The future of the Autonomous Emergency Braking for Powered-Two-Wheelers: field testing end-users' acceptability in realistic riding manoeuvres

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Abstract. Motorcycle Autonomous Emergency Braking system (MAEB), is a technology that introduces also on Powered-Two-Wheelers (PTWs) the autonomous braking, which is able to apply autonomously a braking force to reduce impact speed in emergency situations. This system was shown to be possibly effective in reducing numbers of deaths and serious injuries resulting from motorcycle crashes. However, its safe applicability on standard vehicles and the acceptability among end-users has still to be proven. The goal of the study presented in this paper is to assess the acceptability and the controllability of automatic braking events deployed in realistic riding manoeuvres. Field tests were conducted involving 55 common riders as participants on three test vehicles: a naked motorcycle, a sport touring motorcycle and three-wheels scooter. The automatic braking was tested in four riding manoeuvres (straight-lane, lane-change, slalom, and curve) deployed remotely by an investigator at a travelling speed of 35-50 km/h. The system was tested with the higher levels of interventions tested so far by common users and more than 1100 interventions were recorded. The results of this study will allow having a new understanding on the limits of MAEB system.

1. Introduction

Globally, road traffic injuries are the 8th leading cause of death with more than 1.3 million deaths. Focusing on the vulnerable road users, the Powered-Two-Wheelers’ (PTWs) users represent 28% of all deaths [1]. In recent years, based on the successful impact of active safety systems on four-wheeled vehicles, numerous researches have been conducted on active safety systems for motorcycle. [2]. Motorcycle Autonomous Emergency Braking (MAEB), a system which autonomously deploys a braking force to reduce pre-crash speed or even prevent crashes, has been identified as one of the most promising. Regarding the applicability of the Autonomous Emergency Braking (AEB) on PTWs, some concerns remain about the safety of its intervention, its influence on vehicle dynamics and its interaction with the rider.

In order to maximise safety conditions in motorcycle braking manoeuvre, studies were conducted on identify optimal braking model [3,4], assess the braking skill of riders in hard braking or pseudo-emergency braking [5][6] evaluate rider stability in manual braking [7,8] or identify the capabilities of
the advanced braking systems, such as Anti-Lock Braking System (ABS), Combined Braking System (CBS) or Enhanced Braking System (EBS) [9,10]. Furthermore, riders' behaviours have been analysed when a motorcycle safety system (Frontal Collision Warning, FCW) is triggered in a rear-end collision scenario [11]. Due to the complexity of the PTW's dynamics, the development and implementation of an AEB on motorcycles require specialised and groundbreaking researches on the MAEB system. In the literature, the main efforts to evaluate the applicability of the MAEB have been focused on assessing MAEB benefits via crash reconstructions and identifying riders’ reaction to Automatic Braking (AB) with field and laboratory tests involving participants [2]. Regarding tests with participants, early research was conducted in laboratory thanks to a motorcycle mock-up mounted on an accelerating sledge that made the riders try automatic braking up to 0.3 g [12]. Meanwhile, the first field tests were carried out with experimental PTW ridden by professional riders. In these tests, the PTW was equipped with an obstacle identification system (laser-scanner) that triggered the automatic braking close to an artificial obstacle [13–15]. Afterwards, tests were performed with common riders where the AB interventions were carried out using the so-called “Wizard of Oz” approach to reduce the level of predictability. While the participants were riding the motorcycle in the test track, the investigator deployed unexpectedly AB events via remote control with decelerations of the vehicle up to 0.2 g [16]. Recently, field tests were conducted with professional riders testing undeclared AB interventions with increasing deceleration till 0.7 g and deceleration ratio up to 1.2 g/s [17]. Hence, all studies conducted previously seem to suggest that no dangerous conditions are generated when MAEB is activated during a straight ride with decelerations down to 0.3 g with common PTW users.

Nevertheless, a preliminary study on MAEB benefits assessment suggested that these deceleration level and deceleration ratio (jerk) may be underperforming to reduce serious injuries suffered by PTW users in case of crashes [18]. Besides, all experiments have been carried out with PTWs travelling in a simple straight-line motion. In order to increase the range of applicability of the MAEB and identify critical conditions, other scenarios of intervention must be tested with field experiments. Therefore, it is necessary to test the MAEB activations in manoeuvres closer to realistic PTWs pre-crash scenarios and with parameters of intervention more helpful for PTW injuries reduction.

The purpose of this study is to extend the MAEB applicability range by testing new parameters of intervention (deceleration and jerk) in a more realistic pre-crash scenario. To achieve this objective, the acceptability of MAEB by end-users and vehicle handling during undeclared AB activations will be assessed. The results of this study will provide new MAEB working parameters that will have a tangible impact in the reduction of serious injuries for PTWs users.

2. Methods
In the preliminary stage, the literature review on MAEB system and pilot tests were carried out simultaneously. In the analysis of the literature, both field tests experiments and studies on the MAEB benefits identified through simulations have been analysed [19]. Through this approach, it was possible to define original MAEB working parameters, intervention scenarios and manoeuvres that were both safe to be tested and effective in reducing injuries. To validate parameters and manoeuvres, extensive pilot tests were conducted with an experimental motorcycle equipped with prototype AB [19] ridden by researchers and skilled riders. Moreover, the pilot tests made it possible to identify the risks of the experiment and adopt the appropriate security precautions. Finally, a field test procedure was defined based on the guidelines carried out in a previous study [20].

Consequently, the study obtained ethical approval by the Ethics Committee of the University of Florence (Written opinion N. 46, 20/03/2019) to be executed with volunteer participants. The criteria of the participants who could take part in the experiment were to be an active rider with license by 2 years or 10000 km travelled and aged between 20 and 65. To obtain a stratified sample of participants, the volunteers were recruited through the university web page, social media, flyers and bikers groups.

In the field tests were involved three experimental vehicles, reported in Figure 1. The first vehicle was a Ducati Monster 821, a naked motorcycle equipped with standard ABS (Anti-lock Braking System), and an 821cc double cylinder engine. The second vehicle was a Ducati Multiistrada 1260S, a
sport-touring motorcycle equipped with Bosch ABS combined braking, four-stroke engine with a displacement of 1262 cm³ and semi-active suspensions. To prevent the vehicle from lateral falling during manoeuvres involving lateral dynamics, these two vehicles were provided with outriggers. Along with these two motorcycles, a two front-wheels scooter was equipped for the field tests. The vehicle was a Piaggio MP3 Business 500 with 500cc automatic power transmission and ABS independently actuated by hand levers. The intervention of AB was tested in straight-line and lane-change manoeuvre with all the vehicles (naked motorcycle, sport-touring motorcycle and two-front wheels scooter from now on called Monster, Multistrada and MP3 respectively). For the lateral manoeuvres, such as slalom and curve, the vehicles used were Monster and Multistrada and they were equipped with outriggers.

![Test vehicles: Ducati Monster 821 (top-left), Ducati Multistrada 1260 (top-right) and Piaggio MP3 500 (down).](image)

The vehicles were equipped with three different Automatic Braking (AB) devices capable to remotely brake each vehicle with a nominal deceleration of 0.3g ± 0.5g. For the fade-in jerk, the AB devices installed on the motorcycle (Monster and Multistrada) were configured to perform nominal jerk of 1.5 g/s. Instead, the MP3’s device was set to provide two different nominal fade-in jerks, 1.5 g/s and 2.5 g/s. As presented in a previous study, a remote controller has been used to activate the AB device [19].

During the tests, vehicle data (throttle, brake pressure, steering angle, vehicle tri-axis acceleration, gyro, etc.) were recorded from PTW’s CAN-bus. In addition, the recording unit was equipped with an internal tri-axis accelerometer and a GPS receiver for recording the position of the vehicle in the test track area. The movement of the rider’s body has been recorded with an action camera “GoPro Hero 4 Black” installed on the top case for Multistrada and MP3 or the backseat for Monster. Moreover, a second action camera “GoPro Hero 4 Black” was mounted on the right outrigger (see Figure 2) for Multistrada and Monster to document riders’ movement from right-side in case of AB intervention.
The riders’ body movement was also recorded with an *Inertial Measurement Unit* (IMU) that was fixed on the back of the participants. Finally, questionnaires were created to collect subjective data from the participants regarding their opinion on the tests, on the AB tested interventions and the vehicle behaviour during AB triggering in all the four manoeuvres.

The tests were performed in two different flat areas closed to traffic during the daytime (see Figure 3). The velocity range of the AB tested interventions were from 30 km/h to 60 km/h depending on the manoeuvres. Regarding the activation scenarios, the AB was tested in straight-line riding, lane-change, slalom and curve. The experiment was started with a brief explanation of the test to the participant from an investigator. In the second phase, the participant was free to ride the vehicle in the test track in order to familiarise with the test vehicle and the track for about ten minutes. Thereafter, the investigator required the participant to perform five manual braking at increasing deceleration levels in a straight-line trajectory that will be used to assess her/his motorcycle control skills. In the following phase, the participant tested few declared AB interventions in straight-line to familiarise with the system.
After that, the participant tested the AB interventions in unexpected conditions while she/he rode the vehicle along the test track. In fact, in these sessions, the AB activations were triggered remotely by the investigator when the rider was performing the manoeuvres located on the test track. For all the vehicles, the order of activations in the distinct manoeuvres was pseudo-random with an average frequency of one activation every 100s of riding time. The sequences and the number of activations were not previously communicated to the participants to minimise the learning effect and to obtain as many unexpected activations as possible. Before every session, the investigator communicated at the participant which level of deceleration and manoeuvres she/he will test in that phase and the participant could choose in what conditions she/he wanted to test the AB. Moreover, in the case of wet surfaces, the set of activation was reduced in order to ensure safe conditions for the participants. In the Monster and Multistrada tests, the participants tested the AB in two phases with two different levels of deceleration (0.3g and 0.5g) and a unique fade-in jerk (1.5g/s) while the participants performed all the manoeuvres (straight-line, lane-change, slalom and curve). For the test with the MP3, the participants tested two manoeuvres (straight-line, lane-change) in four phases where the AB working parameters were a combination of two levels of deceleration (0.3g and 0.5g) and two levels of jerk (1.5 g/s and 2.5 g/s). To obtain immediate subjective evaluations of the test, at the end of each session the participant filled in a questionnaire and had a short interview with the investigator.

3. Results

3.1. Test participants
Among all eligible candidates, 55 participants (10 females, 45 male) were selected to perform the experiment. The sample (see Figure 4) was stratified considering age, gender, level of education, riding experience, frequently used vehicle type and opinion regarding safety systems. Furthermore, every participant owned at least one PTW (various type) and rode it at least on a weekly basis. Considering the participants selected to test the Monster, most of them used their PTW mainly for commuting and or for work. Regarding the Multistrada participants, the majority of riders owned a motorcycle as the main vehicle and rode it for leisure, travel or sport reason. By contrast, a lower group rode a PTWs primarily for commuting and or for work. For the MP3 tests, the selected participants used PTWs mainly for moving in the urban area.

![Participants age distribution](image_url)

**Figure 4.** Participants age and gender for Monster, Multistrada and MP3 tests.
3.2. Characteristics of the tested Automatic Braking interventions

As previously mentioned, before every test session where AB interventions were deployed pseudo-randomly and unexpected, each participant had to authorise the manoeuvres where the system could be triggered remotely by the investigator. Indeed, few participants required to test declared AB activations before testing them unexpected, but all of them authorized to perform the tests with all the manoeuvres. The fact that all the participant agreed to test the AB interventions unexpectedly in the different manoeuvres is the first important result of this study. A summary of AB tested activations for the three test vehicles is reported in Table 1.

Table 1. AB activations divided by test vehicle, deceleration level and fade-in jerk.

| PTW                  | Manoeuvre     | Reference speed [km/h] | Nominal deceleration [g] | Nominal fade-in jerk [g/s] | Participants | Unexpected AB for each participant |
|----------------------|---------------|------------------------|--------------------------|-----------------------------|--------------|-----------------------------------|
| Ducati Monster 821   | Straight-line | 45                     | 0.3                      | 1.5                         | 35           | 2                                 |
|                      | Lane-change   | 40                     | 0.3                      | 1.5                         | 35           | 2                                 |
|                      | Slalom        | 35                     | 0.3                      | 1.5                         | 35           | 2                                 |
| Ducati Multistrada 1260S | Curve      | 35                     | 0.5                      | 1.5                         | 35           | 2                                 |
|                      | Straight-line | 45                     | 0.5                      | 1.5                         | 35           | 2                                 |
|                      | Lane-change   | 40                     | 0.5                      | 1.5                         | 35           | 2                                 |
|                      | Slalom        | 40                     | 0.5                      | 1.5                         | 35           | 2                                 |
| Piaggio MP3 500      | Straight-line | 40                     | 0.3                      | 1.5                         | 20           | 2                                 |
|                      | Lane-change   | 40                     | 0.3                      | 1.5                         | 20           | 2                                 |
|                      | Straight-line | 40                     | 2.5                      | 3                           | 20           | 2                                 |
|                      | Lane-change   | 40                     | 2.5                      | 3                           | 20           | 2                                 |

For the tests involving motorcycles (Monster and Multistrada), the AB interventions were performed in four manoeuvres: straight-line, lane-change, slalom and curve (see Figure 5). The sessions with AB unexcepted interventions were executed with two nominal levels of deceleration (0.3 g and 0.5 g) and a single level of jerk (1.5 g/s). In particular, the AB interventions in the curve was performed for all the participant with a right-hand curve and a left-hand curve to reduce the influence their riding style. Regarding the familiarization with the test vehicle and the track, all the participants were capable to rode along the test track and performed the manoeuvres at the indicated speeds range (30-50 km/h). The test procedure was successfully completed with all the participants and, globally, it was recorded more than 700 AB unexpected interventions distributed between the two sessions and the four manoeuvres.
In the MP3 tests, the manoeuvres to be tested were limited to straight-line and lane-change and the outriggers were not necessary as there was a lower risk of lateral fall. It has been chosen to restrict the experiment to these manoeuvres in order to focus mainly on the evaluation of the influence of different levels of fade-in jerk. The MP3 test protocol has been designed to test the same nominal levels of deceleration as the motorcycle tests (0.3 g and 0.5 g). In addition, the AB interventions were tested with two different fade-in jerk levels (1.5 g/s and 2.5 g/s) in separate test sessions. Globally, the AB unexpected interventions were tested in four sessions where the AB working parameters were a combination of the two levels of decelerations and two levels of fade-in jerk. All the MP3 test participants successfully performed the full protocol except for those who tested the shorter protocol due to wet asphalt. Overall, the manoeuvres were carried out close to the nominal speed (40 km/h) with slight variations due to participants riding style. At the end of the MP3 tests, the AB unexpected activations were triggered almost 400 times distributed in the two manoeuvres with the four combinations of deceleration and fade-in jerk.
In Figure 7 are reported an example of AB intervention deployed in straight-line manoeuvres with the prototype AB designed for the Monster [19].

![Figure 7](image.png)

**Figure 7** Example of AB activations in straight-line manoeuvres (Monster test).

The AB deceleration profile chosen is the so-called “ramp profile” [17] in which three different phases can be identified. The first phase is called “fade-in ramp” where the AB device was able to apply a braking force in order to obtain a constant jerk and reach the nominal deceleration. The fade-in jerk was nominally set up to produce 1.5 g/s for Monster and Multistrada while the MP3 tests were performed with two nominal values, 1.5 g/s and 2.5 g/s. The central sector of the AB intervention was kept at a constant level of deceleration (corresponding at the target deceleration) and the time of intervention was around 1 s. After the constant deceleration phase, the AB device was designed to reduce the braking force and produced a fade-out jerk of 1.5 g/s. All the three AB devices mounted on the test vehicles was able to produce this type of deceleration profile although each system was developed differently with slightly distinct approaches.

### 3.3. Automatic Braking assessment

At the end of the test, each participant gave their subjective evaluation of the test and the AB tested interventions through a questionnaire specifically prepared for the experiment. The assessments obtained by all 55 participants are shown in the bar chart reported in Figure 8. Globally, a high number of participants (49/55) positively assessed the tested AB interventions. In detail, the AB system was rated as excellent by 10 participants (18%), very good by 18 (33%) and good by 21 (39%). The AB system was neutrally rated (fair) or negatively (bad) by 3 participants (5%). Comparing the different test vehicles, not significantly difference can be observed in the assessments of the participants. Although some feedback was negative, the test was completed by all 55 participants and no AB tested interventions generated dangerous circumstances. In addition, the investigator did not have to interrupt the test of any participants for inadequate behaviour during the test.
4. Discussion

This paper presents a study focusing on the Motorcycle Autonomous Emergency Braking (MAEB). Fifty-five common riders tested pseudo-unexpected automatic decelerations deployed via remote control by an investigator on three different vehicles, a conventional street style motorcycle, a sport-touring motorcycle and a two-front-wheels scooter. This large sample size of participants was stratified by age, gender, level of education, rider skills ability, main PTW used and opinion on motorcycle advanced assistance systems. Despite the large number of riders that took part of the tests, this sample may not be entirely representative of all PTW user populations.

The Automatic Braking (AB) interventions were deployed remotely by an investigator, an approach previously used to experiment MAEB function in field tests [16]. The test protocol was developed to test the AB with pseudo-unexpected activations while the participants performed four manoeuvres (straight-line, lane-change, slalom and curve). Regarding the AB working parameters, two nominal levels of deceleration (0.3 g and 0.5 g) and two distinct fade-in jerks (1.5 g/s and 2.5 g/s) were tested. The AB deceleration profile selected for this study was the so-called “ramp profile”, a profile which was previously tested by professional riders who judged it manageable and safe for common riders [17]. The two deceleration levels and the two fade-in jerks were tested to assess the feasibility of new working parameters of MAEB that could improve safety for PTW users without increasing risks for participants who take part in the tests. All the participants were able to complete the experiment and there were never verified unsafe conditions, either for the riders or the investigators. Overall, few participants asked to test expected AB intervention before starting the session with unexpected AB intervention. Despite this request, no participant declined to perform the session where the AB intervention was deployed unexpectedly in the manoeuvres included in the test protocol.

Overall, the AB interventions were tested more than 1100 times distributed among the manoeuvres and sessions defined by the test procedure. In addition, the manoeuvres were carried out by the participants with a range of velocities consistent with the nominal one defined in the test protocol. The participants' feedback on the test and the system were largely positive. In fact, the 90% of participants (49 riders) rated positively (excellent, very good or good) the tested AB system while 5% (3 riders) judged them as negative.
5. Conclusion
In the experimental field testing presented in this paper, automatic braking interventions on powered-two-wheelers have been intensively tested with the largest sample of common riders so far. Thanks to the analysis of the collected data, it will be possible in the near future to deeply investigate the acceptability and the feasibility of the Motorcycle Autonomous Emergency Braking (MAEB). This will allow to develop a safety system which can have a strong impact on the reduction of fatalities and severe injuries for PTWs’ users. Moreover, the consistent and repeatable test protocol employed in these tests, which is the result of an intensive pilot test programme carried out by the authors, can be used as a benchmark for future activities on motorcycles active safety systems.

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