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Assessment of the effect of motorcycle autonomous emergency braking (MAEB) based on real-world crashes

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ABSTRACT

Objective: Vehicles are increasingly being equipped with Autonomous Emergency Braking (AEB) and literature highlights the utility to fit a similar active safety system in Powered Two-Wheelers (PTWs). This research attempts to analyze the efficacy of PTW Autonomous Emergency Braking (MAEB) when functioning solely, and in the case where both the PTW and Opponent Vehicle (OV) have AEB installed.

Methods: 23 crashes involving motorcyclists that occurred in metropolitan areas of Italy between 2009 and 2017 were selected. The “In-depth Study of road Accidents in FlorencE (InSAFE)” provides data for the study. Each crash was reconstructed in PC-Crash 12.1 software. The obtained simulation of the crash dynamics was then used to create the dataset of cases fitted with AEB and MAEB systems. A custom MAEB system was implemented with specifications based on literature.

Results: The majority of crashes occurred on urban roads, at intersections, on dry asphalt, with clear visibility, and in daylight. The passenger vehicle was the most frequent opponent vehicle (70%). Almost half the sample involved the PTW rider traveling beyond the speed limit permitted on urban roads. MAEB was found to be applicable in 19 out of 23 real-world crashes allowing the avoidance of two crashes with the progressive triggering criteria (Time to Collision (TTC) – 1.0 s) and one crash in the case where both the PTW and OV have AEB installed with more conservative setups. MAEB simulations show important trends in the reduction of the PTW impact speed (ISR) from the conservative (TTC-0.6s) to standard (TTC-0.8s) to progressive (TTC-1.0s) triggering criteria. The mean impact speed reduction (ISR) becomes 8.6 km/h, 13.8 km/h, 19.1 km/h, respectively.

Conclusions: The results suggested that MAEB may be extremely effective in the PTW impact speed reduction and that an earlier MAEB intervention is beneficial in achieving higher reductions in the PTW impact speed. Further, the effect of opponent vehicles also possessing AEB was studied, and it was found that this increased the likelihood of crash avoidance and greater reduction in crash severity in unavoidable circumstances.

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Motorcycle; active safety; motorcycle autonomous braking system; PTW; crash in-depth investigation

Introduction

Powered Two-Wheeler (PTW) vehicles are typically used for different purposes in different parts of the world. In high-income countries, PTWs are mostly used for leisure and to escape the problems of urban traffic congestion, while in low- and middle-income countries they are more commonly used for commercial purposes (WHO, 2017). Their global spread is set to increase as a result of an increase in transport demand and traffic congestion in urban settings, convenience and ease of parking and maintenance. However worldwide, between 2010 and 2018, crash deaths among passenger vehicle users fell about twice as much as among motorcyclists (OECD, 2020). Excessive and inappropriate speed for the PTW is the leading cause of road trauma in many countries. The lack of protection for PTW users during a collision means they are particularly vulnerable to severe or fatal injury associated with excessive speed (WHO, 2017).

Passenger vehicles are increasingly being equipped with active safety systems such as Autonomous Emergency Braking (AEB) (Fildes et al. 2015), but this is not the case for PTW vehicles. Literature highlights the utility to fit a similar active safety system in PTW although this technology is still in an experimental phase in such kind of vehicles (Savino et al. 2020).

Most recent field test studies were carried out testing Motorcycle Automatic Emergency Braking (MAEB) with different decelerations of the test vehicle. Savino et al. (Savino et al. 2016a) experiment decelerations up to 0.2 g while Merkel et al. (Merkel et al. 2018) conducted tests with decelerations up to 0.7 g with expert PTW riders, overall suggesting that automatic decelerations greater than 0.3 g can be managed by common PTW riders in straight-line motion. Lucci et al. (2020), testing end-user acceptability of unexpected, automated braking events deployed in typical pre-crash trajectories on 31 common PTW riders with decelerations up to 0.5 g (5 m/s²), found no dangerous

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situation in the triggering of automatic braking in such conditions, suggesting that the benefits could be higher than those estimated in previous simulation studies (Savino et al. 2016b, Piantini et al. 2020, Savino and Piantini, 2019).

Concerning MAEB efficacy assessment based on real-world crashes, Lucci et al. (2021) found that the system produces appreciable impact speed reductions, with an average of 5 km/h when the PTW rider does not apply any braking and an average of up to 7.3 km/h when the system works as enhanced braking. Resulting in an injury risk reduction of up to 12% for MAIS2+ and up to 21% for fatal injuries.

The objective of this study was to evaluate the effects of three different MAEB triggering criteria on the reduction of PTW impact speed using a commercial accident reconstruction software; simulations assumed the case of only the PTW being equipped with AEB and the case of both PTW and Opponent Vehicles (OVs) being equipped with AEB.

Methods

Data sources and selection

The InSAFE crash database provides the data for this study. InSAFE (In-depth Study of road Accidents in Florence) is an ongoing in-depth crash study being conducted by the University of Florence in the metropolitan area of Florence, Italy. All the cases involved at least one severely injured PTW rider or PTW-pillion, which means to have an Injury Severity Score (ISS) higher than 15 and admission to the Intensive Care Unit (ICU) of the Careggi University Hospital (Florence) post the occurrence of the crash (Piantini et al. 2013).

The InSAFE database currently includes about 250 in-depth crash investigations, related to cases that occurred between 2009 and 2018, inclusive of 46 crash cases fully reconstructed via PC-Crash software. The eligible cases were chosen based on the following criteria: (i) PTW impacting against a passenger vehicle, (ii) a roll angle not exceeding 10 degrees in the pre-crash phase (i.e., the pre-crash trajectory of the PTW must be straight or slightly curved), (iii) the PTW's point of impact is on its frontal or frontal-lateral side, (iv) no restriction regarding pre-crash PTW rider braking conditions, and finally, v) only crashes with PC-Crash reconstructions, where the reconstruction list followed the order of occurrence.

We, therefore, excluded single-vehicle crashes where the benefit of the MAEB is more difficult to predict as the obstacle, where present, is not easily characterized. We also excluded bicycle crashes where it is common to see major injuries on the opposing user while our focus is on the PTW users. We also exclude cases with a large roll angle due to the difficulty of correctly identifying the forthcoming impact condition. Indeed, previous studies on the inevitable collision state considered a PTW moving straight. To consider the curved trajectory, a different tool from the reconstruction software here adopted would be required. Concerning the crash configuration, we assumed that MAEB does not give any benefit when the motorbike is struck from behind or in its rear-lateral part.

New in-depth crash investigation and reconstruction performed via PC-Crash 12.1 software were included in the InSAFE database ($N=46$). Single PTW crashes were filtered out from the dataset ($N=33$). Further, cases having the PTW with a roll angle higher than 10° were discarded ($N=23$). A total of $N=23$ crashes involving PTW riders were selected.

Motorcycle autonomous emergency braking (MAEB) system

The MAEB intervention algorithm was based on a fixed triggering time before the crash (TTC, Time-To-Collision) without considering the assessment of PTW rider's crash avoidance opportunities by braking and/or steering as in previous studies (Savino et al, 2016a, 2016b, Lucci et al. 2021). The algorithm works as a low-pass filter, i.e., cutting off every braking higher than the deceleration applied by the system. Moreover, we hypothesized that the use of a MAEB system is always in combination with an Anti-Lock Braking System (ABS) to prevent the PTW rider from falling even in the case of hard braking (Rizzi et al. 2009).

The default PC-Crash AEB input parameters and settings are shown in (Figure 1). No changes were made to the default system apart from the input parameters specified in (Table 1). When the algorithm's calculated TTC becomes less than t_{brake} the MAEB system triggers. The MAEB parameters have been chosen based on the most recent literature (Savino et al, 2016b, Lucci et al. 2021).

Considering that a typical radar sensor has a distance range of about 60 m and a field of view (FoV) of $\pm 45^\circ$, the sensor range and FoV were set as shown in (Table 1). The TTC was assumed to have three different levels (0.6, 0.8 and 1.0 s) to depict a conservative, standard and progressive system intervention. Lastly, according to the most recent and encouraging field test results (Lucci et al. 2021), a deceleration of 5 m/s^2 was chosen.

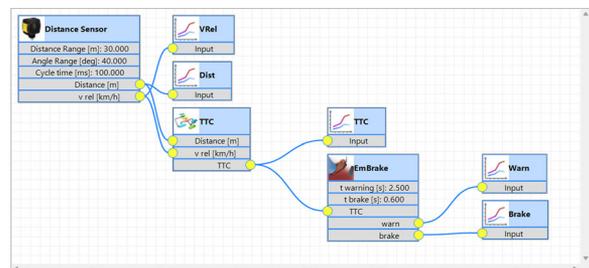


Figure 1. Configuration of the PC-Crash default AEB system.

Table 1. MAEB and AEB input parameters.

Input parameter	MAEB			AEB	
Detection distance range	30			150	(m)
Detection Field of view (FoV) (half cone angle)	40			40	($^\circ$)
Cycle time		100		100	(ms)
TTC (s)	0.6	0.8	1.0	0.6	(s)
Braking deceleration		5		8	(m/s^2)

Passenger vehicle autonomous emergency braking (AEB) system

The AEB algorithm was based on a fixed TTC without taking into account the assessment of the driver’s avoidance opportunities by braking and steering. No changes were made to the default PC-Crash AEB system apart from the distance range and FoV as specified in (Table 1).

Numerical simulations

PC-Crash’s models govern the pre-crash, crash, and post-crash dynamics of the vehicles, allowing simulations to be performed in the forward or backward direction. The forward simulation covers all vehicle motions with a positive time step (crash and post-crash phases), while the backward simulation moves vehicles with a negative time step (pre-crash phase). The combination of the two is the typical layout used to numerically reconstruct the crash. Nonetheless, an “only forward simulation with positive time step” which entails the complete motion of the vehicles from their starting position (for around 1.5–3 s before the point of impact) to the rest position has been necessary to implement the MAEB system in the PC-Crash. Optimization of the ‘point of impact’ and ‘contact plane’ was necessary to solve some differences between the crash parameters, such as the EES

(Energy Equivalent Speed) and delta-V, relative to the two simulation methods. These values were considered acceptable if they were within a tolerance of 10% of the reference value.

The simulations have been performed under the following assumptions: i) no PTW rider falls on the ground before the first impact due to the hypothesis of having an ABS installed system, ii) fixed obstacles are ignored, iii) PTW rider steering input is smooth and minimal, causing the PTW trajectory to be close to a straight line (roll-angle < 10°), iv) unmodelled weather and light conditions, and, lastly, v) the MAEB system can be able to avoid the crash.

Results

The study is a cross-sectional study of severe crashes on a local basis and over a fixed reference period. Forty-six new crash cases occurred between 2009 and 2017 which were fully reconstructed via PC-Crash 12.1 software and added to the InSAFE database. $N=23$ out of 46 cases were eligible for the MAEB study.

Dataset description

Most crashes occurred on urban roads, dry asphalt, and in clear visibility (91%, 21/23). Over half of the cases occurred in daylight (61%, 14/23) and an almost similar number of crashes took place in single carriageways (43,5%, 10/23) and dual carriageways (56,5%, 13/23). Most crashes occurred at intersections (56,5%, 13/23) followed by straight road (39%, 9/23). Notably, ‘crossroads’ (a four-way intersection) are the most frequent crash zone among the intersections with 43.5% occurrences (13/23). Most of the PTWs involved belonged to the L3 category (engine $\geq 125\text{cm}^3$) (65%, 15/23) and scooter style (91%, 21/23). As for the opponent vehicle, the car was the most frequent (78%, 18/23) followed by vans (17%).

In half of the crashes, the PTW rider’s traveling speed exceeded road speed limits (48% at 50+ km/h), while in the remaining half of the crashes, the PTW rider was traveling between 26-50 km/h. Before the crash occurred, PTW riders did not perform any braking in 43,5% of cases, and in an almost similar number of cases, they performed braking (39%, 10/23) which then become hard braking ($>5\text{ m/s}^2$) in half of the cases (5/10). Vice versa, passenger vehicle drivers exceeded road speed limits in only 13% of the crashes, while the majority were traveling in the range from 26 to 50 km/h

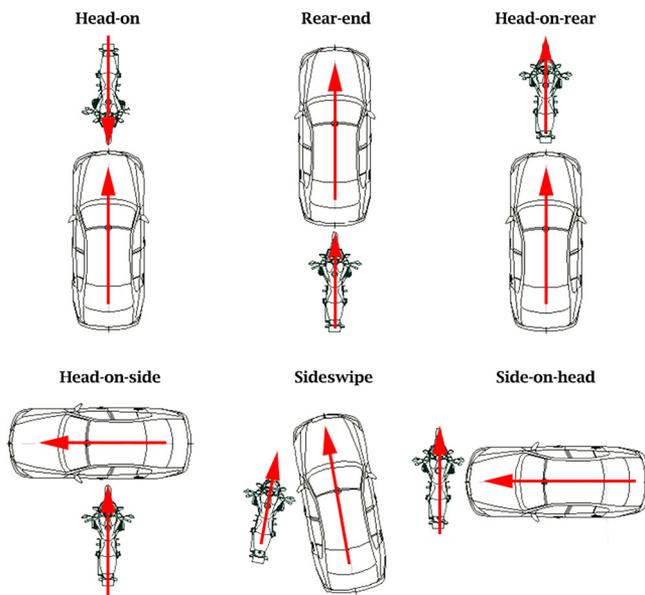


Figure 2. Crash configuration convention. The first type of impact is relative to the PTW (e.g., head-on-side collision means a PTW hitting frontally a car on its side).

Table 2. Summary of reduction in the PTW Impact Speed (I.S.R), ΔV ($\Delta V.R$), and the Relative Impact Speed (R.I.S.R) in the case of the use of MAEB with a TTC of 0.6, 0.8 and 1.0 s, and in the case of the use of MAEB and AEB with a TTC of 0.6 s.

	MAEB TTC 0.6s			MAEB TTC 0.8s			MAEB TTC 1.0s			MAEB0.6 + AEB0.6		
	I.S.R (km/h)	$\Delta V.R$ (km/h)	R.I.S.R (km/h)	I.S.R (km/h)	$\Delta V.R$ (km/h)	R.I.S.R (km/h)	I.S.R (km/h)	$\Delta V.R$ (km/h)	R.I.S.R (km/h)	I.S.R (km/h)	$\Delta V.R$ (km/h)	R.I.S.R (km/h)
Min	0.0	-4.7	0.0	0.0	-3.7	0.0	0.0	-5.4	0.0	0.0	-8.8	0.3
Max	14.2	15.3	14.2	31.7	23.1	24.0	45.0	46.9	30.1	17.3	35.2	27.3
Mean	7.3	4.8	6.9	11.7	6.3	10.9	16.2	9.0	15.9	7.9	9.5	12.3
Median	8.8	3.7	7.5	15.4	3.2	14.3	17.8	5.9	19.6	8.8	6.4	12.6

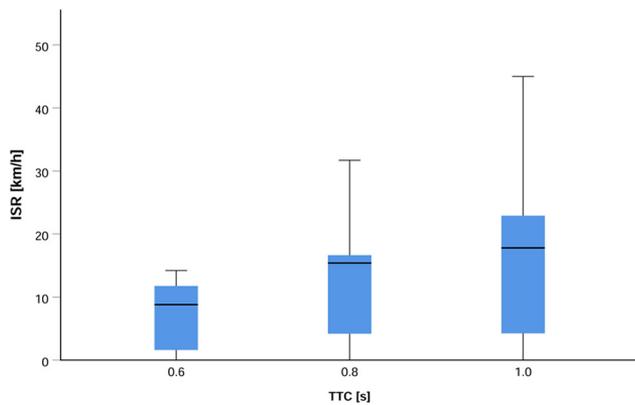


Figure 3. Influence of the TTC on the PTW Impact Speed Reduction (ISR).

(30.5%, 7/23). Only 26% (6/23) of passenger vehicle drivers applied pre-crash braking.

Concerning the crash, most belonged to the head-on-side impact configuration (T-bone) (48%, 11/23), with roughly a balance between head-on-side and side-on-head crash configuration (55% vs 45%), followed by sideswipe (22%), head-on (13%) and head-on-rear impacts of vehicles regularly parked (13%) (Figure 2). PTWs impacted at a speed ranging from 26 to 50 km/h in 52% (12/23) of cases with 17% above 50 km/h, and with a delta-V ranging from 1 to 25 km/h (52%, 12/23). Vice versa, most of the passenger vehicle drivers impacted at a speed ranging from 1 to 25 km/h (43.5%, 10/23), followed by the range 26–50 km/h (26%). In four cases the Opponent Vehicle (OV) was at rest during impact, because the vehicles were regularly parked on the roadside.

The 23 crashes involved a total of 29 people, of which six of them were PTW-pillions. Most of the motorcyclists were male (76%, 22/29), their age ranging from 16 to 76 years, with 83% less than 50 years old and 52% less than 35 years old. Two PTW riders were positive for alcohol and/or drugs (hospital data may underestimate this circumstance), and vice versa no passenger vehicle drivers were under the influence of substances. All the motorcyclists suffered a major trauma (ISS 15+) with 17% (5/29) fatality within 30 days from the crash, while no passenger vehicle occupants were injured.

The representativeness of the InSAFE sample has been assessed by comparing the proportion of the national crashes in which the MAEB system is applicable with those from the sample studied. Based on findings from Savino et al. 2018, the crash scenarios in which the MAEB is the most significant application and the relative percentage are the following: A (Intersection AND collision at an angle), B (Intersection AND sideswipe), C (Straight Road AND sideswipe), E (Head-on), F (Rear-end), G (Hit obstacle OR hit pedestrian) and H (Straight road AND collision at an angle), equivalent to 25% (A), 8% (B), 9% (C), 6% (E), 11% (F), 9% (G), 12% (H). Corresponding to the overall applicability of 62% out of 472,535 total crashes in the reference period 2009–2016. On the other hand, the InSAFE sample showed overall applicability of 57%, with a single scenario percentage of A (21%), B (17%), C (0%), E (15%), F (0%), G (0%), H (4%), respectively. Highlighting that the sample considered was overall representative of the national statistics, but

with some differences within the crash scenarios. Lastly, it is interesting to note that the 23 applicable MAEB cases correspond to 50% of the available case series.

MAEB numerical simulations

The 23 cases resulted in a total of 92 MAEB numerical simulations. Considering the cases simulated implementing only MAEB in the conservative (TTC 0.6 s), standard (TTC 0.8 s) and progressive (TTC 1.0 s) triggering criteria, mean reductions in impact speed (ISR) of 7.3 km/h, 11.7 km/h and 16.2 km/h, respectively, are obtained (Table 2 and Table 3A in the online appendix). The ISR ranging from 0 to 14.2 km/h (conservative), from 0 to 31.7 km/h (standard), and from 0 to 45 km/h for the progressive triggering criteria. Negative values which mean an increment in the PTW impact speed due to a lower MAEB braking action compared to the crash reference values have been replaced with zero (ID-10). The ISR takes also into account the avoidance of a crash. If the case the ISR will be equal to the baseline impact speed. In 3 out of 23 cases, the Opponent Vehicle (OV) was external to the MAEB FoV with any of the three triggering criteria (ID 1, 18, 22), while in one case (ID 15) the system did not trigger only with TTC = 0.6 s. Vice versa, in two cases, both in the progressive triggering criteria, the MAEB was fully able to stop the PTW and avoid the impact (ID13, 14). While in two crash configurations (ID 15, 23) the MAEB intervention was very limited. Notably, in the crash configuration of ID 8, even though the MAEB system was able to stop the PTW, the collision still occurred because the OV did not stop.

Comparing the ISR and the TTC triggering criteria a Kruskal Wallis test was chosen due to the absence of a normal distribution of the ISR and homogeneity of variances. The Kruskal Wallis test provided evidence of a difference ($H = 9.098$, $p = 0.011$, $df = 2$) between the mean ranks of at least one pair of groups (Figure 3). Dunn's pairwise tests were carried out for the three pairs of groups. There was strong evidence ($p < 0.008$, adjusted using the Bonferroni correction) of a difference between the MAEB which had the TTC = 0.6 s and those which had the TTC = 1.0 s. The median ISR for the group having TTC = 0.6 s was 8.8 km/h compared to 17.8 km/h in the group with TTC = 1.0 s. Nonetheless, there was no evidence of a significant difference between the other pairs.

Excluding from the computation (Figure 3) the cases (ID 1,15,18,22) where the MAEB technology is unable to trigger because the OV is out of MAEB FoV, the mean ISR become 8.9 km/h, 14.2 km/h, 19.4 km/h for a TTC of 0.6 s, 0.8 s and 1.0 s, respectively. And again, the Kruskal Wallis test provided stronger evidence of a difference ($H = 14.785$, $p = 0.001$, $df = 2$) between the mean ranks of at least one pair of groups; as well as the Dunn's pairwise tests point out even stronger evidence ($p < 0.0001$) of a difference between the groups TTC = 0.6 s and TTC = 1.0 s. Moreover, although not yet significant, also the differences between the mean ranks of the groups TTC = 0.6 s and TTC = 0.8 s improve.

Considering the sideswipe crash sample, the mean ISR becomes 0.4 km/h, 18.1 km/h, 26.9 km/h for a TTC of 0.6 s, 0.8 s and 1.0 s, respectively.

Considering the change in velocity reduction ($\Delta V.R$) experienced by the PTW during the impact, Table 2 shows overall growth in the mean corresponding to 4.8 km/h, 6.3 km/h and 9.0 km/h for a TTC of 0.6 s, 0.8 s and 1.0 s, respectively. While in the crash subset where both vehicles were using an autonomous braking system (MAEB + AEB) the ΔV reaches 9.5 km/h of reduction.

Focusing on cases where the MAEB was able to trigger, again, the mean velocity reduction ($\Delta V.R$) increased going from a TTC of 0.6 s to 0.8 s and then to 1.0 s, assuming the values of 5.8 km/h, 7.6 km/h and 10.9 km/h, respectively. But it was not the same for the median which, compared to a TTC of 0.6 s (3.3 km/h), firstly dropped at TTC 0.8 s (2.7 km/h) and then at TTC 1.0 s (2.2 km/h). There was no evidence of a significant difference between the pairs.

MAEB and AEB numerical simulations

Looking at the cases simulated implementing both the MAEB and AEB on the PTW and Opponent Vehicle (OV), respectively (MAEB + AEB group), the overall mean and median reductions in ISR of 7.9 km/h and 8.8 km/h are obtained (Table 2), with a range between 0 and 17.3 km/h. Within that subset, in 10 out of 23 cases the AEB was able to trigger (43,5%). In 5 cases (21.7%), the crash scenario was not significant to apply an AEB system (the obstacle was constantly behind the AEB sensor cone), while in 8 cases (34.8%), although the obstacle could have been detected from the AEB sensor cone, the PTW was outside the AEB FoV. Lastly, only one crash was avoided (ID 8) with both vehicles able to stop before the impact.

Taking into account crashes where the AEB could be triggered (ID 1, 6, 7, 8, 10, 11, 15, 17, 18 and 22), the mean PTW ISR increase from 3.2 km/h (MAEB) to 4.5 km/h (MAEB + AEB) while the mean relative impact speed reduction (RISR) from 3.1 to 15.4 km/h, respectively. A Mann-Whitney U test showed that there was a significant difference ($U = 6.5$, $p = 0.001$) between the MAEB + AEB group compared to the MAEB group in terms of RISR. The median RISR was 15.5 km/h for the MAEB + AEB group compared to 1.2 km/h for the MAEB group.

By a further narrowing focus on those cases where both the MAEB and AEB systems have been triggered (6 cases, ID 6, 7, 8, 10, 11 and 17), data show a general mean reduction of the PTW ISR and the RISR ranging from 2.7 to 17.3 km/h, from 3.7 to 27.3 km/h, respectively.

Discussion

This paper describes potential trends in the efficacy of autonomous emergency braking systems applied to PTW vehicles based on real-world crashes involving seriously injured motorcyclists, as well as the advantages of using this active safety system in a traffic context where all vehicles are equipped with autonomous emergency braking. Additionally, the research illustrates the potential of using crash reconstruction and simulation platforms to assess the efficacy of active safety systems in real-world crash scenarios.

Despite the limited sample size, some insights, proof, and confirmation on the efficacy of a PTW autonomous emergency braking system (MAEB) came up from the study which can significantly enhance PTW safety.

The PTW to Opponent Vehicle (OV) head-on side collision, mostly at intersections, is still an impact configuration to tackle to significantly enhance PTW safety on urban roads. Nonetheless, as also reflected by the relatively high frequency in the national crash statistics, sideswipe crashes are dangerous particularly in cases in which the relative impact speed is high as shown by Savino et al. (2013). Comparing the maximum Impact Speed Reduction (ISR) range obtained by Savino et al. (2013) (1.5–5.1 m/s), results highlight how the MAEB system can be effective also in this crash configuration, reaching a mean ISR from 2.6 to 7.5 m/s based on different TTC.

Crash data confirms that in serious and fatal crashes, despite an urban environment with speed limits between 30 and 50 km/h, PTW riders more often exceeded the speed limit compared to drivers who did not. That also increases the frequency of crashes occurring at a high impact speed (30+ km/h). The observance of speed limits is an important issue for the crash severity reduction and cannot be only achieved using active braking systems. Other Advanced Rider Assistance Systems (ARAS) such as speed limit indicators or even better intelligent speed adaptation (ISA) systems, as well as police enforcement actions, maybe other safety systems or actions useful to contrast this unsafe motorcyclists' behavior.

The presence of a high number of real-world crashes where the PTW rider did not perform any pre-crash braking, or they braked but not with the maximum practicable deceleration, highlights again the importance to equip the PTWs with automatic braking systems, as is de facto already the case with other vehicles. For example, the EU commission has made the use of such systems mandatory for the vehicle categories M2-3 and N2-3 since 2012 and from 2020 for vehicle categories M1 and N1 (EU Regulation N. 347/2012). An additional analysis for future work is to assess the effect of MAEB when used to enhance the braking action of the rider in the pre-crash phase, as suggested by Lucci et al. (2021).

MAEB simulations show important trends in the reduction of the PTW impact speed (ISR) from the conservative (TTC-0.6s) to standard (TTC-0.8s) to progressive (TTC-1.0s) triggering criteria. Compared to the conservative triggering criteria, the standard was able to reduce the PTW impact speed by 1.5 times, while the progressive criteria by more than twice. This suggested that an earlier MAEB intervention is beneficial in achieving higher reductions in the PTW impact speed, also confirmed by the Pairwise comparisons using Dunn's test that indicated that group TTC-1.0s was observed to be significantly different from the group TTC-0.6s ($p < 0.0001$), although, on the other hand, no statistically significant differences have been found between the TTC-0.6s and TTC-0.8s groups. Similar ISR in the conservative triggering criteria were found by Lucci et al. (2021) in the MAEB plus manual braking mode.

The non-activation of MAEB in the three cases (ID 1, 18, 22) was foreseeable and expected since this kind of crash configuration is a typical off-design configuration for the MAEB system (the OV is usually outside the PTW FoV). By the way, it is interesting to point out how the MAEB has been able to trigger even in some not optimal crash configurations such as the ID-4 case (Table A4 in the online appendix). Notably, in the progressive triggering criteria, the MAEB was able to reduce the speed to such levels that the crash was completely avoided in two cases. While in another one, the MAEB was able to stop the PTW (standard and progressive criteria, ID-8) before the impact, but not to avoid the crash as the OV did not stop (Table A4 in the online appendix).

Moreover, comparing the subsets of crashes where i) no vehicles were equipped with an active safety braking system (crash reference), ii) only PTW provided with such a system (MAEB, TTC-0.6s), and iii) all vehicles were equipped with an AEB or MAEB (both TTC-0.6s), the increase in effectiveness is evident. In the subset iii), the PTW impact speed dropped by nearly 1.5 times and the relative impact speed by roughly 4 times compared to subset ii), highlighting that the use of autonomous braking in all vehicles, by increasing the probability of the system's intervention, increases the likelihood of avoiding a collision and a greater reduction in crash severity (when unavoidable).

Given that PTW riders and pillioners are vulnerable road users, small improvements toward PTW safety can potentially have a significant impact. This study addresses the potential of MAEB to improve PTW safety either by reducing the severity of impact or complete avoidance of impact. Real-world PTW crashes were reconstructed using PC-Crash software, which was followed by an analysis of the crashes had MAEB been incorporated.

The results suggested that MAEB may be extremely efficient in the PTW impact speed reduction (ISR) and that an earlier MAEB intervention is beneficial in achieving higher reductions in the PTW impact speed. Further, the effect of opponent vehicles also possessing AEB was studied, and it was found that this increased the likelihood of crash avoidance and greater reduction in crash severity in unavoidable circumstances.

Limitations

Although the overall proportion of the MAEB system applicability is similar to the national figure, no extrapolation is possible due to the limited number of cases and differences within each crash scenario. Regarding the benefits, it is not excluded that the MAEB also helps in special cases of single vehicles. This has not been investigated to date. A further possible underestimation derives from the exclusion of cases in curves or with large roll maneuvers where MAEB intervention is possible (reference "The application of a Motorcycle Active Curve assistant system for crash avoidance and injury reduction" - forthcoming) and where benefits are expected (Savino et al. 2015). Under non-canonical scenarios, i.e., where it is the PTW that hits the other

vehicle head-on, the benefits of the MAEB are predictable with a lower degree of reliability. However, a reduction in the impact speed leads to the passive protection of the motorcyclist to work closer to their design conditions, thus increasing their effectiveness.

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References

- Fildes B, Keall M, Bos N, Lie A, Page Y, Pastor C, Pennisi L, Rizzi M, Thomas P, Tingvall C. 2015. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. *Accid Anal Prev.* 81:24–29. [10.1016/j.aap.2015.03.029](https://doi.org/10.1016/j.aap.2015.03.029).
- Lucci C, Allen T, Pierini M, Savino G. 2021. Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: estimating the potential for injury reduction using real-world crash modeling. *Traffic Inj Prev.* 22(sup1):S104–S110. doi: [10.1080/15389588.2021.1960319](https://doi.org/10.1080/15389588.2021.1960319).
- Lucci C, Baldanzini N, Savino G. 2021. Field testing the applicability of motorcycle autonomous emergency braking (MAEB) during pre-crash avoidance maneuver. *Traffic Inj Prev.* 22(3):246–251. doi: [10.1080/15389588.2021.1884235](https://doi.org/10.1080/15389588.2021.1884235).
- Lucci C, Huertas-Leyva P, Marra M, Pierini M, Savino G, Baldanzini N. 2020. Autonomous Emergency Braking system for Powered-Two-Wheelers: testing end-user acceptability of unexpected automated braking events deployed in typical pre-crash trajectories. 13th International Motorcycle Conference (IFZ). Cologne, Germany.
- Merkel N, Pless R, Scheid K, Winner H. 2018. Limits of autonomous emergency brake systems for powered two-wheelers – an expert study. 12th International Motorcycle Conference (IFZ). Cologne, Germany, p. 122–144.
- OECD/ITF 2020., Road Safety Annual Report.
- Piantini S, Bourdet N, Savino G, Rosalie S, Pierini M, Deck C, Willinger R. 2020. Potential head injury mitigation of M-AEB in real-world motorcycle crashes. *Int J Crashworthiness.* 25(6):591–602. doi: [10.1080/13588265.2019.1626531](https://doi.org/10.1080/13588265.2019.1626531)
- Piantini S, Grassi D, Mangini M, Pierini M, Zagli G, Spina R, Peris A. 2013. Advanced accident research system based on a medical and engineering data in the metropolitan area of Florence. *BMC Emerg Med.* 13:3. [10.1186/1471-227X-13-3](https://doi.org/10.1186/1471-227X-13-3).
- Powered two- and three-wheeler safety: a road safety manual for decision-makers and practitioners. Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO
- Rizzi M, Strandroth J, Tingvall C. 2009. The effectiveness of antilock brake systems on motorcycles in reducing real-life crashes and injuries. *Traffic Inj Prev.* 10(5):479–487. doi: [10.1080/15389580903149292](https://doi.org/10.1080/15389580903149292).
- Savino G, Giovannini F, Baldanzini N, Pierini M, Rizzi M. 2013. Assessing the potential benefits of the motorcycle autonomous

- emergency braking using detailed crash reconstructions. *Traffic Inj Prev.* 14(sup1):S40–S49. doi:[10.1080/15389588.2013.803280](https://doi.org/10.1080/15389588.2013.803280)
- Savino G, Giovannini F, Piantini S, Baldanzini N, Pierini M. 2015. Autonomous emergency braking for cornering motorcycle. 24th ESV Conference. Gothenburg, Sweden, June 8–11.
- Savino G, Lot R, Massaro M, Rizzi M, Symeonidis I, Will S, Brown J. 2020. Ioannis Symeonidis, Sebastian Will & Julie Brown (2020) Active safety systems for powered two-wheelers: A systematic review. *Traffic Inj Prev.* 21(1):78–86. doi: [10.1080/15389588.2019.1700408](https://doi.org/10.1080/15389588.2019.1700408).
- Savino G, Mackenzie J, Allen T, Baldock M, Brown J, Fitzharris M. 2016. A robust estimation of the effects of motorcycle autonomous emergency braking (MAEB) based on in-depth crashes in Australia. *Traffic Inj Prev.* 17(sup1):66–72. doi:[10.1080/15389588.2016.1193171](https://doi.org/10.1080/15389588.2016.1193171)
- Savino G, Piantini S. 2019. 13588265 Analysis of effects of a motorcycle pre-crash braking system using in-depth crash data and drive-through data: a case study. In *Proceedings of the International Research Council on Biomechanics of Injury*. Florence, Italy. p. 550–551.
- Savino G, Pierini M, Thompson J, Fitzharris M, Lenné MG. 2016. Exploratory field trial of motorcycle autonomous emergency braking (MAEB): considerations on the acceptability of unexpected automatic decelerations. *Traffic Inj Prev.* 17(8):855–862. doi: [10.1080/15389588.2016.1155210](https://doi.org/10.1080/15389588.2016.1155210).
- Savino G, Zanovello L, Magnini N, Gil G, Fitzharris M, Pierini M. 2018. The proposed approach of Knowledge Base for the identification of promising countermeasures to reduce casualties amongst motorcyclists. 12th International Motorcycle Conference 2018. Cologne, Germany.