to design and implement a Safe System that can address health loss among motorcyclists. While motorcycle manufacturers ought to immediately engage in a wide fitment of ABS in new motorcycles, the development of other technologies to improve stability, for instance Electronic Stability Controls (ESC) for motorcycles, will likely have significant benefits. Furthermore, the development and testing procedures of future road barriers will need to have greater focus on upright crashes, and the possibility of interacting with protectors integrated in the motorcycles. The development of motorcycle crashworthiness can be encouraged by consumer testing, i.e. the European New MotorCycle Assessment Programme (Euro NMCAP). Injury risk functions form the basis for the design of a Safe System, where the speed limit and crash protection are strictly connected. Such functions need to be developed for motorcyclists, and further research in this area should be prioritised.

KEYWORDS: ABS, Antilock Brakes, Motorcycle, Powered Two Wheelers, Safe System, Stability

TABLE OF CONTENTS

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Finally, my thoughts go to a few good friends who have lost their lives in tragic motorcycles crashes.

Matteo Rizzi
Stockholm, February 2016

LIST OF APPENDED PAPERS

Paper 1 Rizzi M, Strandroth J, Sternlund S, Tingvall C, Fildes B. *Motorcycle Crashes into Road Barriers: the Role of Stability and Different Types of Barriers for Injury Outcome*. In proceedings of the 2012 International IRCOBI Conference; Dublin, Ireland.

Contribution Rizzi, Strandroth and Tingvall designed the study. Rizzi made the analysis with support from Strandroth and Sternlund. The paper was authored by Rizzi with the supervision of Tingvall; it was later reviewed by Fildes.

Paper 2 Rizzi M, Kullgren A, Tingvall C. *The Combined Benefits of Motorcycle Antilock Braking Systems (ABS) in Preventing Crashes and Reducing Crash Severity.* Traffic Injury Prevention (2015) 22:1-7.

C*ontribution* Rizzi and Tingvall designed the study. Rizzi made the analysis with the supervision of Tingvall. The paper was authored by Rizzi with the supervision of Kullgren and Tingvall.

Paper 3 Rizzi M, Strandroth J, Holst J, Tingvall C. *Does the Improved Stability Offered by Motorcycle Antilock Brakes (ABS) Make Sliding Crashes less Common? In-depth Analysis of Fatal Crashes Involving Motorcycles Fitted with ABS.* Traffic Injury Prevention (2016) (e-published ahead of print).

C*ontribution* Rizzi and Standroth designed the study. Rizzi and Holst collected the in-depth data. The analysis was performed by Rizzi with the support of Strandroth and Holst. Rizzi authored the paper with the supervision of Kullgren, Tingvall and Krafft.

Paper 4 Rizzi M. *Can a Boxer Engine Reduce Leg Injuries Among Motorcyclists? Analysis of Injury Distributions in Crashes Involving Different Motorcycles Fitted with Antilock Brakes (ABS).* Traffic Injury Prevention (2015) 16:7.

C*ontribution* The study was designed by Rizzi. The analysis was performed by Rizzi. The paper was authored by Rizzi with the supervision of Tingvall, Kullgren and Krafft.

Paper 5 Rizzi M, Strandroth J, Sternlund S, Tingvall C, Fildes B. *Effectiveness of Motorcycle Antilock Braking System (ABS) in Reducing Crashes, the First Multinational Study.* Traffic Injury Prevention (2015) 16: 2.

Contribution Rizzi, Tingvall and Fildes designed the study. Rizzi and Strandroth made the analysis work with the supervision of Tingvall and Kullgren. The paper was authored by Rizzi with the supervision of Kullgren and Tingvall; it was later reviewed by Fildes.

ABREVIATIONS

AAAM	Association for the Advancement of Automotive Medicine
ABS	Antilock Braking Systems
AEB	Autonomous Emergency Braking
AIS	Abbreviated Injury Scale
CBS	Combined Braking Systems
CI	Confidence Interval
EC	European Commission
ESC	Electronic Stability Controls
Euro NCAP	European New Car Assessment Programme
Euro NMCAP	European New MotorCycle Assessment Programme
FSI	Fatally and Severely Injured
HLDI	Highway Loss Data Institute
IMMA	International Motorcycle Manufacturers Association
ISA	Intelligent Speed Assistance
ISO	International Organization for Standardization
ISS	Injury Severity Score
MAEB	Motorcycle Autonomous Emergency Braking
MAIDS	Motorcycle Accidents In-Depth Study
MAIS	Maximum Abbreviated Injury Scale
MPS	Motorcyclist Protective Systems
mRPMI	Mean Risk of Permanent Medical Impairment
NPRA	Norwegian Public Roads Administration
OECD	Organization for Economic Co-operation and Development
PMI	Permanent Medical Impairment
PTW	Powered Two Wheeler
rel RPMI	Relative Risk of Permanent Medical Impairment
RPMI	Risk of Permanent Medical Impairment
STA	Swedish Transport Administration
STRADA	Swedish Traffic Accident Data Acquisition
TC	Traction Controls
TRL	Transport Research Laboratory
WHO	World Health Organization

1 MOTORCYCLE SAFETY IS A GLOBAL ISSUE

Health loss in the road transport system is one of the leading global public health problems. Every year approximately 1.25 million people are killed worldwide in road traffic crashes, and up to 50 million people are injured (World Health Organization; WHO 2015). Road traffic injuries are estimated to be the ninth leading cause of death globally, and their impact has been compared to many communicable diseases, such as malaria (WHO 2013). They are the leading cause of death in the age group 15 to 29 years old, and are also associated with enormous costs to society, accounting for 3% of the global Gross Domestic Product (GDP). Current trends also suggest that road traffic injuries will become the seventh leading cause of death by 2030, if proper countermeasures are not implemented (WHO 2015). In 2015, the United Nations set a target for a 50% reduction in the number of deaths and injuries in road crashes by 2020 among the global targets for good health and well-being (UN 2015).

Half of the road traffic deaths in the world involve vulnerable road users (WHO 2015): pedestrians (22%), cyclists (4%) and users of Powered Two Wheelers (PTWs) (23%). Approximately 90% of road traffic casualties live in low and middle income countries, and depending in which country, up to 74% of casualties are PTW riders (i.e. in Thailand and Laos, OECD 2015). Estimated figures indicate that in 2010 there were more than one billion motor vehicles in the world (Ward's AutoWorld 2011; Sperling et al, 2009), of which approximately 300 million were PTWs (OECD 2015). PTWs, however, are not evenly spread across the world: around 75% in Asia, 16% in North America and Europe, 5% in Latin America, 1% in Africa and 1% in the Middle East (Rogers 2008). Moreover, the utilisation mode of PTWs varies across different regions of the world. In North America and Australia, for instance, the primary use is for recreation (i.e. leisure riding). The function of PTWs is much more mixed in Europe, where they are also used for urban commuting. In other regions of the world, PTWs may serve a mainly utilitarian function (OECD 2015).

The number of PTWs continues to grow. During the period 2005-2011, the PTW fleet in India, Indonesia and Brazil increased by 73%-141%. During the same period, a steady increase of the PTW fleet was also registered in USA (36%) and in Europe (10%; IMMA 2015). This trend can partly be explained by the reduction in space available for cars in urban areas (Spyropoulou et al, 2013), where PTWs are more attractive means of transportation due to shorter travel times and easier parking (Spyropoulou et al, 2013; Blackman et al, 2010; Transport for London 2004). Furthermore, PTWs are excluded from congestion charge plans in several large urban areas in Europe (Spyropoulou et al, 2013; Duffy et al, 2004).

While remarkable improvements in traffic safety for all road users (including motorcyclists) have been accomplished in the OECD countries[1] (OECD 2015), the use of motorcycles has increased to the point that in some countries the number of motorcyclists who died in road crashes increased over the past three or four decades (Shinar 2012), while the number of fatalities among other road users declined significantly. As stated by Elvik (2009), the current road transport system is unfair to PTW users, as they are confronted with excessive risks on the roads, compared to other road users (OECD 2015). Previous research has shown that the fatality rates for motorcyclists are 20 to 40 times higher than for car occupants per distance travelled (Blackman et al, 2013). Similar trends have been seen in Sweden as well (see Figure 1), where the number of motorcyclists killed per passenger-kilometre has been reported to be 29 times higher than for passenger car occupants. However, PTWs do not pose the same risk to other road users, since the majority of motor vehicles injuring pedestrians and cyclists are passenger cars, trucks and buses (Juhra et al, 2012; Transport Analysis 2014). Therefore, the potential of reducing injury risk among motorcyclists (rather than their collision partners) is investigated in the present thesis.

[1] OECD includes Albania, Argentina, Armenia, Australia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Chile, China (People's Republic of), Croatia, Czech Republic, Denmark, Estonia, Finland, France, Former Yugoslav Republic of Macedonia, Georgia, Germany, Greece, Hungary, Iceland, India, Ireland, Israel, Italy, Japan, Korea, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Mexico, Republic of Moldova, Montenegro, Morocco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Serbia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States.

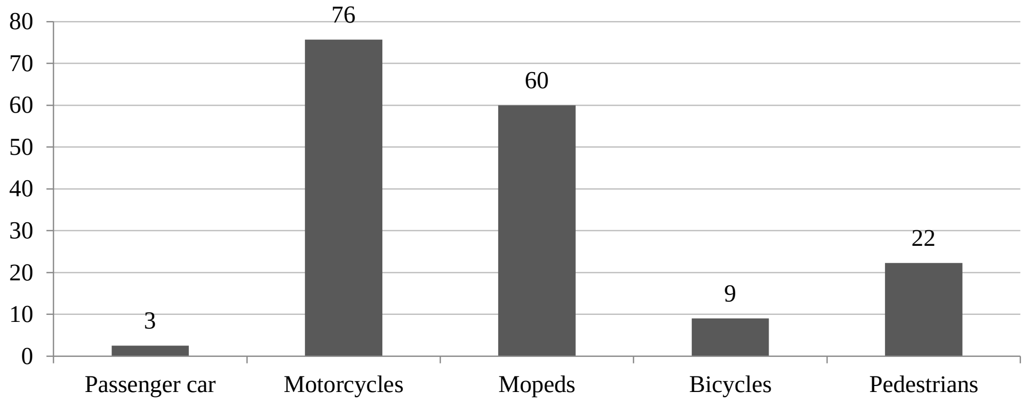


Figure 1: Number of killed road users per billion passenger-kilometres in Sweden. Source: Björketun et al (2006).

During the period 2010-2014 approximately 37 riders of motorcycles and eight of mopeds were killed on Swedish roads every year, respectively (Swedish Transport Agency 2016). With regard to motorcycle fatalities, the most common crash type was single-vehicle (40%), followed by intersection (30%) and head-on crashes (20%). Road barriers were the most common collision object in fatal single-vehicle crashes, with approximately four fatalities in Sweden every year. In 84% of intersection crashes, the crash scenario involved a passenger car turning in front of the motorcycle.

The mixed nature of PTW use in Europe is also outlined in Table 1, where the percentage of fatal single-vehicle crashes range between 29% (UK) and 78% (Romania). Similarly, the percentage of fatal crashes in rural areas varies between 21% (Romania) and 81% (Belgium). In 2013, the highest number of PTW fatalities was in Italy (849), France (817) and Germany (641).

Table 1: Overview of PTW fatalities in Europe 2013. Source: ERSO (2015a) and ERSO (2015b).

	% single-vehicle crashes	% crashes in rural areas	% crashes with mopeds	n PTW fatalities
Austria	44%	81%	15%	102
Belgium	46%	81%	11%	115
Croatia	43%	41%	22%	63
Czech Republic	56%	56%	8%	72
France	36%	65%	19%	817
Germany	45%	76%	11%	641
Greece	45%	32%	8%	296
Hungary	40%	62%	29%	82
Italy	36%	49%	15%	849
Netherlands	51%	46%	59%	70
Norway	47%	*n.a.*	13%	24
Poland	35%	40%	20%	315
Portugal	38%	27%	40%	129
Romania	78%	21%	43%	91
Spain	45%	66%	16%	358
Sweden	52%	72%	7%	43
United Kingdom	29%	72%	1%	341
European Union	41%	58%	16%	4603

2 BACKGROUND

2.1 The Safe System approach in the road transport system

In 1997, the Swedish parliament decided on a road transport safety strategy called Vision Zero, with the long-term vision of no fatal or impairing injuries within the road transport system (Tingvall 1997). As stated by Gilb et al (1988), "*any system which depends on human reliability is unreliable*" and therefore the road transport system has to be able to handle human errors, mistakes or misjudgement in order to avoid health loss, without limiting the needs for individual mobility or social growth. In other words, the road transport system should be adapted to the limitations of the road users, by anticipating and allowing for human error. This means that the designers of the road transport system are ultimately responsible for the design, operation and use of the road transport system, and therefore responsible for the level of safety within the entire system (Oxley et al, 2006; Johansson 2009). If road users fail to follow the rules of the transport system due to lack of knowledge, acceptance or ability, it is still the system designers' responsibility to prevent health loss. With the Safe System approach, an injured or killed road user is a victim of an inadequately designed road transport system unable to protect him/her from the human inability to handle certain complex traffic situations. The aim of the Safe System approach is not to totally eliminate the number of crashes but to align the crash severity with the potential to protect from bodily harm. Thereby, health loss among road users can be minimised by adapting roads and vehicles to be more tolerant of human error in a passive sense (i.e. crash protection) or to support users should an error be detected (OECD 2008; Stigson 2009).

While the Safe System approach has been adopted by several countries (OECD 2008; Eugensson et al, 2011), it has been debated whether or not it is practically achievable in a road transport system including motorcyclists, as they are more easily exposed to energy levels beyond which death or health loss are no longer avoidable. It has been suggested that only draconian measures would reduce injury risks for motorcyclists to acceptable levels (SWOV 2006). On the other hand, in 2010 PTWs were formally acknowledged as a natural component of a road transport system by the joint strategy for improved safety for motorcycle and moped riders in Sweden. Stakeholders agreed on prioritised intervention areas for PTW safety to meet the national interim targets, thus implying that the system designers are responsible for avoiding health loss among PTW users (STA 2010).

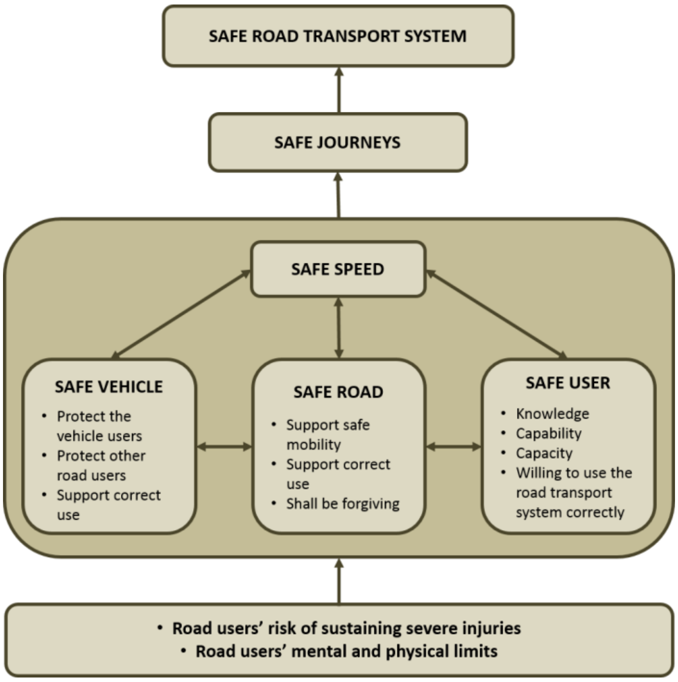


Figure 2: The model for safe traffic adopted by the Swedish Transport Administration. Adapted from Linnskog (2007).

The Safe System approach can be further illustrated by the model for safe road traffic adopted by the Swedish Transport Administration (STA; see Figure 2), where the road, the vehicle and the road user, together with a safe speed limit, should interact to create a safe road transport system (Tingvall et al, 2000; Linnskog 2007; Stigson 2009). The system is designed based on road users' risk of sustaining severe injuries, as well as the mental and physical conditions of human beings. Deficiencies in safety are balanced and controlled by adapting the speed limit to the safety level for the system (Tingvall 1997). This is the fundamental idea behind the Safe System approach: speed limit compliance and crash protection are closely connected and work together in synergy, and the set speed limit depends on the safety standards of the road. Effectively this means that the more vulnerable a certain road user group is, the lower the speed they are exposed to should be, in order to avoid health loss. This may naturally lead to the following questions: What is health loss? At what speed can health loss be prevented among motorcyclists today?

2.1.1 Defining the final outcome: Health loss

An (un)safe road transport system is traditionally measured using police-reported deaths and severe injuries, i.e. recorded shortly after a crash (Malm et al, 2008). However, there are a number of other ways to measure health loss. While several studies have shown that police records do not reflect the true injury outcome (Amoros et al, 2006; Tingvall et al, 2013), underreporting of injuries among vulnerable road users is also a known issue (Juhra et al, 2012). Therefore, hospital data may be more relevant for the analysis of crashes involving these road users (Amoros et al, 2006). With hospital data, the most common predictive scale to assess risk of death based on the immediate diagnosis following a crash is the Abbreviated Injury Scale, AIS (AAAM 2005). The AIS is a consensus-based scale, which is mainly a threat-to-life scale and only assesses a single injury. Several other predictive scales based on the AIS address multiple injuries and the risk of fatality, i.e. Injury Severity Score (ISS; Baker et al, 1974), New Injury Severity Score (NISS; Osler et al, 1997) and Maximum Abbreviated Injury Scale (MAIS; AAAM 2005).

Since 2008, a further approach has been used to manage the national road safety work in Sweden (STA 2014a). As a complement to fatalities, long-term consequences of injury are taken into account by using the Risk of Permanent Medical Impairment (RPMI). The risk of impairment for different body regions and AIS levels is based on an impairment scale used by Swedish insurance companies (Malm et al, 2008). The number of persons who are expected to suffer at least a 1% impairment (PMI 1+) or a 10% impairment (PMI 10%) can also be calculated.

The present thesis uses the RPMI approach as well as other injury scales such as AIS, MAIS and ISS. As pointed out by Tingvall (2013), it is clear that the use of different injury scales and thresholds (i.e. MAIS 2+ or MAIS 3+) can give different injury distribution for the same initial population of injured. This issue is illustrated in Table 2, where the injury distribution of Swedish helmeted motorcyclists are presented for ISS 4+, ISS 9+, MAIS 2+, MAIS 3+, PMI 1+ and PMI 10+. While skin injuries were the most common injury among all injured (44%), they accounted for 24% of injuries among MAIS 2+, and only 1% of PMI 10+ injuries. On the other hand, head injuries accounted for only 3-4% among all injured and MAIS 2+, although they were calculated to be the second most common PMI 10+ injury, at 21%.

The number of motorcyclists included in each group is also shown in Table 2. Clearly, not only the injury distribution will change depending on the injury scale and thresholds; the magnitude of the problem will also be affected. For instance, the number of impaired motorcyclists (PMI 1+) is more than three times lower than the number of MAIS 2+ which in effect means that the picture and the magnitude of the health problem to be addressed (in this case, motorcycle crashes) may change dramatically depending on the injury scale and threshold adopted.

Table 2: Injury distribution among helmeted motorcyclists in Sweden 2007-2015, for different injury criteria. Source: STRADA 2007-2015.

	All injuries	ISS 4+	ISS 9+	MAIS 2+	MAIS 3+	PMI 1+	PMI 10+
Head	3%	4%	5%	4%	5%	4%	21%
Face	1%	2%	3%	2%	2%	1%	3%
Cervical Spine	4%	2%	3%	2%	3%	6%	9%
Thorax	9%	13%	22%	13%	24%	3%	3%
Thoracic Spine	3%	4%	7%	4%	7%	7%	12%
Upper Extremities	19%	26%	16%	26%	15%	33%	21%
Abdomen	2%	3%	4%	3%	4%	0%	1%
Lumbar Spine	2%	2%	3%	2%	3%	5%	4%
Lower Extremities /Pelvis	14%	20%	17%	20%	19%	36%	25%
Skin and Thermal Injuries	44%	24%	20%	24%	17%	5%	1%
n injuries	24006	14356	6900	14257	5603	4167	517
n individuals	9111	4560	1220	4548	1009	2444	354

2.1.2 Defining the injury risks: What is a safe speed limit for motorcyclists today?

As mentioned earlier, the design of a safe transport system should be based on human injury tolerance. Clearly, the risk of human injury differ for different road user groups and may be influenced by several parameters, i.e. age, gender, crash type, types of protective systems, etc.

At the present stage, the knowledge of injury risks for motorcyclists is limited, and proper statistical injury functions have not been developed yet, as they have been for passenger car occupants and pedestrians (see for example Kullgren 2008; Gabauer et al, 2006; Rosen et al, 2009; Niebuhr et al, 2016). A number of studies based on real-world crashes (summarised below) provide some point estimates of injury risk for motorcyclists based on pre-crash travelling speed, or collision speed. Please note that these studies had different sampling criteria, and were conducted in different regions of the world during different periods. This means that the included injury outcomes, helmet wearing rates, distribution of crash types, etc., may vary across these studies, thus making an overall interpretation of the results more difficult. Despite these limitations, Table 3 suggests that, at a pre-crash travelling speed of 50-60 km/h, motorcyclists may approximately have a 10% fatality risk. The risk for non-fatal injuries, often expressed as the risk for MAIS 2+ or MAIS 3+, are even higher (see Table 4), although the differences between the studies makes it difficult to draw more general conclusions.

The 10% fatality risk threshold is often used for the design of the road transport system (Johansson 2009). As a reference, in 2012 the mean travelling speed of motorcycles in Sweden was approximately 77 km/h (STA 2013), which underlines the need for new countermeasures to reduce health loss among motorcyclists.

Table 3: Overview of previous research, point estimates of fatality risks for motorcyclists.

Country	**DEU**	**SWE**	**DEU**	**USA**	**FRA, DEU, NLD, ESP, ITA**
Database	GIDAS	STA	GIDAS	NASS	MAIDS
Study	Fredriksson et al, 2015	Savino et al, 2014	SMART RRS 2012	Bambach et al, 2011	MAIDS 2004
n cases	79	92	32	34 746 (weighted)	921
Collision Speed (km/h)	mean 69 (range 5-145)	mean 85 (range 5-180)	38% fatality risk between 50-70 km/h against guardrail barriers	*n.a.*	*n.a.*
Pre-crash Travelling Speed (km/h)	mean 83 (range 25-184)	mean 94 (range 30-190)	*n.a.*	10% fatality risk at 55 km/h	mean 65 (range 0-185) 10% fatality risk at 50-60 km/h
% single-vehicle Crashes	25%	28%	100%	100%	16%
% helmeted Riders	100%	92%	*n.a.*	61%	92%
% fatally Injured	100%	100%	44%	7%	11%
Non-fatally Injured	0%	0%	27% MAIS 3+	*n.a.*	27% MAIS 3+ (including fatalities)

Table 4: Overview of previous research, point estimates of non-fatal injury risks for motorcyclists.

Country	**AUS**	**ITA**	**DEU, CHN**	**DEU**	**FRA, DEU, NLD, ESP, ITA**	**DEU, UK, FIN**	**USA**
Database	NeuRA	InSAFE	GIDAS, IVAC	DEKRA	MAIDS	COST 327	USC
Study	Savino et al, 2014	Savino et al, 2014	Li et al, 2013	SIM 2007	MAIDS 2004	COST 2001	Hurt et al, 1981
n cases	80	40	259	436	921	253 (181 with known collision speed)	900
Collision Speed (km/h)	mean 45	mean 48	scooter to car front: mean relative speed 35 scooter to side of car: mean relative speed 27 50% risk MAIS 2+ at 58 km/h relative collision speed against car 50% risk AIS 2+ head injury at 50 km/h relative collision speed against car	mean approx. 70 (range 10-195)	mean 54 (range 0-170) 45% risk MAIS 3+ at 50-60 km/h 13% MAIS 3+ head injury at 50-60 km/h, with helmet, regardless of helmet contact	mean 44 (range 0-120) 50% risk AIS 3+ head injury at 65 km/h (head collision speed)	median 35 (range 0-121) 20% risk SS* 43+ at 50-65 km/h
Pre-crash Travelling Speed (km/h)	*n.a.*	*n.a.*	*n.a.*	mean approx. 60 (range 5-190)	*n.a.*	*n.a.*	median 50 (range 0-158)
% single-vehicle Crashes	28%	10%	*0%*	*n.a.*	16%	27%	25%
% helmeted Riders	100%	100%	*n.a.*	*n.a.*	92%	100%	41%
% fatally Injured	0%	5%	*n.a.*	32%	11%	47%	7%
Non-fatally Injured	22% ISS 15+	68% ISS 15+	14% AIS 2+ injuries	47% severely injured	27% MAIS 3+ (including fatalities)	38% AIS 3+ head injury. Inclusion criteria: helmeted riders with AIS 1+ head/neck injuries, or helmet contact with no head/neck injuries	25% MAIS 3+ (including fatalities)

2.2 Theoretical framework

2.2.1 A previous theory: The Haddon Matrix

Injury control has been adopted throughout history, for instance by evacuating populations exposed to environmental disasters such as floods or volcanic eruptions (Haddon 1980). The focus has not only been on the cause of the hazards themselves, but also on the countermeasures to prevent injuries (Haddon 1980). Haddon's approach is one of the most well-known examples of injury prevention theories, which has been used for road safety as well as in other fields.

Haddon's approach can be represented by a 3x3 matrix in which countermeasures addressing the pre-crash, crash and post-crash phases are separated depending on which part of the road transport system they relate to (user, vehicle or infrastructure). While this facilitated a more structured injury control strategy, with this approach each element is considered separately from the other. For instance, active and passive safety are seen as two separate areas.

Table 5: The Haddon Matrix. Source: Haddon (1980).

Phase	User	Vehicle	Infrastructure
Pre-crash (crash prevention)	Information Education Attitudes Impaired driving Enforcement	Roadworthiness Lighting Braking Handling Speed Management	Road design and layout Speed limits Pedestrian facilities
Crash (injury prevention)	Use of protective equipment	Protective equipment Other safety devices Crash protective design	Crash protective road side objects Median barriers
Post-crash (life sustaining)	First-aid skills Access to medics	Ease of access Fire risk	Rescue facilities Congestion

2.2.2 The integrated chain of events

The integrated safety chain is a further development of the Haddon Matrix (Kanianthra 2007; Tingvall 2008). With this approach, which is commonly used in the automobile industry (Nissan 2004; Schoeneburg 2005; Eugensson et al, 2011), the whole chain of events, from normal driving to a crash, can be treated like a process in time where interventions can take place at any stage. The integrated view reflects the fact that the output from one phase becomes the input in the next, which may be difficult to distinguish using the Haddon's matrix, where each phase is more isolated.

The integrated chain of events is the theoretical framework of the present thesis. As an example, the interaction between different safety technologies is illustrated. The starting point of the chain of events leading to a crash is when a road user enters a road and operates normally. Normal driving is defined by the speed at which health loss will be prevented, should a crash occur. While road users are supposed to comply with a set speed limit, other factors such as their education, motivation and cognition, as well as social norms (i.e. what is, and what is not, generally considered acceptable in their community) are defining factors. Drivers deviating from normal driving, due to unawareness, inattention or violation, can be brought back to normal driving by warning and supporting countermeasures. For instance, Intelligent Speed Assistance (ISA) or speed warnings would address speeding thus bringing the driver back to normal driving. However, this may not be enough, or other situations could occur, like drifting out of the lane or driving too close to other vehicles. This means that the chain of events is still in force and an intervention in the driving process would be needed to break the chain. An example would be Lane Keeping Assist (LKA) systems. Should a critical situation occur, such as skidding or loss-of-control, a prompt intervention would be needed to break the chain, as the crash may be just 1-2 seconds (or less) away. At this point the crash is no longer avoidable and the vehicle needs to prepare itself for the collision by, for instance, activating Autonomous Emergency Braking (AEB) systems, which would decrease the collision speed. Finally, health loss can be prevented with proper crash protection (helmets, airbags, road barriers, etc.), quick access to medical treatment and health care.

In other words, each step of the chain of events represent an opportunity to go back (i.e. returning to normal driving as long as the crash is still avoidable), but also for changing and affecting the next phase. The latter principle applies all the way to the crash, which means that an intervention in the early stages of the chain can generate two completely different chains of events. For instance, ISA supports drivers to comply with speed limits, to avoid crashes in the first place, but compliance may also lead to a different chain of events should a crash occur. Another example is how Electronic Stability Controls (ESC) in cars may prevent crashes from occurring at all, and also create the conditions for AEB systems to be effective by preventing skidding, and potentially changing some side impacts to frontal impacts (Sferco et al, 2001; Lie 2012). Hence, the link between crash avoidance and crash protection becomes more evident with the integrated chain of events, compared to the Haddon Matrix.

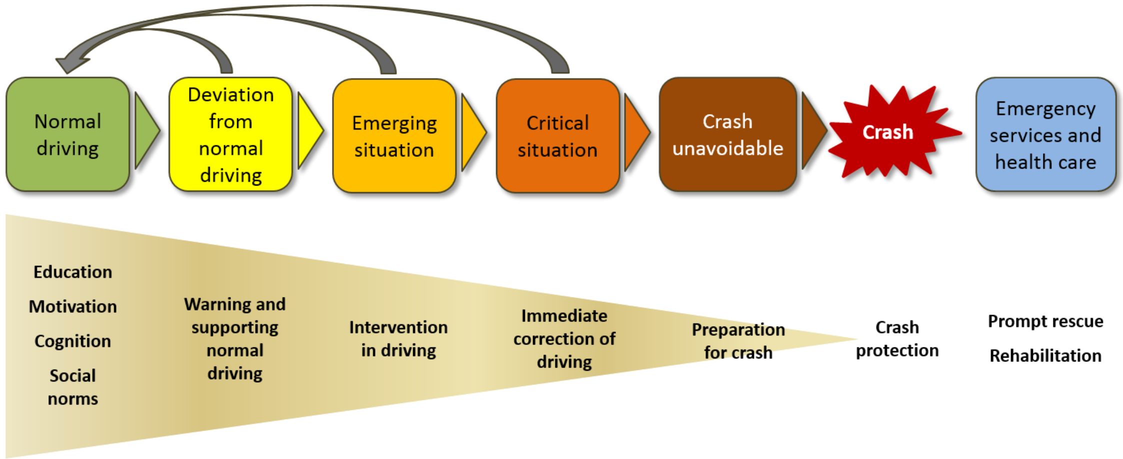


Figure 3: The integrated chain of events. Source: Lie (2012).

2.3 The traditional approach to motorcycle safety

With regard to motorcycle safety, the traditional approach is mainly based on two pillars: rider training and use of protective gear (i.e. helmets and protective clothing). As explained in Bjørnskau et al (2010), there are different steps in the rider training and education: mandatory training, graduated licensing and voluntary training. Mandatory training is the initial step that must be taken in order to receive a motorcycle license; graduated licensing imposes limitations on riding with passengers, engine size for certain age groups, etc.; voluntary training is individually undertaken by the motorcyclist. Several studies (Bjørnskau et al, 2010; Ulleberg, 2003; French et al, 2009) have confirmed that mandatory training reduces crash involvement among motorcyclists, although it is unclear whether graduated licensing has any safety benefits or not (Bjørnskau, 2010). While voluntary training seems to be counterproductive (Bjørnskau et al, 2010, Ulleberg, 2003), an important factor is whether education focuses on riding skills or on hazard perception, i.e. addressing the motivation causing deliberate risk taking on the roads (Bjørnskau et al, 2010, Ulleberg, 2003). Already in 1988, it was suggested by Glad (1988) that ice driving courses led to increased crash risks among young car drivers, although there is evidence suggesting that training addressing motorcyclists' risk perception does have positive effects (Forward et al, 2011; Liu et al, 2009).

With regard to protective gear, the mandatory use of helmets has been shown to be effective in reducing serious and fatal head injuries by almost 50% (Ulleberg 2003; Liu et al, 2008). However, the majority of fatal injuries are to the head, even among riders with helmets (DaCoTa 2012a; NHTSA 2008). Earlier theories have argued that the increased safety provided by helmets was offset by more risk-taking while riding (i.e. risk compensation; Wilde 1998), although this has been proven not to be the case among motorcyclists (Ouellet 2011), bicyclists (Lardelli-Claret et al, 2003) as well as in winter sports (Scott et al, 2007). Other protective equipment has been proven to be effective in reducing injuries in real-life crashes. De Rome et al (2011; 2012) have shown that motorcyclists are significantly less likely to be admitted to hospital if they crash while wearing motorcycle jackets, trousers or gloves. However, there are limits to the extent clothing can prevent injuries in high-impact crashes (de Rome et al, 2011), as protective clothing is thought to offer the greatest injury reductions in low-impact crashes (Hell et al, 1993; Noordzij et al; 2001; Otte el al, 2002). In particular, Noordzij et al (2001) suggested that protective clothing can prevent most lacerations and abrasions when a rider slides on the road surface, prevent contamination of open fractures, and reduce the severity of contusions, fractures and joint damage. However, severe bending, crushing and torsional forces to the legs (i.e. when the leg becomes trapped between the motorcycle and another vehicle or the road), or massive penetrating injuries on any part of the body may not be addressed by protective clothing (Noordzij et al, 2001).

A number of other countermeasures have also been adopted. In order to increase motorcyclists' visibility, Daytime Running Lights (DRL) and reflective clothing have been introduced (Ulleberg 2003), as well as campaigns among other road users to increase their awareness of motorcycles (DFT 2016). Also, the quality of the road surfaces, obstructions at intersections limiting other road users' vision (MAIDS 2004), improved design of road barriers and road side areas (Ulleberg 2003; MAIDS 2004) have been identified as important intervention areas for motorcycle safety.

If the integrated chain of events is applied to the traditional motorcycle safety approach explained above, it seems clear that no systematic safety interventions between normal driving and the actual crash are present, other than those at the two ends of the chain of events: rider training (left end) and crash protection (right end). Therefore, there is a need for further countermeasures to fill this safety gap, which needs to be investigated with a systematic approach to be fully understood.

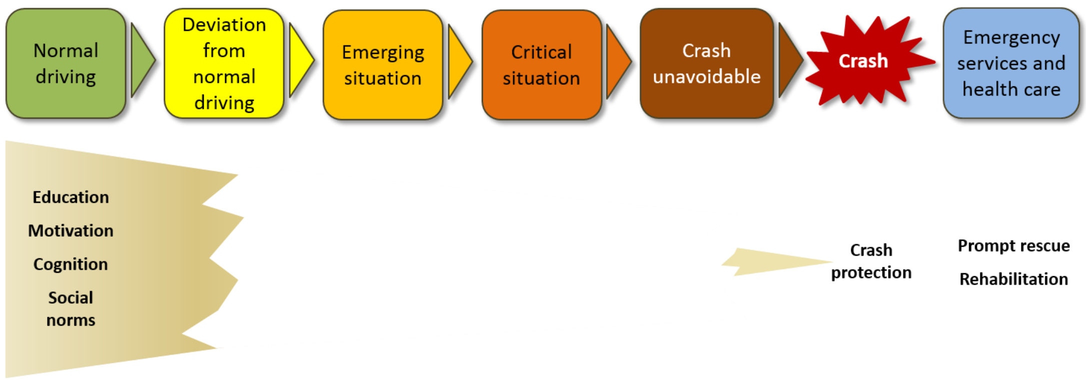


Figure 4: The traditional approach to motorcycle safety, seen with the integrated safety chain model.

While a number of studies have aimed at providing guidelines for stakeholders (STA 2010; 2BeSafe 2012), the interaction between different countermeasures has not been evaluated. In other words, the potential or effectiveness of a certain countermeasure has been estimated on a one-dimensional basis, i.e. on the principle "everything else is constant". The present thesis investigates this issue by using the integrated chain of events as a theoretical framework. In particular, the role of motorcycle stability is explored.

2.4 The role of the motorcycle and its stability

Motorcycles are intrinsically unstable vehicles (Massaro et al, 2012). While in motion, they are kept stable by the gyroscopic effect of the wheels and the lateral grip of the tyres (HLDI 2009; Seiniger et al, 2012). If one of these factors is compromised, i.e. one wheel is locked during braking (no gyroscopic effect) or lateral grip while cornering is insufficient, a motorcycle is immediately destabilised and the most likely consequence will be that the rider is separated from the motorcycle, falling to the ground (HLDI 2009; Seiniger et al, 2012). In this case, limited actions can be taken by the rider (i.e. braking, swerving, etc.). Basically, the only countermeasure to prevent health loss is the rider's protective gear, or a forgiving road infrastructure.

Previous crash analyses have shown that motorcycle instability is a common situation in crashes and that it is often associated with crash avoidance attempts: Hurt et al (1981) reported that in 40% of crashes, the rider had lost control of the motorcycle prior to collision. It was also found that the rider attempted to avoid the collision by braking (36%), swerving (10%) or both (20%). Similarly to Hurt et al (1981), MAIDS (2004) reported that 71% of PTW riders attempted some form of collision avoidance immediately prior to impact. Loss-of-control occurred in approximately 31% of cases while braking by the motorcycle rider was coded in 49% of cases. Clearly, these overall figures also depend on the distribution of crash types. In single-vehicle crashes, which accounted for 16% of cases in Hurt et al (1981) and 25% in MAIDS (2004), loss-of-control was more common, up to 80% (MAIDS 2004). In crashes against passenger cars, other studies indicated that braking prior to collision occurred in 65-75% of cases (Sporner et al, 2003; Rizzi et al, 2009). Previous research also suggest that the injury severity in a crash could be reduced if the rider is in an upright position (Sporner et al, 2003; Berg et al, 2005a; Rizzi et al, 2009).

2.4.1 The role of stability for crashes with road barriers

The crash posture issue, i.e. whether the motorcyclist is in an upright position or not during a crash, is of particular importance in crashes involving road barriers (Berg et al, 2005a). Today, these crashes represent an area of great concern to the motorcycle community as they often result in serious injuries for motorcyclists (MAIDS 2004; Ulleberg 2003).

While recent research (Daniello et al, 2011; Bambach et al, 2013) has shown that roadside barriers provide a significant reduction in the risk of serious injury to motorcyclists compared to various roadside hazards (trees, posts, etc.), previous studies have also shown that crashes involving barriers pose a higher injury risk, compared to all motorcycle injury crashes in general (Outlett 1982; Gibson et al, 2000). Also, the likelihood of being fatally injured in a collision with a road barrier was reported to be 80 times higher for motorcyclists than for passenger car occupants in the USA (Gabler 2007).

While a number of different barrier types are commonly used (Karim 2011), the injury risk for motorcyclists may differ in the event of a crash (Gabler 2007; Daniello et al, 2011) depending on their design. Concerning crash posture, previous research has shown that approximately half of all motorcyclists are in an upright position when they strike road barriers, whereas half slide into the barriers (Grzebieta et al, 2013; Berg et al 2005a; Ruiz et al, 2010; Quincy et al, 1988). It is suggested that the injury mechanisms may change depending on the crash posture and that sliding riders may have different injury distribution than upright ones (Berg et al 2005a). It is also reported that being ejected from the motorcycle after striking the barrier increases the odds of serious injury (Daniello et al, 2014). On the other hand, Grzebieta et al (2013) reported that thorax and head injuries were the most common in fatal crashes involving barriers, regardless of impact posture. While this study analysed fatal injuries, to date no research is available regarding impairing injuries (PMI) in collisions with road barriers.

The crash posture may be of particular importance considering that barrier design and testing have mainly focused on protecting riders who slide into a barrier. Most often, this is done by installing Motorcyclist Protective Systems (MPS) on a W-beam barrier (see Figure 5). While it is argued that MPS do have positive effects in upright collisions as well (Nordqvist et al, 2015), it has been noted by Grzebieta et al (2013) that barrier design and testing according to the European Technical Specification CEN/TS 1317-8 have neglected upright crashes. This specification prescribes crash tests in which an anthropomorphic crash test dummy (ATD) with a helmet is launched head first into a barrier. The impact angle and speed are 30° and 60 km/h, respectively (CEN 2012). Previous studies suggest that the 30° impact angle is not common in real-life crashes (Ruiz et al, 2010; Peldschus et al, 2007). Therefore, it would be important to understand how the crash posture may influence the injury outcome for the development of new barrier designs and testing procedures.

Figure 5: A W-barrier fitted with MPS.

2.4.2 Motorcycle stability and Antilock Braking Systems (ABS)

Motorcycle Antilock Braking Systems (ABS), also known as Antilock Brakes, were introduced in the late 1980s in order to improve stability by maintaining wheel rotation during hard braking. While ABS have been shown to generally provide shorter stopping distances (Green 2006) for both experienced and novice riders (Vavryn et al, 2004), ABS can also increase braking stability and therefore prevent the motorcyclist from falling to the ground, as pointed out by Teoh (2013; 2011) and Lich et al (2015). Without ABS, front wheel lock events have to be extremely short to prevent the rider from falling off, i.e. less than 0.5 seconds, as shown in the tests performed by Gail et al (2009), see Figure 6. Other tests also indicate that the latest versions of ABS, also known as cornering ABS (Bosch 2014), can safely handle maximum braking with leaning angles up to 45° (Motorrad 2016).

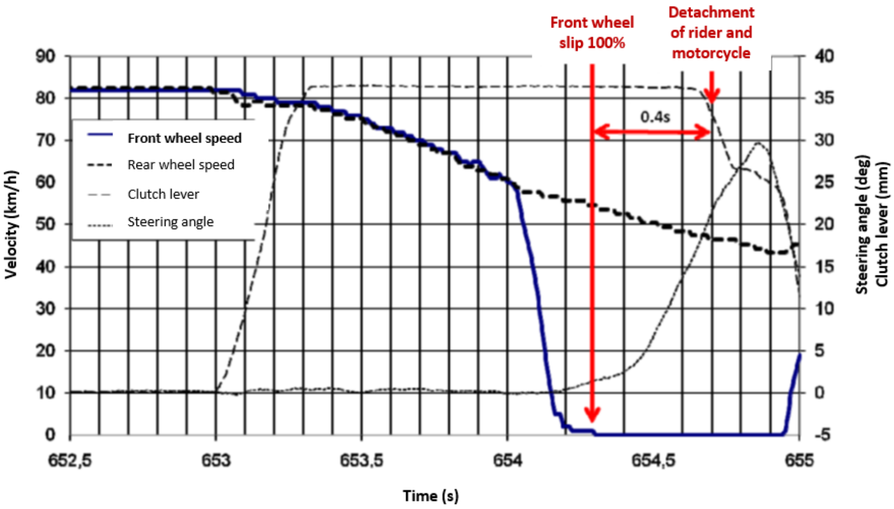


Figure 6: Front wheel speed during hard braking without ABS. Adapted from Gail et al (2009).

As early as in 1979, the Transport Research Laboratory (TRL) performed braking manoeuvres on a wet surface with a prototype version of Motorcycle ABS, showing that falling off the motorcycle due to wheel-locking was eliminated (Watson 1979). While more recent tests support these findings (Kato et al, 1996; Vavryn et al, 2004; Green 2006; Gail et al, 2009; Anderson et al, 2010), there is limited research showing to what extent sliding crashes are reduced by ABS in real-life conditions. A Swedish study (Olai 2011) based on interviews with 37 seriously injured riders with ABS showed that five (14%) fell off the motorcycle prior to collision. It was also reported that in none of these cases the riders had applied the brakes. However, this study did not include a control group of crashes with similar motorcycles not equipped with ABS, which made it difficult to draw general conclusions. Therefore, there is a need to understand whether ABS do increase stability in real-life conditions.

ABS on motorcycles are increasingly integrated with Combined Braking Systems (CBS), which essentially link the front and rear brakes (HLDI 2013). This system applies braking force to both wheels when either control is engaged. While there are a variety of implementations on the market (Teoh 2013), wheel lock-up is not prevented with CBS alone. In terms of the effectiveness on reduction of real-life crashes, several studies have reported significant benefits of Motorcycle ABS.

Rizzi et al (2009) found head-on crashes to be a non-sensitive scenario to ABS and therefore used those crashes with an induced exposure approach to evaluate the effectiveness of ABS in Sweden during the period 2003-2008. The study estimated the overall effectiveness of ABS to be 38% on all injury crashes and 48% on all severe and fatal crashes. In 2013, the Highway Loss Data Institute (HLDI) used regression analysis to quantify the effects of ABS on insurance loss in the US during 2003-2012. The study estimated a statistically significant 31% reduction in collision claims frequency for motorcycles fitted with ABS together with CBS. As ABS alone were associated with a 20% reduction in collision claims, this suggested that CBS could provide a benefit additional to that of ABS alone. Another study by Teoh (2013) compared motorcycle driver involvement in fatal crashes per 10,000 registered vehicles in the US. The comparison was made between motorcycles models with optional ABS and the same models without ABS. The fatality rate was found in this study to be 31% lower for the model versions with ABS compared to the non-ABS versions. A recent study by Fildes et al (2015a) analysed police-reported crashes from five Australian states for the period 2000-2011 using induced exposure. The results showed a 33% reduction of all motorcycle injury crashes and 39% of serious and fatal motorcycle crashes, respectively.

Further results were found in Rizzi et al (2009) suggesting that crashes involving ABS-equipped motorcycles generally resulted in fewer severe injuries, possibly due to the improved braking performance with ABS which had the capacity to reduce collision speeds, as suggested by Lich et al (2015). At the present stage, however, further research is needed to understand to what extent the large reductions in injury crashes with ABS is due to crash avoidance and/or reduction of the crash severity.

Until the early 2000s, Motorcycle ABS were mostly fitted in up-market models, similar to ESC in passenger cars (Lie et al, 2006). While HLDI (2014), HLDI (2013) and Teoh (2013) did include some light motorcycles in their studies, these were based on data from the US, where motorcycling is mostly for leisure (Haworth 2012). Previous research on real-life crashes in Europe also focused on large displacement motorcycles, often used for leisure riding (Rizzi et al, 2009). Therefore, there is limited research regarding the effectiveness of ABS on light motorcycles in other riding conditions, i.e. scooters used for commuting in urban environments. Using in-depth data, a recent study reconstructed motorcycle crashes in India and reported that 33% of crashes could have been avoided with ABS, and in a further 16% of cases the collision speed could have been reduced (Lich et al, 2015). While these were important results, they were not based on real-life crashes with Motorcycle ABS, due to the limited fitment of ABS in India (Lich et al, 2015).

As mentioned earlier, motorcycle fleets and usage may vary across different countries. For instance, scooters accounted for 12% of all registered new motorcycles in Sweden in 2012 (McRF 2013), while scooters represented the 10 most sold motorcycle models in Italy and Spain during the same period (ACEM 2013). Also, motorcycle fleets in Spain and Italy are larger - in 2012, 6.4 million motorcycles were registered in Italy, 2.8 million in Spain, and only 0.3 million in Sweden (ACEM 2013). A different distribution of crashes in urban areas and during the May-September period (DaCoTA 2012b) also suggests different motorcycling habits across these countries. Therefore, it would be useful to expand the evaluation of ABS with crash data from countries with different motorcycling habits.

2.4.3 The role of stability for motorcycle crashworthiness

Today's motorcycles provide little protection against injuries in the case of an upright crash (DaCoTa 2012a), and virtually none in a sliding crash. As noted by Berg et al (2005b), motorcycle crashworthiness seems to still be underdeveloped, even though research has been carried out for decades in this area. A brief historical background with a few milestones of this research is given below.

When the Experimental Motorcycle Safety (ESM) project was presented, Aoki (1973) pointed out that "*special attention must be paid to the fact that it is impossible to apply to the motorcycle the concept of Experimental Vehicles Safety (ESV) particularly concerning the concept of crashworthiness. By doing so, the motorcycle will become something else which can no longer be called a motorcycle*". However, a number of countermeasures have been tested since then. With regard to leg injuries, a rather simple countermeasure are conventional crash bars, usually made out of loops of steel tubes projecting to the side of the motorcycle (Rogers et al, 1998). Studies based on in-depth investigations of 133 real-life crashes showed no overall benefits, as the proportion of injured leg regions was nearly identical for motorcycles with and without crash bars (Ouellet et al, 1987). While there was evidence suggesting that crash bars were sufficient to preserve the leg space in many crashes, it was argued that leg space preservation was not strongly related to serious leg injuries, mainly because the leg often did not remain in the leg space during the collision (Ouellet et al, 1987). Furthermore, frontal crash tests in an upright position showed greater chest and head accelerations due to the rotation of the upper body (Rogers et al, 1998; Noordzij et al, 2001). In the 1980s a more advanced leg protector concept was presented by the TRL to address leg injuries in upright crashes against passenger cars (Chinn et al, 1984; Chinn et al, 1985), see Figure 7.

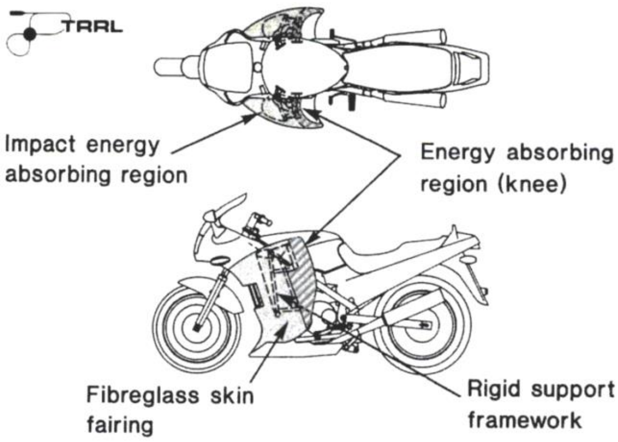


Figure 7: The leg protector concept proposed by the TRL. Source: American Motorcyclist (1991).

Several crash tests using different methods were performed independently by the TRL and by the International Motorcycle Manufacturers Association (IMMA), resulting in contradictory claims for the effectiveness of the TRL leg protectors (Chinn et al, 1990; Rogers 1991; Rogers 1994). While all crash tests involved an upright collision against a passenger car, according to Sakamoto (1990), one of the main reasons for such divergence in conclusions was considered to be due to the substantial differences in evaluation methods, including impact dummies, test conditions, measured data and injury criteria. In order to address this issue, in 1996 the standard ISO 13232 "*Test and Analyses Methods for Evaluation of Rider Crash Protective Devices Fitted to Motorcycles*" was developed (Van Driessche 1994; Berg et al, 2005b). Based on real-life data provided by Otte (1980) and Hurt et al (1981), the standard proposed seven upright crash tests against a passenger car (see Figure 8) and a further 200 crash configurations for simulations.

Further testing was then carried out based on the ISO standard, using an extensively modified Hybrid III dummy fitted with frangible legs (Rogers et al, 1998). Overall, the crash tests showed a disadvantage for the TRL leg protectors: the risk for leg fractures was reduced, although head injury risks were increased (Rogers et al, 1998). As a result of these findings, the proposed leg protectors were rejected by the IMMA (Rogers et al, 1998) as well as motorcycle lobbies (French 1995; American Motorcyclist 1991, 1992, 1996). It was later argued that the implementation of airbags on the fuel tank would probably address the increased head injury risks due to the rotation of the upper part of the body caused by the leg protectors, and that the combined benefit of these two systems could probably be superior to the sum of its parts (Noordzij et al, 2001). As a matter of fact, the TRL leg protectors never saw real-life implementation, although they led to the development of common methodologies for testing motorcycle crashworthiness (Sakamoto 1990).

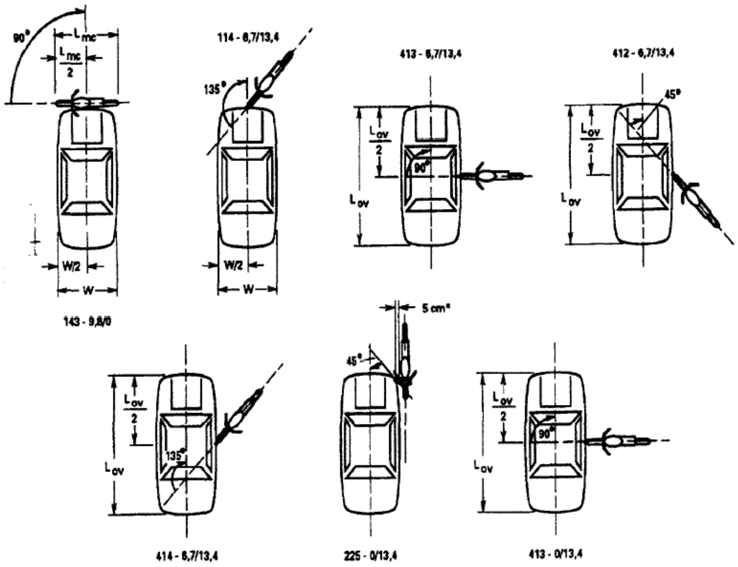


Figure 8: The crash test configurations proposed in ISO 13232. Source: Van Driessche (1994).

While the leg protection debate between TRL and IMMA was still ongoing, BMW started the development of an unconventional motorcycle design (called C1), with the objective of concentrating measures to protect the rider through components incorporated in the vehicle itself rather than personal protective gear (Osendorfer et al, 2001). The C1 is based on a scooter layout with a roof, and the rider is restrained by seat belts and protected by a tuned crumple zone at the front. Protection is also offered in sliding crashes due to the frame construction that acts as a roll-bar, see Figure 9 (Osendorfer et al, 2001). Kalliske et al (1998) reported crash testing the C1 in six impact configurations: two according to ISO 13232, two into the rear of a car, one into the side of a car and one into a rigid barrier. The results showed that the seat belts were able to hold the rider within the safety zone during a crash and that injury risks were lower than for a conventional scooter. However, the C1 was discontinued in 2002 with approximately 30,000 units sold (BMW 2015). Evaluations based on real-life crashes have not been published.

Another manufacturer used a different approach, i.e. equipping a traditional motorcycle with an airbag "*to reduce the injuries to a rider when impacting with an opposing vehicle and/or opposing object in frontal collisions by absorbing rider kinetic energy and by reducing rider separation velocity from motorcycle in the forward direction*" (Kuroe et al, 2005). The airbag was mounted on a large touring motorcycle and developed over several years (Iijima et al, 1998; Yamazaki et al, 2001). In 2005 the final results were presented, based on 12 full-scale impact tests in seven upright configurations, based on ISO 13232. These showed that the airbag system had the potential to be effective in reducing fatal and serious injuries to riders (Kuroe et al, 2005). The airbag was commercialised from 2006 on the Honda Goldwing, and later crash tests by ADAC (2013) showed similar results. While similar tests have also been performed with a large-sized scooter (Kuroe et al, 2004), a mid-sized touring motorcycle (Berg et al 2005b) and a 125cc scooter (Aikyo et al, 2015) with convincing results, at the present stage the Honda Goldwing 1800 is still the only motorcycle on the market with a frontal airbag as an optional fitment, and evaluations based on real-life crashes have not yet been published.

Figure 9: The BMW C1 (left side) and the airbag-fitted Honda Goldwing 1800 (right side). Source of crash test pictures: BASt (BMW C1) and ADAC (Honda Goldwing).

Evidently, significant research efforts have been made to improve the crashworthiness of motorcycles during the last four decades, but few innovative solutions have actually reached the market, and if they have, only in very limited volumes. While it is clear that most of these countermeasures may be relevant only in upright crashes (the only exception is the C1), all evaluations were based on crash tests, and few studies have been conducted on real-life crashes. However, the possibility that some motorcycle designs may inherently offer some degree of protection may not have been investigated thoroughly in previous research. The overall motorcycle design can vary across different categories and manufacturers; for instance, based on in-depth data collected from 139 motorcycle crashes in Australia, it was found that certain fuel tank designs may increase the risk of pelvis injuries (Meredith et al, 2014). Some motorcycles have been equipped since the 1920s with a horizontally opposed flat-twin engine, which means the cylinders are overhanging horizontally in front of the riders' legs. This engine configuration is also known as boxer-twin engine. Figure 10 shows an illustration of a motorcycle equipped with a boxer-twin engine (left) and a similar one with a single-cylinder engine (right).

A previous study (Hurt et al, 1981) collected in-depth data of 900 motorcycle crashes in the Los Angeles urban area (US) based on on-scene investigations during the period 1976-1977. The findings showed that leg injuries were less common among riders of motorcycles with boxer-twin engines, although this was based on a very limited number of cases (n=11). Therefore, further analysis on this particular issue is carried out in the present research.

Figure 10: A front-view illustration of a motorcycle equipped with a boxer-twin engine (left) and a similar one with a single-cylinder engine (right).

2.5 Summary of background

The facts presented here show that fatalities and health loss among motorcyclists are global road safety problems for which innovative countermeasures are needed. While the traditional safety approach has focused on protective gear and rider education, the Safe System approach adopted in Sweden and other countries implies that the road, the vehicle and the road user, together with a safe speed limit, should interact to create a safe road transport system.

Motorcycles are intrinsically unstable vehicles and their design appears to be a critical factor which has not been fully explored in the past. However, the lack of a systematic approach makes it difficult to understand the true potential of present and future countermeasures. Such an approach is needed to comprehend the implications of stability for motorcycle safety and may yield significant savings in health loss among motorcyclists.

3 AIMS

In order to fill the safety gap illustrated in Figure 4, the overall aim of this thesis is to understand the chain of events leading to crashes with ABS-fitted motorcycles, compared to similar motorcycles without ABS. More specifically, the aim is to test the following hypotheses.

- ABS can prevent some crashes, thus bringing the rider back to normal driving.
- Not all crashes can be prevented, and some riders will proceed further in the chain of events. The crash is still unavoidable, but more favourable conditions may result by crashing in an upright position, thus providing some sort of crash protection, i.e. an injury mitigating effect.
- The injury distribution in upright crashes differs from sliding crashes, and the role of motorcycle design for rider protection becomes more important with ABS. Because of the lack of crash data involving the innovative designs described earlier, an example with a specific design (i.e. boxer-twin engine) can be used to test this hypothesis.
- The benefits of ABS are applicable to other countries with different motorcycling habits, other than leisure riding as in Sweden.

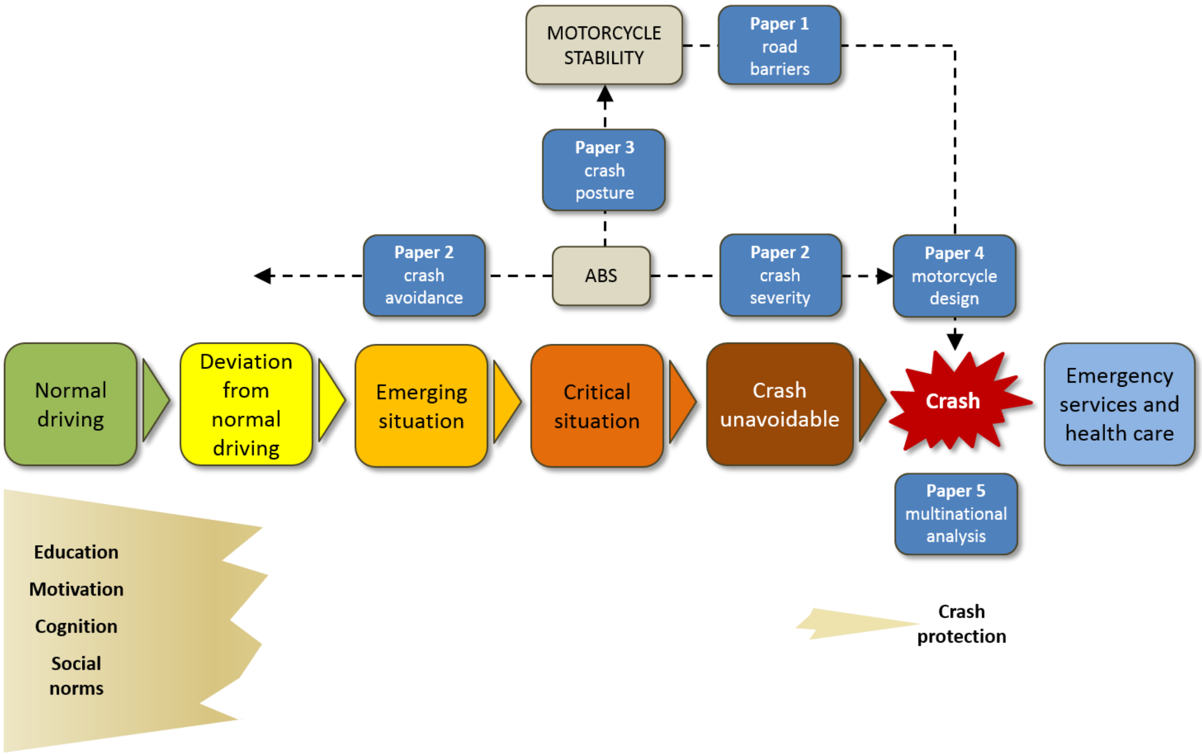


Figure 11: The research plan.

Figure 11 illustrates the research plan for this thesis: five papers were written, investigating the following issues: Paper 1 investigated whether the crash posture may affect the injury outcome, Paper 2 analysed if ABS may prevent crashes (return to normal driving) as well as lower the severity of the crashes that do occur, Paper 3 studied whether ABS improve stability in real-life crashes, Paper 4 analysed if the design of ABS-motorcycles may also affect the injury outcome, and finally Paper 5 studied whether ABS may be effective in different traffic environments.

The specific aims of each paper were as follows.

Paper 1 – Road Barriers

a. Investigated if motorcyclists' injury risk differs in collisions with different types of road barriers.
b. Analysed whether the injury outcome in motorcycle crashes into road barriers can be reduced if the motorcyclist is in an upright position prior to collision.

Paper 2 – Crash Prevention and Crash Severity

a. Evaluated the effectiveness of Motorcycle ABS in reducing emergency care visits.
b. Compared the Risk of Permanent Medical Impairment (RPMI) in motorcycle crashes with and without ABS.
c. Analysed the injury distribution in crashes with and without ABS.
d. Estimated the total effect of ABS in terms of crash avoidance and mitigation of impairing injuries.

Paper 3 – Crash Posture in Fatal Crashes

a. Investigated the distribution of sliding and upright fatal crashes involving motorcycles with and without ABS, regardless of whether the riders applied the brakes or not.
b. Studied the main characteristics of sliding fatal crashes with ABS with regard to the road environment, the riders, the motorcycles and the crash dynamics.
c. Calculated the reduction in fatal crashes involving braking with ABS, compared to similar motorcycles without ABS.

Paper 4 – Motorcycle Design

a. Analysed the distribution of all injuries in crashes involving ABS-equipped motorcycles with boxer-twin engines, compared with similar ABS-motorcycles with other engine configurations.
b. Compared the risk for impairing injuries in those crashes.
c. Investigated whether leg injuries may be reduced in crashes involving ABS-motorcycles fitted with boxer-twin engines.

Paper 5 – Multinational ABS Analysis

a. Estimated the effectiveness of Motorcycle ABS in reducing crashes resulting in injuries involving a wide range of motorcycle models, including scooters.
b. Compared the effectiveness of Motorcycle ABS between Sweden and two other countries, Italy and Spain, which may have dissimilarities in vehicle fleet characteristics, different motorcycling habits and road environments.

4 SUMMARY OF PAPERS

4.1 Overview of materials and methods

4.1.1 Materials

Several types of materials were used in the five papers. An overview of the data and methods is given in Table 6. Overall, Papers 1, 2 and 4 used Swedish police records derived from the Swedish Traffic Accident Data Acquisition (STRADA) combined with other sources: telephone interviews in Paper 1 and hospital data in Papers 2 and 4. In-depth studies of fatal motorcycle crashes collected by the Swedish Transport Administration (STA) and the Norwegian Public Roads Administration (NPRA) were used in Paper 3. Paper 5 was based on police records included in the national road crash databases of Italy (managed by the Italian Institute of Statistics; ISTAT), Spain (managed by the General Directorate of Transport; DGT) and Sweden (STRADA).

Swedish police data should include all reported road crashes including personal injuries. Four injury levels are assigned by the officer attending the crash scene: fatal, serious, slight and uninjured. The crash type definition normally describes the pre-crash direction of travel of the vehicles rather than the direction of force during the impact (i.e. a head-on crash can involve a frontal-side impact).

If a crash is also police-reported, it is normally recorded in STRADA with the same crash identification number as the hospital report, which means that hospital data can be automatically merged with police records to obtain vehicle information. The hospital data collection started in 2003 with a gradually increasing national coverage. In 2014, all emergency hospitals (but one) in Sweden were reporting injuries. Hospital reports normally include a number of parameters describing the crash (brief description of the crash, crash type, location, etc.), personal information about the patient (age, gender, use of protective equipment, etc.) and full diagnosis classified according to the AIS 2005 scale (AAAM 2005).

In the Road Barriers paper (1), police records were expanded with telephone interviews. These included questions regarding the subject's motorcycling habits, details of use of protective equipment, injuries sustained in the crash, as well as the pre-crash and crash phases. The injuries were coded according to the Abbreviated Injury Scale (AIS) 2005 system (AAAM 2005), based on the participants' description.

The STA and the NPRA carry out in-depth studies for all road fatalities that were used in Paper 3. Crash investigators at the STA and NPRA systematically inspect the vehicles involved and record direction of impact, vehicular intrusion, seat belt and helmet use, airbag deployment, tyre properties, etc. The crash site is also inspected to investigate road characteristics, collision objects, etc. Further information is provided by forensic examinations, witness statements from the police and reports from the emergency services (STA 2005). Collision speeds are generally derived by vehicular deformation, and the initial driving speed is mostly based on eye-witness accounts, brake skids, etc. Pre-crash braking is also coded based on eye-witness accounts, brake and skid marks. The final results of each investigation are normally presented in a report. Because all fatal crashes are included in the sampling criterion, the material can be considered fully representative for Swedish and Norwegian road fatalities.

Paper 5 was based on police records from different countries. In Italy, Spain and Sweden, crashes on public roads injuring at least one person are recorded by the police. However, there are some differences. For instance, in Italy, it is not possible to distinguish between slight and severe injuries. The crash type classification includes the following main categories:

- Frontal collisions
- Side-frontal collisions
- Side collisions
- Rear-end collisions
- Single-vehicle
- Collisions with a pedestrian

In Spain, four injury levels are assigned by the officer attending the crash scene: fatal, serious, slight and uninjured. The Spanish crash type classification is similar to the Italian.

Table 6: Overview of methods and materials.

	Paper 1 - Road Barriers	**Paper 2 - Crash Prevention and Crash Severity**	**Paper 3 - Crash Posture in Fatal Crashes**	**Paper 4 - Motorcycle Design**	**Paper 5 - Multinational ABS Analysis**
Main Aim	Analysed if the injury outcome may be affected by the crash posture	Estimated the effect of ABS in terms of crash avoidance and mitigation of impairing injuries Analysed the injury distribution in crashes with and without ABS	Analysed to what extent sliding crashes are reduced by ABS in fatal crashes	Investigated if leg injuries may be reduced in crashes involving ABS-motorcycles fitted with boxer-twin engines	Estimated and compared the effectiveness of ABS in reducing crashes in countries with different motorcycle fleets
Analytical Method	Comparison with chi-square statistics and independent two sample t-test	Induced exposure and independent two sample t-test	Comparison with chi-square statistics and induced exposure	Comparison with chi-square statistics and independent two sample t-test	Induced exposure
Data	Interviews of injured motorcyclists involved in police reported crashes into road barriers	Hospital and police reported motorcycle crashes	In-depth studies of fatal motorcycle crashes	Hospital and police reported motorcycle crashes	Police reported motorcycle crashes
Country	Sweden	Sweden	Norway Sweden	Sweden	Italy Spain Sweden
Number of Cases	160 police records 55 interviews	665	168	182	Italy 3197 Spain 6613 Sweden 890
Data Time Period	2003-2010	2003-2012	2005-2014	2003-2014	Italy 2009 Spain 2006-2009 Sweden 2003-2012

4.1.2 Methods

4.1.2.1 Induced exposure

Papers 2, 3 and 5 applied an induced exposure approach, which can be used when the true exposure is not available (Evans 1998; Lie et al, 2006; Strandroth et al, 2012). With this approach, the key point is to identify at least one crash type or situation in which the system under analysis (i.e. ABS) can be reasonably assumed (or known) not to be effective. Then, the relation between motorcycles with and without ABS in a non-affected situation would be considered as the true exposure relation (Evans 1998; Lie et al, 2006; Strandroth et al, 2012). The effect of ABS is considered to be zero if R in Eq.1 is equal to 1.

$$R = \frac{A_{ABS}}{N_{ABS}} \div \frac{A_{non-ABS}}{N_{non-ABS}} \qquad (\text{Eq. } 1)$$

A_{ABS} = number of crashes *sensitive* to ABS, involving motorcycles *with* ABS
$A_{non-ABS}$ = number of crashes *sensitive* to ABS, involving motorcycles *without* ABS
N_{ABS} = number of crashes *non-sensitive* to ABS, involving motorcycles *with* ABS
$N_{non-ABS}$ = number of crashes *non-sensitive* to ABS, involving motorcycles *without* ABS

The effectiveness in reducing crashes in relation to non-sensitive crashes was calculated as follows:

$$E_s = 100 \times (1 - R)\% \qquad (\text{Eq. } 2)$$

The standard deviation of the effectiveness was calculated on the basis of a log odds ratio variance, see below (Evans 1998; Lie et al, 2006; Strandroth et al, 2012). This method gives symmetric confidence limits but the variance estimate is conservative.

$$\text{Sd}(\ln R) = \sqrt{\frac{1}{A_{ABS}} + \frac{1}{A_{non-ABS}} + \frac{1}{N_{ABS}} + \frac{1}{N_{non-ABS}}} \qquad (\text{Eq. } 3)$$

The 95% confidence limits are given in Eq. (4-6).

$$\Delta E_s = 100 \times R \times \text{Sd}(\ln R) \times 1.96 \qquad (\text{Eq. } 4)$$

$$E_{s\ LOWER} = E_s - \Delta E_s \qquad (\text{Eq. } 5)$$

$$E_{s\ UPPER} = E_s + \Delta E_s \qquad (\text{Eq. } 6)$$

The effectiveness in reducing *all* crashes and the 95% confidence limits can therefore be calculated as follows (Evans 1998; Lie et al, 2006; Strandroth et al, 2012):

$$E = E_s \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS} + A_{ABS} + A_{non-ABS}} \qquad (\text{Eq. } 7)$$

$$\Delta E = \Delta E_s \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS} + A_{ABS} + A_{non-ABS}} \qquad (\text{Eq. } 8)$$

4.1.2.2 Risk for Permanent Medical Impairment

Papers 1, 2 and 4 analysed injury outcomes using the Risk for Permanent Medical Impairment (RPMI), see Gustavsson et al (1985).

In insurance claims, the principles of grading medical impairment of injuries have been established in consensus between specialised medical doctors. Here, medical impairment is defined as a reduction in physical and/or mental function, independent of cause and without regard to occupation, income, hobbies, etc. A medical impairment is considered permanent when no further improvement in physical and/or mental function is expected with additional treatment; this would in most cases occur within three to five years after a crash. When an injury is classified it is given a degree of medical impairment between 1% and 99%. As an example, amputation of a tibia is set to an impairment of 19%, whiplash injury 1-15%, limited motion of shoulder 1-20% and total loss of hearing 60%. The abbreviation PMI is often used to refer to impairing injuries. While PMI 1+ injuries include all levels of impairment, PMI 10+ injuries generally result in persistent symptoms affecting activities on a daily basis.

The Risk for Permanent Medical Impairment is an estimation of the risk of a patient suffering a certain level of medical impairment, based on the injuries diagnosed according to the AIS 2005 scale (AAAM

2005). Basically, a prediction of the number of impaired persons (or impairing injuries) can be made by multiplying the immediate injury outcome with the RPMI. This process is further described below. The RPMI is derived from risk matrices for at least 1% permanent medical impairment (RPMI 1+) as well as at least 10% medical impairment (RPMI 10+, see Table 7), as presented in Malm et al (2008). This study was based on approximately 35,000 diagnoses from 20,000 injured car occupants who reported an injury to Folksam Insurance between 1995 and 2001. After the initial injury, the injured car occupants were followed for at least five years to assess the risk of permanent medical impairment for different body regions and AIS severity levels. The results are shown in Table 7.

The material included in Malm et al (2008) was not large enough to produce the RPMI assigned to single diagnoses. Instead, injuries were grouped according to the 11 AIS 2005 body regions, except for the region “external”, which includes all lacerations, contusions, abrasions and burns, independent of their location on the body surface. This was done because these soft tissue injuries often show a completely different risk of permanent medical impairment compared with other AIS 1 injuries in the same body region (Malm et al, 2008).

The study was mostly based on AIS 1 or AIS 2 injuries. Fatalities were not included, therefore there were very few AIS 5 and no AIS 6 injuries. Moreover, some of the risks were by definition 100%. These involved diagnoses that were immediately and permanently disabling, i.e. AIS 4 injuries to the cervical, thoracic and lumbar spine, where the sole diagnosis is incomplete cord syndrome (preservation of some sensation or motor function), and AIS 5 complete cord syndrome (quadriplegia, C-4 or below, or paraplegia with no sensation). Also for AIS 4 upper extremities, where the only diagnosis is amputation at the elbow or above, the risk of impairment is by definition 100%.

Table 7: Risk of Permanent Medical Impairment (left side: at least 1% impairment; right side: at least 10% impairment). Source: Malm et al (2008).

	RPMI 1+						**RPMI 10+**				
Body region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	Body region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5
Head	8.0%	15%	50%	80%	100%	Head	2.5%	8%	35%	75%	100%
Face	5.8%	28%	80%	80%	*n.a.*	Face	0.4%	6%	60%	60%	*n.a.*
Cervical Spine	16.7%	61%	80%	100%	100%	Cervical Spine	2.5%	10%	30%	100%	100%
Upper Extremities	17.4%	35%	85%	100%	*n.a.*	Upper Extremities	0.3%	3%	15%	100%	*n.a.*
Thorax	2.6%	4.0%	4%	30%	30%	Thorax	0.0%	0%	0%	15%	15%
Thoracic Spine	4.9%	45%	90%	100%	100%	Thoracic Spine	0.0%	7%	20%	100%	100%
Abdomen	0%	2.4%	10%	20%	20%	Abdomen	0.0%	0.0%	5%	5%	5%
Lumbar Spine	5.7%	55%	70%	100%	100%	Lumbar Spine	0.1%	6%	6%	100%	100%
Lower Extremities	17.6%	50%	60%	60%	100%	Lower Extremities	0.0%	3%	10%	40%	100%
External (Skin)	1.7%	20%	50%	50%	100%	External (Skin)	0.03%	0.03%	50%	50%	100%

Clearly, RPMI can refer to a specific injury, as shown in Table 7, but also to an individual. The overall RPMI for an individual with several injuries can be calculated as follows: the product of the risk of not being injured can be calculated, as described by Gustavsson et al (1990), where n is the number of injured body regions for each motorcyclist, and *risk* is the risk for each body region and AIS level shown in the risk matrices (see Table 7). Only the highest scored AIS coded injury per body region is included in the calculation.

$$\mathrm{RPMI} = 1 - (1 - \mathrm{risk}_1) \times (1 - \mathrm{risk}_2) \times \ldots \times (1 - \mathrm{risk}_\mathrm{n}) \qquad \text{(Eq. 9)}$$

Given an individual with several injuries, Eq. (9) basically represents the risk that at least one of those injuries will lead to PMI. As a simple example, assume that a person sustained the following injuries in a crash:

- AIS 1 hand abrasion
- AIS 2 shoulder dislocation
- AIS 2 patella fracture

As shown in Table 7, these injuries have the following RPMI:

- "External" AIS 1 injury: RPMI 1+ = 1.7%; RPMI 10+ = 0,03%
- Upper extremity AIS 2 injury: RPMI 1+ = 35%; RPMI 10+ = 3%
- Lower extremity AIS 2 injury: RPMI 1+ = 50%; RPMI 10+ = 3%

The individual's RPMI can be calculated based on Eq. (9), as follows:

$$\text{RPMI } 1+ = 1 - (1 - 0.017) \times (1 - 0.35) \times (1 - 0{,}5) = 68.1\% \qquad (\text{Eq. } 10)$$

$$\text{RPMI } 10+ = 1 - (1 - 0.0003) \times (1 - 0.03) \times (1 - 0{,}03) = 5{,}9\% \qquad (\text{Eq. } 11)$$

The mean values of RPMI 1+ and RPMI 10+ can be calculated for different groups of individuals, as well as for different body regions. The relative difference (*rel RPMI)* between the mean values of RPMI *(mRPMI 1+* and *mRPMI 10+)* can also be calculated and tested by an independent two sample t-test, conducted for unequal sample sizes and variance (Standroth et al, 2011).

The number of impairing injuries (PMI 1+) is given by the accumulated risk for permanent medical impairment (RPMI 1+) for each body region. The same process may be used to calculate the number of severely impairing injuries (PMI 10+). The distribution of PMI 1+ and PMI 10+ injuries can then be analysed. This approach has been used in Sweden to manage the national road safety work (STA 2014a) and in a number of previous studies to analyse hospital-reported injuries among car occupants (Stigson et al, 2011), pedestrians (Strandroth et al, 2011) and cyclists (Rizzi et al, 2013).

4.2 Specific methods and results

The specific methods and results are summarised below for each paper. While the findings and implications of each paper are discussed in the general discussion, some limitations connected to specific papers are discussed in this chapter.

4.2.1 Paper 1 – Road Barriers

As mentioned above, the overall aim of Paper 1 was to understand if the injury outcome may be affected by the crash posture.

4.2.1.1 Method

The STRADA database does not keep records of collision objects, i.e. crashes involving road barriers are not assigned a specific code. However, the data include a brief description written by the police officer attending a crash scene. Motorcycle crashes into road barriers were identified by searching the word "barrier" ("*räcke*" in Swedish) in the crash description of all police reports included in STRADA. This resulted in 160 crashes during the period 2003-2010. The descriptions were read to ensure that the motorcyclists had collided into a road barrier. The STRADA data were merged with the National Road Database (NVDB) to retrieve further information regarding the type of barrier as well as other infrastructure details. Cross-checks were also performed through Google Street View to gain a better understanding of how the crash site may have looked. Crashes involving different barrier types on roads with similar safety standards and speed limits were compared using the Fatal-Serious-Injury Ratio (FSI).

$$\text{FSI ratio} = \frac{\text{number of fatally and severely injured}}{\text{number of injured}} \qquad (\text{Eq. } 12)$$

Self-reported injuries, acquired through 55 telephone interviews, were coded according to AIS 2005. Cross-checks were also made in those cases with an available hospital record to identify possible discrepancies in the diagnoses. Injuries among motorcyclists who crashed into a road barrier in an upright position were compared with injuries among other motorcyclists who fell to the ground before the collision and slid into the barrier. While proper controls were performed on other factors, the Injury Severity Score (ISS; Baker et al, 1974) as well the share of AIS2+ and AIS3+ injuries were used to compare injury outcomes. Each subject's injury scores were also converted to RPMI 1+ and RPMI 10+.

4.2.1.2 Results

The analysis of 160 police records showed that in 19% of all available crashes the type of barrier was unknown. Among the remaining 81% of crashes, 73% involved wire rope, Kohlswa-beam and W-beam barriers (see Figure 12).

Figure 12: A wire rope barrier (left), a Kohlswa-beam barrier (middle) and a W-beam barrier (right). Source: Karim (2011).

The material including pipe-beam and concrete barriers was too limited and was excluded from the analysis. Further analysis showed no statistically significant difference at the 95% level between the FSI-ratios for wire rope, Kohlswa-beam and W-beam barriers, although these FSI-ratios were generally above 50%.

Table 8: FSI-ratios for different road barriers in speed areas of 90 km/h, or above.

90 km/h speed limit, or above	n crashes	FSI-ratio
Wire Rope	29	52%
Kohlswa-beam	9	44%
W-beam	20	60%
Kohlswa and W-beam	29	55%

The 55 interviews, however, showed that injury severity was lower in crashes in which the motorcyclists were in an upright position during the collision, see Table 9.

Table 9: Comparison between injury outcomes in sliding crashes and upright crashes, based on interviews.

	Sliding Crashes	Upright Crashes	Difference	
AIS 2+	33 (75%)	40 (53%)	-22%	p<0.01
AIS 3+	13 (30%)	13 (17%)	-13%	p<0.01
MAIS 2+	16 (80%)	25 (71%)	-9%	*p=0.48*
MAIS 3+	7 (35%)	8 (23%)	-12%	*p=0.33*
ISS 1-8	11 (55%)	25 (71%)	+16%	*p=0.22*
ISS 9-15	2 (10%)	6 (17%)	+7%	*p=0.23*
ISS 16+	7 (35%)	4 (11%)	-24%	p=0.02
mean RPMI 1+	57.2%	53.2%	-7%	*p=0.60*
mean RPMI 5+	33.5%	24.8%	-26%	*p=0.30*
mean RPMI 10+	19.9%	9.8%	-51%	*p=0.21*

The proportion of subjects with ISS 16+ was 24% lower in upright crashes compared to those who slid into the barrier. In addition, the share of AIS 2+ and AIS 3+ injuries were 22% and 12% lower, respectively. The mean RPMI 10+ was 51% lower, although this result was not statistically significant. However, leg injuries were more common. Only six participant rode a motorcycle equipped with ABS: all of them crashed into the road barrier in an upright position.

4.2.1.3 Discussion - Limitations
Paper 1 was based on a number of limitations and assumptions. First of all, crashes involving road barriers are not assigned a specific code in STRADA, which means that the material used in Paper 1 may not represent the actual number of motorcycle-barrier collisions that occurred in Sweden during 2003-2010. While this is a clear limitation, it could be argued that whether the crash description included the word “barrier” or not should not depend on the type of barrier involved.

The analysis of police records showed no statistically significant difference at the 95% level between the FSI-ratios for wire rope, Kohlswa-beam and W-beam barriers. Kohlswa-beam and W-beam barriers were also grouped and compared with wire rope barriers alone. This was based on the assumption that Kohlswa-beam and W-beam barriers are structurally similar. Another critical assumption was that roads with speed limits of 90 km/h or above, as well as divided roads and roads with Annual Average Daily Traffic above 4000 would have similar safety standards and would therefore be suitable for comparison. Crashes in 50 km/h and 70 km/h speed areas were excluded because only two injury crashes involving wire rope barriers occurred in those speed areas. Normally the speed limit on a Swedish road is a function of its safety standards which also depend on the Annual Average Daily Traffic. In most cases, a road with more than 4000 Annual Average Daily Traffic needs to be divided (with a median barrier or median reserve) in order to be assigned a speed limit of at least 90 km/h. It was therefore argued that by applying these criteria, roads with similar injury risks for motorcyclists would be selected. Therefore, it was also important to compare road barriers in similar speed areas due to the fact that the FSI-ratio may be affected by the speed limit.

To address the second aim, self-reported injuries were AIS-coded by the research team and the overall injury outcome was analysed with MAIS, ISS and RPMI. While this method has clear limitations, the results indicates that the diagnoses made by the research team generally agreed quite well with the hospital records, although minor differences were found for AIS 1 injuries. The level of detail given by the participants about the injuries sustained in the crash was normally sufficient to assign AIS levels. Approximately 76% of all injuries were to the upper or lower extremities. The AIS level of such injuries is relatively easy to code, as for instance, a fracture could range from AIS 1 to AIS 3 (i.e. finger or open tibia fracture, respectively). While head injuries require much more detailed information (i.e. time of unconsciousness, depth of brain contusion, etc.), it could be argued that such injuries only accounted for 4% of the analysed material, and thereby did not influence the results in any significant way.

4.2.2 Paper 2 – Crash Prevention and Crash Severity
The overall aims of Paper 2 were to estimate the effect of ABS in terms of crash avoidance and mitigation of impairing injuries, and to analyse the injury distribution in crashes with and without ABS.

4.2.2.1 Method
The calculations included similar motorcycles with and without ABS within the following motorcycle categories: touring, standard, sport touring and on/off-road (also known as dual-purpose). ABS-equipped motorcycles across these four categories were grouped for analysis; the same operation was performed for non-ABS motorcycles. The overall crash and injury risks for each group were then calculated and compared in three steps.

***First step*:** the reduction of emergency care visits for motorcycles with ABS was calculated using an induced exposure approach. Head-on crashes were used as non-sensitive to ABS (Rizzi et al, 2009). Further analysis was made within the ABS and non-ABS groups to check the presence of confounding factors, i.e. to ensure that ABS and non-ABS crashes were derived from similar crash populations.

Second step: the injury mitigating effects of ABS were investigated. The mean RPMI 1+ and RPMI 10+ were analysed for different crash types; hypothetically, if head-on crashes were the least ABS-affected crash type (Rizzi et al, 2009), mRPMI 1+ and mRPMI 10+ with or without ABS should not differ substantially in those crashes. The relative difference (rel RPMI) between the mean values of RPMI was also calculated. The distribution of impairing injuries (PMI 1+) and severely impairing injuries (PMI 10+) were analysed.

Third step: the total reduction of PMI 1+ and PMI 10+ injured motorcyclists was calculated by combining the reductions found in the previous steps. The statistical significance of the difference between the number of expected impaired motorcyclists with ABS and without ABS was calculated using Fisher's exact test (Agresti 1992). An additional analysis of CBS together with ABS was also performed.

4.2.2.2 Results

First step: it was found that hospital-reported crashes were reduced with ABS by 47% (95% CI: 15%-79%) and that intersection crashes were reduced by 48% (95% CI: 9%-87%). The reduction of rear-end crashes was not statistically significant (43%; 95% CI: -3%-89%).

Second step: analysis of the mean RPMI 1+ and RPMI 10+ showed no statistically significant difference between ABS and non-ABS when different crash types were analysed separately. The smallest relative difference was found in head-on crashes. The reductions for the mean RPMI 1+ and RPMI 10+ with ABS in all crash types were 15% and 37%, respectively. These were statistically significant at the 95% and 99% level, respectively.

Analysis of the distribution of impairing injuries showed that the most common PMI 1+ injuries across both groups were injuries to the lower extremities, although these were even more common among ABS riders (see Table 10). With regard to PMI 10+, injuries to the legs and head were most common among riders with and without ABS, respectively.

Table 10: Distributions of PMI 1+ and PMI 10+ injuries across the ABS and non-ABS groups.

	ABS		**non-ABS**	
	PMI 1+	**PMI 10+**	**PMI 1+**	**PMI 10+**
Head	2%	11%	6%	26%
Cervical Spine	3%	5%	9%	10%
Face	2%	9%	2%	3%
Upper Extremities	30%	22%	29%	16%
Lower Extremities	38%	28%	30%	22%
Thorax	3%	4%	3%	3%
Thoracic Spine	8%	11%	8%	13%
Abdomen	0%	1%	1%	2%
Lumbar Spine	10%	9%	8%	5%
External (skin)	4%	0%	4%	0%
n impairing injuries	79	8	279	42
Total	100%	100%	100%	100%

Third step: at the end of the chain of events leading to at least a 10% permanent medical impairment, these results corresponded to a 67% total reduction of PMI 10+ with ABS ($p=0.01$). The total reduction of PMI 1+, calculated in the same way, was found to be 55% ($p<0.01$). Indications were found suggesting that the benefits of ABS together with CBS may be greater than ABS alone.

4.2.2.3 Discussion - Limitations

Hospital reports were used in Paper 2, which means that the average crash severity in these crashes probably was higher than in insurance claims, as used in the studies by HLDI (2013; 2014). This was the first study to calculate the effects of Motorcycle ABS in reducing impairing injuries. It could be argued that the reduction of emergency care visits (47% ± 32%) was not unreasonable if compared with the reduction in fatality rates reported by Teoh (2013), which may suggest that the Swedish material is generally robust, despite the limited size.

A limitation was that the ABS and non-ABS groups were not based on exactly the same motorcycle models with and without ABS, due to the limited size of the material. Instead, the analysis was based on make/models that were believed to be similar with respect to vehicle characteristics and user groups. Possible confounding factors in the first and second steps were analysed by performing simple calculations, which showed that the ABS and non-ABS groups were similar in terms of rider and vehicle age, helmet use rate and types of roads. Therefore no model for statistical treatment of confounders was introduced. However, there were a few differences that should be kept in mind. The most important one was the fitment of CBS, which was handled separately.

It should also be noted that ABS is not standard equipment in all motorcycles on the roads, which means that those who choose to purchase these technologies are probably more concerned about their safety in the first place (i.e. selective recruitment). This aspect could lead to lower collision speeds and consequently lower injury risks, thus confounding the results. If this is the case, however, the mean RPMI with ABS would be expected to be lower in all crashes types, even those that are less affected by ABS (i.e. head-on). In this study, it was found that the mean RPMI in head-on crashes with and without ABS was similar, thus suggesting that the reduction of RPMI was mostly due to the ABS itself.

4.2.3 Paper 3 – Crash Posture in Fatal Crashes

The overall aim of Paper 3 was to understand to what extent sliding crashes are reduced by ABS in fatal crashes.

4.2.3.1 Method

Fatal crashes were grouped depending on whether braking had occurred prior to collision, as well as the crash posture (upright or sliding). There were a total of 22 ABS cases in Sweden and 16 in Norway, involving helmeted riders of motorcycles with engine displacement >125cc. The types of motorcycles involved in these crashes were: touring, sport touring, standard, on/off-road, scooters (STA database only, n=1) and super sports (STA database only, n=4). These were compared with crashes involving similar motorcycles without ABS, resulting in 98 relevant cases in Sweden and 32 cases in Norway.

The Swedish and Norwegian datasets were analysed separately and also merged together. The difference between the proportions of sliding crashes regardless of braking was analysed; selective recruitment was handled with a sensitivity analysis of possible confounders: the proportions of sliding crashes were calculated for a number of different subgroups, by including only sober riders (BAC<0.02% and no illegal drugs), licensed riders, cases devoid of excessive speeding (less than 30 km/h over the speed limit), motorcycles without CBS, Traction Control (TC), or other than super sports. Induced exposure was used to calculate the reduction of all crashes, and those involving braking. Crashes without braking were considered as non-sensitive to ABS.

4.2.3.2 Results

It was found that the distribution of sliding and upright crashes (regardless braking) were similar in the Swedish and Norwegian materials. Among all the 38 ABS cases, four (11%) involved falling off the motorcycle prior to collision, while 35% of the non-ABS crashes involved sliding. This difference was statistically significant (p=0.004). Overall, the sensitivity analysis showed that the results were stable. The relative difference of sliding crashes ranged between 65% and 78%, although the statistical power of some subgroups was reduced due to the limited number of cases.

None of the four sliding fatal crashes with ABS involved braking, i.e. all ABS riders who applied the brakes prior to collision crashed in an upright position. In these four cases, the riders lost control of their motorcycles: two while accelerating on asphalt with very poor friction, one while negotiating a curve with an excessive lean angle, and one by abruptly releasing the throttle in the middle of a curve.

Further comparison between the ABS and non-ABS groups showed that the distribution of sliding and upright collisions among crashes without braking were similar (see Table 11), thus suggesting that the crash posture would not be affected by ABS if no braking occurred. This finding was used in the calculations with induced exposure; the merged results showed that upright crashes involving braking were reduced with ABS by 79% (see Table 11). As mentioned above, no sliding crashes involving braking occurred with ABS, i.e. all ABS riders who applied the brakes prior to collision crashed in an upright position. The calculations performed with induced exposure also showed a 52% reduction in all fatal crashes with ABS (regardless of braking or crash posture).

Table 11: Distribution of sliding and upright fatal crashes, with and without braking in Sweden and Norway; results for the induced exposure calculations. Please note that braking was unknown for one case in Norway (n=37).

		n		%		Ratio		E
		ABS	no ABS	ABS	no ABS	ABS	no ABS	
SWE								
Braking	Sliding		30	0%	42%	0.00	1.11	100%
	Upright	7	41	100%	58%	0.47	1.52	69%
	Sum	*7*	*71*	*100%*	*100%*	*0.47*	*2.63*	*82%*
No Braking	Sliding	2	4	13%	15%	-	-	-
	Upright	13	23	87%	85%	-	-	-
	Sum	*15*	*27*	*100%*	*100%*	-	-	-
NOR								
Braking	Sliding		9	0%	47%	0.00	0.75	100%
	Upright	1	10	100%	53%	0.07	0.83	91%
	Sum	*1*	*19*	*100%*	*100%*	*0.07*	*1.58*	*95%*
No Braking	Sliding	2	2	14%	17%	-	-	-
	Upright	12	10	86%	83%	-	-	-
	Sum	*14*	*12*	*100%*	*100%*	-	-	-
SWE + NOR								
Braking	Sliding		39	0%	43%	0.00	1.00	100%
	Upright	8	51	100%	57%	0.28	1.31	79%
	Sum	*8*	*90*	*100%*	*100%*	*0.28*	*2.31*	*88%*
No Braking	Sliding	4	6	14%	15%	-	-	-
	Upright	25	33	86%	85%	-	-	-
	Sum	*29*	*39*	*100%*	*100%*	-	-	-

4.2.3.3 Discussion - Limitations

The findings of Paper 3 seemed to be well in line with Olai (2011), showing a similar distribution of sliding crashes among ABS riders: 14% in Olai (2011) and 11% in this study. While it should be kept in mind that Paper 3 and Olai (2011) were based on different inclusion criteria (i.e. different injury outcomes), these results were consistent with each other. Another important finding of Paper 3 was that ABS reduced fatal crashes by 52%, which was also in line with previous research, although Teoh (2011) indicated a somewhat lower reduction in fatal crash rates (37%).

An important issue in Paper 3 was data quality: it is evident that a limited material would be more sensitive to miscoding in the crash reconstructions. While precise routines have been set at the STA and NPRA for data collection and crash reconstructions, it should be kept in mind that a detailed reconstruction of some motorcycle crashes may be a challenging task, due to their complexity. While it is rather straight-forward to determine whether a collision is sliding or upright, based on the deformation of vehicles, marks on the asphalt and the final position of the rider, this may not be the case for braking prior to collision. Skid marks are a clear indicator of braking without ABS, but these may be uncommon with Motorcycle ABS, which means that this information is mostly based on eye-witness accounts. Here, comparison between the ABS and non-ABS groups showed that the distribution of sliding and upright collisions among crashes without braking were similar (see Table 11), thus suggesting that these particular data were reliable with regard to braking prior to collision.

4.2.4 Paper 4 – Motorcycle Design

The overall aim of Paper 4 was to investigate if leg injuries may be reduced in crashes involving ABS-motorcycles fitted with boxer-twin engines.

4.2.4.1 Method

Crashes involving motorcycles fitted with boxer-twin engines were identified and compared with similar ones fitted with other engine configurations. These motorcycles were included in the categories touring, standard, custom, sport touring and on/off-road. In total, 55 crashes involving ABS-equipped motorcycles with boxer engines were compared with 127 involving ABS-motorcycles with other engine configurations. Due to the limited size of the material, the 10 body regions originally used in the RPMI matrices were re-grouped into six body regions, as shown in Table 12.

Table 12: The body regions used in the analysis, compared to the body regions used in the RPMI matrices.

Body regions used in RPMI	Grouped body region used in Paper 4
Head Face	Head and Face
Abdomen Thorax	Torso (Abdomen, Thorax)
Cervical Spine Thoracic Spine Lumbar Spine	Spine (Cervical, Thoracic, Lumbar)
Upper Extremities	Upper Extremities
Lower Extremities	Lower Extremities
External (Skin)	External (Skin)

AIS and PMI injury distributions of the six body regions were compared across the two groups using the Fisher's exact test (Agresti 1992). This was done in order to investigate the possibility that leg injuries may be reduced in crashes with boxer-twin engines, but also that other injuries to the upper body may be increased, as previously reported for conventional crash bars and the TRL prototype (Noordzij et al. 2001). Clearly, any reduction of the percentage of leg injuries among boxer riders will be accompanied by an increase in another body region, for instance the upper body. However, this does not necessarily mean that injuries to the upper body increased.

In order to compare the distributions of injuries to other body regions, the number of expected leg injuries among boxer riders were also calculated, i.e. the number that would give an equal percentage of leg injuries across the two groups. This was done by calculating x in Eq. (13) for AIS 1+, AIS 2+ and PMI 1+ injuries. Basically, this process can be seen as calculating the missing leg injuries (x) among boxer riders. It was then possible to compare the distributions of injuries to other body regions.

$$\frac{\text{n actual leg injuries}_{\text{boxer}} + x}{\text{n actual all injuries}_{\text{boxer}} + x} = \frac{\text{n actual leg injuries}_{\text{others}}}{\text{n actual all injuries}_{\text{others}}} \qquad \text{(Eq. 13)}$$

The overall RPMI for each rider was calculated. The relative difference between the two groups mean values of RPMI was calculated and tested by an independent two sample t-test which was conducted for unequal sample sizes and variance. Finally, the location and AIS severity of leg injuries among the two groups were compared by calculating the risk for AIS 1+ and AIS 2+ injuries for specific leg portions (hip, femur, knee, tibia, ankle, foot).

4.2.4.2 Results

It was found that AIS 1+, AIS 2+ and PMI 1+ leg injuries among riders with boxer engines were reduced by approximately 50%. The calculations based on Eq. (13) showed that the injury distribution across the other body regions would have been very similar had the share for the two groups been equal between AIS 1+, AIS 2+ and PMI 1+leg injuries (see Table 13). No substantial difference was found in the mean values of RPMI 1+ and RPMI 10+ across different body regions. Indications were found suggesting that the overall mean RPMI 1+ among riders with boxer engines was lower than for those with other engine configurations, although this result was not statistically significant (p=0.23). The mean values of the overall RPMI 10+ were similar (p=0.94). Further analysis of injuries of the lower extremities showed that no knee or foot injuries had been reported among riders with boxer engines, see Table 14.

Table 13: Distribution of AIS 1+, AIS 2+ and PMI 1+ injuries (* indicates the expected number of leg injuries among riders with boxer-twin engines).

AIS 1+ injuries	n injuries		*p*	Boxer-twin		Others
	Boxer-twin	Others		% actual	% expected	% actual
Head and Face	10	13	*0.25*	6%	5%	4%
Torso (Abdomen, Thorax)	28	47	*0.22*	17%	15%	13%
Spine (Cervical, Thoracic, Lumbar)	17	24	*0.16*	11%	9%	7%
Upper Extremities	30	59	*0.53*	19%	16%	16%
Lower Extremities	***14 (37*)***	73	*0.001*	***9%***	***20%***	20%
External	62	145	*0.77*	39%	34%	40%
Total	*161 (184*)*	361	-	100%	100%	100%
AIS 2+ injuries	**n injuries**		***p***	**Boxer-twin**		**Others**
	Boxer-twin	**Others**		**% actual**	**% expected**	**% actual**
Head and Face	5	6	*0.32*	7%	5%	4%
Torso (Abdomen, Thorax)	23	39	*0.26*	32%	24%	24%
Spine (Cervical, Thoracic, Lumbar)	9	12	*0.23*	13%	10%	8%
Upper Extremities	22	44	*0.64*	31%	23%	28%
Lower Extremities	***12 (34*)***	58	*0.003*	***17%***	***36%***	36%
External	1	1	*0.53*	1%	1%	1%
Total	*72 (94*)*	160	-	100%	100%	100%
PMI 1+ injuries	**n injuries**		***p***	**Boxer-twin**		**Others**
	Boxer-twin	**Others**		**% actual**	**% expected**	**% actual**
Head and Face	2	2	*0.58*	7%	5%	3%
Torso (Abdomen, Thorax)	2	2	*0.58*	7%	5%	3%
Spine (Cervical, Thoracic, Lumbar)	6	8	*0.22*	22%	15%	12%
Upper Extremities	9	18	*0.62*	33%	23%	27%
Lower Extremities	***7 (20*)***	33	*0.04*	***26%***	***50%***	50%
External	1	3	*1*	4%	3%	5%
Total	*27 (40*)*	66	-	100%	100%	100%

Table 14: Number of injuries to the lower extremities by AIS severity, and risk for AIS 1+ and AIS 2+ injuries.

	Boxer-twin			Others			risk AIS 1+		risk AIS 2+	
Leg portion	**AIS 1**	**AIS 2+**	**Total**	**AIS 1**	**AIS 2+**	**Total**	**Boxer-twin**	**Others**	**Boxer-twin**	**Others**
Hip	1	3	4	1	4	5	7%	4%	5%	3%
Femur		1	1		1	1	2%	1%	2%	1%
Knee			0	2	12	14	0%	11%	0%	9%
Tibia		1	1		9	9	2%	7%	2%	7%
Ankle	1	7	8	4	18	22	15%	17%	13%	14%
Foot			0	8	14	22	0%	17%	0%	11%
Number of leg injuries	2	12	14	15	58	73	-	-	-	-
Number of patients			55			127				

4.2.4.3 Discussion - Limitations

Paper 4 was based on a number of assumptions and limitations. First of all, the available crash data were limited. ABS-motorcycles with boxer-twin engines were compared with similar motorcycles (also fitted with ABS) from the same manufacturer as well as from other ones. Checks on possible confounding factors were made to ensure their comparability in terms of crash and injury risks. The distribution of crash type, speed area, rider age and gender, use of helmets and other protective gear were in fact very similar across the two groups. However, the distribution of motorcycle type (i.e. touring, standard, on/off-road, sport touring) were not similar. On/off-road motorcycles (also known as dual-purpose) were over-represented among motorcycles with boxer engines, due to the limited crash data involving large on/off-road machines with other engine configurations. While this aspect could confound the results, it was argued that the riding position was similar across the included motorcycles.

A further limitation is that, the original 10 body regions used in the RPMI matrices were grouped for analysis, due to the limited material. While it could be argued that such grouping was made for logical reasons, see Table 12, it is clear that the injury distribution analysis would have been more powerful with the original 10 body regions. Similarly, all crash types were analysed together, as the material was too limited for a separate analysis of single-vehicle crashes and multi-vehicle ones.

4.2.5 Paper 5 – Multinational ABS Analysis

The overall aim of Paper 5 was to estimate and compare the effectiveness of ABS in reducing crashes in Sweden, Italy and Spain.

4.2.5.1 Method

Previous research (Rizzi et al, 2009) found that head-on crashes were the least ABS-affected crash type and these were therefore used as the non-sensitive crash type for ABS in the calculations. These findings, however, were based on Swedish crashes only. It was therefore necessary to make assumptions on which crash types could be used as non-sensitive in the Italian and Spanish datasets. It was hypothesised that frontal and side-frontal crashes in non-intersections could be a reasonable proxy of the Swedish head-on crash definition. For instance, a crash in which a PTW rider fell off in a curve on a rural road and slid into the side of an oncoming car would be classified as side-frontal in Spain and Italy. Analysis of the distribution of ABS-equipped motorcycles per crash type was also made to verify this hypothesis, as ABS motorcycles would logically be over-represented in a non-sensitive crash type to ABS. The Vehicle Identification Numbers (VINs) of the motorcycles involved in the crashes were included in the Italian data. With regard to the Spanish and Swedish crash data, it was possible to identify the ABS fitment through model name and model year. The additional fitment of CBS and TC was also checked. The same motorcycle models, with ABS (n=1596) and without (n=9104) were compared and the calculations were carried out for each country separately. Crashes involving only scooters (at least 250cc) in the Italian and Spanish databases were further analysed (418 with ABS and 2677 without ABS). In total, some 90 motorcycle models were included in the analysis.

4.2.5.2 Results

The analysis showed that the crash type with the highest percentage of ABS-equipped motorcycles in the Swedish dataset was head-on, thus supporting the findings of the previous study (Rizzi et al, 2009). The results for Italy and Spain suggested that frontal and side-frontal crashes in non-intersections could be used as non-sensitive crashes, as the involvement of ABS-motorcycles in those crashes was the highest.

The effectiveness of Motorcycle ABS in reducing injury crashes ranged from 24% (95% CI: 12%-36%) in Italy to 29% (95% CI: 20%-38%) in Spain and 34% (95% CI: 16%-52%) in Sweden. The reductions in severe and fatal crashes were even greater, at 34% (95% CI: 24%-44%) in Spain and 42% (95% CI: 23%-61%) in Sweden. It was not possible to distinguish between slight and severe injuries in the Italian database and therefore it was excluded from the effectiveness calculations for severe and fatal crashes. The overall reduction of crashes involving ABS-equipped scooters (at least 250cc) was 27% (12%-42%) in Italy and 22% (2%-42%) in Spain. ABS on scooters with at least a 250cc engine reduced severe and fatal crashes by 31% (12%-50%), based on Spanish data alone.

4.2.5.3 Discussion - Limitations

Data quality may represent a limitation of Paper 5. Police-reported crashes from different time periods were used, and it is well-known that these suffer from a number of quality issues. Injury severity measures relied on police assessments, which have previously been shown to have clear limitations (Farmer 2003). However, it was assumed that these limitations would affect both the ABS and non-ABS group equally, therefore it was not expected to affect the overall results to any large degree. A possible way of addressing the injury assessment issue would be to analyse fatal crashes separately. However, the number of fatal crashes in the present material was too limited.

A further limitation is that VINs were not available for the Spanish and Swedish material. It should be noted, however, that a misclassification between ABS and non-ABS motorcycles would give a conservative estimation of the actual benefit of ABS.

4.3 Overall results

The five papers included in this thesis showed a number of findings regarding the effectiveness of ABS in reducing different types of crashes. These are summarised in Figure 13, including the 95% confidence limits if available. Overall, injury crashes were reduced by ABS to a lower degree than severe and fatal ones, i.e. the more severe the injury outcome, the higher the reduction of crashes with ABS. The reduction of crash types that typically involve braking (i.e. rear-end or intersection crashes) was also higher. As shown in the Crash Posture paper (3), fatal sliding crashes involving braking were reduced by 100%.

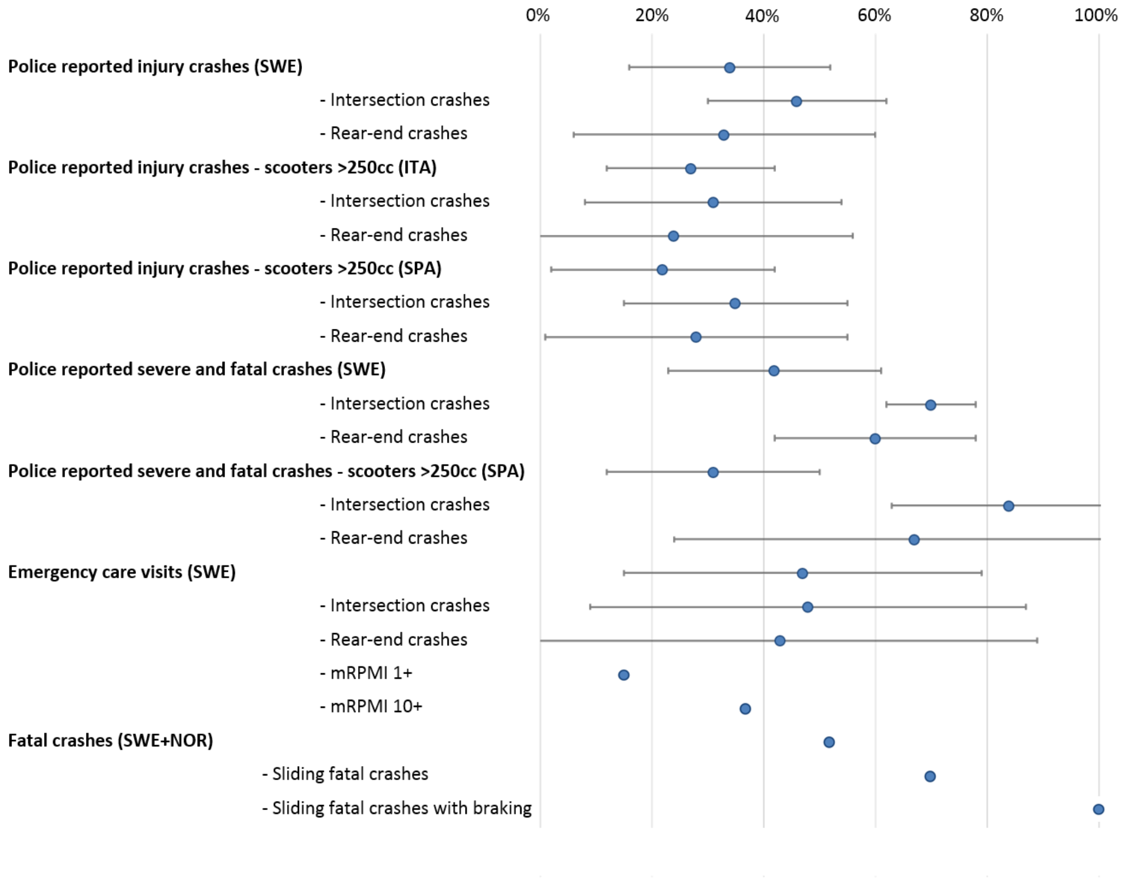


Figure 13: Summary of results on ABS effectiveness in reducing crashes and injuries.

The results of Papers 1, 2, 3 and 4 can be combined as illustrated in Figure 14. Hypothetically, if 100 riders with ABS and 100 riders without ABS are given the same boundary conditions and exposure, 47 ABS riders would avoid critical situations and may go back to normal riding (Paper 2, corresponding to 14.6 PMI 1+ injured). The remaining 53 ABS riders would go further in the chain of events, and eventually crash. However, these ABS riders would crash in approximately 90% of cases in an upright position, as shown in the Crash Posture paper (3), which would result in an overall lower injury outcome (Paper 1 and 2), even though leg injuries would not be addressed to the same extent (Paper 1 and 2). This leg issue could be addressed through suitable motorcycle designs, as shown in Paper 4. Finally, the Multinational ABS Analysis (5) suggests that ABS have important benefits in different road environments.

In fact, it could be calculated that a portion of the mRPMI 1+ and mRPMI 10+ reductions calculated in Paper 2 were actually due to the protecting effects of boxer engines. The ABS-group included in Paper 2 could be divided between motorcycles with boxer-engines and other configurations; using the same approach as in Paper 2, it could be calculated that mRPMI 1+ with boxer engines and ABS would be 24%, instead of 27% with ABS and other engine configurations. The distribution of leg injuries would be 26% and 50%, respectively, thus giving an overall PMI 1+ reduction of 59% (compared with 55% with ABS and other engine configurations).

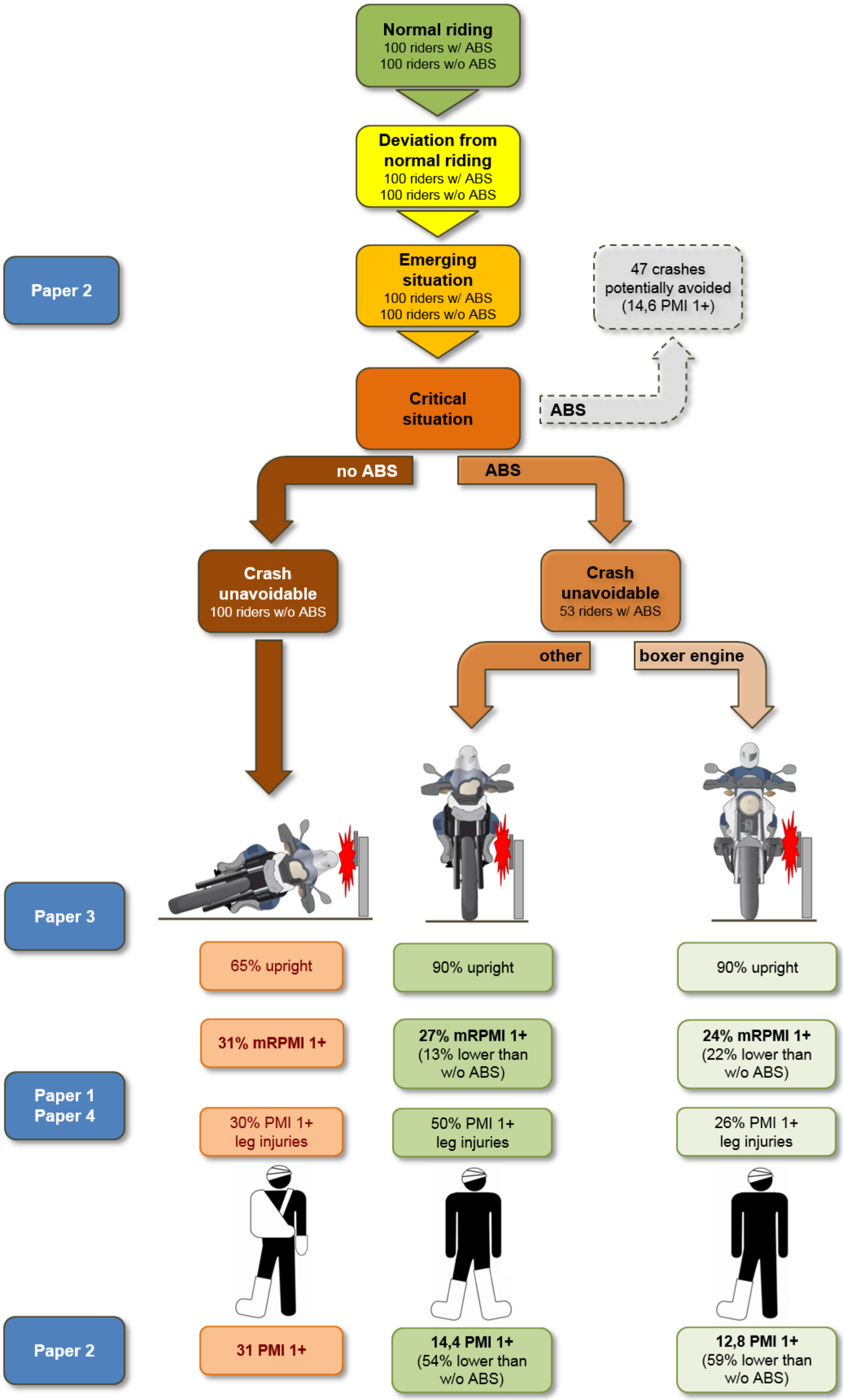


Figure 14: The combined results of Papers 1-4.

5 GENERAL DISCUSSION

Even though the overall trends in many countries have shown impressive reductions in road traffic fatalities (Shinar 2012), motorcyclists are still the most vulnerable road users (OECD 2015). While the traditional safety approach has focused on protective gear and rider education, with the Safe System approach, designers of the road transport system are considered responsible for its design and operation (Johansson 2009). The Swedish strategy for safer PTW use (STA 2010) has represented a milestone in the road safety work in Sweden as this strategy symbolises the acknowledgement of PTWs as a natural component of a road transport system. Future countermeasures were discussed and agreed on by stakeholders, with the common objective of reducing health loss among motorcyclists in order to meet the national interim targets. While the research presented by the STA (2010) was mostly based on fatal crashes, it was stressed that, also non-fatal injuries should be addressed. As pointed out in the recent Swedish strategy for safer cycling (STA 2014b), different intervention areas may need to be prioritised, depending on the injury outcome to address.

While there may be great challenges ahead in the future development of motorcycle safety, a few aspects that characterise motorcycles should be kept in mind; some of these are common to other vulnerable road users too. For instance, the high injury risks in the case of a crash are mostly isolated to their own users, rather than to occupants of other vehicles or other vulnerable road users. This is not the case for passenger cars, for which great engineering efforts have been made over the last decade to protect those outside the vehicle, for instance, by autonomously braking before crashing with other vehicles or vulnerable road users, as well as by deploying external airbags on the car hood to mitigate injuries among pedestrians. Other crucial differences are that intrinsically, motorcycles are unstable vehicles and that riders are not restrained. Critical situations such as skidding or loss-of-control are therefore more likely to occur with more serious consequences, as the rider is likely to fall off the motorcycle. In such cases, the only countermeasure to avoid health loss is the rider’s protective gear, or a forgiving road infrastructure.

5.1 Improved motorcycle stability creates new scenarios

Previous research based on real-life data has shown that Motorcycle ABS have important benefits, with reported reductions in motorcycle collision claims frequency ranging from 21% (HLDI 2014) to 31% in combination with CBS (HLDI 2013). Other research has shown greater reductions in serious and fatal crashes (Fildes et al, 2015a; Teoh 2013; Rizzi et al, 2009), by up to 48%. While these were important findings, a full understanding of the reasons behind these results was limited due to data and methodological issues. In other words, it was difficult to understand whether these effects were due to crash avoidance, reduction in crash severity, or a combination of both. This issue was also influenced by the limited in-depth data regarding crashes with ABS, which made it difficult to fully understand how these may differ from non-ABS crashes.

The findings of Paper 2 indicated that Motorcycle ABS can prevent crashes in the first place, but may also lower the severity of the crashes that do occur. While the biggest contribution to the overall PMI reduction was due to fewer emergency care visits with ABS, a significant reduction of injury severity was also found. While the latter finding could possibly be explained by lower collision speeds due to the optimised braking provided by ABS, Paper 3 showed that approximately 90% of crashes with ABS were upright, and the Road Barrier paper (1) showed that upright crashes generally resulted in fewer severe injuries.

In the present thesis, it is also noted that the more severe the analysed injury outcome, the higher the reduction of crashes with ABS. A similar finding was also reported by Lie (2012) with regard to ESC for passenger cars. An interpretation of the present findings is that the consequences of wheel-locking on a motorcycle (similarly to loss-of-control with a car) may be more critical at a higher speed. The present thesis suggests that ABS on a motorcycle fulfil similar functions to ESC on a passenger car, i.e. not only reverting a critical situation to normal driving, but also changing the characteristics of crashes that cannot be prevented (Lie 2012). Therefore the overall findings of the present thesis suggest that the benefits of Motorcycle ABS may be greater than previously thought (Fildes et al, 2015a; HLDI 2014; HLDI 2013; Teoh 2013). ABS can prevent crashes from occurring in the first place, but they also increase stability and change the phases following critical situations, making crashes that do occur more predictable. This finding may have important implications for the designers of the road transport system, i.e. future safety countermeasures could be designed with greater focus on upright crashes. Consequently, improved motorcycle stability with ABS may create the conditions for other safety systems to be more effective.

Therefore, it is likely that the development of ESC for motorcycles would have significant implications from an integrated safety point of view (De Filippi et al, 2014), although the technical development of such systems may be particularly challenging (Seiniger et al, 2012). Other supporting systems could also address the portion of crashes that are not affected by ABS, i.e. when the rider does not apply the brakes. While Autonomous Emergency Braking (AEB) systems in passenger cars have been proven effective in real-life crashes (Fildes et al, 2015b), the development of similar technologies for motorcycles, Motorcycle Autonomous Emergency Braking (MAEB), is still ongoing with promising results (Savino et al, 2014). It is evident that MAEB will need to make sure that braking riders will remain seated on the motorcycle throughout the entire chain of events, and support non-braking riders to avoid sliding crashes.

Further technologies have already been introduced that could boost the benefits of ABS, for instance CBS (HLDI 2013). Although based on very limited material, the Crash Posture paper (3) suggested that the few sliding crashes that occurred with ABS (n=4) could have been prevented by other vehicle technologies. Two riders lost control while accelerating on asphalt with very poor friction, one while negotiating a curve with an excessive lean angle, and one by abruptly releasing the throttle in the middle of a curve. Traction Control has the potential to improve stability in critical situations while accelerating on slippery surfaces, although there are no evaluations based on real-life data to support this hypothesis. Another solution to improve stability while cornering, regardless of braking, could be the one used for the Piaggio MP3 (a motorcycle design that has two front wheels close together, see Figure 15), which is viewed as a promising step in improving motorcycle safety (2BeSafe 2012). These countermeasures seem promising and should therefore be further investigated.

Figure 15: An example of a three-wheeled scooter, the Piaggio MP3.

Another important aspect is that motorcycle crashworthiness can be expected to provide greater benefits than in the past, since sliding crashes are greatly reduced by ABS. The results in the Motorcycle Design paper (4) may seem somewhat surprising, as boxer-twin engines were not developed to provide leg protection for motorcyclists. The basic idea was (and still is) that, as these engines are air-cooled, the position of the cylinders would be more favourable for the cooling airstream. However, this may not be the first case of vehicle safety being improved as a result of coincidence rather than focused engineering, as shown by Strandroth et al (2011) with regard to the pedestrian protection scoring in the early years of Euro NCAP. Moreover, the location of the injury reductions associated with boxer engines was consistent with the orientation of the leg. While future research should look deeper into the boxer-engine issue, crash tests performed by Folksam support these findings (Folksam 2015a).

Figure 16: Crash tests into a W-beam barrier at 60 km/h at 10° impact angle with a conventional motorcycle (left) and a boxer-engine motorcycle (right). Source: Folksam (2015a)

It should be stressed that the present thesis does not recommend a broad implementation of boxer-twin engines on motorcycles as a solution to address leg injuries since the benefits of boxer-twin engines in terms of leg protection may only be an example of what could be achieved. The present results suggest that the concept of protecting motorcyclists' legs with vehicle technology is indeed feasible, and therefore more focused engineering efforts should be made to address leg injuries. While significant research has been carried out in the motorcycle crashworthiness area, the present findings could be used to accelerate the development of new countermeasures.

However, the question why previous research has not shown any benefits with other leg protecting devices should be raised. In particular, previous research has suggested that the TRL concept may increase head injury risks (Rogers et al, 1998). This important issue was not found in Paper 4, as the mean RPMI to the head and upper body was similar across the two groups. However, it should be kept in mind that the ISO 13232 crash tests represent seven car-motorcycle crash configurations, of which six at the same motorcycle speed (Berg et al, 1998). While a further 200 configurations were also simulated (Van Driessche 1994), in the Motorcycle Design paper (4) all types of crashes (occurring at different speeds) were analysed, including single-vehicle, which accounted for approximately 45% of the material. The issue of increased head velocity due to rotation of the upper body may be most relevant in collisions into the side of a car, which is a typical crash scenario at intersections. This crash type accounted for 21% of the material included in Paper 4. Therefore, caution may be needed when comparing these overall results based on injury crashes with specific crash test configurations. While the mentioned aspects may partly explain the differences between the present findings and previous crash tests, at this stage it could be argued that the ISO 13232 impact constellations would benefit from being further discussed, as suggested by Berg et al (1998). This issue is further discussed later.

Another important aspect is that improved motorcycle stability may also create the conditions for other vehicles to protect motorcyclists, especially passenger cars. For instance, it has been reported that the latest Volvo car model is equipped with an advanced AEB system which is capable of detecting an oncoming PTW in a left-turn situation at intersections (Volvo 2014).

It is evident that the future road infrastructure will also play an important role in keeping motorcycles upright as well as mitigating injuries during a crash. For instance, an interesting finding of Paper 3 was that two (out of four) sliding crashes with ABS were due to the very poor friction of the asphalt. While other systems could have possibly prevented those crashes (i.e. Traction Control), it could be argued that safety technologies on motorcycles will still need a certain level of friction to deliver the expected benefits. Although based on very limited material, these results suggest that proper maintenance of the road surface could be even more important for motorcycle safety in the future. Road barriers will also be more important, as their design and testing have mainly focused on protecting riders who slide into them. Therefore the development and testing of future road barriers will need to have greater focus on upright crashes, and on the possibility of interacting with protectors integrated in the motorcycles. This issue is also further discussed later in this thesis.

The Multinational ABS paper (5) also showed that the large safety benefits of ABS are not isolated to large displacement motorcycles during leisure riding; reductions in crashes involving scooters in Italy and Spain were of the same magnitude. Furthermore, these were in line with the overall findings of previous research (Fildes et al, 2015a; Teoh 2013; HLDI 2013; Rizzi et al, 2009), thus indicating that improved stability during hard braking has important benefits in different riding conditions and environments. While Paper 5 was based on material from southern European countries, these findings have great safety implications for other regions of the world where light motorcycles are the main mean of road transportation, as suggested by Lich et al (2015).

5.2 Methodological reflections

There are a number of methodological issues that need to be discussed. First of all, it could be argued that the present thesis shows that it is possible to perform real-life evaluations with limited data, as long as the data have a sufficient degree of detail and are analysed with robust methods. The first critical step in such analyses is matching the case and controls. Ideally, the crash populations should be as similar as possible and only differentiate on the variable under study. While this may not always be possible, the present research matched case and controls by selecting similar motorcycle models of the same type, which generally resulted in similar distributions of rider age, gender, road environments, etc.

The second critical step is to obtain the exposure. In the present thesis, indirect methods are used, i.e. the exposure is derived from the actual crash data. While it may be possible to obtain data based on real exposure with ABS (Teoh 2013; HLDI 2013), it can be difficult to obtain and compare data between different countries, as done in Paper 5. Furthermore, the data may include confounding factors. For instance, as long as ABS is not standard equipment in all motorcycles on the roads, it could be argued that motorcyclists choosing ABS are probably more concerned about their safety in the first place, which could naturally lead to a lower crash involvement (i.e. selective recruitment). Further differences between the crash populations could also confound the results, for instance age, gender and use of protective equipment, etc. If crash rates are calculated based on real exposure (i.e. number of crashes divided by number of registered vehicle, or vehicle mileage) it is essential to control for possible confounders, as done in Teoh et al (2011). However, adopting an induced exposure approach would normally address this issue, as the result is given by the relative differences within the ABS and non-ABS crash populations. Basically, even though a variable is known to affect the overall crash or injury risk (say rider age), the same variable can only confound the induced exposure results by deviating from the overall sensitive/non-sensitive ratio. If this is found to be the case, the case group can be stratified into different subgroups for further analysis, as done in Paper 2 and 5 with CBS. The induced exposure calculations can be adjusted for confounders, as suggested by Schlesselman (1982), for instance by calculating the weighted average of the individual odds ratios. However, it was argued that this procedure was not necessary in the present research; the cases and controls were similar in terms of rider age, gender, use of protective gear, etc., and therefore it would have had only a minor effect on the overall results.

Nonetheless, it is important to stress that the induced exposure approach is also based on a number of assumptions and limitations. First of all, it should be clear that the basic idea with this method is to calculate the number of crashes that should be included in the data, if ABS had no effect at all. This approach may be considered as calculating the "missing" crashes in the dataset. Therefore, it is evident that a certain reduction in police reported crashes, for instance, does not necessarily mean that no crashes had occurred at all, or that no slight injuries were sustained in a minor crash that was not police recorded. The most critical assumption with the induced exposure approach is to determine the non-sensitive crash type. While the main method for selecting non-sensitive crashes is a-priori analysis of in-depth studies, as done in previous research (Sferco et al, 2001), the distribution of crash types within the analysed data may also provide insights into the non-sensitivity of certain crash types. However, it is very important that such assumptions are based on an actual hypothesis, rather than "trial and error" in the analysis steps (Lie et al, 2006). This may lead to unclear or even misleading results, as in the NHTSA (2010) where no statistically significant results were found to suggest that ABS affect motorcycle crash risk. An explanation for these results is that "at fault" crashes were considered non-sensitive to ABS (i.e. a rear-end crash with a bullet motorcycle would be non-sensitive to improved braking systems). On the other hand, there are examples of elegant study designs where the induced exposure was derived using a motorcycle rider's auto claim frequency (HLDI 2014). Another interesting example for the need of a clear (in this case possibly obvious) hypothesis is Paper 3, i.e. ABS would not affect the crash posture if the rider did not brake prior to collision.

A further reflection is that evaluations of safety technologies based on real-life crashes may imply several factors affecting each other, i.e. these may not be based on the principle "everything else is constant". An example is that the fitment of ABS is increasingly complemented with CBS. It is therefore important to keep this issue in mind in order to differentiate between explanatory variables and confounding variables. If confounders are present as variables that differ between cases and controls, they might be picked up by the effect variable. When selecting possible confounders, it is important that they are based on a hypothesis, and not just invented. If included without any hypothesis they may pick a variation that is not real. In other words, it is important to distinguish between correlation and causation. For instance, the question could be raised of how Paper 4 was able to prove causality between the reported reductions of leg injuries and the fitment of boxer engines on ABS-motorcycles (and not just correlation)? Confounders were carefully analysed, and the cases and controls were very similar in terms of rider age, gender, use of protective gear, etc. The engine configuration was the only reasonable explanatory variable that was based on an actual hypothesis; this was also supported by the fact that the location of the injury reductions was consistent with the orientation of the legs, i.e. the injury reductions were closer to the cylinder heads (knee, tibia and foot).

These issues may become even more challenging in the future when a number of interacting safety countermeasures will be fitted on motorcycles simultaneously. This may already be the case in passenger cars, where safety packages are often commercialised, i.e. a number of safety features such as low-speed AEB, high-speed AEB, LKA, and Blind Spot Detection, are offered as optional fitments together. Therefore, it will be crucial to have clear hypotheses on which crash types will be affected by which safety countermeasure, and which will not.

5.3 Limitations of this research

The present thesis was based on a number of limitations. First of all, the materials used in Papers 1, 2, 3 and 4 were quite limited. It is clear that the statistical power of these analyses would have been greater if based on larger materials. Furthermore, a number of assumptions were made, for instance by grouping motorcycles of the same types in Paper 2 and 3, rather than using the same model with and without ABS. However, it was also shown that these data were generally consistent: for instance, in the Crash Posture paper (3), where the distribution of sliding and upright crashes was very similar if the riders did not apply the brakes. A further example is Paper 2, where mRPMI in head-on crashes with ABS was similar to mRPMI without ABS. Also, the reduction of mRPMI 10+ found in the Road Barriers paper (1) for upright crashes (51%) and in Paper 2 for ABS-crashes (37%) were of the same magnitude.

A further limitation of the present thesis is that it is principally based on crash data from Sweden, where motorcycling is mostly for leisure (Haworth 2012). While Paper 5 aimed at addressing this issue by analysing the benefits of ABS in other traffic environments, future research should be carried out using crash data from different countries.

The present thesis is the first evaluation of the long-term consequences of motorcycle crashes adopting the RPMI approach. While the results from Paper 1, 2 and 4 are consistent, no previous research was found on this specific issue and must therefore be considered with caution. It should be noted the RPMI matrices were initially developed for passenger car occupants. It could be argued that different road users are exposed to different risks of sustaining a certain injury (say, leg injuries for motorcycles and passenger car occupants); however, when the injury is sustained, the risk of not making full recovery from it should be the same. While there is reason to believe that a certain injury should have a certain risk of PMI regardless of how that particular injury was sustained, future research should confirm this

assumption. Furthermore, a recent study (Gustafsson et al, 2015) based on insurance claims has shown differences in PMI depending on age and gender. Investigating these differences was beyond the objectives of the present research, although it could be argued that it would probably affect the ABS and non-ABS groups in a similar manner (given the similar distribution of age and gender).
A limitation of the RPMI approach is that the material included in Malm et al (2008) was not large enough to produce the RPMI assigned to single diagnoses. Instead, diagnoses were grouped in 10 body regions. While this is a clear limitation, future research should attempt to address this issue based on larger materials. For instance, RPMI for leg injuries could be stratified into upper leg, knee and lower leg. Furthermore, the present RPMI for specific body regions is sometimes based on a low number of diagnoses, so there is some uncertainty in these figures, especially for AIS 3+ injuries (Gustafsson et al, 2015).

Another limitation is that different generations of ABS were grouped for analysis. It has been argued that there are significant differences in the safety potentials of the latest generation of cornering ABS, compared to more basic versions (Motorrad 2016). However, the present data were too limited to take this aspect into account.

5.4 Implications of results

The theoretical framework of this thesis is based on the integrated chain of events, which can be a powerful tool for analysis of road transport systems and the interaction of its different components. It is important to stress that, compared to the Haddon Matrix, the integrated chain of events is not a paradigm shift; it is a further development of the same view of injury prevention. In the integrated chain of events, more focus is put on the time-to-crash scale, and the events leading to a crash are no longer viewed in separate blocks as in the Haddon matrix. For instance, active and passive safety are no longer separated; the concept of integrated safety is used, in which one factor in the early stages of the chain can affect the following stages, thus creating the conditions for other countermeasures to be effective. This is the fundamental idea behind the Safe System approach: speed limit compliance and crash protection are strictly connected and work in conjunction, and the speed limit is set depending on the safety standards of the road. Further examples include the analysis of safety technologies as an integrated part in a system where other safety interventions are introduced simultaneously, such as improved infrastructure or change in legislation and education (Tingvall 2008).

It is also important to stress that there is a clear distinction between the integrated chain of events and the Safe System approach. The integrated chain of events can be used as a tool to analyse road crashes and how different countermeasures may interact with each other. The Safe System approach, which can be illustrated by the STA model for safe traffic, describes boundary conditions and a number of known countermeasures or intervention areas that together can create safe traffic. While the integrated safety chain could be used to illustrate in detail the STA model for safe traffic, or to describe possible safety gaps, it is clear that the integrated chain of events is not a model for safe traffic per se.

The present thesis shows that the principle “early interventions affect subsequent ones” can be applied to motorcycle safety as well. This suggests that the Safe System approach is feasible for motorcycles: the basis is a more stable, ABS-fitted motorcycle, and other countermeasures can be built on ABS. The Multinational ABS paper (5) also showed that the benefits of ABS are not solely isolated to leisure riding, thus suggesting that this principle is feasible in different road environments. While the implementation of a number of known countermeasures can guarantee a safe road system for passenger car occupants (Tingvall et al, 2010), further research is needed to create a similar set of countermeasures for motorcycles (i.e. a model for safe motorcycling). This thesis suggests that developing a model for safe motorcycling would be possible in theory, although further countermeasures to prevent injuries among PTW riders would need to be considered and explored. The present thesis has a number of practical recommendations: wide implementation of ABS, as well as improved design and testing procedures for road barriers and motorcycles. Some thoughts are outlined and discussed below.

Today, CEN/TS 1317-8 and ISO 13232 form the basis for crash testing of road barriers and motorcycles, respectively. While it is understood that additional tests may not always be feasible due to financial reasons, a number of modifications to current procedures could be suggested, rather than adding further test configurations. Arguably, the evidence presented here suggests that parts of these procedures may not be up-to-date and would benefit from being revised.

The time frame needed to implement such revisions would also be important. An example is illustrated in Figure 17, where future motorcycle mileage with ABS in Sweden was calculated as in the STA (2014a). Based on these calculations, by 2030 almost 85% of the motorcycle mileage in Sweden will be with ABS, thus stressing the importance of adapting the road transport system to upright crashes.

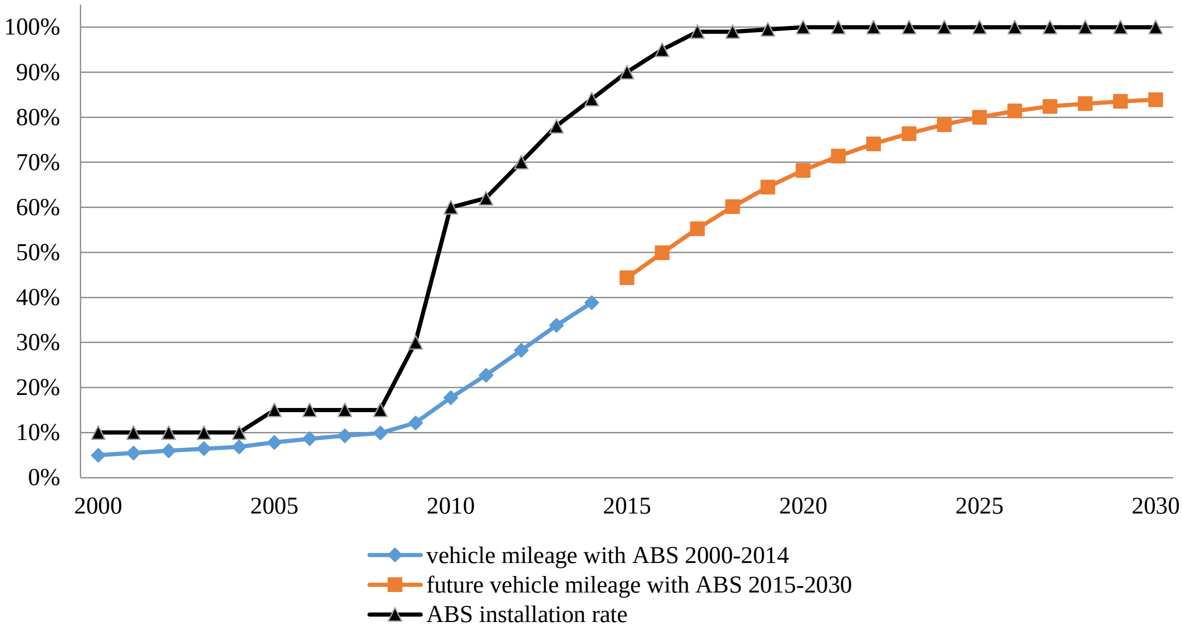


Figure 17: ABS installation rate in Sweden and vehicle mileage with ABS 2014-2030 (motorcycles with engine displacement ≥ 125cc). Source: STA (2014a).

5.4.1 Implementation of ABS

Based on the findings of the present thesis as well as previous research (Fildes et al, 2015a; HLDI 2014; HLDI 2013; Teoh 2013), there are more than sufficient scientific-based proof to support the implementation of ABS on all motorcycles, including light ones. Manufacturers should work toward a broad fitment of ABS, on light scooters as well. According to Bosch (2012), in 2010 the ABS installation rate among motorcycles with more than 250cc displacement was 16% worldwide. However, this was unevenly spread across different regions: 36% in the EU, 24% in the US, 21% in Japan, 6% in Brazil and 2.5% throughout the rest of world. According to the same source, the worldwide installation rate among motorcycles with less than 250cc displacement was less than 1% in 2010 (Bosch 2012). This is a critical issue as these motorcycles account for almost 97% of the worldwide production of PTWs (Bosch 2012).

It is important to note that necessary steps have been taken to increase the fitment of ABS. As of 2016, all newly registered PTWs with more than 125cc displacement throughout the EU must be fitted with ABS (EC 2012). In Japan, ABS will be mandatory from October 2018 for new type approvals for motorcycles with more than 125cc. In emerging markets such as Brazil and Taiwan, too, laws mandating ABS in the future have already been passed. The mandatory fitment of ABS is also on the political agenda in India, China, Australia and the United States (Bosch 2015). However, it should be kept in mind that legislation mandating the fitment of ABS on new motorcycles does not guarantee rapid removal of non-ABS motorcycles from the current vehicle fleet. Further strategies should also be developed to encourage consumers to only purchase used motorcycles equipped with ABS. For instance, insurance discounts and other financial incentives such as scrapping programmes may be suitable interventions, although it is crucial that the latter is introduced when ABS installation rates are sufficiently high. Moreover, the demand for ABS may increase with consumer testing, as discussed below.

5.4.2 Road barrier testing

Other studies have previously proposed that an additional test should be introduced in CEN/TS 1317-8, with the rider in an upright position when striking the barrier and then sliding along the top of the barrier (Grzebieta et al, 2013). The findings of this thesis strongly support this suggestion, as almost 90% of the crashes with ABS (see Paper 3) were upright. In fact, with these results in mind, it could even be suggested that only upright crashes should be tested, or at least highly prioritised.

As indicated by other studies, the impact angle should be quite shallow, probably less than 20° (Peldschus et al, 2007; Ruiz et al, 2010; Grzebieta et al, 2013). Although based on limited material, the Road Barrier paper (1) also indicated that the majority of upright crashes with known run-off angle occurred at less than 20°.

The testing speed may also need to be revised, as 60 km/h seems to be low compared with some of the findings of previous research regarding motorcycle crashes into barriers, which reported mean pre-crash speeds of approximately 100 km/h (Ruiz et al, 2010; Grzebieta et al, 2013). With regard to all crash types with fatal outcome, Fredriksson et al (2015) and Savino et al (2014) reported mean collision speeds between 69 and 85 km/h (see Table 3). The Crash Posture paper (3) also showed that more than 70% of the travelling speeds in fatal crashes in Sweden and Norway were above 60 km/h.

5.4.3 Motorcycle testing – Euro NMCAP

Today, ISO 13232 is the common methodology used by the industry to test protective devices fitted to motorcycles. However, there are no established consumer testing programmes for motorcycles, similar to Euro NCAP and other consumer testing programmes for passenger cars. Based on the findings of the present thesis, the relevance of developing a new consumer testing programme is clear, i.e. Euro NMCAP (New MotorCycle Assessment Programme). Similar to Euro NCAP, different aspects could be tested, as discussed below.

5.4.3.1 Stability assist

A rating system could be developed where points can be given to a specific motorcycle model for all countermeasures that would improve stability in critical situations, i.e. “stability assist”. The testing procedures could be similar to those shown by motorcycle magazines for cornering ABS, see Table 15.

Table 15: Mean decelerations during maximum braking in different roll angles (dry asphalt). Adapted from Motorrad (2016).

Mean deceleration (m/s2)	0°	20°	30°	40°	45°
KTM 1190 Adventure without ABS	9.7	9.5	×	×	×
KTM 1190 Adventure with conventional ABS (Street Mode)	9.2	8.9	7.2	×	×
KTM 1190 Adventure with cornering ABS (Street Mode)	9.0	8.7	8.6	8.0	7.7
BMW S 1000 XR with cornering ABS (Road Mode)	9.4	9.1	8.8	8.2	8.0
Ducati Panigale S with cornering ABS (Mode 2)	8.5	8.1	7.5	7.7	7.4
Ducati Panigale S with cornering ABS (Mode 3)	8.8	7.9	7.7	7.6	7.3
Yamaha YZF-R1 with ABS/UBS	8.9	8.4	8.3	7.8	7.6

Legend	
	safe
	risky
	unstable
×	very unstable

While ABS become standard in the EU from 2016 (EC 2012), this rating system should be able to differentiate between basic and more advanced systems, thus encouraging the development of improved versions – for instance, a 2-channel ABS should be given a lower rating than a cornering ABS. Consumer testing programmes in other regions of the world could set the standard fitment of ABS as a condition to achieve an overall top rating, as done by Euro NCAP with ESC (Euro NCAP 2011).

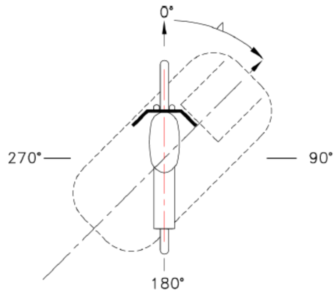
The combination of ABS with CBS, for instance, should be rewarded with additional points, possibly the fitment of TC as well. However, proper testing procedures for TC would need to be developed. It is important that TC improve the stability and also reduce speed in a controlled manner, rather than making it possible to ride through a slippery corner at a higher speed. Finally, innovative designs that improve stability (i.e. the Piaggio MP3) should be adequately rewarded, even if offered without ABS.

5.4.3.2 Crashworthiness

The crash configurations of ISO 13232 could be a suitable basis for Euro NMCAP, although some revisions ought to be considered. As mentioned above, ISO 13232 is based on Hurt et al (1981) and Otte (1980). While these studies were the most comprehensive at the time of the development of the standard, it could be argued that the crash data were collected in the 70s and that they may not fully represent more recent crashes. Already in 1998, Berg et al (1998) suggested that the impact constellations in ISO 13232 may not correspond in all cases with the rank order resulting from the evaluation of the DEKRA database. Comparison with a more recent study also suggests that revisions may be needed. For instance, according to MAIDS (2004) the most common nominal value of the relative heading (i.e. the angle between the PTW and the other vehicle at the time of contact, expressed as a positive angle, clockwise from the vertical) was 0 degrees, which is not included in ISO 13232 (see Table 16).

Table 16: Distribution of nominal relative headings reported in MAIDS (2004), and those tested in ISO 13232.

Relative heading, nominal value (deg)	Distribution in MAIDS 2004	ISO 13232 full-scale crash test configuration nr
0	25%	Not tested
90	17%	1, 3, 7
270	13%	Not tested
135	12%	2, 5
180	10%	6
315	10%	Not tested
45	8%	4
225	5%	Not tested



Therefore, some of the seven full-scale crash tests against a passenger car would benefit from being updated. While passenger cars are the most common collision partner in motorcycle crashes, as reported in Hurt et al (1981), Otte (1980) and more recent studies (MAIDS 2004), it may be suitable to test a single-vehicle crash as well, for instance by replacing at least one of the seven full-scale configurations with a crash test against a road barrier. While it may not be trivial to determine which crash barrier would be most relevant, it would be necessary to include infrastructural aspects in Euro NMCAP, in order to reward motorcycle designs that can interact with road barriers, thus optimising rider protection. As an initial idea, it might be advantageous to test a W-beam fitted with MPS, which is the most common motorcycle-friendly barrier today (Nordqvist et al, 2015).

The collision speeds would also need to be discussed. ISO 13232 includes 0, 24 and 35 km/h for the car; 0 and 48 km/h for the motorcycle. The speeds ought to be higher in the Euro NMCAP tests, as suggested by Berg et al (1998), because the motorcycle should be able to offer some kind of protection at higher speeds. Similarly to road barrier testing, Table 3 also indicates that the mean travelling speed in fatal crashes is well above 48 km/h.

Finally, certain practical and financial issues may first need to be considered. For instance, it could also be argued that the seven full-scale crash tests included in ISO 13232, four of which include two moving vehicles, may be too costly and complex to carry out in a broad and systematic way. While this issue should be further investigated, it is clear that Euro NMCAP would need to include as many motorcycles as possible in order to achieve its goal, i.e. support consumers who would like to buy a new motorcycle. Therefore it is possible that the number and complexity of the full-scale crash tests will need to be reduced.

5.4.3.3 *Rider assistance*

Similarly to Euro NCAP, the fitment of supporting systems such as Forward Collision Warning (FCW), Motorcycle Autonomous Emergency Braking (MAEB) (Savino et al, 2014), improved visibility systems, etc. could be rewarded with extra points.

5.5 Future research

The present thesis can be seen as a first step towards a Safe System approach for motorcycles. However, it is important to understand that the design of a safe transport system should be based on human injury tolerance, and today the knowledge with regard to motorcycle crashes is limited.

Also, further research is needed to develop effective countermeasures to prevent health loss among motorcyclists. Considering the great injury risk for motorcyclists involved in crashes with conventional barriers, as shown in the Road Barriers paper and other studies (Gabler 2007), it is evident that they need to be modified and improved. However, the importance of the motorcycle design may at least be of the same magnitude, as suggested in Paper 4. Moreover, the interaction between these two factors may have a higher potential than the sum of the individual potentials. The same basic idea applies to passenger cars, where the interaction between the vehicle crashworthiness and the road barriers optimises occupant protection.

5.5.1 Barrier design

Considering that sliding crashes will be greatly reduced in the future, due to the fitment of ABS, further development of superior protection for barriers is needed. This may not mean that MPS should be disregarded, as suggested by Nordqvist et al (2015). Crash tests (Berg et al, 2005a; Folksam 2015a) also indicate that MPS are beneficial in upright collisions (Folksam 2015a). However, greater focus should be directed towards road barrier design for upright crashes. This implies that the top of the barrier will have a much more crucial role for reducing health loss among motorcyclists, as suggested by Grzebieta et al (2013) and Folksam (2015a). Upright crash tests with a 10° impact angle against a W-beam barrier without top protection resulted in the dummy sliding on the top of the rail and getting very close to the posts (see Figure 18, left). In this particular series of crash tests, a prototype top protection was built by installing the same W-beam on the back of the posts and a plastic tube pressed in between the beams (Folksam 2015a). This resulted in the dummy sliding on the top of the barrier without getting stuck or near any sharp edges. While more advanced top protections have been tested by Berg et al (2005a) with similar results, it is important to stress that these devices are still very uncommon, although at the present stage there is a commercial product available with the same functionality that, technically, could be retrofitted on existing W-beam barriers (the "Euskirchen Plus" guardrail). However, the development of further technical solutions is needed in order to guarantee large-scale implementation of top protections. The basic idea should, however, still be the same, i.e. the top of the barrier needs to be smoother, softer and possible to retrofit on existing barriers.

Figure 18: Upright crash tests into a W-beam barrier at 60 km/h at 10° impact angle, without top protection (left) and with top protection (right). Source Folksam (2015a).

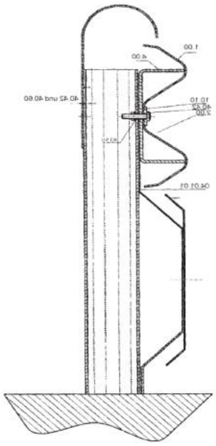


Figure 19: System “Euskirchen Plus” guardrail. Source: left BASt (2010), right Nicol et al (2012).

5.5.2 Improved motorcycle stability and crashworthiness

While the implementation of advanced protective gear based on airbag technology is ongoing (Ducati, 2014), further research and development are needed to improve motorcycle stability and crashworthiness. With regard to the latter, it should be possible to move some of the protection offered by motorcycle clothing to the vehicle, and to optimise the remaining protective gear to the motorcycle.

Based on the findings of the present thesis, it can be argued that the BMW C1 was a milestone for motorcycle safety, i.e. a stable (ABS-fitted) crashworthy motorcycle. However, it is also necessary to take consumer acceptance into account. As a matter of fact, this was quite low for the C1 (BMW 2015). Essentially, a too radical design change in the aspect and handling of a motorcycle may always meet strong opposition. This was also the case for the TRL leg protectors (French 1995; American Motorcyclist 1991, 1992, 1996). On the other hand, more recent designs have succeeded in meeting the needs and demands of a portion of the market. For instance, the Piaggio MP3 has sold more than 150,000 units worldwide since 2006 (Piaggio 2014), which indicates that today’s motorcycling communities are probably more receptive to safety innovations than 20 years ago. Furthermore, new technologies can be used, that could have great safety benefits without radically changing the aspect of a motorcycle. For instance, a gyro-stabilised motorcycle is currently under development (Lit Motors 2016), which, interestingly, is also called C-1. Other technologies to improve stability even when riders do not apply the brakes need to be developed, for instance, Electronic Stability Control (ESC) for motorcycles. While further research is needed to develop more stable and crashworthy motorcycles, an illustrative concept is presented below. The fitment of ABS should clearly be standard, and complemented with technologies that may improve stability such as CBS and TC. Possibly, a double front wheel could also be fitted (similarly to the Piaggio MP3), especially on motorcycles designed for urban commuting.

Potentially, crashworthiness would be improved with a head and thorax airbag, similarly to the Honda Goldwing, as would the development of leg airbags. While a conventional airbag may not be suitable for such an application, other technologies may be appropriate, for instance the Mercedes-Benz brake bag (Breitling et al, 2009). Adaptive crash structures could also be suitable, as shown in Breitling et al (2009) and MATISSE (2015). Moreover, the leg airbags may have the potential to function as crash stabilisers: by mounting two stability airbags on either side of the vehicle they would facilitate the PTW to assume four wheel stability characteristics in the event of a crash (Hoskere 2013). They could also have the potential to function as an additional AEB system if deployed prior to a crash, and could be complemented with MAEB.

Finally, it is worth stressing that all the mentioned solutions already exist, although at different degrees of development: some would need to be borrowed from the automobile industry and adapted, while others are already commercially available on the motorcycle market. Theoretically, it should be possible to fit these technologies on most types of motorcycles, including mid-sized motorcycles and scooters for urban commuting.

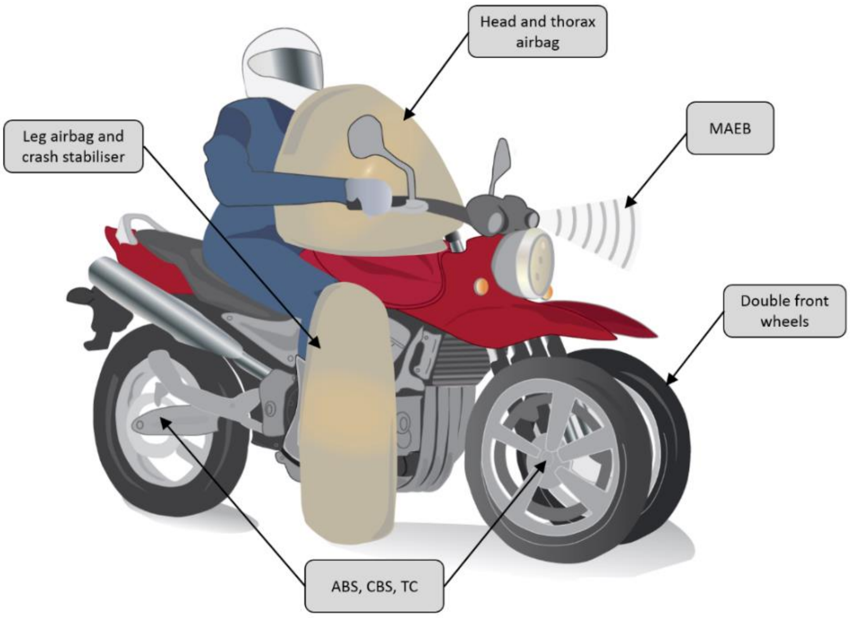


Figure 20: A concept motorcycle with improved crashworthiness.

5.5.3 Injury risk functions

Further research is needed to confirm the point estimates shown in Tables 1 and 2, and generate full injury risk functions. Based on the available knowledge in this area, the fatality risk sustained by motorcyclists at a 50-60 km/h travelling speed is approximately 10%, which is the value often used as the risk threshold for the design the road transport system (Johansson 2009).

As mentioned above, in the Safe System approach speed limit and crash protection are closely connected, and therefore, it could be argued that today's infrastructure and motorcycle design should be based on a 50 km/h speed limit in order to prevent health loss among motorcyclists. However, it is quite likely that the acceptance of such intervention would be very low. For instance, it can be noted that the mean travelling speed of Swedish motorcycles was 77 km/h in 2012 (STA 2013).

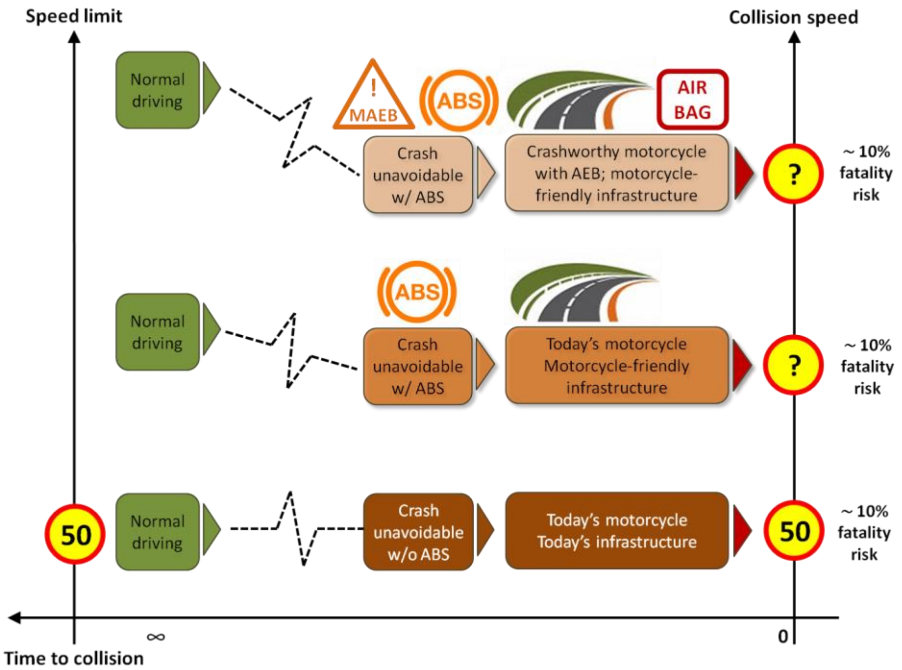


Figure 21: The chain of events leading to a motorcycle crash, as a function of speed limit, maximum collision speed, infrastructure and motorcycle crashworthiness.

It is therefore important to develop integrated rider protection systems so that speed limits with higher user acceptability can be set. This principle is basically illustrated in Figure 21, which shows the chain of events leading to a crash, as a function of speed limit and maximum collision speed. Clearly, the only way to sustain the same fatality risk (say 10%) at higher speed limits would be to improve crashworthiness and link that to the infrastructure. Besides, if further systems are developed to systematically reduce the speed prior to a crash (i.e. AEB), the designated speed limit could be even higher, without necessarily posing an increase in injury risks. However, it is evident that these considerations may remain purely theoretical without a proper injury risk function for motorcyclists. Therefore it is vital that injury risks for upright crashes be developed as soon as possible.

5.6 The role of rider training and use of protective gear in the future

As mentioned earlier, the traditional approach to motorcycle safety is mostly based on rider training/education and the use of protective gear. The minimum level of rider training and protective gear needed to access the road transport system is often determined by legislation (i.e. motorcycle driver's license and mandatory use of helmets). Further steps can be taken voluntarily by the road user, for instance by attending extra courses and/or using motorcycle protective clothing.

Either way, most of the responsibility for motorcyclists' safety is put, quite literally, in their own hands. Their safety is based on their ability to make the right decisions and the protective gear they wear. It can be debated whether the mandatory minimum level of rider training and use of protective gear should be increased. Clearly, the overall safety of riders would be improved, but the responsibility put on motorcyclists would also be increased.

With the Safe System approach, it is the system designers' responsibility to avoid health loss. The present thesis suggests that in the future, system designers will be able to give more responsibility to motorcycles and the infrastructure than today, in order to shift that part of the safety responsibility from the users. Now, it would be pertinent to ask the following questions: How far can this process be brought? Is it possible to move *all* responsibility away from the user, and shift it to the vehicle and the infrastructure?

At the present stage, the development of self-driving motorcycles and infrastructures able to cope with such technologies seems to be far in the future. Therefore, riders will still need to maintain a certain responsibility for their own safety; rider training and the use of protective gear will continue to have an important role in the future. Rider training will be a crucial aspect to keep riders within normal driving, i.e. minimising deviations from normal driving (such as speeding), improving their risk perception and reducing the motivation causing deliberate risk taking. The safety benefits of minimising such motivation could also be boosted by insurance discounts and more efficient speed limit enforcement. However, if these countermeasures should not be enough, further safety barriers will need to be in place in order to break the chain of events leading to a crash. As suggested in this thesis, ABS will be one of those. Should the crash be unavoidable, the level of protection offered by motorcycle clothing can be moved to the vehicle and further improved with new technologies. This also means that the crash protection will always be in place and will not depend on the rider's willingness or motivation to use it. In some regions of the world, the thermal discomfort associated with the use of protective clothing could be also addressed. However, helmets may still be necessary, and will probably need to be further developed and optimised to the crashworthiness standard of the motorcycles. In a way, the future of helmets could be compared to seat belts in modern passenger cars, where the interaction between seat belts and airbags is the key for effective crash protection. Another inspiring example is the airbag-helmet for cyclists, which has been shown to perform almost three times better than other conventional bicycle helmets (Folksam 2015b).

5.7 Motorcycle safety in the future sustainable society

Ambitious targets for a more sustainable society have recently been set by the United Nations (UN 2015). A formulated target regarding good health and well-being includes a 50% reduction in the number of deaths and injuries in road crashes by 2020. In 2010, the European Union (EU) adopted a road safety action plan with a similar target, but is also aiming to move close to zero fatalities by 2050 (EC 2011). Ambitious targets were also set by the EU to reduce road transport CO2 emissions by 2020-2021 (EC 2016). Furthermore, according to the UN Global Goals, by 2030, affordable, accessible and sustainable transport systems should be provided in cities and human settlements (UN 2015). Considering that the proportion of the world's population living in urban areas is expected to reach 66% by 2050 (UN 2014), these targets impose great challenges but also opportunities. Is the use of motorcycles, and PTWs in general, compatible with such ambitious sustainability targets? A few reflections on this issue are outlined below.

The challenge with PTWs is that their users are currently exposed to risks (see Figure 1) which a sustainable society must not tolerate. The basic idea behind the Safe System approach is that the road traffic system should be designed according the injury risks of its most vulnerable users. This is why speed limits in urban areas are often set to 30 km/h (Johansson 2009), in order to prevent health loss among pedestrians and bicyclists, should they be hit by a car. According to the same principle, it could be argued that speed limits on highways (and other rural roads where the presence of pedestrians and bicyclists is very limited) should be based on the injury risks of motorcyclists, rather than passenger car occupants. Based on today's road infrastructure, protective gear and motorcycle design, this would mean a drastic reduction of all rural speed limits and consequently probably a fairly low acceptance among most road users. While this aspect may explain why the high injury risks for motorcyclists seem to be tolerated today, it is clear that this issue will need to be considered with greater attention in the future.

Theoretically, another way to address the PTW safety issue would be to increasingly restrict their use, to such a degree that it would almost eliminate them. In fact, it could be further argued that, if a workplace such as a factory had similar injury risks for their employees, it would be closed immediately and re-opened only when proper countermeasures had been implemented. However, this approach to road safety would not be sustainable per definition: a modern society cannot just prohibit its citizens to move around freely. In fact, the consequence in some regions of the world would be not having a road transport system at all. Therefore, stakeholders must work actively to provide citizens with suitable and sustainable conditions, the quintessence of the Safe System approach: reaching the sweet spot in which safety, mobility and environmental impact harmoniously coexist and even boost each other, instead of limiting each other.

Concerning motorcycles, reaching the sweet spot may not be an easy task. As mentioned above, there may be advantages associated with motorcycles, especially in terms of increased mobility (Spyropoulou et al, 2013; Blackman et al, 2010; Transport for London, 2004) and financial issues (Spyropoulou et al, 2013; Kepaptsoglou 2011; Chiou et al, 2009). As indicated by the Swedish Bus and Coach Federation (2008), on average a passenger car in Northern Europe transports 1.2 persons (including the driver), which indicates clear advantages with the use of PTWs to reduce congestion in large cities, given their smaller size. Considering that the average passenger car is parked 96% of the time (ÅF 2016), PTWs have further advantages. Also, PTWs do not pose the same risk to pedestrians and cyclists as other motor-vehicles. This is shown in Figure 22, where the mean RPMI 10+ among pedestrians and cyclists hit by different types of vehicles is shown.

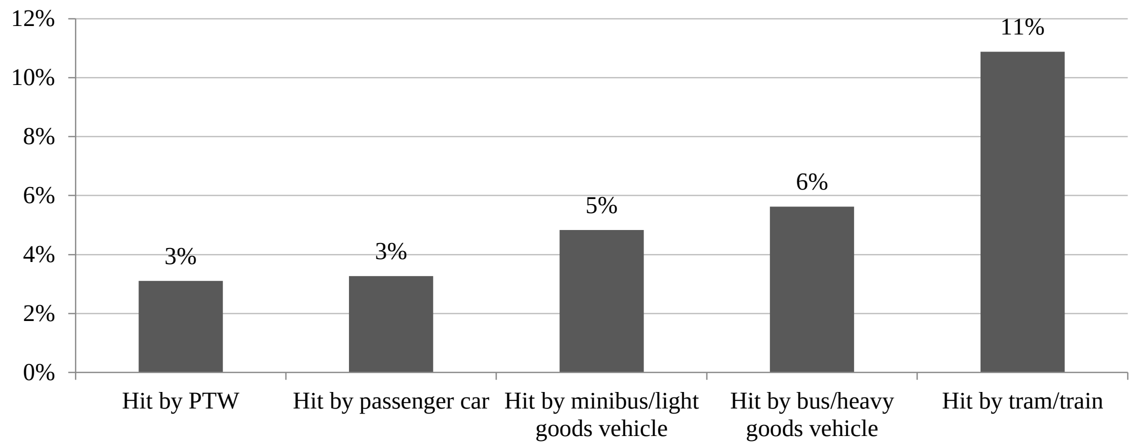


Figure 22: The mean RPMI 10+ among cyclists and pedestrians hit by different vehicles in Sweden 2003-2015. Source: Swedish hospital records (STRADA).

However, the implication of the high injury risks for motorcycles today makes it difficult to combine safety, mobility and environmental impact. Also, the emission limits in terms of exhausts and noise are higher for motorcycles than for passenger cars (STA 2016). Hence, at present the mobility and fiscal advantages of motorcycles are traded off by the lack of safety they expose their users to, as well as their environmental footprint. Therefore, the present research may be seen as a contribution to creating better balance in the "sustainability equation". Considering the current high demand for more energy-efficient and flexible transport modes, it is likely that improving safety for PTWs will be one of the prioritised areas for sustainable road transport systems in the future. The same reasoning can be taken even further: improving safety for PTWs has the potential to make them ever more popular, increasing the need and demand for improving mobility and reducing pollution of PTWs, thus initiating a process in which the balance safety-mobility-environmental impact is constantly moved forward.

6 CONCLUSIONS AND RECOMMENDATIONS

Health loss among motorcyclists is a global road safety problem for which innovative countermeasures are needed. Using the integrated chain of events as a theoretical framework, the present thesis includes analyses of real-life data to understand how ABS can affect the chain of events leading to a motorcycle crash. The findings are as follows.

- **The crash posture affects the injury outcome**. Among motorcyclists who collided into road barriers in an upright position, the share of ISS 16+ subjects was 24% lower. With regard to impairing injuries, the mean RPMI 10+ was 51% lower, although this result was not statistically significant at the 95% level. The FSI-ratios for wire rope, Kohlswa-beam and W-beam barriers were similar and generally above 50%.

- **Motorcycle ABS prevent crashes in the first place, but may also lower the severity of the crashes that do occur.** Emergency care visits were reduced by 47% with ABS. The reduction of the mean RPMI 1+ and mean RPMI 10+ with ABS were 15% and 37%, respectively, although PMI 1+ and PMI 10+ leg injuries were not addressed to the same extent. Overall, the reduction of PMI 1+ and PMI 10+ injured with ABS were 55% and 67%, respectively.

- **ABS improve stability in real-life critical situations.** Almost 90% of fatal crashes with ABS were upright, compared to 65% without ABS. None of the sliding fatal crashes with ABS involved braking.

- **Leg injuries can be addressed by motorcycle design**. AIS 1+, AIS 2+ and PMI 1+ leg injuries among riders with boxer engines were reduced by approximately 50%. The number of injuries to the head and upper body did not increase among riders with boxer engines.

- **ABS are effective in different traffic environments**. The effectiveness of Motorcycle ABS on injury crashes ranged from 24% in Italy to 29% in Spain and 34% in Sweden. Similar results were found for ABS-equipped scooters (at least 250cc).

Overall, it is suggested that Motorcycle ABS can avoid crashes from occurring in the first place. Moreover, they also increase stability and change the phases following a critical situation, making crashes that do occur more predictable. This finding can have important implications for the designers of road transport systems, i.e. future safety countermeasures should be designed with greater focus on upright crashes. Therefore, improving motorcycle stability with ABS can create the conditions for making other safety systems more effective, motorcycle crashworthiness, for instance. It is also shown that these findings are feasible in different riding conditions and environments.

The present thesis can be seen as a first step towards a Safe System Approach for motorcycles. A more stable, ABS-fitted motorcycle provides the basis for such an approach, and other countermeasures can be built on ABS. However, further research is needed to design and implement a Safe System that can address health loss among motorcyclists. Motorcycle manufacturers ought to urgently engage in wide fitment of ABS in motorcycles of all sizes and types. Legislation mandating ABS on all new motorcycles is a prospective powerful tool to increase ABS fitment rates. However, it is important to remember that any changes in legislation would not guarantee rapid removal of non-ABS motorcycles from the current vehicle fleets; therefore further strategies would need to be considered. The development of further technologies to improve stability in critical situations, for instance ESC for motorcycles, is likely to have significant implications from an integrated safety point of view.

Testing procedures of road barriers will need to have greater focus on upright crashes, and on the potential interaction with protectors integrated in motorcycles. It is also recommended that top protection for barriers should be further developed and rapidly implemented. These need to be smoother, softer and possible to retrofit on existing barriers. Motorcycle crashworthiness can be expected to have greater benefits than in the past, since sliding crashes are greatly reduced by ABS. While further development is recommended, there is already a number of existing solutions that are ready for implementation, such as airbags and adaptive crash structures. Consumer testing could be a powerful tool to encourage this development. The European New MotorCycle Assessment Programme (Euro NMCAP) could be based on ISO 13232, although revisions may need to be considered. Also, all countermeasures that improve stability in critical situations should be rewarded, i.e. stability assist. The fitment of other systems, such as Autonomous Emergency Braking or improved visibility, should also be rewarded.

Injury risk functions form the basis for designing a Safe System, where speed limit and crash protection are closely connected. However, such functions still need to be developed and further research in this area should be prioritised.

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