Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: Estimating the potential for injury reduction using

Accepted version of the paper: 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 Injury Prevention*, *22*(sup1). https://doi.org/10.1080/15389588.2021.1960319

Link to publisher version: https://www.tandfonline.com/doi/full/10.1080/15389588.2021.1960319

TITLE: Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: estimating the potential for injury reduction using real-world crash modeling

AUTHORS: Cosimo Lucci[1], Trevor Allen[2], Marco Pierini[1] and Giovanni Savino[1,2]

AFFILIATIONS:

1) Dept. of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy
2) Monash University Accident Research Centre, 21 Alliance Ln, Monash University, Victoria, 3800, Australia

CORRESPONDING AUTHOR: Cosimo Lucci – cosimo.lucci@unifi.it

ABSTRACT

Objective: *Recent field-tests on Motorcycle Autonomous Emergency Braking system (MAEB) showed that higher levels of deceleration to improve its effectiveness were feasible. However, the potential of MAEB in mitigating rider injuries is not well understood, particularly in scenarios where the efficacy of standard MAEB is limited because the rider is manually braking. The purpose of this study was first, to assess the injury mitigation potential of MAEB and second, to test MAEB as an enhanced braking system applied in circumstances where the rider is braking before a crash.*

Methods: *Data from previously investigated motorcycle injury crashes that occurred on public roads in Victoria, Australia were reconstructed using a 2D model. The intervention of MAEB was applied in the simulations to test both MAEB standard and MAEB working as enhanced braking system. The effects of MAEB in mitigating crashes were separated by crash configuration and evaluated based on the modelled reductions in impact speed and injury risk, employing injury risk functions available in the literature.*

Results: *After modelling was applied, MAEB was found to be applicable in 30 cases (91% of those in which was estimated as "possibly applicable"). The modelled Impact Speed Reduction (ISR) among the 30 cases averaged 5.0 km/h. In the cases without manual braking, the mean ISR due to standard MAEB was 7.1 km/h, whereas the relative injury risk reduction ranged from 10% for MAIS2+ to 22% for fatal injuries. In the 14 cases with manual braking, the modelled application of MAEB as enhanced braking led to an average ISR ranging from 5.3 km/h to 7.3 km/h. This resulted in an injury risk reduction ranging from 9% to 12% for MAIS2+ and from 16% to 21% for fatal injuries, depending on the different modes of MAEB.*

Conclusions: *This study modelled the potential benefits of the highest levels of intervention for MAEB field-tested to date. The findings estimate the degree to which MAEB could mitigate motorcycle crashes and reduce injury risks for motorcyclists. New strategies for MAEB intervention as enhanced braking were modelled through crash simulations, and suggest improvements in the benefits of MAEB when riders are braking before the crash. This highlighted the requirement to perform new field-based tests to assess the feasibility of MAEB deployed as enhanced braking system.*

KEYWORDS*:* Motorcycle, Active safety, Autonomous emergency braking (AEB), Enhanced braking, Crash reconstruction, Benefits estimation.

Introduction

Assessing the potential benefits of technologies that are yet to be introduced or are in pre-release stages is a significant challenge for researchers. While estimations can be executed by employing forecasting models or simulations, the challenge is greater when we want to assess the impact of safety systems for road vehicles. This is due to a lack of data recorded in crashes involving vehicles provided with the technology, making retrospective assessments not possible. Assessing the benefits and disadvantages of active safety systems such as Motorcycle Autonomous Emergency Braking (MAEB) is crucial before such systems can be considered for introducing into new vehicles. This includes identifying the types of crashes in which the system is intended to intervene and assessing the outcome of those crashes with the technology implemented. As for Autonomous Emergency Braking (AEB) for cars (Fildes et al. 2015), MAEB is a technology capable of reducing pre-crash speed by applying autonomously a braking force on Powered-Two-Wheelers (PTW). The effect of autonomous braking can also be evaluated through a reduction in the severity of crashes rather than the total elimination of the crash. The intervention of MAEB has been field-tested in straight-line riding conditions and with low decelerations deployed as an unexpected intervention with common riders (Savino et al. 2020). More recently, new field tests suggested that MAEB could be applicable with higher levels of braking intervention and not only in straight-line riding (Lucci et al. 2020; Lucci, Marra, et al. 2021; Merkel et al. 2018). These identified improvements in the applicability of MAEB, mean that its benefits could be higher than those estimated in previous simulation studies (Piantini et al. 2019; Savino et al. 2016; Savino and Piantini 2019). Moreover, studies focusing on crash investigations highlighted that only half of the riders are able to brake before a crash (Penumaka et al. 2014). MAEB was designed in the past to perform a fixed level of deceleration to be handled by a rider that is unaware of the automatic intervention. Such level of deceleration was identified regardless of the amount of manual braking by the rider. In manual braking conditions, the rider's action may produce a deceleration that is close to or even higher than that produced by the automatic action. In such cases MAEB efficacy may be much lower. A second consideration is that excessive automatic braking action applied by MAEB during a manual braking could introduce unintentional hazards for the rider. Therefore, a strategy to optimize MAEB effectiveness when the rider brakes manually in pre-crash conditions would improve its potential benefits in these conditions. These conditions however remain untested in terms of rider's acceptability.

The goal of this study was to assess the potential benefits of MAEB in terms of speed and injury reductions, and, in cases where the rider is braking before a crash, to test two new functions of MAEB as enhanced braking. The MAEB benefits will be evaluated using retrospective data from real-world crash investigation of motorbike crashes that occurred on public roads in Australia, employing the latest working parameters field-tested and considered feasible so far.

Methods

The method was based on a previous study focused on assessing the effectiveness of MAEB (Savino et al. 2016): first, a set of cases characterized by different crash configurations (also called Definitions for Classifying Accidents (DCA) according to VicRoads classification (VicRoads 2013)) were extracted from an in-depth Australian database of motorcycle crashes. Cases were reconstructed using a 2D reconstruction model based in Matlab-Simulink environment. The intervention of MAEB was then simulated with different working parameters and types of intervention with functions of Enhanced Braking. The simulated effects of MAEB were evaluated through impact speed reduction. Finally, these speed reductions were used to estimate effects of MAEB in reducing injuries through injury risk functions published in the literature (Ding et al. 2019).

Crash configurations and data source

Based on the results of previous studies (Savino et al. 2019; Terranova et al. 2020) a set of crash configurations were identified (using DCA codes). MAEB was recently tested in lateral maneuvers including lane-change reproducing a swerve before a crash (Lucci, Baldanzini, et al. 2021), and identified as “possibly applicable”. For each crash configuration in which MAEB was considered applicable, a minimum of two cases (when available) were extracted from a database of motorcycle crashes in Australia. The database includes 235 cases involving a non-fatal motorcycle injury crash occurring on a public road in Victoria, Australia, between 2012 and 2014 (Allen et al. 2016; Day et al. 2013). The following criteria were used to achieve a representative sample of crashes where MAEB was considered possibly applicable: i) all crash configurations in the database identified as “possibly applicable” to MAEB (as defined by previously published studies) should be represented in the reconstructions; ii) the number of cases reconstructed for each crash configuration (DCA) should be matched as close as possible to their prevalence/proportion in crash database. For rare crash configurations, this meant only one case reconstruction (and often only one available crash of that configuration); and iii) PTW speeds of cases included in the reconstructions should be representative of speeds seen for each configuration (see Table 1). Cases involving the following crash configuration types were identified as possibly applicable: vehicles from adjacent directions (DCA 110, 111, and 113), vehicles from opposing directions (DCA 120 and 121), vehicles from same direction - rear-end (DCA 130,132,134, and137), maneuvering (DCA 140,147, and 148), overtaking (DCA 150 and 151) and on path crashes involving parked vehicle or animal (160 and 167). While the intention was to analyze at least two cases per crash configuration, only one case was available for some configurations (n=7) due to either a low prevalence of that crash type or insufficient cases with required detail about travel speed. The list of cases by crash configurations is displayed in Table 1, while in the Appendix the representation by VicRoads (VicRoads 2013) of the included crash configurations is displayed. For each crash configuration, the cases were controlled to have mean crash speed and ISS score close to the mean values within the database. In addition, the cases were controlled to have a similar proportion between cases with manual braking and cases without manual braking before the crash compared with the proportion in MICIMS database, which was respectively, 50.5% and 49.5%.

Table 1 - Summary table of cases by crash configuration; refer to table A1 in the appendix for detailed classification separated by DCA

		Cases		**Average crash speed [km/h]**		**Average ISS**	
Crash description	**DCAs**	**Reconstructed**	**% of database**	**Reconstructed cases**	**All cases**	**Reconstructed cases**	**All cases**
Vehicles from adjacent directions	110, 111, 113 and 116	10	23.8	56.9	58.7	10.4	9.3
Vehicles from opposing directions	120 and 121	5	12.5	60.2	61.8	8.4	8.7
Vehicles from same direction - rear-end	130, 132, 134 and 137	6	26.1	69.5	55.9	8.5	9.4
Maneuvering	140, 147 and 148	5	38.5	70.2	65.2	12.4	11.0
Overtaking	151and 152	2	66.7	43.0	42.0	11.0	9.0
On path crashes involving parked vehicle or animal	160 and 167	5	45.5	65.5	48.3	7.8	8.4

Crash reconstruction model

Based on the crash information collected in the MICIMS database by crash investigators, the last three seconds of trajectories of both PTWs and opponent vehicles involved in the crashes were reconstructed in a 2D model built in Matlab-Simulink environment using a dedicated tool developed in a previous study (Savino et al. 2016). The reconstruction included the trajectories and maneuvers (namely, manual braking action, avoidance actions/swerve, and possible fall of the PTW before the crash) of the two vehicles and details of the crash scenario (namely, road surface adherence, heading angle between vehicle, etc.). Once the crashes were reconstructed, the model was reviewed to ensure its coherence with the crash reconstruction made by crash investigators. The obstacle detection system was set with a field of view of 70 degrees in the frontal part of the PTW with a range of detection of 30 m. The triggering algorithm for MAEB was based on the unavoidable collision state, which has been used in previous studies when the crash is assessed as physically unavoidable (Savino et al. 2015). The triggering algorithm employed in this study was the same for all the cases and generated different trigger time based on the different crash configurations and relative positions of the two vehicles involved in the crash (see Figure A1 in the appendix). We employed an early trigger strategy based on the abilities of common riders (Savino and Piantini 2019).

MAEB function definitions

The intervention of MAEB system was tested in previous studies through both field tests and simulations (Savino et al. 2020). In the most recent studies, MAEB interventions was designed to work with the so-called "Block profile", which is a constant deceleration time achieved through a constant fade-in jerk (Merkel et al. 2018). Based on results of new field tests which validated new riding conditions and higher levels of intervention (Lucci et al. 2020; Marra et al. 2021), 0.5 g of deceleration reached with 2 g/s fade-in jerk were employed in this study as working parameters to simulate MAEB intervention. The limit for the inhibition of MAEB in leaning condition was set in the simulations at 25° of PTW roll (Lucci, Baldanzini, et al. 2021).

The interaction between manual braking executed by riders and the automatic braking deployed by MAEB has been tested in previous studies using two functions. The first one is the MAEB standard, which applies a target value of deceleration as long as the manual braking deceleration is lower, and when the rider performs a manual deceleration higher than the MAEB target the PTW brakes with the manual value. Another type of MAEB function tested in previous studies is the so-called "Enhanced Braking" (EB), which deploys a maximum braking deceleration (e.g. 1 g) when the unavoidable condition is reached and the rider achieves a threshold in terms of manual braking pressure. This represents the theoretical limit of intervention for MAEB. In this study, we propose and test via simulations two new modes of MAEB intervention to enhance the effectiveness of MAEB in the cases where the rider is performing manual braking before the crash. The first mode of intervention is called "MAEB enhanced": the target automatic deceleration is increased in proportion of the intensity of the manual braking deceleration (proportional to the manual braking pressure) executed by the rider to obtain a higher target MAEB deceleration. The higher the manual braking deceleration, the higher the target deceleration for MAEB when it is deployed after the unavoidable crash condition is reached. The second mode of MAEB is called "MAEB + manual": the target value of automatic deceleration is added to the manual braking deceleration to define the target MAEB deceleration. An example of the different MAEB functions and the correlations to determine MAEB target deceleration is displayed in Figure 1.

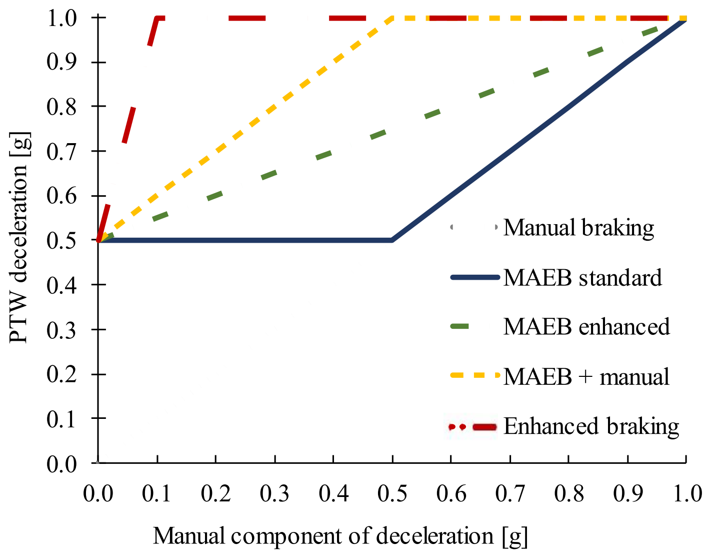

Figure 1 - Correlations to define MAEB target deceleration as used in modelling MAEB intervention. (Example for 0.5 g MAEB target deceleration)

Injury risk assessment

Once the crash speed was calculated with the different MAEB modes, the potential effects in reducing injuries were estimated using injury risk functions published in the literature (Ding et al. 2019). These functions allowed us to evaluate the injury risk for each type of injury reported in the literature (MAIS 2+, MAIS 3+ and FATAL). The injury risk was evaluated based on relative crash speed for crashes against passenger cars or fixed obstacles and based on the crash speed in ground-impact crashes. For each test case, four parameters were required to assess the injury risk: i) point of impact (if PTW frontal or lateral impact with opponent vehicle); ii) crash opponent: (if crash opponent was passenger car or ground); iii) driver impact (if motorcyclist impacted the opponent with directional change or not; and vi) stability conditions (whether PTW was stable or not before the crash).

The absolute injury risk reduction was therefore assessed evaluating the injury risk for each type of injury reported in the literature (MAIS2+, MAIS3+ and FATAL) based on the reduced crash speed output of the intervention of the four modes of intervention of MAEB and compared with the reference crash speed without any MAEB intervention. Moreover, for each case, a relative injury risk reduction was calculated as the ratio between the absolute injury risk reduction and the absolute injury risk in the reference case.

Results

MAEB applicability

Crash scenarios included in this study that were judged as “possibly applicable” for MAEB represented 53% of all cases in the MICIMS database, whereas 3% of the cases were considered as “unlikely applicable” and 44% “not applicable”. The latter include for example single-vehicle crashes, rear-end crashes in which the PTW is hit from behind and all those crash configurations in which the detection system of the host PTW is not able to detect the opponent vehicle/object and therefore cannot deploy anonymously the braking force as the crash is recognized as inevitable. Overall, 33 MICIMS cases of crashes involving one PTW which was considered as "host vehicle for MAEB" and a second vehicle (generally passenger car) or obstacle considered as "opponent vehicle" were reconstructed employing the 2D simulation model. The whole list of cases is provided in the Appendix.

Three of the included cases were found to be not applicable to MAEB. In the first case (DCA 110), due to a very small relative speed among the involved vehicles, the inevitable collision state occurred too close to the crash for MAEB to trigger. In the second case (DCA 116), due to the crash configuration, the opponent vehicle resulted to be out of the field of view of the obstacle detection system. In a third case, MAEB was not triggered (DCA 134) because the impact was mainly lateral with the two vehicles travelling at a similar speed. In these cases, MAEB was considered not applicable and they were therefore excluded from the following analysis.

Among the 30 cases in which MAEB was possibly applicable, in 14 cases the rider reported they performed manual braking before the crash, while in 16 cases the rider reported not being able to perform any braking action. This proportion is similar to that reported previously (Penumaka et al. 2014). The mean time to the collision at MAEB trigger, which represents the inevitable-collision state, was similar among these two groups: manual braking 0.51 s (SD 0.139 s) and 0.53 s (SD 0.111 s) for cases without manual braking action. Among the different crash configurations, the distribution of time to the collision was homogeneous.

MAEB Standard mode

Among the 30 cases in which MAEB was judged as applicable, the Impact Speed Reduction at the crash (ISR) was evaluated using the crash reconstruction both without the intervention of MAEB and with the intervention of MAEB in the standard mode. The ISR was noticeably different among the two groups of cases (manual braking vs no manual braking). In the manual braking cases, the mean speed reduction was 2.5 km/h (SD 2.4 km/h) whereas in the cases without manual braking action it was 7.1 km/h (SD 1.9 km/h). Overall, the impact speed reduction was 5.0 km/h (SD 3.1 km/h).

The impact speed reduction was not strongly associated with the PTW travel speed before the crash (r=0.12) nor impact speed (r=0.38).

For the group of cases without manual braking, the impact speed reduction was similar among the different crash configurations (see Figure 2), as a result of a similar time to the collision at MAEB trigger (see Figure A1). Higher variability was found in the manual braking cases.

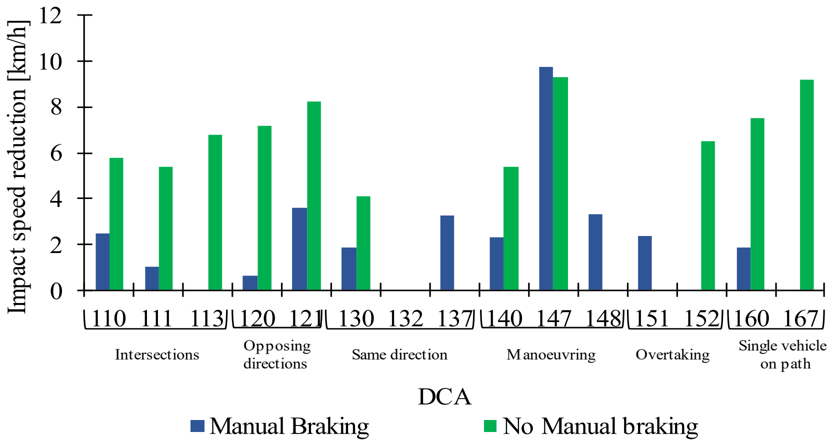

Figure 2 – Mean impact speed reduction achieved by MAEB standard mode: distributed by crash configuration. Crashes separated by the presence of manual braking (blue) and no manual braking (green).

MAEB Enhanced mode

The group of 14 cases in which MAEB was considered applicable and the rider performed manual braking was employed also to test MAEB with three additional modes of intervention: for each mode, the same settings were adopted (triggering time, fade-in jerk, inhibition roll, obstacle detection system) except the target deceleration of MAEB, which was varied following the criteria displayed in the methods section.

Table 2 – Effects of MAEB modes (subsample of 14 manual braking cases)

MAEB modes	PTW pre-crash deceleration [g]		Automatic Braking duration [s]		Impact Speed Reduction [km/h]	
	Mean	SD	Mean	SD	Mean	SD
Ref - No MAEB	0.38	0.126	-	-	0.0	0.00
MAEB standard	0.50	0.004	0.51	0.139	2.5	2.40
MAEB enhanced	0.66	0.089	0.52	0.146	5.3	2.21
MAEB + manual	0.79	0.169	0.54	0.154	7.3	3.13
Enhanced Braking	0.85	0.138	0.57	0.177	10.5	5.33

Table 2 shows the mean deceleration reached in the 14 cases by the different modes of MAEB applied. The mean deceleration obtained through only manual braking reached 0.38g and with the standard MAEB mode, the target value of 0.5g was reached in all the cases. For “MAEB enhanced” mode the PTW deceleration at crash increased by 32%, whereas with the “MAEB + manual” mode and “Enhanced Braking” mode deceleration increased by 58% and 70% respectively. However, with this last mode, the MAEB deceleration was obtained reaching the adherence limits in all the cases, which ranged from 0.5g in wet or slippery road surface to 1g in ideal road conditions.

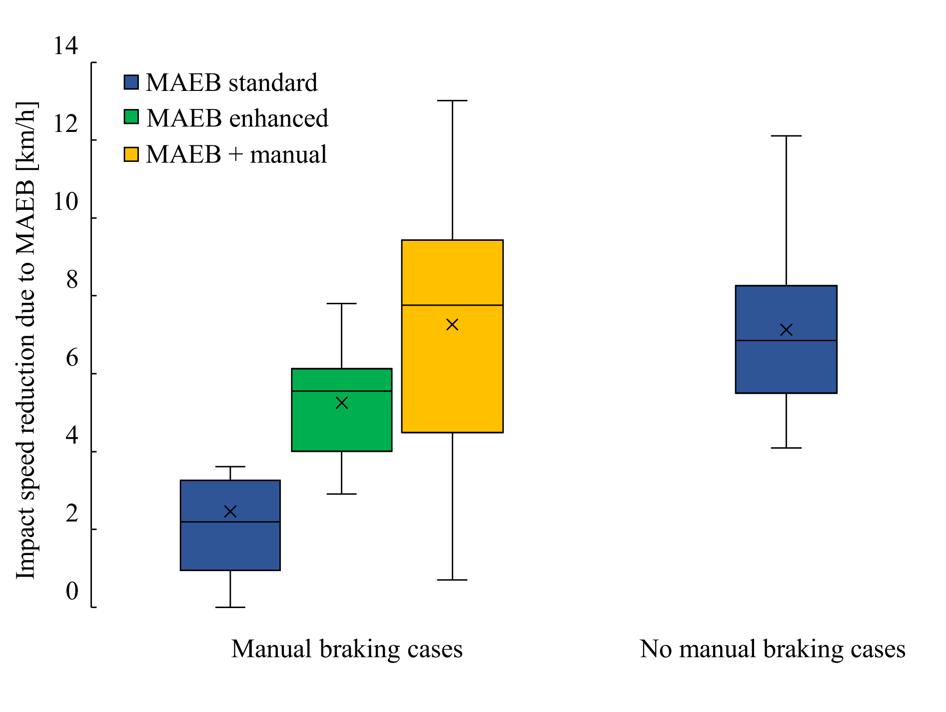

Figure 3 – Comparison of impact speed reduction due to MAEB by intervention mode.

The duration of the automatic braking was similar among the different modes of MAEB intervention. The small variations were due to the different decelerations reached by the PTW before the crash and therefore a smaller speed and a longer time to impact before the crash. In terms of impact speed reduction, the “MAEB enhanced” mode reached on average an increase of around 112% compared to the standard MAEB. Higher impact speed reductions were obtained by “MAEB +manual” mode (+ 192%) and “Enhanced Braking” mode (+ 320%), which reached the highest level. Figure 3 shows the comparison between the ISR obtained when the rider did not perform any manual braking actions before the crash with the cases in which the rider braked.

Injury reduction

Table 3 shows estimations of the mean absolute and relative injury risk reduction calculated with the injury functions obtained from a recent publication (Ding et al. 2019) for the three types of injury (MAIS2+, MAIS3+ and FATAL).

Overall, the higher absolute injury risk reduction was obtained for the least severe injury risk (MAIS2+), which, however, resulted in the lowest relative injury risk reduction due to the higher probability to sustain MAIS2+ injuries compared with more severe injuries.

Among the cases without manual braking action before the crash, the relative injury risk reduction obtained through the application of MAEB in the standard mode ranged from 10% to 22%. In the cases in which the rider was not able to brake before the crash, the MAEB standard resulted in the lowest injury risk reductions, due to the limited additional deceleration provided by MAEB intervention. Similarly with ISR, the injury risk reduction for every level of severity of injuries increased with the enhanced modes of MAEB intervention, reaching values of relative injury risk reduction ranging from 9% to 16% and 12% to 21% for the “MAEB enhanced” mode and “MAEB + manual” respectively.

Table 3 - Injury risk reduction

Sample	MAEB mode	Absolute Injury Risk reduction [%]			Relative Injury Risk reduction [%]		
		MAIS2+	MAIS3+	FATAL*	MAIS2+	MAIS3+	FATAL*
No manual braking cases (16)	MAEB standard	4.4	2.4	0.5	10	13	22
Manual braking cases (14)	MAEB standard	1.7	0.7	0.1	4	5	8
	MAEB enhanced	3.4	1.5	0.2	9	10	16
	MAEB + manual	4.5	1.9	0.3	12	14	22
	Enhanced Braking	6.4	2.7	0.4	17	19	29

* Estimations of fatal injury risk are based on cases involving non-fatal injury.

Discussion

This is the first paper to estimate the potential injury risk benefits of MAEB by applying injury risk functions recently published by others (Ding et al. 2019) as well as estimating Impact Speed Reduction (ISR). Thirty-three real-world motorcycle injury crashes from an in-depth Australian database were selected among 132 cases in which the Motorcycle Autonomous Emergency Braking (MAEB) was expected to be “possibly applicable”. Each case was reconstructed with a 2D simulation model and employed to estimate MAEB system benefits. In 30 out of 33 cases MAEB resulted to be applicable. It is worth noting that among the entire database considered for this study (Day et al. 2013), MAEB was estimated to be possibly applicable in about half (53%) of all crashes.

In the group of cases without manual braking (n=16), the estimated ISR provided by standard MAEB was relatively higher (average 7.1 km/h) than the mean ISR achieved in all the cases and did not appear to be influenced by the crash configurations. In contrast, for cases involving manual braking (n=14), the estimated speed reduction was lower (average 2.5 km/h) and there was greater variability between these cases, mainly due to the different levels of manual braking deceleration. However, the application of the two new strategies of MAEB intervention as enhanced braking simulated in this paper allowed to obtain, respectively, 5.3 km/h and 7.3 km/h of ISR. This suggests that the enhanced braking version of MAEB was able to compensate to some extent for the lower effectiveness of standard MAEB for those crashes where the rider has been able to brake before the crash. This indicates that meaningful benefits of MAEB can be achieved for applicable crash configurations regardless of whether the rider was able to brake or not.

With the hypothesis that all the variables influence a crash in the same way (with or without the presence of MAEB), we supposed that for a specific crash an injury risk curve could be applied based on relative speed (i.e. the change in speed would not significantly change the crash configuration). This allowed us to estimate the injury risk reduction based on the estimated ISR produced by MAEB. The results highlight that standard MAEB in cases involving no-manual braking could bring a reduction from 10% to 22% of the relative risk to sustain, respectively, MAIS2+ to fatal injuries. This suggests that MAEB could prevent around 20% of the fatalities in the cases in which the system is applicable. However, this represents a smaller reduction in terms of absolute injury risk (ranging from 4.4% for MAIS2+ to 0.5% for fatal injuries). For this reason, we must consider that if MAEB interferes with undesired side effects eventually leading to a fatal crash in 0.5% of the cases in which it intervenes, all its benefits are nullified. MAEB intervention must be proved to be safe in at least 99.95% of cases in which it is triggered. In a recent field test campaign, MAEB did not provoke any loss of control in more than 1000 activations (Marra et al. 2021). More details regarding the relationship between relative injury risk reduction and impact speed reduction are provided in the appendix.

Similarly to what was obtained in terms of ISR, for “MAEB enhanced” and “MAEB+manual” modes, the injury reduction of MAEB in the manual braking cases were comparable with those of the standard MAEB mode in cases involving no-manual braking. This suggests that these modes can make MAEB effective even when riders are able to brake before the crash. However, since different modes of MAEB intervention could differently influence its acceptability among end-users, new field tests are required to assess the feasibility of these enhanced functions of MAEB. These tests should determine the applicability of MAEB and its enhanced modes of intervention in manual-braking conditions, which are relevant conditions for safety and controllability of the vehicle in pre-crash situations.

The approach used in this study presents some limitations which should be considered. The first limitations are related to missing information from rider questionnaire or site inspection contained in the crash database, and to possible crash investigators misjudgments due to the time delays between the crash and scene inspection. Another limitation is due to the crash reconstruction modelling, which is a two-dimensional model which cannot consider complex dynamics of the vehicles. These limitations, which are an unavoidable result of this approach, were nevertheless mitigated through an in-depth analysis of cases and model reconstruction made by authors. However, we could not determine whether the cases used for reconstruction were representative of all crashes with respect to the level of manual braking applied by the rider. In previous studies, the major limitation was to estimate MAEB effects only in terms of vehicle dynamic parameters (as impact speed reduction), which cannot be easily translated into benefits for riders (Savino et al. 2016). Despite new possible biases related to injury risk function estimation already reported by the authors of the study we employed (Ding et al. 2019), this paper overcomes the main limitation of previous studies presenting MAEB benefits in terms of injury risk reduction.

This paper for the first time estimated the potential benefits of MAEB in terms of injury risk reduction using the highest MAEB levels of intervention field-tested so far. Our findings highlight how much promise this technology has in mitigating serious injury PTW crashes. Two new strategies of intervention for MAEB as enhanced braking were also proposed and tested through crash simulations. The results support the idea that these MAEB strategies could also provide benefits when riders have been able to brake before the crash. In the future, new field tests are required to assess the applicability and acceptability among end-users of these new MAEB functions in real-world conditions.

Acknowledgement

The authors would like to acknowledge Jude Charlton and Jennie Oxley for their support and valuable mentoring in this study. The MICIMS study was funded by the Australian Research Council (LP110100057), VicRoads, the Transport Accident Commission of Victoria, and the Victorian Government Department of Justice with in-kind support from Victoria Police, the Victorian Automobile Chamber of Commerce and Ambulance Victoria.

Disclosure statement: All authors have read and agreed to the submitted version of the manuscript. The authors declare no conflict of interest.

Data availability statement: “Data available on request from the authors”

References

Allen T, McClure R, Newstead S V., Lenné MG, Hillard P, Symmons M, Day L. Exposure factors of Victoria's active motorcycle fleet related to serious injury crash risk. *Traffic Inj. Prev.* 2016;17(8):870–877.

Day L, Lenné MG, Symmons M, Hillard P, Newstead S, Allen T, McClure R. Population based case-control study of serious non-fatal motorcycle crashes. *BMC Public Health*. 2013;13(1).

Ding C, Rizzi M, Strandroth J, Sander U, Lubbe N. Motorcyclist injury risk as a function of real-life crash speed and other contributing factors. *Accid. Anal. Prev.* 2019;123(June 2018):374–386. Available at: https://doi.org/10.1016/j.aap.2018.12.010.

Fildes B, Keall M, Bos N, Lie A, Page Y, Pastor C, Pennisi L, Rizzi M, Thomas P, Tingvall C. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. *Accid. Anal. Prev.* 2015;81:24–29. Available at: http://dx.doi.org/10.1016/j.aap.2015.03.029.

Lucci C, Baldanzini N, Savino G. Field testing the applicability of motorcycle autonomous emergency braking (MAEB) during pre-crash avoidance manoeuvre. *Traffic Inj. Prev.* 2021;22(3). Available at: https://www.tandfonline.com/doi/full/10.1080/15389588.2021.1884235.

Lucci C, Huertas-Leyva P, Marra M, Pierini M, Savino G, Baldanzini N. Autonomous Emergency Braking system for Powered-Two-Wheelers: testing end-user acceptability of unexpected automated braking events deployed in typical pre-crash trajectories. In: *13th International Motorcycle Conference (IFZ)*. Cologne, Germany; 2020:12. Available at: https://www.ifz.de/imc-2020-sessions/.

Lucci C, Marra M, Huertas-Leyva P, Baldanzini N, Savino G. Investigating the feasibility of Motorcycle Autonomous Emergency Braking (MAEB): design criteria for new experiments to field test automatic braking. *MethodsX*. 2021;8:101225. Available at: https://linkinghub.elsevier.com/retrieve/pii/S2215016121000182.

Marra M, Lucci C, Huertas-Leyva P, Baldanzini N, Pierini M, Savino G. The future of the Autonomous Emergency Braking for Powered-Two-Wheelers: field testing end-users' acceptability in realistic riding manoeuvres. *IOP Conf. Ser. Mater. Sci. Eng.* 2021;1038(012016):11. Available at: https://iopscience.iop.org/article/10.1088/1757-899X/1038/1/012016.

Merkel N, Pless R, Scheid K, Winner H. Limits of Autonomous Emergency Brake Systems for Powered Two-Wheelers – an Expert Study. In: *12th International Motorcycle Conference (IFZ)*. Cologne, Germany; 2018:122–144.

Penumaka AP, Savino G, Baldanzini N, Pierini M. In-depth investigations of PTW-car accidents caused by human errors. *Saf. Sci.* 2014;68(October):212–221.

Piantini S, Bourdet N, Savino G, Rosalie S, Pierini M, Deck C, Willinger R. Potential head injury mitigation of M-AEB in real-world motorcycle crashes. *Int. J. Crashworthiness*. 2019;0(0):1–11. Available at: https://doi.org/10.1080/13588265.2019.1626531.

Savino G, Brown J, Rizzi M, Pierini M, Fitzharris M. Triggering algorithm based on inevitable collision states for autonomous emergency braking (AEB) in motorcycle-to-car crashes. In: *IEEE Intelligent Vehicles Symposium, Proceedings*.Vol 2015-Augus. Seoul, Korea; 2015:1195–1200.

Savino G, Lot R, Massaro M, Rizzi M, Symeonidis I, Will S, Brown J. Active safety systems for powered two-wheelers: A systematic review. *Traffic Inj. Prev.* 2020;21(1):78–86. Available at: https://www.tandfonline.com/doi/full/10.1080/15389588.2019.1700408.

Savino G, Mackenzie J, Allen T, Baldock M, Brown J, Fitzharris M. A robust estimation of the effects of motorcycle autonomous emergency braking (MAEB) based on in-depth crashes in Australia. *Traffic Inj. Prev.* 2016;17:66–72.

Savino G, Piantini S. 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; 2019:550–551.

Savino G, Pierini M, Fitzharris M. Motorcycle active safety systems: Assessment of the function and applicability using a population-based crash data set. *Traffic Inj. Prev.* 2019;20(4):406–412. Available at: https://doi.org/10.1080/15389588.2019.1594795.

Terranova P, Dean M, Gabler HC, Piantini S, Savino G. Active safety systems for motorcycles : where are we ? A novel transnational comparison of applicability in the Australian, American and Italian fleets. In: *AAAM Student Symposium*. Portland, Oregon Active; 2020:2018–2020.

VicRoads. *Crashstats user guide - Road Crash Statistics Victoria*. Melbourne; 2013.

TITLE: Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: estimating the potential for injury reduction using real-world crash modeling

AUTHORS: Cosimo Lucci[1], Trevor Allen[2], Marco Pierini[1] and Giovanni Savino[1,2]

AFFILIATIONS:

1) Dept. of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy
2) Monash University Accident Research Centre, 21 Alliance Ln, Monash University, Victoria, 3800, Australia

CORRESPONDING AUTHOR: Cosimo Lucci – cosimo.lucci@unifi.it

Appendix

Table A1 – Summary table of cases by crash configuration separated by DCA (Definition for Classifying Accidents)

			Cases		Average crash speed [km/h]		Average ISS	
Crash configuration	**DCA**	**Crash description**	**Reconstructed**	**% of database**	**Reconstructed cases**	**All cases**	**Reconstructed cases**	**All cases**
Vehicles from adjacent directions	**110**	Cross Traffic	3	14	62.0	55.7	12.0	9.5
	111	Right far	3	43	53.1	55.7	12.3	11.1
	113	Right near	3	25	59.5	66.5	8.7	8.8
	116	Left near	1	50	45.0	53.1	5.0	4.5
Vehicles from opposing directions	**120**	Head on	2	50	56.3	56.3	7.0	7.8
	121	Right thru	3	8	62.8	62.4	9.3	8.8
Vehicles from same direction - rear-end	**130**	Rear end	3	20	70.1	52.2	10.3	8.8
	132	Right end	1	100	93.5	93.5	5.0	5.0
	134	Lane change right	1	20	71.0	63.7	10.0	14.6
	137	Left turn side swipe	1	50	42.3	45.3	5.0	3.0
Maneuvering	**140**	U turn	2	22	71.3	66.8	7.0	10.0
	147	Emerging from driveway/lane	2	67	62.5	54.2	9.0	7.7
	148	From footway	1	100	83.5	83.5	30.0	30.0
Overtaking	**151**	Out of control	1	50	46.0	46.0	5.0	5.0
	152	Pulling out	1	100	40.0	40.0	17.0	17.0
On path crashes involving parked vehicle or animal	**160**	Parked	2	100	38.8	38.8	10.0	10.0
	167	Animal (not ridden)	3	33	83.3	93.4	6.3	8.0

Table A2 – List of crash configurations (DCA) included in the study modified from (VicRoads 2013)

Vehicles from adjacent directions (intersections only)	Vehicles from opposing directions	Vehicles from same direction	Manoeuvring	Overtaking	On path
CROSS TRAFFIC 110	1 – Wrong side 2 - other HEAD ON (NOT OVERTAKING) 120	VEHICLES IN SAME LANES REAR END 130	U TURN 140	OUT OF CONTROL 151	PARKED 160
RIGHT FAR 111	RIGHT THRU 121	RIGHT END 132	EMERGING FROM DRIVEWAY/LANE 147	PULLING OUT 152	ANIMAL (NOT RIDDEN) 167
RIGHT NEAR 113		LANE CHANGE RIGHT (NOT OVERTAKING) 134	INC BIKES FROM FOOTWAY 148		
LEFT NEAR 116		LEFT TURN SIDE SWIPE 137			

Table A3 – List of MICIMS cases included in the study

Case number	DCA	PTW DCA	Manual braking	Collision description	N. of vehicles involved	Pre-crash speed [km/h]	Max AIS score	ISS
1	110	2	NO	Bike into car	2	88	3	17
2	110	1	NO	Car into Bike	2	30	3	13
3	110	2	YES	Bike into car	2	68	2	6
4	111	1	YES	Bike into car	2	48	2	9
5	111	1	NO	Bike into car	2	76	3	22
6	111	1	NO	Car into Bike	2	35	3	10
7	113	2	NO	Bike into car	2	65	2	9
8	113	2	NO	Bike into car	2	69	2	8
9	113	2	YES	Bike into car	2	45	3	9
10	116	1	YES	Bike into car	2	45	2	5
11	120	2	NO	Car into Bike	2	66	2	5
12	120	2	YES	Car into Bike	2	47	3	9
13	121	2	NO	Car into Bike	2	64	3	9
14	121	2	YES	Bike into car	2	61	2	5
15	121	2	NO	Car into Bike	2	57	3	14
16	130	1	NO	Bike into car	2	83	2	9
17	130	2	YES	Bike into car	2	48	2	9
18	130	2	YES	Bike into car	2	80	3	13
19	132	1	YES	Bike into Car across road	2	94	2	5
20	134	2	NO	Car into Bike	2	71	3	10
21	137	1	YES	Bike into car	2	42	2	5
22	140	2	YES	Bike into car	2	45	2	5
23	140	1	NO	Bike into car	2	98	3	9
24	147	2	YES	Bike into car	2	71	3	9
25	147	2	NO	Bike into car	3	54	2	9
26	148	2	YES	Bike into car	2	84	5	30
27	151	1	YES	Bike into car - out of control	2	46	2	5
28	152	2	NO	Bike into car	2	40	3	17
29	160	2	YES	Bike into car	2	39	3	10
30	160	1	NO	Bike into car	2	40	2	5
31	167	1	NO	Bike into animal	1	69	3	13
32	167	1	NO	Bike into animal	1	104	2	5
33	167	1	NO	Bike into animal	1	77	1	1

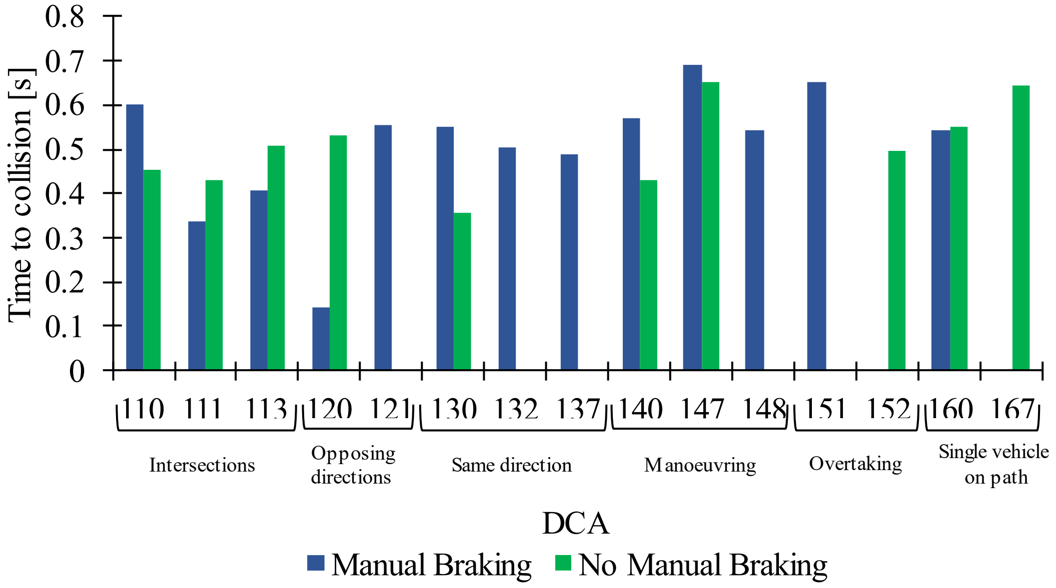

Figure A1 - *Mean time to collision at MAEB trigger distributed by crash configuration. Crashes separated by the presence of manual braking (blue) and no manual braking (green)*

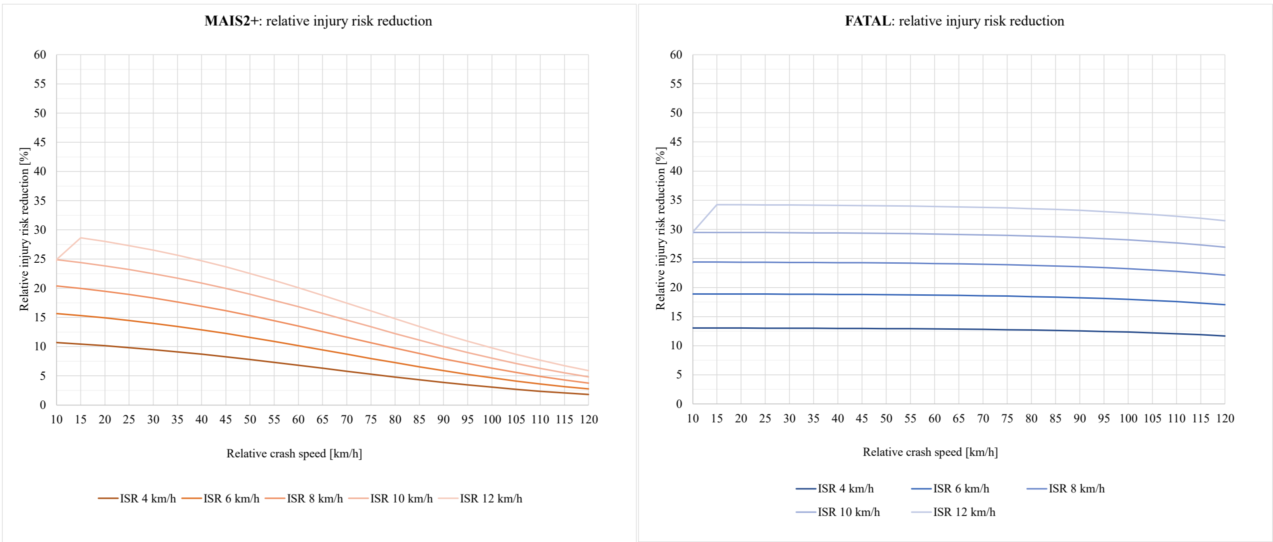

Figure A2 – Relative injury risk reduction for MAIS2+ (left) and FATAL (right) injuries: influence of Impact Speed Reduction (ISR)