EFFECTIVENESS OF ANTILOCK-BRAKES (ABS) ON MOTORCYCLES IN REDUCING CRASHES, A MULTI-NATIONAL STUDY

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ABSTRACT

This study set out to evaluate the effectiveness of Antilock-Brakes (ABS) on motorcycles in reducing real-life crashes.
Since the European Parliament has voted a legislation to make ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in the entire Europe is likely to increase in the years to come. Previous research, however, analyzed mostly large displacement motorcycles. Therefore the present study used police-reported crash data from Spain (2006-2009), Italy (2009) and Sweden (2003-2012) in an attempt to analyze a wide range of motorcycles, including scooters, and compare countries with different motorcycling habits.

The statistical analysis used an induced exposure method. As shown in previous research, head-on crashes were the least ABS-affected crash type and were therefore used as non-sensitive to ABS in the calculations. The same motorcycle models, with and without ABS, were compared; the calculations were carried out for each country separately. Crashes involving only scooters were further analyzed.

The effectiveness of motorcycle ABS in reducing injury crashes ranged from 24% in Italy to 29% in Spain and 34% in Sweden. The minimum effectiveness with 95% confidence limits was 12%, 20% and 16%, respectively. The reduction of severe and fatal crashes was even greater, at 34% and 42% in Spain and Sweden, respectively. The minimum effectiveness was 23%-24%.
The overall reduction of crash involvement with ABS-equipped scooters (at least 250cc) in Italy and Spain was 27% and 22%, respectively.
The minimum effectiveness was 12% in Italy and 2% in Spain. ABS on scooters with at least a 250cc engine was found to reduce the involvement in severe and fatal crashes by 31%, based on Spanish data only.

At this stage, there are more than sufficient scientific-based proofs to support the implementation of ABS on all motorcycles, even light ones. However, further research should be aimed at understanding the injury mitigating effects of motorcycle ABS.

INTRODUCTION

In 2011, 30,500 persons were killed in road traffic crashes in the European Union (CARE, 2012). That corresponds to a fatality reduction by 43% since 2001 when 54,000 persons were killed. The positive trend in road safety could be observed in all modes of transport, except for motorcycles. Instead the number of killed motorcyclists has been rather constant with a slight decrease only in 2011, from about 5,000 killed in 2000 to 5,200 in 2005 and just over 4,400 in 2011 (CARE, 2012). As the number of fatalities in other transport modes is decreasing, motorcycle fatalities account for an increasing share of all road fatalities in Europe, from 10% in 2001 to 15% in 2011. Furthermore, the Swedish Transport Administration (STA, 2012a) has predicted that this trend is likely to continue and that by 2020 motorcycle fatalities might account for 23% of all road deaths in Sweden, which stresses the importance of taking appropriate countermeasures in this area.

Previous studies have calculated that the risk of being killed on a motorcycle per passenger mileage is approximately twenty times higher than for a passenger car occupant (Strandroth and Knudsen, 2008). Also, the risk of being killed or severely injured when a casualty crash occurs has been approximately the same since the 1980s for motorcycle riders, while the risk for passenger car occupants has systematically reduced by more than 50% (Rizzi et al, 2009). Consequently, there is a need for interventions aimed at reducing both crash

risk and crash severity in order to reduce injury risk for motorcyclists.
Analysis of in-depth studies (MAIDS, 2004; Hurt et al, 1981) has shown that braking prior to collision had occurred in 49%-56% of all investigated crashes. In crashes between passenger cars and motorcycles, braking has been reported to occur in 65%-75% of cases (Sporner and Kramlich, 2003; Rizzi et al, 2009). Hence, enhanced stability during braking could have a great potential in reducing motorcycle crashes and injuries. Anti-lock brakes (ABS) on motorcycles were introduced in the late 1980s in order to improve stability by maintaining wheel rotation under hard braking. While ABS has been shown to generally provide shorter stopping distances (Green, 2006), ABS could also increase braking stability and thereby prevent the motorcyclist from falling to the ground, as pointed out by Teoh (2011).

In terms of effectiveness on crash reduction, several studies based on real-life data have reported the benefits of motorcycle ABS (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). 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. The study estimated the overall effectiveness of ABS to be 38% on all injury crashes and 48% on all severe and fatal crashes, with 95% lower confidence limits of 11 and 17%, respectively. In 2009 the Highway Loss Data Institute (HLDI) used regression analysis to quantify the effectiveness of ABS on motorcycle losses in the US. The analysis showed a 22% significant reduction in claim frequencies for motorcycles equipped with ABS. However, no significant differences were found regarding claim severity. A later study by Teoh (2011) 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 those same models without ABS. The fatality rate was found in this study to be 37% lower for the model versions with ABS compared to the non-ABS versions.
As ABS has been proved by several studies to significantly improve motorcycle safety, actions have been taken by many stakeholders in Sweden in order to increase the fitment rate of motorcycle ABS (STA, 2012b). According to the Swedish Moped and Motorcycle Industry Federation (McRF), the fitment rate among new motorcycles in Sweden has increased from approximately 15% in 2008 to 70 % in 2012. Furthermore, according to Bosch Corporation the ABS installation rate in Europe among motorcycles with at least 250cc engine size has increased from 27% in 2007 to 36% in 2010. Since the European Parliament has voted for a legislation to make ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in the entire Europe is likely to increase even more in the years to come.

Until the early 2000s, ABS was mostly fitted on up-market motorcycle models, similarly to ABS and ESC (Electronic Stability Control) on passenger cars (Lie et al, 2006). Therefore previous research on real-life crashes could analyze mostly large displacement motorcycles. Teoh (2011) and HLDI (2009) did include some light motorcycles in their studies, showing impressive overall results; however, further research may be needed in order to confirm the effectiveness of ABS on scooters. Another issue is that previous studies only included real-life crash data from countries where motorcycles are primarily used for leisure riding, i.e. Sweden and the US. It could therefore be useful to expand the evaluation of ABS with crash data from countries with different motorcycling habits, i.e. countries in southern Europe where motorcycles are also used for everyday transportation.

STUDY OBJECTIVES

The purpose of this study was to:

- estimate the effectiveness of ABS in reducing real-life crashes involving a wide range of motorcycle models, including scooters;
- compare the effectiveness of ABS between Sweden and two other countries, Italy and Spain, that may have dissimilarities in vehicle fleets characteristics, different motorcycling habits and road environments.

MATERIAL

The present study used police records from three different countries: Italy, Spain and Sweden. Each database from which the data was collected is briefly described below.

Italy

In Italy, the national road crashes database is managed by the Italian Institute of Statistics (ISTAT). Crashes included in the national database must have occurred on the public road network and involved at least one injured person. However, it is not possible to distinguish between slightly and severely injured. 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
- Collisions with a train

Spain

The Spanish road crash database is managed by the General Directorate of Transport (DGT). Crashes occurring on public roads causing at least one injured are recorded by the police. The crash type classification is similar to the Italian one. The injury outcome is normally judged for each casualty by a police officer at the crash scene. Four levels are used: fatal, serious, slight and uninjured.

Sweden

The Swedish Transport Accident Data Acquisition (STRADA) is managed by the Swedish Transport Agency and includes police as well hospital reports. Crashes occurring on public roads and having caused at least one injured person are recorded by the police. 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 movement of the vehicles involved rather than the direction of force during the impact (i.e. a head-on crash can involve a frontal-side impact).

A brief overview of the material available for analysis is given in Table 1. The material from a previous Swedish study (Rizzi et al, 2009) based on STRADA 2003-2008 was expanded with the latest crash data (2009-2012). The Italian material included crashes occurred in 2009, while the Spanish one was the larger dataset in the study, including crash data from 2006 to 2009. The share of motorcycle crashes occurred in urban areas was higher in Italy and Spain (72% and 66%, respectively) than in Sweden (47%). Also, the share of scooters varied greatly across these three countries, from 4% in Sweden to 63% in Italy. The age group 18-34 had lower crash involvement in Sweden (38%) than in Italy and Spain (46% and 49%, respectively).

Table 1.
Overview of available crash data

	ITA	SPA	SWE
Period	09	06-09	03-12
n crashes available for analysis	13,695	57,160	8,720
% urban roads	72%	66%	47%
% scooters	63%	42%	4%
% 18-24 years old riders	19%	10%	14%
% 25-34 years old riders	27%	39%	24%

METHOD

An analysis using induced exposure can be used when 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 can be reasonably assumed (or known) not to be effective. In this case, motorcycles with and without ABS were compared. If the only noteworthy difference in terms of crash risk is ABS, the relation between motorcycles with and without ABS in that non-sensitive situation would be considered as the true exposure relation. This means that any deviation from the relation in non-sensitive situations is considered to be a result of ABS. Therefore the effect of ABS is considered to be zero if R in Equation 1 is equal to 1.

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

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

Thus, the effectiveness in crash reduction in relation to non-sensitive crashes can be expressed as:

$$E = 100 \times (1 - R)\% \quad (2).$$

The standard deviation of the effectiveness was calculated on the basis of a simplified odds ratio variance, according to Equation 3. This method gives symmetric confidence limits but the effectiveness is not overestimated.

$$Sd = R \times \sqrt{\sum_{i=1}^{4} \frac{1}{n_i}} \quad (3).$$

Where n is the number of crashes of each type. The 95% confidence limits are given in Equation 4.

$$\Delta E = 100 \times R \times Sd \times 1{,}96 \quad (4).$$

The overall effectiveness in crash reduction and the 95% confidence limits can therefore be calculated as follows:

$$E_T = E \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS}} \quad (5).$$

$$\Delta E_T = \Delta E \times \frac{A_{ABS} + A_{non-ABS}}{N_{ABS} + N_{non-ABS}} \quad (6).$$

The analysis was performed in three main steps. The first one was to identify ABS fitment across the datasets, also based on the generally different standard fitment rates in the three countries. The possible fitment of Traction Control Systems (TCS) was also checked. The second step was to determine which crash type was to be used as non-sensitive in the calculations (see Equation 1) and to check whether the share of such non-sensitive crashes in the analyzed material was comparable with official statistics or previous studies. Finally, in the third step controls were made on factors that could affect crash involvement (i.e. rider age and gender, engine displacement etc) in order to make sure that any crash risk difference between the ABS and non-ABS groups was most reasonably due to the ABS fitment itself. The effectiveness of ABS was calculated with an induced exposure approach as presented above. Each step is further described below.

Step 1

The Vehicle Identification Numbers (VIN) of the motorcycles involved in the crashes were included in the Italian data. Each VIN was checked and in some cases the manufactures were contacted in order to retrieve information about ABS and TCS fitments. During the process, the crash data were handled according to confidentiality restrictions.

With regard to Spanish and Swedish crash data, it was possible to identify ABS fitment through model name and MY. This was based on the standard fitment rate for each models or the presence of the word ”*ABS*” in the model name when ABS was optional at the time of the crash. Most of BMW and Harley Davidson models with optional ABS had therefore to be excluded from the Spanish material, as they normally do not include this information in their model names. The same process was carried out separately as Sweden and Spain had different ABS fitment rates during the analyzed periods. The possible optional fitment of TCS was also checked through the material.

While previous research (Rizzi et al, 2009) has grouped ABS and non-ABS motorcycles of the same category (i.e. standard, on/off or dual purpose, touring, sport-touring), the material in the present study was considered to be large enough to attempt a more direct comparison between the same motorcycle models, with and without ABS, as in Teoh (2011). However, crash data involving only the ABS-version of some models (i.e. most of BMW models in Sweden) were included in the study.

The ABS and non-ABS motorcycles that belonged to the standard, on/off, touring and sport-touring categories had an engine displacement of at least 600cc. The MY ranged from 1997 to 2012 in Swedish material, while in Italian and Spanish ones it was 2004 and onwards. While the number of scooters in the Swedish material was too limited for analysis, two super-sport models were included (Honda CBR1000RA and BMW S1000RR). Scooters included in the Italian and Spanish materials had an engine displacement ranging from 250cc to 600cc. Table 2 shows the number of ABS and non-ABS motorcycles included in the analysis, per motorcycle category; the make/models used for calculations in each database are shown in Appendix I. In total, some 90 motorcycle models were included in the analysis.

Table 2.
Number of ABS and non-ABS motorcycles, per motorcycle category

	ITA		**SPA**		**SWE**	
	ABS	**non-ABS**	**ABS**	**non-ABS**	**ABS**	**non-ABS**
Standard	45 12%	1032 37%	188 24%	2897 50%	65 15%	147 31%
On/off	88 23%	305 11%	58 7%	259 4%	113 27%	52 11%
Scooter	183 49%	1332 47%	235 29%	1345 23%	- -	- -
Supersport	- -	- -	- -	- -	23 5%	33 7%
Sport-touring	45 12%	128 5%	109 14%	1133 19%	103 25%	146 31%
Touring	16 4%	23 1%	209 26%	180 3%	116 28%	92 20%
Total	**377 100%**	**2820 100%**	**799 100%**	**5814 100%**	**420 100%**	**470 100%**

Step 2

Previous research based on Swedish in-depth studies of motorcycle fatal crashes (Rizzi et al, 2009) has shown that head-on crashes, as defined in Sweden, were the least ABS-sensitive crashes. However, the crash type classification used in Italy and Spain differs from the Swedish one, as mentioned above. In Sweden, a crash is classified as head-on when two oncoming vehicles (i.e. approaching each other with opposite travelling directions) crash with any direction of force. For instance, a crash in which a rider falls off the motorcycle in a bend and slides into the side of an oncoming car would be classified as head-on in Sweden. 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 hypothesized that frontal and side-frontal

crashes in non-intersections could be a reasonable proxy of the Swedish head-on crash definition. Analysis of the share 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, compared to the whole population of ABS-crashes.
Checks were also made to ensure that the analyzed material included a representative share of non-sensitive crashes for the three countries. The Spanish and Italian materials were compared with a previous analysis of crashes involving Powered-two-wheelers (PTW) in Europe (2 Be Safe, 2010), while official crash statistics were used for the Swedish material.
Caution is needed when comparing police-reported crash data from different countries, as these are generally known to suffer from a number of data quality problems. However, it was assumed that this limitation would equally affect both the ABS and non-ABS group, therefore it was not expected to affect this analysis to any large degree.

Step 3

Calculations were made within the ABS and non-ABS group to verify that the only relevant difference was ABS. This was done by analyzing the variation of the ratios $\frac{A_{ABS}}{N_{ABS}}$ and $\frac{A_{non-ABS}}{N_{non-ABS}}$ (see Equation 1), depending on a number of factors that may affect crash risk involvement. These factors were speed area, road conditions, driver age and gender, vehicle age, weight-to-power ratio, engine displacement, motorcycle category, reported speeding (when available) and possible TCS fitment. The effectiveness calculations were performed according to Equations 1-6 for each country. Crashes involving only scooters were further analyzed.

RESULTS

The analysis described in step 2 showed that the largest share of ABS-equipped motorcycles in Swedish crashes was involved in head-on crashes (58%), which confirmed the finding of the previous study (Rizzi et al, 2009). The results for Italy and Spain (see Table 4) 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 (15% and 16%, respectively).
Side crashes also had a higher share of ABS-motorcycles (14%) than the average (12%), suggesting that these crashes were not particularly sensitive to ABS. Side crashes, however, were included in the sensitive group as this would give a conservative approach to the analysis, see Equation 1. It should be noted that considering a partly non-sensitive crash type as sensitive to ABS would lead to an underestimation of the overall effectiveness.

Table 3.
Share of ABS-equipped motorcycles per crash type in Sweden

	SWE
Crashes in intersections	43%
Head-on crashes	58%
Rear end crashes	48%
Single-vehicle crashes	47%
Average for all crash types	**47%**

Table 4.
Share of ABS-equipped motorcycles per crash type in Italy and Spain

	ITA	SPA
Front + front-side crashes in intersection	12%	12%
Front + front-side crashes in non-intersection	15%	16%
Multiple collision	-	13%
Rear end crashes	11%	14%
Side crashes	14%	14%
Single-vehicle crashes	10%	11%
Average for all crash types	**12%**	**12%**

Checks were also performed to compare the share of non-sensitive crashes in each country with official statistics or previous studies (2 Be Safe, 2010). The findings showed that these were very similar, if not identical, which suggested that the analyzed material was representative and that the effectiveness would not be overstated (see Appendix II for further results). Analysis of the variation of the ratios $\frac{A_{ABS}}{N_{ABS}}$ and $\frac{A_{non-ABS}}{N_{non-ABS}}$ showed no substantial variations from the overall trends, except for Swedish riders aged 18 to 24 in the non-ABS group which were found to have a greater sensitive/non-sensitive ratio (see Appendix II). A similar result was found in the previous study (Rizzi et al, 2009). While this aspect could give an overestimation of the actual effectiveness of ABS in Sweden, it should be noted that riders between 18 and 24 accounted for only 15% of the non-ABS group. It was therefore decided to include them in the study as this would have only a minor effect on the overall results. The possible fitment of TCS was not found to influence the sensitive/non-sensitive ratio, although the number of case motorcycles that could have been fitted with TCS was limited (n=37 for Italy; n=71 for Spain; n=50 for Sweden).

The results of the analysis with induced exposure are presented in the tables below with 95% C.I. As mentioned above, the calculations were performed for each country separately; it was not possible to distinguish between slightly and severely injured in the Italian database and therefore it was excluded from the effectiveness calculations for severe and fatal crashes. With regard to injury crashes, the overall reduction of crash involvement with ABS was statistically significant in all countries. The reductions were 24% +/- 12% in Italy, 29% +/-9% in Spain and 34% +/-18% in Sweden. All results for rural and urban areas were statistically significant at the 95% level, except from Swedish rural roads. However, no statistically significant difference between the effect of motorcycle ABS on rural and urban roads was found for any country. The results for injury crashes in intersections as well as rear-end injury crashes were also statistically significant, with exception of rear-end in Italy. The effectiveness of ABS in these crash types was similar to the one for all injury crashes, although the Swedish results for crashes in intersections was higher at 46%, with a 95% lower confidence limit of 30%.

The reductions of fatal and severe crashes with motorcycle ABS were generally greater, compared to all injuries, as they ranged from 34% to 42% for the Spanish and Swedish data, respectively. The 95% lower confidence limits were almost identical, at 23% and 24% for Spain and Sweden. The effectiveness of ABS in rural and urban areas was similar to the overall results for severe and fatal crashes for both countries, although the result for Swedish urban roads was not statistically significant. The results for severe and fatal rear-end crashes were even more impressive, ranging from 57% to 60% in Spain and Sweden, respectively. The 95% lower confidence limits were similar, at 45% and 42% respectively. With regard to fatal and severe crashes in intersections, motorcycle ABS was found to reduce crash involvement by at least 62% in Sweden. The result for Spain was impressive too, with a 48% reduction and a 95% lower confidence limit of 33%.

Table 5.
The overall effectiveness of motorcycle ABS on injury crashes, with 95% confidence limits

Injury crashes	**ITA**	**SPA**	**SWE**
All crash types	24% +/- 12%	29% +/- 9%	34% +/- 18%
All crash types in urban areas	22% +/- 15%	28% +/- 12%	46% +/- 21%
All crash types in rural areas	27% +/- 19%	30% +/- 14%	*21% +/- 31%*
Crashes in intersections	25% +/- 20%	29% +/- 13%	46% +/- 16%
Rear-end crashes	27% +/- 21%	*15% +/- 20%*	33% +/- 27%

Table 6.
The overall effectiveness of motorcycle ABS on fatal and severe crashes, with 95% confidence limits

Severe and fatal crashes	**SPA**	**SWE**
All crash types	34% +/- 10%	42% +/- 19%
All crash types in urban areas	41% +/- 10%	*40% +/- 42%*
All crash types in rural areas	29% +/- 17%	38% +/- 25%
Crashes in intersections	48% +/- 15%	70% +/- 8%
Rear-end crashes	57% +/- 12%	60% +/- 18%

Table 7.
The overall effectiveness of motorcycle ABS on injury crashes, only scooters (at least 250cc), with 95% confidence limits

Injury crashes	**ITA**	**SPA**
All crash types	27% +/- 15%	22% +/- 20%
All crash types in urban areas	29% +/- 16%	*20% +/- 25%*
All crash types in rural areas	*19% +/- 42%*	34% +/- 26%
Crashes in intersections	31% +/- 23%	35% +/- 20%
Rear-end crashes	*24% +/- 32%*	28% +/- 27%

Table 8.
The overall effectiveness of motorcycle ABS on fatal and severe crashes, only scooters (at least 250cc), with 95% confidence limits

Severe and fatal crashes	SPA		
All crash types	31%	+/-	19%
All crash types in urban areas	41%	+/-	15%
All crash types in rural areas	*21%*	*+/-*	*44%*
Crashes in intersections	84%	+/-	3%
Rear-end crashes	67%	+/-	14%

Crashes involving only scooters were further analyzed, although Swedish material was excluded because of the limited number of scooters in the crash data (see Table 2). The findings for injury crashes in Italy and Spain are presented in Table 7: both results are statistically significant and similar to the effectiveness found for all ABS-equipped motorcycles, see Table 5. The reduction of crash involvement with ABS-equipped scooters was found to be 27% in Italy and 22% in Spain. Interestingly, in Italy the 95% lower confidence limit for scooters was the same as for all case motorcycles, 12%. However, this was not the case for Spanish data as the 95% lower confidence limit for scooters was only 2%. The reduction of crash involvement in rural and urban areas did not seem to deviate from the overall results for all case motorcycles, although two results were not statistically significant. The results for crashes in intersections were statistically significant and were in line with the findings for all motorcycles, ranging from 31% to 35% with a 95% lower confidence limit of 11% and 15% for Italy and Sweden, respectively. With regard to rear-end injury crashes with scooters, the Italian and Spanish results were also similar to each other and to the overall results. The effectiveness in those crashes ranged from 24% to 28%, although the Spanish result was not statistically significant.

The calculations for fatal and severe crashes involving only scooters could be carried out on the Spanish material only. ABS on scooters was found to reduce the involvement in severe and fatal crashes by 31%. This result was statistically significant and similar to the effectiveness for all case motorcycles in Spain (34%). However, the 95% lower confidence limit was lower, 12%. Again, the results for urban and rural areas did not deviate from the overall results, although the effectiveness for rural roads was not statistically significant. The effectiveness of ABS on scooters in reducing severe and fatal crashes in intersection was found to be at least 81%. The results for severe and fatal rear-end crashes with scooters were also impressive, with at least a 53% reduction. Both results were higher than the ones for all case motorcycles in Spain which had a 95% lower confidence limit of 33% and 45%, respectively (see Table 6).

DISCUSSION

Previous research has shown the positive effect of ABS on motorcycles (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). However, these studies were based on real-life crashes involving mostly large displacement motorcycles in countries where leisure riding is probably more common. Also, with the upcoming EU legislation making ABS mandatory for all new motorcycles over 125cc from 2016, the fitment rate in Europe will increase among light motorcycles too. Therefore the present study set out to evaluate the effectiveness of ABS on a wide range of motorcycle models, including scooters. A further objective was to compare the effectiveness of ABS between three countries that may have different vehicle fleets, motorcycling habits and road environments.

An induced exposure approach was used, as explained and used in several previous studies (Evans, 1998; Lie et al, 2006; Strandroth et al, 2012). While true exposure, such as number of registered vehicles or vehicle mileage, can also be used for this kind of evaluations, it can be difficult to compare between different countries and may also include confounding factors. For instance, as long as ABS is not standard equipment on all motorcycles on the roads, it could be argued that the choice of purchasing an ABS-equipped motorcycle is not randomly spread throughout the rider population. In other words, motorcyclists who choose ABS are probably more concerned about their safety in the first place, which could naturally lead to a lower crash involvement. While it is possible to control for these factors (Teoh, 2011), an induced exposure approach would normally compensate for this, as the result is given by relative differences within the ABS and non-ABS groups. It should also be noted that any behavioral adaptation, if at all present, would intrinsically be present in real-life crash data and included in the overall results.

The present method, however, is based on some assumptions that are important to discuss. The most critical step in the analysis is to determine which crash types are non-sensitive to the analyzed system. In this case, previous research addressing this issue was used (Rizzi et al, 2009), although this referred to Swedish crashes only. Assumptions were then made in order to identify the non-sensitive crash types in the Italian and Spanish databases. Checks were also made to ensure that this assumption was reasonable, which was found to be the case (see Table 4). Side crashes were found not to be particularly sensitive to ABS either, although it was argued that this would give conservative results: including such crashes among the sensitive ones would most likely decrease the calculated effectiveness of ABS.
Furthermore, it is important to stress that the non-sensitive crash type used in the calculations does not need to be identical across the three databases. With this method, the overall effectiveness of ABS in the three countries is believed to still be comparable, as E is multiplied with the total share of sensitive crashes in each country (see Equation 5). In fact, this aspect would imply a more robust analysis: positive results were found by using slightly different induced exposures (non-sensitive crash types), which would suggest that motorcycle ABS does have the calculated benefits.

Another critical step in this study was to properly match the ABS and non-ABS motorcycles. While crashworthiness is limited for motorcycles irrespective of model, the only reasonable difference in terms of crash and injury risk between the analyzed motorcycles should result from ABS itself. Previous research has shown that it is also possible to compare different motorcycle models with similar properties (Rizzi et al, 2009); however, it is clear that the present method is more robust. Also, the rider population with and without ABS should be better targeted in terms of age, driving experience etc. A limitation of this study is that VINs were not available for the Spanish and Swedish materials. While several checks were made to ensure a sound categorization, the possibility of merging VINs with crash data is always preferable when performing an evaluation of a vehicle safety system. On the other hand, this is less of an issue if the fitment of a safety system is standard on at least one model with sufficient selling volumes. It should be noted, however, that any misclassification would give an underestimation of the results.

The analysis showed statistically significant crash reductions for all ABS-equipped motorcycles, ranging between 24% in Italy and 34% in Sweden. The reduction of severe and fatal crashes was even more impressive, at 34% and 42% for Spain and Sweden, respectively. In general, the results for Italy and Spain seemed in line with the Swedish ones. It can be argued that this did not necessarily need to be case, because of different distributions of rural and urban crashes, crash types as well as scooters across these three countries (see Table 1). However, no evidence of a different effectiveness of motorcycle ABS in rural and urban areas was found. Besides, the results for scooters were comparable across the analyzed countries. The combination of these specific results can fully explain the similarity of the overall results for the three countries. While data quality issues could also be a possible explanation, the overall results would be most likely conservative. It should also be noted that the results for crashes at intersections were also similar and generally higher than for all crash types. This is consistent with previous research (Rizzi et al, 2009) as these crashes often involve braking (MAIDS, 2004), which also suggests that the material is reliable.
In conclusion, the findings of this study do not seem unreasonable as they are in line with previous research (Teoh, 2011; HLDI, 2009; Rizzi et al, 2009). ABS is effective in reducing crashes with scooters as well, which may have great safety implications in those regions of the world where this kind of motorcycles is used on a daily basis as a mean of transportation, often the only available one.

There might be several interpretations of these results. It should also be noted that the present study used police records and therefore could not perform any analysis of the actual functionalities of motorcycle ABS. However, previous research has shown that ABS generally provides shorter stopping distances and increased stability (Green, 2006; Vavryn and Winkelbauer, 2004). Tests of avoidance maneuvers performed on gravel surfaces by a Swedish motorcycle magazine (MC Folket, 2011) also reported similar results. Roll et al (2009) suggested that ABS may increase riders' confidence when applying full brakes, although stability improvements per se could also explain the large benefits of ABS.
While all these aspects can explain the effectiveness of motorcycle ABS in avoiding crashes, it should be noted that they could also be relevant for mitigating the crash severity and injury severity in crashes with ABS-equipped motorcycles. Little research is available on this issue at the moment, although some insights were given in the previous study (Rizzi et al, 2009). An increased deceleration during hard braking, as reported by the studies mentioned above, would logically decrease the impact speed if a crash occurs, thus mitigating injuries. Other studies also suggest that injury severity is reduced in crashes in which the rider is an upright position, compared to similar crashes

with prone riders (Sporner and Kramlich, 2003; Rizzi et al, 2012). The latter study reported statistically significant reductions of serious injuries among upright riders, as well as a 51% risk reduction of sustaining long-term injuries, although non-significant. Interestingly, none of the 6 riders with ABS had fallen off the motorcycle prior to the crash. It is important to stress that this study (Rizzi et al, 2012) was based on limited material and only analyzed crashes into road barriers. However, these findings could raise the question of whether the reduction of injury crashes with ABS is due to crash avoidance only. The possibility that a system that was originally designed to avoid crashes, such as ABS, might also have injury mitigating effects is intriguing and could have great safety implications. These effects, if confirmed, could be boosted even further by Autonomous Emergency Braking (AEB), which is being developed and evaluated for motorcycles too (Savino et al, 2012). These issues seem promising and should therefore be further investigated by future research.

During the latest years other vehicle safety systems have been introduced on motorcycles, although with generally lower fitment rate than for ABS. Such systems are Combined Brake Systems (CBS), Traction Control Systems (TCS) and integrated airbags, among others. In general, these systems are optionally fitted on ABS-equipped motorcycles and, in the case of TCS, even share some of the ABS sensors. While real-life crash data are still too limited for evaluation of these systems, this raises the possibility of combined effects that could enhance the total effectiveness of these systems. This aspect should also be investigated as soon as possible.

While these, among others, are important research questions that should be addressed in a near future, at the present stage there are more than sufficient scientific-based proofs to support the implementation of ABS on all motorcycles, even light ones. Manufactures should work toward a broad fitment of ABS, on light scooters as well, before 2016 in Europe and other regions of the world, while consumers should be encouraged to purchase only ABS-equipped motorcycles.

CONCLUSIONS AND RECOMMENDATIONS

- The effectiveness of ABS on injury crashes ranged from 24% in Italy to 29% in Spain and 34% in Sweden. The minimum effectiveness was 12%, 20% and 16%, respectively.

- The reduction of severe and fatal crashes with ABS ranged from 34% to 42% in Spain and Sweden, respectively. The minimum effectivenesses were 23% and 24%.

- The overall reduction of crash involvement with ABS-equipped scooters (at least 250cc) was found to be 27% in Italy and 22% in Spain. The minimum effectiveness was 12% and 2%, respectively.

- ABS on scooters with at least a 250cc engine was found to reduce the involvement in severe and fatal crashes by 31%, based on Spanish data only.

- Manufactures should therefore work toward a broad fitment of ABS, on light scooters as well, before 2016 in Europe and other regions of the world. Consumers should be encouraged to purchase only ABS-equipped motorcycles, for instance by insurance discounts, scrapping programs and other countermeasures.

- Further research should be aimed at understanding the injury severity mitigating effects of ABS, possibly in combination with AEB.

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APPENDIX I

The table below shows the motorcycle models included in the induced exposure analysis.

n ABS / non-ABS	ITA	SPA	SWE	n ABS / non-ABS	ITA	SPA	SWE
APRILIA MANA 850		3 / 8		HONDA CBR 1000 R			2 / 30
APRILIA SCARABEO 500	6 / 38			HONDA FJS 400	1 / 141	1 / 74	
APRILIA SHIVER 750	3 / 11			HONDA FJS 600	3 / 22	1 / 2	
BMW F 650 CS			8 / 0	HONDA GL 1800	2 / 0	1 / 13	8 / 5
BMW F 650 GD			2 / 1	HONDA NSS 250	35 / 20	2 / 0	
BMW F 650 GS	3 / 13		17 / 14	HONDA NT 700		1 / 115	2 / 2
BMW F 800 GS	8 / 14		17 / 0	HONDA SH 300	8 / 486	9 / 0	
BMW F 800 R	1 / 0		1 / 0	HONDA ST 1100			10 / 0
BMW F 800 S			12 / 0	HONDA ST 1300	1 / 1	7 / 48	16 / 2
BMW F 800 ST	3 / 4		13 / 0	HONDA VFR 1200			2 / 0
BMW G 650 X	0 / 3		1 / 0	HONDA VFR 800	2 / 13	4 / 63	7 / 37
BMW K 1100 LT		4 / 0	9 / 0	HONDA XL 1000	2 / 16		5 / 17
BMW K 1200 GT	0 / 4	22 / 0	6 / 0	HONDA XL 700	5 / 40	11 / 10	3 / 0
BMW K 1200 LT		20 / 0	6 / 0	KAWASAKI ER-6 F/N	11 / 190	33 / 281	19 / 34
BMW K 1200 R	6 / 10		4 / 0	KAWASAKI GTR 1400			1 / 0
BMW K 1200 RS			22 / 6	KAWASAKI VERSYS 650	3 / 39		
BMW K 1200 S	1 / 6	34 / 0	9 / 0	KAWASAKI Z 1000	2 / 67	5 / 68	3 / 11
BMW K 1300 GT			2 / 0	KAWASAKI Z 750	4 / 288	23 / 561	4 / 20
BMW K 1300 R	0 / 1			KAWASAKI ZZR 1400			3 / 0
BMW R 1100 GS			3 / 0	MOTO GUZZI 1200 SPORT	2 / 0		
BMW R 1100 RT			6 / 2	MOTO GUZZI NORGE 1200	12 / 0	3 / 0	1 / 0
BMW R 1100 S			12 / 1	MOTO GUZZI STELVIO	2 / 0		
BMW R 1150 GS			15 / 0	PIAGGIO VESPA GTS 250	3 / 86	5 / 45	
BMW R 1150 R	1 / 9		7 / 0	PIAGGIO X9 EVO	4 / 18	13 / 56	
BMW R 1150 RT		27 / 0	17 / 2	SUZUKI AN 650		99 / 26	
BMW R 1200 CL			2 / 0	SUZUKI DL 650	3 / 105	47 / 249	
BMW R 1200 GS	61 / 57		36 / 0	SUZUKI GSF 1200		3 / 0	2 / 28
BMW R 1200 R	12 / 23		2 / 0	SUZUKI GSF 1250	4 / 0	8 / 0	2 / 2
BMW R 1200 RT	0 / 18	104 / 0	4 / 0	SUZUKI GSF 650	11 / 33	43 / 322	
BMW R 1200 S			1 / 0	SUZUKI GSR 600	1 / 150	20 / 533	1 / 6
BMW R 1200 ST	3 / 6		1 / 0	SUZUKI GSX 650		1 / 21	
BMW R 850 GS			1 / 1	SUZUKI SV 650			2 / 43
BMW R 850 R			8 / 2	TRIUMPH SPRINT ST	3 / 1		1 / 14
BMW S 1000 RR			7 / 0	TRIUMPH TIGER 1050	2 / 23		3 / 18
DUCATI MONSTER 1100			2 / 1	YAMAHA FJR 1300	1 / 0	20 / 4	18 / 20
DUCATI ST4	2 / 1		1 / 2	YAMAHA FZ-1		6 / 91	2 / 13
HARLEY DAVIDSON FLHRCI			5 / 29	YAMAHA FZ-6		1 / 1224	9 / 26
HARLEY DAVIDSON FLHRSI			0 / 2	YAMAHA TDM 900	5 / 8	4 / 6	
HARLEY DAVIDSON FLHTCU			3 / 14	YAMAHA V-MAX			1 / 7
HARLEY DAVIDSON FLHTCUI			0 / 11	YAMAHA XJ-6			3 / 2
HARLEY DAVIDSON FLHX			3 / 5	YAMAHA XP 500	102 / 336	91 / 354	
HONDA CB 1000 R	1 / 34		11 / 4	YAMAHA XT 1200			1 / 0
HONDA CB 1300		3 / 6	2 / 5	YAMAHA XT 660 TENERE			1 / 2
HONDA CB 600	3 / 295	4 / 515	2 / 27	YAMAHA YP 250		8 / 571	
HONDA CBF 1000	8 / 5	7 / 11	5 / 1	YAMAHA YP 400	21 / 185	6 / 217	
HONDA CBF 600		95 / 320	3 / 1	**TOTAL**	**377 / 2820**	**799 / 5814**	**420 / 470**

APPENDIX II

The table below shows a comparison of the share of non-sensitive crashes in each country with official statistics or previous studies.

	ITA	SPA	SWE
Present study	16%	10%	8%
2 Be Safe, 2010	17%	11%	-
STRADA 2008-2012	-	-	6%

The table below shows the sensitive to non-sensitive (head-on collisions) ratios in the Swedish non-ABS group, per driver age.

age groups	non-sensitive crashes	Sensitive crashes	ratio	% non-ABS group
18-24	0	72	∞	15%
35-34	8	118	15	27%
35-44	10	92	9	22%
45-54	7	95	14	22%
44-64	5	51	10	12%
65+	0	12	∞	3%
all age groups	**30**	**440**	**15**	**100%**