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TITLE: Does Motorcycle Autonomous Emergency Braking (MAEB) mitigate rider injuries and fatalities? Design of effective working parameters and field test validation of their acceptability

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HIGHLIGHTS:

- *Autonomous Emergency Braking is a promising safety system to be fitted on motorcycles*
- *Defined methodology to design effective working parameters for this system*
- *Working parameters validated through field tests involving 31 end-users*
- *Impact speed reduction up to 15 km/h, estimated serious injury reduction of 15%*
- *System intervention also feasible during avoidance manoeuvres*

AUTHOR STATEMENT:

Cosimo Lucci: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision. **Giovanni Savino:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Review & Editing, Supervision. **Niccolò Baldanzini:** Conceptualization, Methodology, Investigation, Supervision, Project administration, Funding acquisition.

ABSTRACT

Motorcycle Autonomous Emergency Braking (M-AEB) was shown to be a promising technology to improve Powered-Two-Wheeler (PTW) users safety, deploying autonomously a braking action to reduce impact speed when pre-crash conditions are detected. The applicability of MAEB with effective working parameters still needs to be proved in real-world working conditions. The goal of this paper is to define MAEB working parameters for effective mitigation of injuries and to validate their real-world applicability through field tests in representative riding scenarios of intervention.

The results of previous studies and injury risk functions for motorcyclists were employed to define a set of MAEB working parameters (duration of intervention ≥ 0.60 s, target deceleration of 0.5 g, fade-in jerk of 2 g/s) which enable MAEB impact speed reductions capable of mitigating injuries. Field tests were then carried out involving common riders as participants and employing a test protocol consistent with previous studies. Participants were exposed to Automatic Braking (AB) interventions with two levels of target deceleration (respectively 0.3 g and 0.5 g) in two separate test sessions. The AB interventions were intended to reproduce unexpected MAEB activations in different riding conditions including straight-line riding and lane-change manoeuvres reproducing an avoidance action. The tests were carried out using a sport-touring motorcycle provided with extension arms to prevent capsizing and equipped with an automatic braking system which was activated remotely by researchers.

The thirty-one participants involved in the test experienced AB interventions riding in straight-line and lane-change at a mean speed ranging from 41 km/h to 47 km/h. In the 0.5 g test session, the AB system performed mean deceleration 0.48 g reached with 2.0 g/s fade-in jerk for a duration of around 1.1 s. Both subjective assessment and vehicle data analysis indicated that the participants were consistently able to easily control the vehicle during the automatic braking interventions and were always able to complete the lane-change manoeuvre. Any signal of incipient loss of vehicle control was recorded in on-board videos nor identified in the behaviour and body movement by participants. The tested MAEB working parameters performed speed reductions capable to reduce impact speed up to 15 km/h and serious injuries (MAIS3+) by 15%.

The proposed MAEB working parameters were proved as effective in reducing vehicle speed and feasible from end-users' perspective. The designed MAEB intervention was shown to be applicable in straight line riding and to allow the rider to manoeuvre the vehicle for the execution of avoidance actions.

KEYWORDS: Motorcycle; Active safety; Autonomous emergency braking; Users'acceptability; Injury reduction.

1 Introduction

Motorcycle Autonomous Emergency Braking (M-AEB) is the Powered-Two-Wheeler (PTW) derivative of the AEB (Autonomous Emergency Braking), a system that is available for passenger cars and trucks with proven effectiveness in mitigating crashes (Fildes et al., 2015; Rizzi et al., 2014). This system autonomously deploys a braking force when pre-crash conditions are detected by environmental sensors such as radars and lidars (Gil et al., 2018) to reduce the impact speed of the host vehicle or even prevent crashes. After the introduction of the Antilock Braking System (ABS) (Rizzi et al., 2016, 2013), MAEB was indicated as one of the most promising technologies for improving PTW users' safety (Savino et al., 2020). In a recent multinational analysis, MAEB showed to be possibly applicable in between 47.9% and 78.4% in PTW crashes in developed countries (Terranova et al., 2022). Simulations based on in-depth crash reconstructions of PTW crashes highlighted that it can potentially reduce impact speed in different crash configurations (Savino et al., 2016b). However, to be effective in mitigating PTW user injuries, the pre-crash impact speed of the host vehicle needs to be reduced significantly. In that regard, simulations based on real-world crashes suggested that for reducing head injuries a minimum impact speed reduction of around 8 km/h is required (Piantini et al., 2019). Such impact speed reductions can be obtained through working parameters that increase the intensity of the intervention, making a safe deployment of MAEB more critical due to vehicle controllability. The definition of these working parameters and their acceptability among end-users is still an open issue: previous studies assessed MAEB feasibility in limited circumstances. Studies involving professional riders tested automatic decelerations up to 0.7 g (g indicating the acceleration of gravity) in correspondence with a fixed obstacle (Giovannini et al., 2013) thus not allowing for an unexpected intervention, or a moving target obstacle (namely, a car mock-up trailer) (Merkel et al., 2018), where the level of unexpectedness of MAEB interventions was not discussed. Further studies involved common riders as participants to test without obstacles Automatic Braking (AB) events, which were triggered by an investigator via remote control reproducing unexpected MAEB interventions. In the first test campaign, automated decelerations with peaks up to 0.3 g were tested in straight line riding and considered by participants easy to be managed (Savino et al., 2016c). The following study (Lucci et al., 2021b) focused on the applicability of MAEB during pre-crash avoidance actions with mean decelerations up to 0.3 g, highlighting that the manoeuvrability of the PTW is not limited by the AB intervention and therefore avoidance action is possible. The results of these studies highlighted that MAEB is applicable and easily controlled by common riders with constant decelerations up to 0.3 g. However, early studies based on real-world crash reconstruction, suggested that such MAEB working parameters may not be sufficient to reduce the pre-crash impact speed to lower the chance of sustaining serious or fatal injuries for PTW users (Piantini et al., 2019; Savino et al., 2016b).

In order to make MAEB effective in real-world crashes, higher levels of MAEB intervention (which tests involving professional riders indicated as possibly feasible (Merkel et al., 2018) needs to be employed, by defining new MAEB working parameters. These parameters have nevertheless to cope with common riders' acceptability and guarantee safe vehicle controllability and manoeuvrability, which must be proved through field tests.

The goal of this paper is to identify MAEB working parameters which could make it effective in mitigating serious and fatal injuries of PTW crashes, and to validate their feasibility and acceptability among end-users through field testing in conditions representative of real-world scenarios of intervention.

2 Methods

2.1 Definition of MAEB

The results of previous studies indicated that the intervention of MAEB can be effectively deployed employing the so-called “Block profile” as deceleration profile (Merkel et al., 2018). It consists of a constant deceleration time segment achieved through a constant fade-in jerk (see Figure 1). This deceleration profile resulted more suitable than ramp or peak profiles as it combines good acceptance by riders, good performances in terms of speed reduction over a given time frame and a given maximum deceleration, and easiness of implementation.

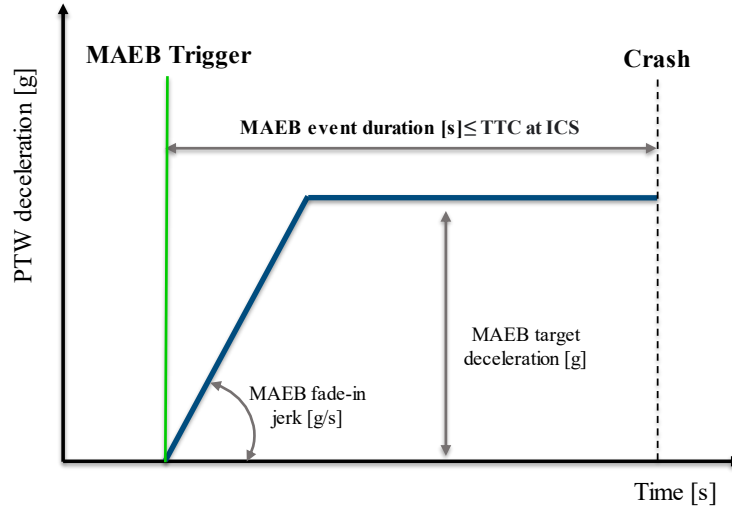


Figure 1 – Block profile for MAEB deceleration

Based on the selected profile of deceleration, the intervention of MAEB is defined by three parameters: the duration of the intervention, which is related to the time to collision at which MAEB is triggered, in the assumption that the intervention ends with the crash; the target deceleration value; and the fade-in jerk, being the deceleration rate employed in the initial fade-in ramp of deceleration (see Figure 1).

An estimate of the duration of MAEB intervention is linked to the Time To Collision at deployment (TTC) with the following formula:

$$T_{MAEB} = \frac{V_{ICS} - \sqrt{V_{ICS}^2 - 2 \times AB_{decel} \times (TTC - T_{AB}) \times V_{ICS}}}{AB_{decel}}$$

where V_{ICS} is the PTW speed at Inevitable Collision State (ICS), AB_{decel} is the MAEB target deceleration and T_{AB} is the time required by MAEB to deploy the braking action after the recognition of ICS. This formula provides a good estimation of T_{MAEB} under the assumption of no braking action in pre-crash conditions and fade-in jerk time being a small fraction of TTC, or ISR being a small fraction of V_{ICS} . Both conditions are typically fulfilled in MAEB applications.

This duration depends on the strategy selected for the system to trigger MAEB intervention: earlier deployment leads to longer time of intervention. One critical design choice is to define whether to allow the intervention of the system when the collision is still avoidable, and the rider may still in control of the situation, or only after the collision has become physically unavoidable. In the first case, durations of intervention (and TTC) may be longer with larger effects, but MAEB acceptability for end-users becomes more critical. In fact, riders

were found to be against systems that may take over the vehicle control (Beanland et al., 2013). In addition, in those critical situations where the rider may still control the motorcycle to avoid the crash, any intervention of MAEB could jeopardize vehicle controllability and stability, thus introducing unnecessary additional risks for the rider. On the other hand, if MAEB is deployed after the crash has become physically unavoidable, its efficacy is limited due to the short TTC at triggering, which constrains the overall time of intervention till the collision. In previous evaluation studies, MAEB was supposed to trigger when the Inevitable Collision State (ICS) is reached: this represents the condition at which the crash is considered unavoidable and therefore defines the maximum possible duration of the MAEB intervention (Savino et al., 2016a). Based on this “last resort” strategy of intervention, a different threshold for the parameters employed to estimate the ICS condition can be used. For instance, the threshold of longitudinal deceleration, in real-world conditions can be assumed lower than the reference 1g physical limit (Cossalter et al., 2004) if the rider is not able to achieve such value of deceleration. In particular, field tests highlighted that many riders in emergency braking are not able to reach more than 0.7 g decelerations (Huertas-Leyva et al., 2019). The different thresholds employed to compute ICS lead to different TTC at which MAEB is triggered.

A first strategy of intervention for ICS computation based on the physical limits for crash avoidance (the so-called “ABRAM” strategy from the name of the research project) was defined in (Savino et al., 2016a). A following study proposed a second strategy of intervention (called “ABRAM+”) which employed lower thresholds considering riders braking performances (Savino and Piantini, 2019). This allowed to obtain higher TTC at ICS and therefore a longer duration of MAEB intervention, resulting in greater effects of MAEB on the host vehicle speed (see Figure 2).

Table 1 collects the main thresholds, in terms of longitudinal deceleration and lateral acceleration, for the definition of the ICS in a generic crash scenario involving a host PTW and an opponent passenger car, employed in previous studies (ABRAM and ABRAM+). A further algorithm, the so-called “PIONEERS” strategy, was added to assess a more invasive strategy of intervention with lowered thresholds for the identification of the ICS.

Table 1 – Thresholds for Inevitable Collision State (ICS) definition algorithms

Inevitable Collision State (ICS) algorithm	PTW ICS thresholds		Car ICS thresholds	
	Longitudinal deceleration [g]	Lateral acceleration [g]	Longitudinal deceleration [g]	Lateral acceleration [g]
ABRAM	0.90	0.70	0.90	0.70
ABRAM+	0.70	0.60	0.70	0.60
PIONEERS	0.50	0.35	0.50	0.35

The three algorithms were employed to calculate the ICS event in a set of pre-crash scenarios using the 2D crash simulation tool developed in a previous study (Savino et al., 2016b). First, two reference crash scenarios were simulated, representing typical PTW-passenger car collisions in crossing and a front/rear-end configuration (Puthan et al., 2021). These are respectively, DCA 110 and 130 based on the Australian crash classification by VicRoads (VicRoads, 2013), often used in MAEB evaluations in literature. Then, 16 real-world crash cases were simulated, based on the MICIMS database reconstructions (Allen et al., 2017; Day et al., 2013) used in a previous study for MAEB evaluation purposes (Lucci et al., 2021a) (Table 2).

Table 2 – Time To Collision (TTC) at inevitable collision state (ICS), estimated from simulations of two reference crash configurations and a convenience sample of 16 real-world crash cases extracted from the MICIMS database.

Crash configuration (DCA)	Reference crashes		Real-world crashes (16)	
	Crossing (110)	Rear-end (130)	All	
Inevitable Collision State (ICS) algorithm	TTC [s]	TTC [s]	TTC [s]	
			Mean	SD
ABRAM	0.49	0.42	0.43	0.093
ABRAM+	0.70	0.49	0.53	0.112
PIONEERS	0.88	0.65	0.68	0.123

The more conservative triggering strategy called “ABRAM”, which deploys the MAEB intervention only when the imminent impact becomes inevitable even using the acceleration levels that are typically achieved by riders in emergency conditions (Huertas-Leyva et al., 2019), showed in previous studies a reference value for TTC at MAEB trigger around 0.60 s (Savino et al., 2016b). However, in order to anticipate MAEB intervention to make it more effective, more intrusive triggering approaches can be adopted, deploying MAEB intervention when the imminent impact becomes inevitable when assuming that the rider may operate the vehicle with accelerations in the range of standard road riding maneuvering (as the one proposed in this paper called “PIONEERS”).

Concerning the fade-in jerk of a motorcycle automated braking, values of around 1 g/s were tested in previous studies adopting a 0.5 g target deceleration (Merkel et al., 2018); with lower values of target deceleration (0.3 g), a fade-in jerk up 1.5 g/s was tested (Lucci et al., 2021b). The latter value was shown to be safely manageable by common riders. With small values of MAEB target deceleration and typical durations of the intervention, the value of fade-in jerk has not-negligible impact on the Impact Speed Reduction (ISR). For instance, with target deceleration of 0.5 g and TTC of 0.60 s, the ISR obtained with a fade-in jerk of 1 g/s, 2 g/s and 3 g/s is, respectively, 6.5 km/h, 8.4 km/h, and 9.1 km/h. However, it is reasonable to assume that first MAEB implementations will adopt jerk values under the threshold of those reached by expert riders in emergency braking conditions of 2.5 g/s (Huertas-Leyva et al., 2019). For the purposes of this study, we will consider a fade-in jerk of 2 g/s.

With a fixed fade-in jerk of 2 g/s, the expected performance of MAEB in terms of Impact Speed Reduction (ISR) can be computed as a function of TTC for different values of MAEB target deceleration.

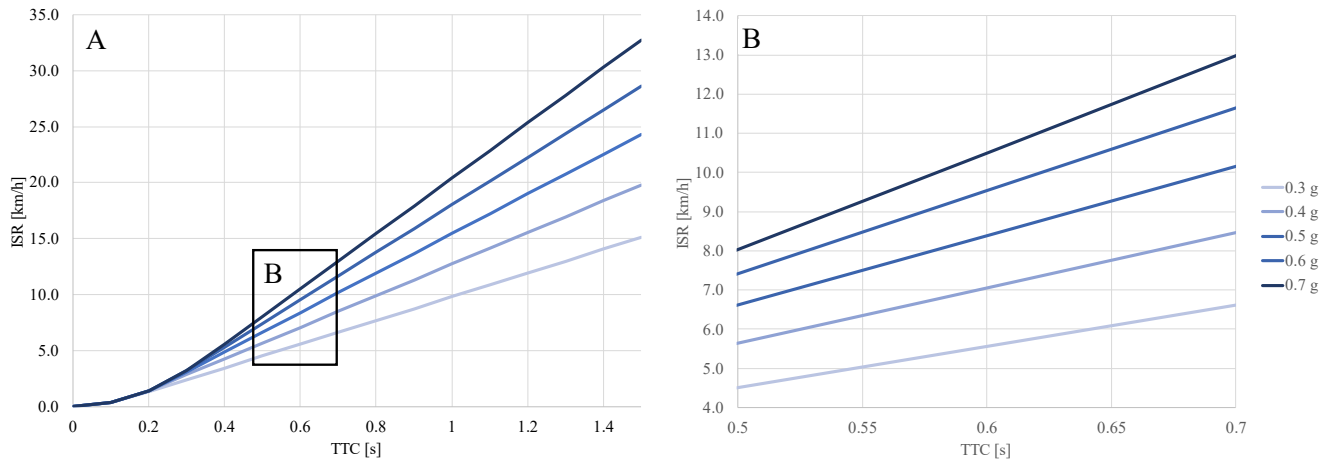


Figure 2 – Theoretical Impact Speed Reduction (ISR) achieved due to MAEB intervention, expressed as a function of Time To Collision (TTC) at triggering, computed for a range of values of target deceleration. Image B shows a close up of image A in the range of TTC 0.5 s - 0.7 s.

Figure 2 illustrates the influence of MAEB target decelerations on ISRs, with larger effects for high TTC at MAEB triggering. So far, field tests proved the feasibility of MAEB with target decelerations up to 0.3 g and assessed its acceptability among common riders (Savino et al., 2016c)(Lucci et al., 2021b). However, this value of deceleration is likely to be inadequate for mitigating crashes due to the limited ISR (Savino and Piantini, 2019). For example, with TTC of 0.60 s the resulting ISR is 5.6 km/h. Higher MAEB target decelerations produce a significant increase of ISR at a fixed TTC. Setting 0.5 g as target deceleration allows reaching a reference ISR of 8.4 km/h with an increase of 50% compared to the 0.3 g condition. With higher TTC the effects would become even larger. However, the feasibility and riders' acceptability of higher levels of deceleration still misses being confirmed through experimental testing.

To attempt a translation of ISR into an estimate of injury risk reduction, we will employ the injury risk functions proposed by (Ding et al., 2019), who developed multivariate injury risk models for PTW users able to estimate the risk to sustain different levels of injuries based relative speed and crash characteristics. The levels of injury severity considered were three: MAIS2+F, MAIS3+F and Fatal injuries, where MAIS stands for Maximum injury score reported by a subject in the Abbreviated Injury Scale (Gennarelli and Wodzin, 2008). The injury severity was defined based on the variation of relative impact speed of the PTW, absolute and relative injury risk reductions were calculated, as detailed in a previous study (Lucci et al., 2021a). Assuming a TTC at MAEB triggering of 0.60 s, 50 km/h of PTW travel speed in a rear-end crash scenario (PTW about to impact into a stationary passenger car), 0.5 g of MAEB target deceleration, the relative injury risk reduction for the PTW rider is, respectively, 3.0%, 8.1%, 22.2% for MAIS2+F, MAIS3+F and fatal injuries. Comparing these reductions with the one obtained with 0.3 g of MAEB target deceleration (respectively, 1.9%, 5.3%, and 15.2% for MAIS2+, MAIS3+ and fatal injuries), interestingly the relative injury risk reduction is increased by 50%. However, even if these benefits of MAEB depend on the relative impact speed and therefore the travel speed of the PTW and the opponent vehicle, the influence of speed is limited for relative velocities up to 90 km/h (see Figure 3), especially for fatal injuries, and therefore a reference speed of 50 km/h can be considered suitable for testing.

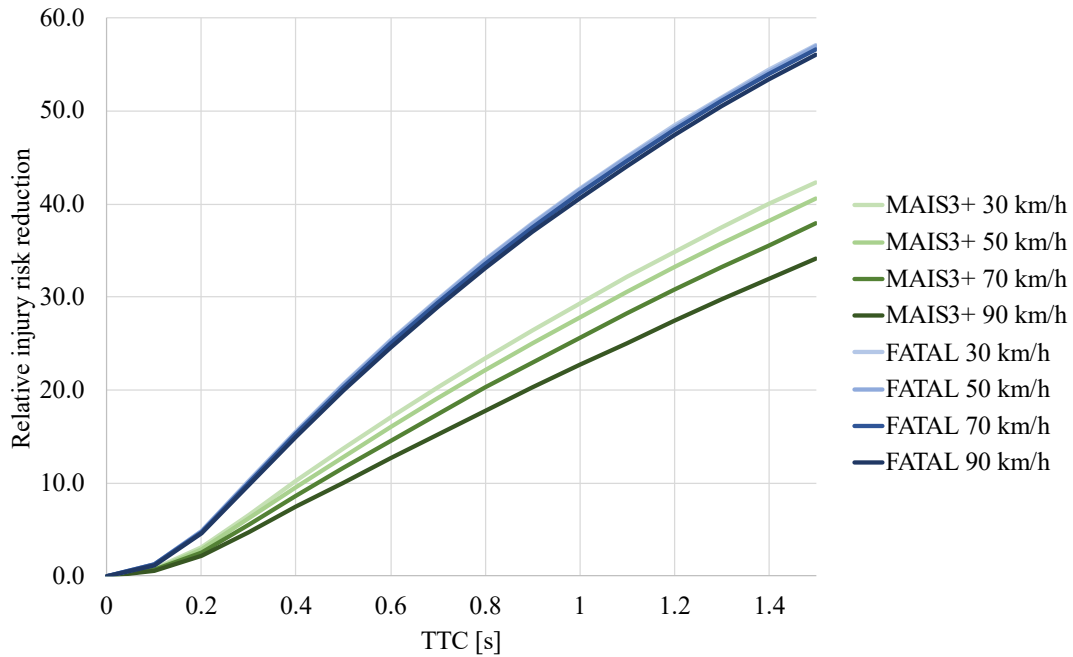


Figure 3 – Relative injury risk reduction for MAIS3+ and Fatal injuries by Time To Collision (TTC) at different crash speed, computed from the injury risk functions provided by (Ding et al., 2019) assuming 0.5 g MAEB target deceleration, 2 g/s fade-in jerk, and rear-end crash configuration.

Based on the results of previous studies and the estimations made through the ISR and injury risk reduction curves, new working parameters compared to those tested so far are required to make MAEB effective in mitigating PTWs crashes. It is, therefore, necessary to assess the applicability of 0.5 g of target deceleration, reached with a reference fade-in jerk of 2 g/s and for a duration of the intervention of at least 0.60 s.

2.2 Field tests description

In order to validate the feasibility and acceptability among end-users of the MAEB working parameters identified as potentially effective in mitigating PTW crashes, a field test campaign was performed. The field test was designed following the principles and guidelines presented in previous work (Lucci et al., 2021c, 2019) based on literature review and pilot testing. As carried out in previous studies (Merkel et al., 2018; Savino et al., 2016c), to assess MAEB feasibility and acceptability among end-users Automatic Braking (AB) events were studied. A comprehensive overview of the field test campaign, which is presented in brief in the following paragraphs, was presented in (Lucci et al., 2020; Marra et al., 2021).

2.2.1 Participant recruitment

The invitation to participate in the tests was advertised through the website of the University of Florence, via social media, and through flyers distributed to biker groups. Potential participants were invited to fill in a questionnaire on demographic information and riding habits. Before the registration, volunteers were informed that no economic incentive would be provided to take part in the study. They were also advised that if selected, they would have tested an advanced safety system for PTWs, with no specific mention to MAEB. Among the 115 riders who registered for participating in the test campaign, active riders having a minimum of two years

or 10,000 km of riding experience and aged between 20 and 65 were selected. The selection of participants aimed at obtaining a heterogeneous sample of riders in terms of age, gender, riding experience, type of PTW user, and attitude towards rider assistance systems.

All the participants involved in the study gave their informed written consent for inclusion before participating. The test protocol of the study was approved by the Ethics Committee of the University of Florence (Decision N. 46, 20/03/2019).

2.2.2 Test vehicle and instrumentation

To achieve the goal of validating the feasibility of the proposed levels of intervention for MAEB, a test vehicle was equipped with a remote-controlled braking device that was able to perform an Automatic Braking (AB) event when activated by the investigator (i.e., without any intervention by the rider).

The test vehicle was a Ducati Multistrada 1260S, a sport-touring motorcycle equipped with Bosch cornering ABS (Anti-lock Braking System), combined braking, four-stroke engine with a displacement of 1262 cm³ and semi-active suspensions (Figure 4). The motorcycle was equipped with a top case to install the AB control unit and data recording instrumentation. A lowered seat was in place with nominal height of 825 mm from the ground, to give to all the participants a comfortable seat and control of the motorcycle at standstill.



Figure 4 – Test vehicle (Ducati Multistrada 1260S) with extension arms during lane-change maneuver

The vehicle was provided with a remote-controlled Automatic Braking (AB) system developed from that presented in a previous study (Lucci et al., 2019): when a specifically designed electronic control unit received an external signal by the remote control, the AB system built up a predefined fluid pressure profile in the hydraulic braking system, based on a set of parameters. The parameters were designed and calibrated to tune the MAEB intervention in order to produce the target profile of deceleration depicted in Figure 1; different values of AB target deceleration, fade-in jerk and AB duration of intervention were possible. The trigger signal, sent by a researcher via a radio remote control, was intended as a surrogate of the activation signal to be provided by a fully operational MAEB system in the event of imminent impact recognition. The anti-lock

braking function was always active, including during AB, to prevent any wheel lock event. The AB system was set to decelerate the motorcycle in two consecutive test sessions at a nominal target deceleration of, respectively, 0.3 g and 0.5 g. The system was set to perform a fade-in jerk ranging from 1.5 g/s to 2.0 g/s. The nominal duration of the AB intervention was set to be 1.2 s: this included the fade-in time to reach the target deceleration and the constant deceleration time.

The test vehicle was provided with a pair of extension arms to prevent the motorcycle from falling sideways. The extension arms were installed on special plates linked to the motorcycle frame and they were built and installed by a specialized company. Each extension arm ended with a freewheel with the function of absorbing a possible impact and allowing continuing the manoeuvre also in case of contact of the wheel with the ground. The device was set to allow a maximum roll angle of 25 degrees.

Data from the CAN-Bus of the motorcycle were recorded with a sample rate of 100 Hz to monitor vehicle state during AB intervention (wheel speed, front and rear wheel braking pressure, vehicle tri-axis acceleration and gyro, engine RPM, gear number) and rider usage of vehicle controls (throttle, clutch, gear switch, front and rear brake, steering angle). In addition, 20 Hz GPS position and 50 fps video from two Go-pro Hero4 cameras installed on the motorcycle were recorded. One camera was positioned on the top case to provide an environmental overview of the ride whereas the second one was placed in a lateral position on the right-side extension arm to monitor rider behaviour during AB intervention.

Subjective data about participants' experience during the test were collected from questionnaires. The questionnaires were developed based on those employed in previous studies focusing MAEB and standardized questionnaires, in order to employ a robust self-report measure in agreement with the recommendations of (Frison et al., 2020). Participants were required to assess the AB intervention, the controllability of the vehicle during AB intervention and to give an overall assessment of MAEB after testing AB. In order to assess the vehicle controllability during AB intervention, an adjusted controllability rating scale was employed. This scale, which is an adaptation of the Cooper-Harper rating scale (Cooper and Harper, 1969), allowed the participants to rate the effort required to complete the desired trajectory when the vehicle stability was perturbed by AB intervention deployed during, or immediately before, the execution of a manoeuvre. Being it referred to the execution of the manoeuvre planned by the rider before AB intervention, the rating is by definition a comparative measure to the same manoeuvre without AB intervention (Lucci et al., 2021b). The rating scale ranged from one (very easy to control, no effort required to maintain the desired trajectory) to ten (impossible to control).

2.2.3 Test procedure

The field test procedure was developed based on the specific guidelines presented in previous work (Lucci et al., 2021c, 2019) and the test protocol of a previous study focusing on MAEB (Savino et al., 2016c). The test protocol was designed to expose participants to automatic decelerations through an automatic braking action executed by the motorcycle without a braking action of the rider. The final goal of this approach was to reproduce an unexpected intervention (i.e., rider not aware of a collision about to happen) or a false activation (i.e., rider unprepared to a sudden deceleration operated by the vehicle) as postulated in a previous study (Savino et al., 2016c). This allowed testing the most challenging working condition for MAEB related to safe controllability of the vehicle and rider acceptability of the system (Lucci et al., 2021c). The following test protocol was designed to make AB interventions unexpected for the rider by triggering pseudo-random AB activations without the presence of any obstacles. The AB was deployed in a set of representative riding conditions for real-world applications including straight riding, curves, and manoeuvres such as lane-change reproducing an avoidance action (Lucci et al., 2021c). Based on the injury risk curves, which highlighted a limited influence of PTW travel speed in MAEB injury mitigation potential, a nominal speed of 50 km/h was

selected as representative of urban scenarios and overall representing a good compromise with field test limitations. The field test took place in a flat parking lot closed to the traffic.

The test protocol consisted in the following phases: 1) the participant was informed about the field test procedure and signed the informed consent. Then, he/she was provided with full protective equipment, including airbag-jacket and he/she was introduced to the test vehicle including extension arms. 2) The participant performed a warm-up session to become familiar with the vehicle and the track (see Figure 5) in the two senses of rotation. This took on average 10 minutes, never exceeding 15 minutes. 3) Following that, a familiarization with the AB system was carried out. The AB intervention was deployed three times in straight-line with three different levels of target deceleration, respectively 0.3 g, 0.5 g, and 0.6 g. The participant was informed about the intervention of AB, with declared triggering at a given marked point in space. 4) The participant was involved in a first test session in which pseudo-unexpected AB activations were tested, with nominal deceleration of 0.3 g. During this session, the participant was free to ride along the test track for 20 laps (approximately 15 minutes), while the automatic braking (AB) was manually deployed at pseudo-random times when he/she went through different spots of the test track. The spots included straight line sections, curves, and manoeuvres including lane-change (see Figure 5). The latter was always executed by swerving to the left while approaching a set of transversally aligned street markers (see Figure 4) representing a virtual obstacle (width 1.8 m, for further details regarding the lane-change manoeuvre see (Lucci et al., 2021b)) . In this session, each participant tested the AB intervention twice in the straight-line section and twice in the lane-change section, once for each sense of rotation of the track. The test session ended with a short break in which the participant filled in a brief questionnaire. 5) The participant was then involved in a final test session involving pseudo-unexpected AB interventions using a nominal deceleration of 0.5 g. Similarly with the previous session, the participant rode along the test track for 15 laps (approximately 12 minutes) while the automatic braking (AB) was triggered at pseudo-random times. In this session, each participant tested the AB intervention twice in the straight-line section and twice in the lane-change section. A final AB intervention, that will be addressed as ‘Out of the Blue’ (OB) activation, was performed along one straight segment. At the end of the test the participant filled in a final questionnaire.

The test protocol of this study was specifically designed to test AB interventions in different manoeuvres with unprepared participants (Huertas-Leyva et al., n.d.; Lucci et al., 2021c). Both sessions included also testing AB intervention in manoeuvres other than straight-line riding or lane-change: overall, the AB intervention was deployed on average once every 100 s of riding. To test the response to unexpected AB interventions and to minimize any learning effect in the participants, two major strategies were adopted. First, in each session, for each manoeuvre the participants experienced no more than two AB interventions (except for the curve) and each deployment was separated in time by several passages through the same track sections without any AB intervention. Second, the track was designed to include manoeuvres characterized by different trajectories and control actions, minimizing global learning effects across manoeuvres. These AB events were considered “pseudo-unexpected” interventions.

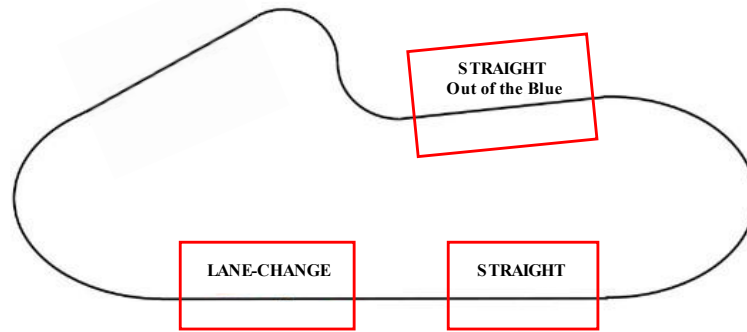


Figure 5 – Test track and AB triggering areas

3 Results

3.1 Test participants

In this study 31 participants (6 female, 25 male) were involved in field testing AB events. Overall, participants' age ranged from 21 to 59 years (mean age 39.8 years, SD 12.2 years). The 31 participants were characterized by different levels of education (10% lower secondary, 45% upper secondary, and 45% university degree or higher) and riding experience (26% 2-10 years, 35% 11-20 years, and 39% more than 20 years). Overall, the mean riding experience was 19.6 years (SD 11.9 years). All the participants included in the tests owned at least one motorcycle and rode it at least on a weekly basis. The majority of participants used PTWs for leisure, travel or sports reasons (68%), whereas 29% of them used PTWs mainly for commuting and 3% for work. Concerning the type of PTW more frequently used, 32% rode road or naked motorcycles, 29% crossover motorcycles, 13 % scooters, 13% sport motorcycles, and 13% off-road motorcycles.

3.2 AB intervention

Table 3 shows the values for the initial speed of the vehicle at AB intervention and the tested parameters characterizing the AB intervention (event duration, level of deceleration and fade-in jerk).

For each participant, the AB intervention was tested two times in the straight line with the level of deceleration at 0.3 g and three times with the level of nominal deceleration of 0.5 g. One “Out of the blue” AB intervention in straight-line was not recorded due to data acquisition failure. The mean speed at AB trigger in straight-line was 47.2 km/h and the mean AB deceleration performed in the two levels of intervention was, respectively, 0.30 g and 0.48 g. Regarding the fade-in jerk, the mean value was around 1.5 g/s for the 0.3 g nominal deceleration level and 2.0 g/s for the 0.5 g nominal deceleration level. The duration of the intervention (which includes the time required for the fade-in ramp and constant deceleration time) was around 1.05 s. No relevant differences in terms of AB performed parameters were measured between the pseudo-unexpected straight-line AB intervention and the “Out of the blue” ones.

Concerning the lane-change manoeuvre, each participant tested the AB intervention two times in the 0.3 g nominal deceleration level and two times in the 0.5 g one. Due to AB activation errors (missed or delayed triggering by the investigator) 60 AB activations instead of the expected number of 62 were analysed for the lower level of intervention. The mean speed at AB trigger during the lane-change manoeuvre was around 42 km/h. For both the manoeuvres, the variability of the speed was due to the different riding styles and behaviours of the participants. The fade-in jerk was slightly lower compared to the straight-line trials, while the declaration

performed was very similar: the variability in the jerk and deceleration performed by the AB system was due to the automatic braking system, which operated open-loop control of the braking pressure. In addition, the deceleration was influenced by the different body mass and aerodynamic drag of participants.

Table 3 – AB tested intervention

Manoeuvre	Nominal deceleration [g]	N° of AB activations	Initial Speed [km/h]		Event duration [s]		Deceleration [g]		Fade-in jerk [g/s]	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Straight-line	0.3	62	47.2	4.7	1.07	0.03	0.30	0.034	1.53	0.407
Lane change		60	41.7	6.0	1.05	0.11	0.31	0.037	1.28	0.423
Straight-line	0.5	62	49.1	4.7	1.14	0.03	0.48	0.035	2.06	0.402
Lane change		62	41.5	5.4	1.05	0.20	0.49	0.035	2.00	0.742
Straight-line – OB		30	48.5	6.5	1.15	0.04	0.47	0.037	2.08	0.517

The timing of in the AB invention in relation to the manoeuvre of lane-change (and therefore the distance to the virtual obstacle) was already discussed in a previous paper for the 0.3g level of nominal deceleration (Lucci et al., 2021b). Concerning the 0.5 g level of deceleration, similar values of distance from the virtual obstacle at which AB were triggered (mean 13.4 m, SD 2.5 m) and the time to obstacle (mean 1.19 s, SD 0.21 s) were measured. Similarly to the results presented in the previous work (Lucci et al., 2021b), this resulted in triggering the automatic braking mainly in the first two phases of the lane change manoeuvre: 39% in the straight-line motion and 41% in the increasing vehicle roll phase. Eighteen percent of AB interventions were triggered when the motorcycle was near to the roll peak, while just 2% during the decreasing roll phase.

3.3 Subjective assessment

In the questionnaire by the participants any loss of control was reported. The results of the controllability rating asked to participant through the adjusted Cooper-Harper (CH) rating scale (range: 1 easy to control – 10 impossible to control) are displayed in Figure 6. According to the rating of participants, the AB intervention in lane-change with 0.5g nominal deceleration turned out to be the most difficult to handle (mean CH rating 2.6, SD 0.9) while the easiest was during straight-lane (mean CH rating 1.5, SD 0.7). However, all the ratings given by the 31 participants indicated good vehicle behaviour and easiness of control, with a limited compensation required by the rider to execute the desired trajectory during the automatic braking.

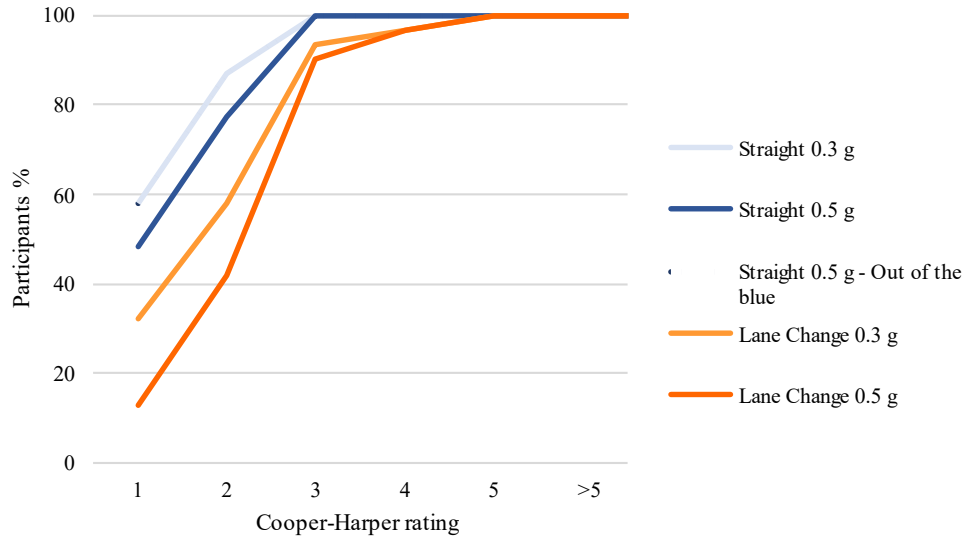


Figure 6 – Cumulative Cooper-Harper rating

The participants were also asked to give an assessment of their perception of deceleration and fade-in jerk for the two levels of intervention (respectively, 0.3 and 0.5 g nominal deceleration – see Figure 7). As for the Cooper-Harper ratings, these ratings were given immediately after each test session, so the answers about 0.3 g level are not influenced by testing the higher 0.5 g level. Overall, the participants rated the deceleration as right or “a bit high”; a small percentage of participants (ranging from 3% in straight-line to 10% in lane-change) rated the highest level of deceleration tested as “too high”, despite of they were constantly able to control the vehicle as declared in the CH controllability rating. Similarly to the deceleration, also the jerk level was considered as just right by the majority of participants, with a few riders rating it as “a bit high” or “too high”, especially for the higher level of intervention.

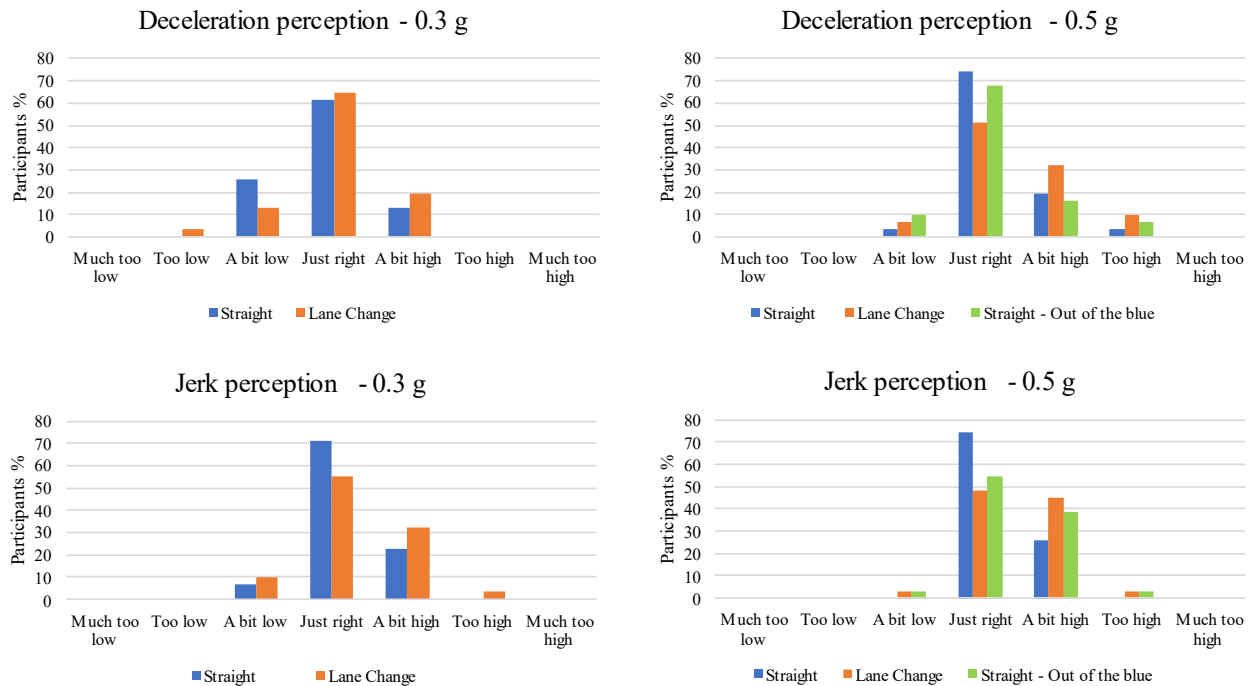


Figure 7 – Participants ratings of tested AB deceleration and fade-in jerk

Regarding the predictability of the tested AB interventions (the method employed was validated in a linked study by (Huertas-Leyva et al., n.d.)), more than 80% of the participants indicated that, overall, considered the pseudo-unexpected activations as not predictable or unexpected, and in the “Out of the blue” AB interventions, 93% of them declared the intervention at least “not predictable”. Overall, in all test sessions, more than 50% of participants rated the AB intervention as highly unexpected or completely unexpected.

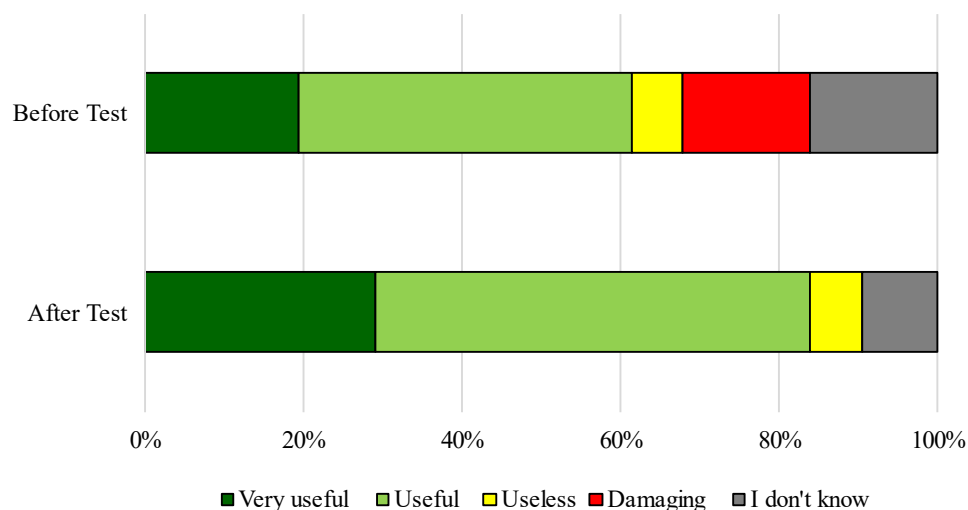


Figure 8 - Participants' opinion on MAEB before and after testing AB

When asked about the usefulness of advanced assistance systems for PTW including MAEB (e.g., ABS, Traction Control, Active Cruise Control etc.), the 31 participants generally expressed a good opinion on the assistance systems; this was the case especially for those systems that are already available on series PTWs, such as ABS. Noticeably, MAEB was considered as the least useful system, with 12.8% of participants indicating it as damaging (see Figure 8). After testing AB however, the overall opinion regarding the MAEB markedly improved: about 85% of the participants considered MAEB as potentially “useful” or “very-useful”, with anyone considering it damaging anymore.

Among the 31 participants, only one reported a final bad opinion of the system. This was mainly caused by the reduced manoeuvrability of the vehicle during the AB activation, as stated by the participant. Two participants expressed indifferent opinion about MAEB and the other 28 had an overall opinion ranging from “excellent” to “good”. In appendix A a concise translation of the comments on MAEB made by each of the 31 participants is provided.

Participants were also asked whether they would feel comfortable to test AB intervention without safety outriggers installed on the vehicle: 30 and 29 out of the 31 participants involved in the tests declared that they would be available to test AB intervention without outriggers in straight-line and in lane-change manoeuvres, respectively.

A final question was asked to the participants regarding their willingness to pay in order to have MAEB on their own PTW. Even if 13% of participants declared not to be willing to pay any extra cost to have MAEB on their next PTW, 29% of participants declared to be available to spend up to 500€ for MAEB, with 10 % of the participants indicating MAEB worth more than 1000€. Overall, 87% of participants declared to be available to pay up to 200€ to have MAEB installed on their next PTW.

3.4 Participants’ reactions to AB intervention

During the tests, the participants were monitored by the researcher in charge of the test session and AB activation who should have taken note of any loss of control event. The participants’ reactions during the AB activations were also recorded by onboard and fixed action cameras. A compilation of the AB interventions in straight-line (Video 1) and lane-change manoeuvre (Video 2 and Video 3) is attached to this paper. The recorded videos were checked individually after tests completion: even if different body movements among participants were noted, no incipient loss of control was observed. The body movements recorded were those coherent with a braking deceleration, (e.g., forward movement of the body and head). The video analysis verified that none of the following events did occur due to a loss of control or stability of riding position: impact of helmet or torso on handlebars or tank, separation of hand from handlebars, slipping foot on footpeg, accidental action on brake/shift pedal, sliding sideways from the seat, sliding longitudinally with impact on the tank, lifting from the seat, twist of the torso, and accidental opening of throttle. These results were confirmed by the participants’ subjective assessment, who mainly declared to have perceived “no body movement” (83.9%) during AB intervention or a “forward body movement” (12.8%). One participant (3.2 %) declared to have performed a lateral movement, whereas no participant (0%) perceived a “backward body movement” or other body movements.

As declared in the subjective assessment, the participants were constantly able to maintain the straight trajectory during the straight-line AB activations and they were always successful to complete the lane-change manoeuvre, avoiding the markers representing the virtual obstacle. In a small set of cases (9/122 recorded AB interventions in lane-change) the test vehicle touched with the extension arm wheels the ground during the lane-change manoeuvre. In-depth analysis of these AB activations through videos and vehicle data showed

that these contacts with the outrigger wheels to the ground were common during the tests, and linked with their riding styles involving large leaning angles and high roll rates, with any relation to incipient loss of control.

Vehicle data was analysed to monitor the usage of vehicle controls (brakes, clutch, and throttle) by participants during AB interventions. Overall, the participants showed very limited usage of vehicle controls during AB interventions. A few cases of usage of brakes were recorded: one participant used the front brake during two AB interventions in straight-line (duration of braking action around 0.1 s and with a small increase of braking pressure) whereas the other 30 participants did not use the front brake during AB intervention. Two participants used rear brake during ten AB intervention with a limited increase of braking pressure: further analysis highlighted that slight pressure on the rear brake control was part of their riding style and not a reaction to AB intervention. Only two participants used the clutch disengagement control during a few AB interventions (6) in order to shift gears. Concerning the usage of throttle during AB intervention, we analysed positive and negative peaks after intervention, being respectively positive and negative variations compared to throttle value at triggering. Throttle opening events greater than 10% were common during AB intervention (33.9%). Focusing on 0.5 g straight intervention and considering a time window of 0.400 s after triggering, we did not observe both positive and negative peaks greater than 10%, except for one case. This means that a solid acceleration (or release) was never followed by a solid release (or acceleration). Small variations in terms of both accelerations and release (with absolute values lower than 10%) were also very common (45.2%). Cases of a release of acceleration greater than 10% were less common (19.3%).

The analysis of the subjective evaluation regarding the actions required during AB interventions showed that the majority of participants (54.8%) declared that they had to “hold handlebar” during AB intervention, whereas 35.5% of participants reported no action was required during AB intervention and one participant (3.2%) declared he had to push on footpeg. Regarding the controls, 19.4% of participants answered that they had to disengage clutch or downshift, whereas 9.7% needed to open throttle. This percentage is quite in line with the actual number of participants who actually opened the throttle during AB intervention (16.1%, considering a threshold of 25% acceleration peak. No participant indicated braking as an action required during AB intervention, consistently with the recorded brake pressure data.

3.5 Impact speed reduction

The AB system tested in this study allowed to reach a mean speed reduction of 10.0 km/h for the 0.3g nominal deceleration level and 15.8 km/h for the 0.5 g nominal deceleration level, as a result of a duration of the AB intervention of, respectively, 1.07 s and 1.11 s. Limited differences in terms of the duration of intervention (and therefore maximum TTC usable) and ISR were observed between the two manoeuvres tested (see Table 4). Even if there was a slight difference in the vehicle initial speed among the two manoeuvres and two levels of intervention (ranging, on average, from 41.5 km/h to 49.1 km/h), the ISR and its variability performed by the AB system resulted to be dependent only by the set level of deceleration.

Table 4 – Calculated TTC and ISR

Manoeuvre	Nominal Deceleration [g]	TTC [s]		ISR [km/h]	
		Mean	SD	Mean	SD
Straight	0.3	1.07	0.027	9.9	1.65
	0.5	1.14	0.031	16.1	1.81
Lane-change	0.3	1.07	0.037	10.1	1.31
	0.5	1.08	0.098	15.5	1.80

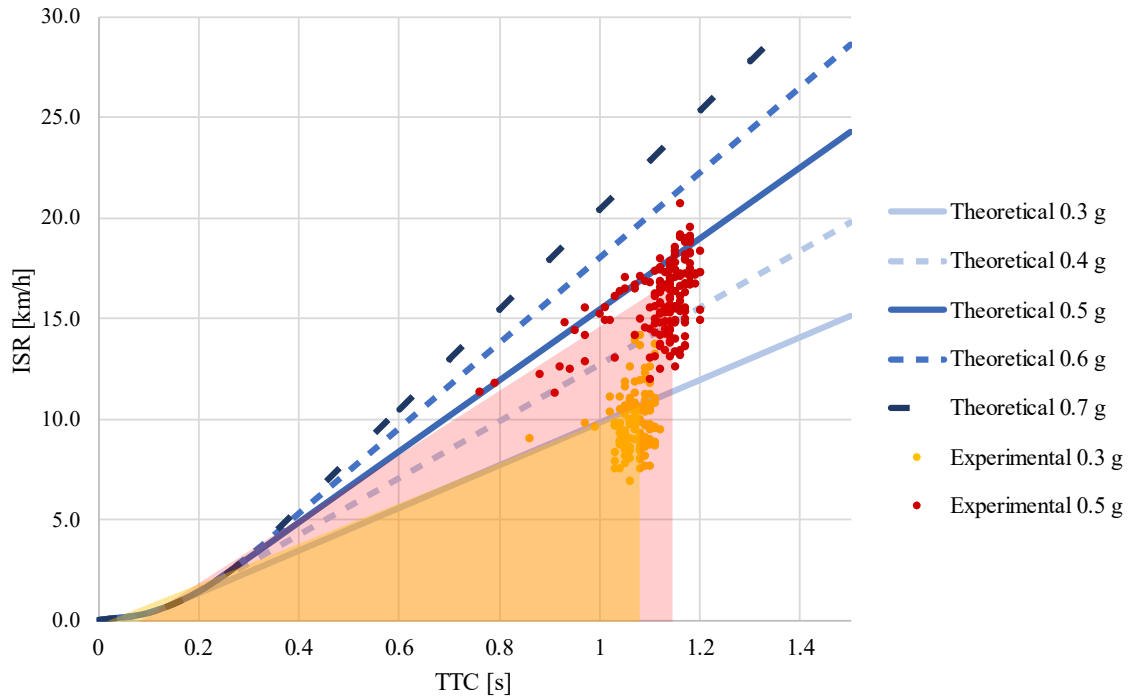


Figure 9 – Tested AB intervention (experimental data) and MAEB feasibility regions (coloured area)

Based on the tested AB interventions, two regions (one for each level of AB intervention tested) defined by mean values of TTC and ISR in which MAEB can be considered applicable from rider perspective were defined (see orange and red coloured areas in Figure 9).

The aforementioned values of TTC and ISR tested in this study were employed to estimate the relative injury risk reduction based on the injury risk functions provided in literature (Ding et al., 2019). The curves (see Figure 10) were calculated for the relative speed of 50 km/h, representing the case of a PTW traveling at 50 km/h which crashes against a stationary passenger car. With the maximum values of TTC and ISR tested and considered safely applicable from rider perspective in this study (respectively 1.14 s and 16 km/s), it would be possible to reach relative injury risk reduction of approx. 8%, 15%, and 40% for, respectively, MAIS2+, MAIS3+, and fatal injuries. Employing the TTC of 0.6 s, it would be possible to reach relative injury risk reduction of approx. 3%, 7.5%, and 20% for, respectively, MAIS2+, MAIS3+, and fatal injuries.

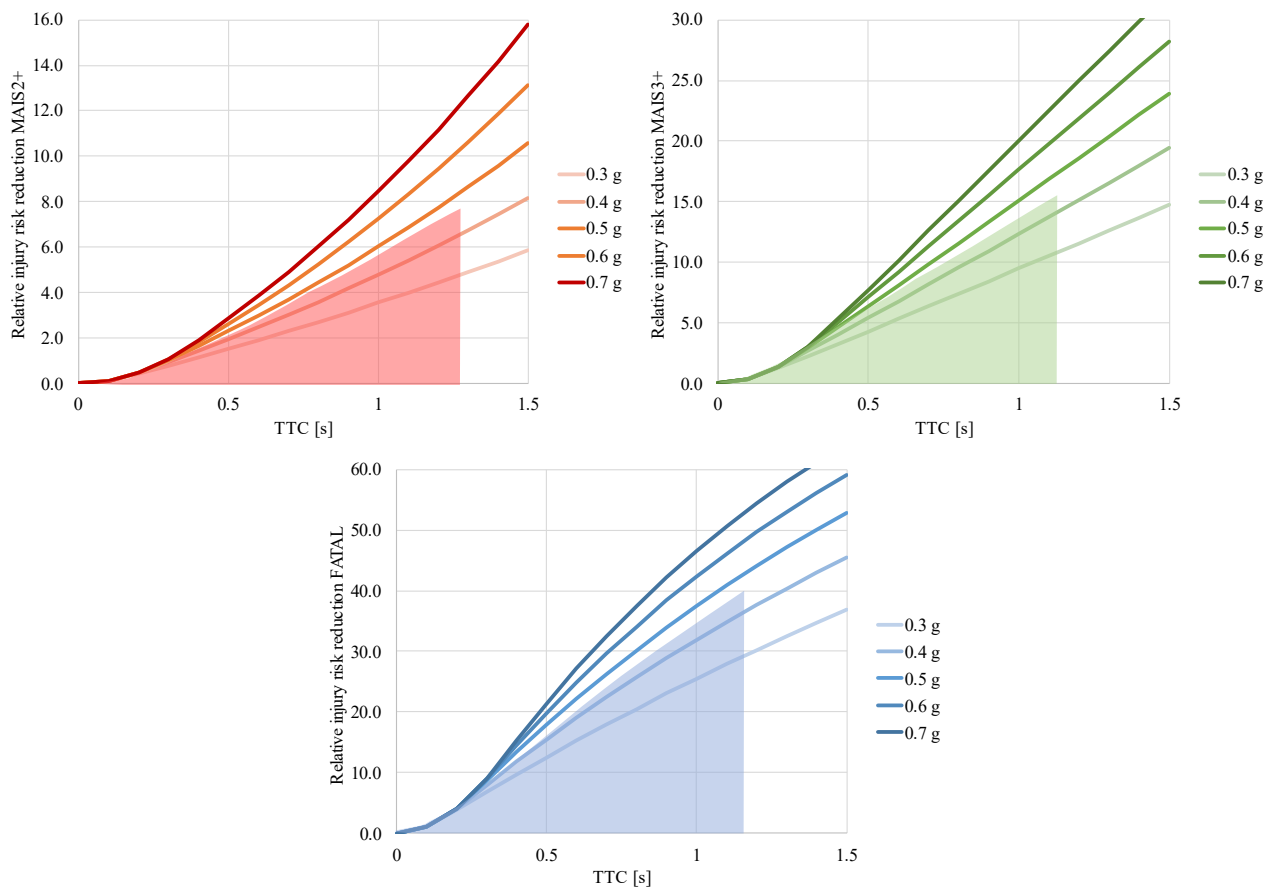


Figure 10 – Relative Injury Risk reduction curves and MAEB feasibility regions (coloured area) for MAIS2+, MAIS3+ and Fatal injuries

4 Discussion

One important open issue for MAEB application is the identification of the trade-off between high levels of MAEB intervention (in terms of target deceleration and fade-in jerk) potentially able to mitigate PTW users' injuries and lower levels of intervention which can be easily controlled by riders. In this paper, based on the findings of previous studies focusing on Motorcycle Autonomous Emergency Braking (MAEB) and injury risk functions for motorcyclists (Ding et al., 2019), a new set of MAEB working parameters potentially effective in mitigating PTWs crashes was defined. These parameters include 0.5 g of target deceleration, reached with a fade-in jerk of 2 g/s and an overall duration of the intervention of at least 0.60 s. The applicability of such MAEB working parameters was then assessed through field tests involving 31 common riders as participants and employing a comparable approach to previous studies (Lucci et al., 2021b; Savino et al., 2016c). Pseudo-unexpected Automatic Braking (AB) events were deployed via remote control on a sport-touring motorcycle while the participant was riding in conditions including straight-line riding and lane-change manoeuvres. Consistently with the theorizing of an earlier study testing 0.5 g automatic decelerations in straight-line involving professional riders, which were then asked to estimate common riders' ability to handle an automated intervention (Merkel et al., 2018), our results showed that in such conditions, automatic decelerations up to 0.5 g were managed with ease by common riders. As it was previously showed with lower levels of target declaration and of fade-in jerk (Lucci et al., 2021b), the same AB intervention deployed in any of the key phases of the lane-change manoeuvre, did not prevent the rider from manoeuvring nor from successfully avoiding the virtual obstacle. No destabilization of the vehicle was observed in the tests. In addition, the subjective evaluation suggested that small extra effort compared with the straight-line AB intervention was required to control the vehicle along a quick lane-change manoeuvre during the intervention of the system.

In order to validate the proposed MAEB working parameters, this study involved the largest sample size of participants in MAEB field testing. Participants were selected to gather the wide range possible in terms of age, riding experience and motivations for riding. Still, given the safety requirements and practical constraints, also linked with the specific test vehicle in place, our sample may not represent all the characteristics of the general motorcycle rider population. The sample included participants with both initial positive and negative opinion on MAEB (when surveyed before the test). However, a residual bias coming from more technology-oriented PTW users towards a positive opinion on MAEB may still have affected the results.

The AB interventions were tested in this study following the procedure proposed in previous studies (Lucci et al., 2021c; Savino et al., 2016c), which showed that AB interventions applied "out of the blue" had very similar effects compared to pseudo-unexpected interventions (Huertas-Leyva et al., n.d.). Even if AB interventions cannot be considered as genuinely unexpected as MAEB interventions in real-world conditions would be, these, as the results of previous studies, are likely to be representative of the effects of real-world MAEB that may be observed in unexpected activation conditions.

The range of speed at which the AB was tested in both lane-change and straight-line was selected because it can be considered representative of the urban scenario and suitable with constraints of the field-test area. Even if in this paper it was shown that the different travel speed of the PTW has limited influence on the estimated benefits of MAEB, the speed has a relevant influence from rider and vehicle control perspective. With higher velocities, the effort required to the rider to control the vehicle (e.g., forces on the handlebar to perform the swerve manoeuvre) is higher and therefore the effort to control the vehicle during an automatic deceleration is expected to be higher.

The MAEB working parameters (fade in-jerk and target deceleration) were considered suitable by most participants, even if a few participants considered them to be set too high. Notwithstanding that, the controllability ratings (adjusted Cooper-Harper rating) indicated that the controllability of the vehicle during

AB intervention was never in question. The overall subjective assessment by participants regarding MAEB intervention improved after testing AB: none of the participants involved in the test considered it damaging at the end of the experiment and about 85% considered it useful. This was confirmed by the wide availability of participants to pay to have MAEB installed on their next PTW (87% of participants available to pay up to 200€ for the system to be fitted on a newly purchased motorcycle).

No events of body movement that could be associated to a possible loss of control were observed in videos recorded by onboard action cameras. The forward body and head movements generated by AB intervention did not hinder the vehicle control coherently with what was observed in a previous AB study (Merkel and Winner, 2020). In addition, in correspondence of AB interventions, the participants showed very limited usage of vehicle controls (brakes, throttle, gears and clutch). Also, the usage of controls detected through vehicle data was confirmed by the participants in the subjective assessment, indicating that they mainly felt the need to hold handlebar or no impulse to act during AB intervention. Noticeably, the comparison between recorded vehicle data and questionnaire data showed quite accurate self-reported behavior related to reactions to AB events.

Based on the MAEB working parameters defined in the first part of this paper and tested through AB interventions in the field tests, it was possible to define a range of impact speed reduction potentially achievable based on the time to collision at which MAEB is deployed. As a result of field test validation, we can consider these working parameters (and consequently the corresponding achievable values of ISR) feasible in real-world riding conditions. MAEB applicability in real-world emergency conditions, where the disturbing effect of an imminent crash may cause unpredicted rider behaviour and body reactions, is currently an open issue. Rider reactions under emergency are difficult to be reliably assessed, even adopting the naturalistic approach, where near-crash events are rare and non-repeatable, or using riding simulations, where realistic emergency conditions are difficult to be attained. These elements set the next challenge of a structured field-testing of MAEB intervention under realistic emergency scenarios in a safe environment.

Employing the MAEB working parameters proposed in this paper, the goal of 8 km/h of impact speed reduction required in literature to reduce head injuries (Piantini et al., 2019), is achievable with the time to collision of 0.60s at MAEB triggering predicted with real-world crash case simulations (Savino et al., 2016a). When employing triggering algorithms that anticipate MAEB deployment at TTC higher than 0.60 s, the benefits (in terms of ISR) could be even greater. This is also confirmed by the estimations of MAEB relative injury risk reduction made in this paper based on the injury risk functions provided by (Ding et al., 2019), which highlighted that, at the reference speed of 50 km/h and with TTC of 0.60 s, the proposed MAEB working parameters would allow relevant reductions of relative injury risk (approx. 3%, 7.5% and 20% for, respectively, MAIS2+, MAIS3+ and fatal injuries).

5 Conclusions

This paper proposed a method to define the target working parameters required to make Motorcycle Autonomous Emergency Braking effective for rider injury mitigation in case of crash. Thanks to this method, MAEB parameters can be set to achieve a desired target for injury or fatality reduction. The application of the method allowed the identification of a set of working parameters that represent a good trade-off to achieve significant crash mitigation. Promisingly, the feasibility and the end-users' acceptability of such parameters was successfully validated through field tests involving common riders as participants. The validated set of intervention parameters represents the main innovative contribution of this work: our findings indicate that substantial autonomous braking - required to slow down the vehicle quickly enough to mitigate rider injuries

in case of crash - is feasible, even during the execution of avoidance manoeuvres. This work paves the way to future testing of MAEB in real-world emergency scenario towards its implementation on standard vehicles for improved motorcyclists' safety.

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9 Appendices

9.1 Appendix A

Overall Opinion on MAEB	Participant	Comments
Excellent	1	The MAEB is helpful to increase rider safety
	2	The MAEB is helpful to avoid falls
	3	The MAEB is helpful in case of emergency or rider distraction
	4	No comment
	5	No comment
	6	After MAEB intervention it is easy to take control of the vehicle
	7	During the intervention of the system the vehicle is stable and the braking has a good effect
Very good	1	The MAEB is helpful and the braking smooth
	2	The MAEB is helpful to increase rider safety
	3	The MAEB is helpful in case of emergency or rider distraction
	4	The MAEB is helpful in case of emergency or unexpected obstacle
	5	The braking is smooth and manageable
	6	The MAEB is helpful in case of emergency or rider distraction
	7	No comment
Good	1	The braking is manageable
	2	The MAEB is helpful in case of emergency
	3	The MAEB is helpful to increase rider safety
	4	The MAEB is not intrusive nor annoying
	5	No comment
	6	The MAEB is helpful for emergency braking especially in straight lane, in the other manoeuvres can be dangerous if the rider is distracted
	7	The MAEB is helpful to increase rider safety
	8	The MAEB is helpful to reduce speed before an obstacle
	9	The MAEB is intrusive but does not reduce the handling of the vehicle
	10	The MAEB is promising, before testing it, I didn't think that automatic braking was so easy to handle
	11	In some conditions the MAEB can also help to manoeuvre the vehicle
	12	If the MAEB is applied on standard vehicles could be useful
	13	The MAEB is helpful in case of rider distraction
	14	The MAEB is not too much intrusive
Fair	1	No comment
Bad	2	Maybe the manual braking could be more effective
	1	The MAEB is very helpful in straight lane, in the other manoeuvres reduce the handling of the vehicle