TITLE: Autonomous Emergency Braking system for Powered-Two-Wheelers: testing end-user acceptability of unexpected automated braking events deployed in typical pre-crash trajectories

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ABSTRACT

Research question / Starting point for investigation:

One of the emerging technologies in road vehicles safety is Autonomous Emergency Braking (AEB), which applies autonomously a braking force to reduce impact speed in pre-crash conditions. Some studies showed that motorcycle AEB (MAEB), could be very effective and reliable in reducing serious consequences of Powered-Two-Wheelers (PTWs) accidents. The main issue before the introduction of MAEB on standard vehicles is related to the acceptability of the system to end-users and the controllability of the vehicle.

This study, organized within the EU funded project PIONEERS, wants to assess with common users the acceptability and the controllability of MAEB, deployed in realistic pre-crash scenarios and avoidance manoeuvres.

Methods:

Field test involved common riders on two test vehicles (a scooter and a tourer motorcycle style) equipped with MAEB functionality. The intervention was triggered in the speed range 35-50 km/h during riding manoeuvres: straight path, lane-change, slalom (meant to mimic traffic filtering), and curve. The participants rode in a circuit; MAEB was activated via remote control unexpectedly at random times. The tested decelerations and jerks were nominally 3 m/s^2 and 5 m/s^2, and 15 m/s^3 and 25 m/s^3 respectively.

Results:

A total of 51 participants took part in the study, each one riding one of the two vehicles; MAEB was activated more than 900 times in different conditions. Participants reported that they were always able to manage the interventions and control the vehicle with minor effort in straight activations and moderate effort in lateral manoeuvres.

Impacts / Effects / Consequences:

This study investigated the acceptability of MAEB among end-users. Results indicate that the conditions of safe intervention of MAEB may be broader than riding along a straight path. Also, the higher levels of tested deceleration turned out to be safe and acceptable by end-users, suggesting that MAEB intervention could be more effective than what was assessed assuming more conservative decelerations.

KEYWORDS: Motorcycle, Scooter, Active safety, Autonomous emergency braking, Feasibility tests, Rider acceptability

1 Introduction

The worldwide growing diffusion and usage of Powered-Two-Wheelers (PTWs) is linked with an increasing burden of the PTWs users' crashes (WHO, 2018). In order to mitigate injuries and reduce fatalities among this vulnerable road users, in recent years researchers worked to develop on motorcycles the Autonomous Emergency Braking (AEB) system, available on four-wheeled vehicles that are inherently more stable than single-track vehicles. This technology, which is capable to reduce pre-crash speed or even prevent crashes by autonomously deploying a braking force, showed great efficacy and reliability among passengers cars and trucks (Fildes et al., 2015). The main concerns related to AEB application on motorcycles and generally PTWs (MAEB), are related to its interaction with the rider and the safety of its intervention.

Previous research on motorcycle braking to increase safety has focused mainly on optimal braking models (Cossalter et al., 2004; Sharp, 2009), braking performance of riders during hard braking or pseudo-emergency braking (Davoodi and Hamid, 2013; Huertas-Leyva et al., 2019), rider stability (Gail et al., 2009; Huertas-Leyva et al., 2020) or assessment of the effectiveness of advance braking systems such as anti-lock braking systems, combined braking systems or braking enhancing systems (Anderson et al., 2010; Dinges and Hoover, 2018). At the same time, riders' reactions to a frontal collision warning in a rear-end collision scenario have also been studied (Biral et al., 2010). Nevertheless, to develop and implement AEB on motorcycles, comprehensive and specific research on MAEB providing new insights is required. Early research focused on assessments of MAEB benefits via crash reconstructions and field tests to evaluate rider stability during the deployment of Automatic Braking (AB), involving PTW prototype systems and participants (Savino et al., 2020). The first study focusing on field testing MAEB was conducted in 2010 involving professional riders with a PTW equipped with a laser-scanner and producing automatic decelerations in correspondence with a target obstacle (Giovannini et al., 2013; Savino et al., 2012). A following study, in order to reduce the level of predictability of AB tested by participants, was carried out testing AB with decelerations of the test vehicle up to 0.2 g deployed unexpectedly via remote control (Savino et al., 2016). The latest experiments were conducted with professional riders testing undeclared AB events with decelerations up to 0.7 g and jerk up to 1.2 g/s (Merkel et al., 2018). In conclusion, the results of these studies suggest that automatic decelerations greater than 0.3 g can be managed by common riders in straight-line motion.

However, some preliminary studies which analysed the effectiveness of MAEB suggested that these working parameters and conditions may not be sufficient to reduce the likelihood of sustaining serious injuries in case of crashes (Piantini et al., 2019). Moreover, the scenarios other than the simple straight-line motion which are currently untested need to be evaluated to better understand the possible risks and possible applications of MAEB. It is therefore crucial to test the applicability of MAEB in a broader range of manoeuvres more representative of the PTWs pre-crash scenarios and with more effective parameters of intervention.

The goal of this study is to evaluate both the acceptability of the MAEB among end-users and the controllability of the vehicle during AB activations in more realistic pre-crash scenarios and with higher levels of deceleration and jerk than those tested in previous studies. The results of this study will allow extending the field of applicability of MAEB in conditions which are relevant to improve the safety of PTWs users.

2 Methods

This study obtained ethical approval by the Ethics Committee of the University of Florence (Written opinion N. 46, 20/03/2019). The participants were recruited among active riders characterized by two years or 10000 km of riding experience and aged between 20 and 65. The advertisement for the participants' recruitment was disseminated through the university web page, social media, flyers and biker groups.

Two test vehicles were involved in this study. The first vehicle was a Ducati Multistrada 1260S, a sport-touring motorcycle equipped with Bosch ABS (Anti-lock Braking System), combined braking, four-stroke engine with a displacement of 1262 cm^3 and semi-active suspensions. This motorcycle was provided with outriggers to prevent the vehicle from lateral fall. The second test vehicle was a Piaggio MP3 500, a two-front-wheels scooter with automatic power transmission, brakes with ABS independently actuated by hand levers. Both test vehicles (sport-touring motorcycle and two-front wheels scooter, from now on called Multistrada and MP3 respectively) were employed to test the intervention of AB in straight-line and lane-change manoeuvre. In addition, the intervention of AB in lateral manoeuvres such as cornering and slalom was tested with the sport-touring motorcycle (Multistrada) that was equipped with outriggers.

The two test vehicles were provided with two different Automatic Braking (AB) devices, which were able to brake each PTW with nominal values of deceleration of 0.3 and 0.5 g. The AB devices were set to provide a nominal fade in-jerk of 1.5 g/s for the Multistrada and 1.5 and 2.5 g/s for the MP3. The ABs were triggered manually by an investigator using a remote control (Lucci et al., 2019). Both test vehicles are shown in Figure 1.

Figure 1 – Test vehicles: Ducati Multistrada 1260 (left) and Piaggio MP3 500 (right)

The two vehicles were provided with a similar data acquisition system, able to record signals from the PTWs' CAN-Bus (throttle, brake action, steering angle, vehicle tri-axis acceleration and gyro). The recording unit was also provided with a second tri-axes accelerometer and GPS receiver to record position during the field tests. Both test vehicles were provided with a "GoPro Hero 4 black" action camera placed on the top cover of the top case, to record the driver's body and at the same time provide an environmental overview of the ride. The Multistrada was also provided with a second "GoPro Hero 4 black" placed in a lateral position on the right-side extension arm (see Figure 2). The aim of this camera was recording the rider from the right side and monitor his/her behaviour during the AB.

Figure 2 – Action camera view on Multistrada: Back position (left-side), Right side position (right-side)

Moreover, an Inertial Measurement Unit (IMU) was attached on the back of the participants to record the chest movement during the tests. In order to collect subjective data, questionnaires were adopted to ask participants their opinion on the test, on the tested AB system and the controllability of the vehicle during the AB activation in the different manoeuvres.

The field test procedure to test the AB with the two test vehicles was developed based on a test protocol of a previous study (Savino et al., 2016) and a work of pilot testing and literature review carried out by authors (Lucci et al., 2020). For both vehicles, the tests took place in a flat area closed to traffic only during daytime hours (see Figure 3). The AB interventions were tested at different velocities ranging from 30 km/h to 60 km/h (depending on the requested manoeuvres) in conditions that included the following: straight-line riding, lane-change, slalom, cornering. After a brief explanation of the test, the participants were free to ride the PTW in the test track for about ten minutes, in order to familiarize with the vehicle (especially if it was provided with outriggers) and the track. After that, the participants were required to perform five manual brakings in straight-line conditions with increasing decelerations. Before testing the AB in unexpected conditions, the participants also experienced a familiarization with the AB system, consisting of deploying declared AB interventions in straight-line.

Figure 3 – Test area: Ducati Multistrada 1260 (up) and Piaggio MP3 500 (down)

Finished the familiarization session with the PTW and the AB, the participants tested unexpected AB in different phases. In these sessions, the participants rode along the test track and the AB activations were manually triggered by one investigator via remote control. The AB was triggered only when the PTW was in precise spots of the track while the participants were performing the specific manoeuvres. For the Multistrada the test included two phases with a nominal value of deceleration of respectively 0.3 g and 0.5 g and fade-in jerk of 1.5 g/s^2 tested in four manoeuvres (straight-line, lane-change, slalom, and curve). For the MP3 the test included four phases to test a combination of two levels of deceleration (0.3 g and 0.5 g) and two levels of fade-in jerk (1.5 g/s^2 and 2.5 g/s^2), tested in two manoeuvres (straight-line and lane-change). For both vehicles, the AB was deployed in the different manoeuvres with a pseudo-random order and with an average frequency of one activation every 100 s of riding. The participants were not aware of the sequence of activations or the timing. This approach was devised to obtain AB events that are as unexpected for the rider as possible while keeping a low learning effect.

In case the road surface was not completely dry, a reasonable subset of the planned activations was performed in order to guarantee the execution of the tests in safe conditions for the participants. In any way, before each test session started, the set of AB interventions (i.e., the type of manoeuvres and level of deceleration) was disclosed to the participant and each participant was allowed to choose under what conditions to test the AB or not. At the end of each test session, the participant had a short break and was required to fill in a questionnaire.

3 Results

3.1 Test participants

Fifty-one participants (10 female, 41 male) were included in this study testing only one of the two test vehicles (see Figure 4). The age of participants ranged from 21 to 59 years and they were characterized by different levels of education and a broad range of riding experience. All the participants included in the tests owned at least one PTW and rode it at least on a weekly basis. The majority of participants selected to test the Multistrada used their own PTW mainly for leisure, travel or sports reasons and a lower percentage used PTWs mainly for commuting and or for work. On the contrary, among the participants selected to test the AB intervention on the MP3, most of the participants used PTWs mainly for commuting.

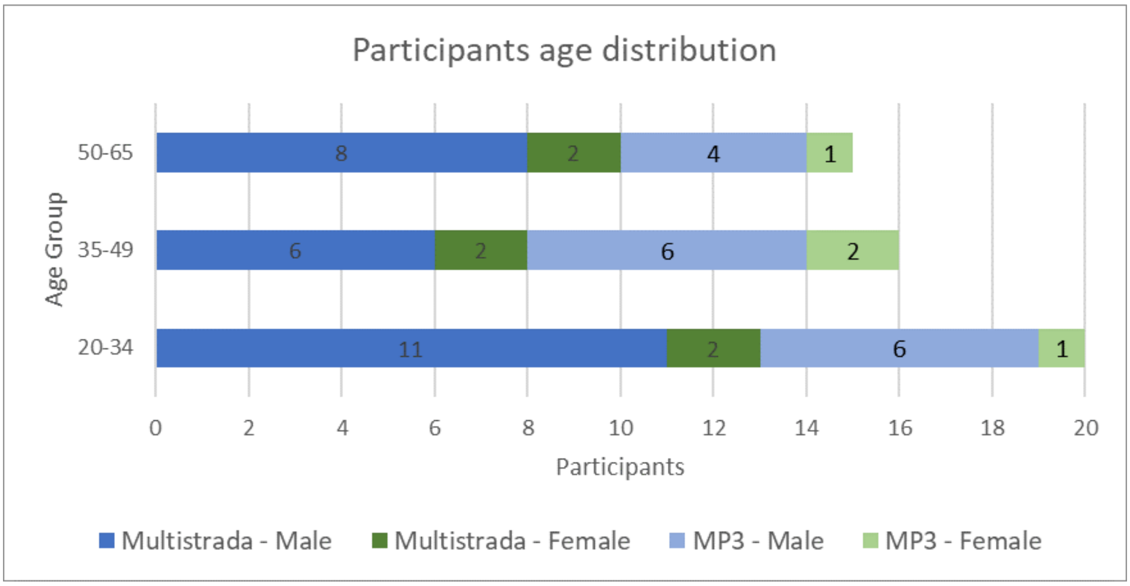

Figure 4 – Participants age and gender distribution for Multistrada and MP3 tests

3.2 Tested Automatic Braking intervention

For both test vehicles, the Automatic Braking (AB) was deployed at pseudo-random times and unexpectedly for the participants in the manoeuvres established with the participants before of every test session. A first important result is that all the participants accepted to test the intervention of the AB unexpectedly in the manoeuvres proposed by the investigator and only a few of them required to test a declared AB intervention in the manoeuvres before testing them unexpectedly. Table 1 shows a summary of the AB tested intervention for the two test vehicles.

Table 1 – Summary of AB tested interventions

PTW	Manoeuvre	Nominal deceleration [g]	Nominal fade-in jerk [g/s]	Reference speed [km/h]	Participants	N° of AB tested
Ducati Multistrada 1260S	Straight-line	**0.3**	*1.5*	45	31	63
	Lane change			40	31	65
	Slalom			35	29	62
	Curve			35	29	115
	Straight-line	**0.5**	*1.5*	45	31	62
	Lane change			40	31	65
	Slalom			35	29	59
Piaggio MP3 500	Straight-line	**0.3**	*1.5*	40	20	42
	Lane change			40	18	34
	Straight-line		*2.5*	40	20	37
	Lane change			40	16	32
	Straight-line	**0.5**	*1.5*	40	20	40
	Lane change			40	18	33
	Straight-line		*2.5*	40	20	39
	Lane change			40	16	33

The participants involved in the test with the Multistrada test vehicle tested the intervention of the AB in four manoeuvres: straight-line, lane-change, slalom and curve (see Figure 5). Due to the weather conditions, not all the participants were involved in testing the AB with all the manoeuvres included in this study. The AB was deployed with two different levels of nominal deceleration, respectively 0.3 g and 0.5 g. The nominal fade-in jerk applied in these tests was the same for all the participants and manoeuvres and equal to 1.5 g/s. The participants executed the manoeuvres in a range of speed from 30 km/h to 50 km/h according to their natural feelings and skills. Overall, the AB was tested with the Multistrada almost 500 times in the different conditions and manoeuvres planned by the test protocol. AB was tested on the curve manoeuvre at the 0.3 g level and sessions included right-hand curve and left-hand curve AB interventions for all participants.

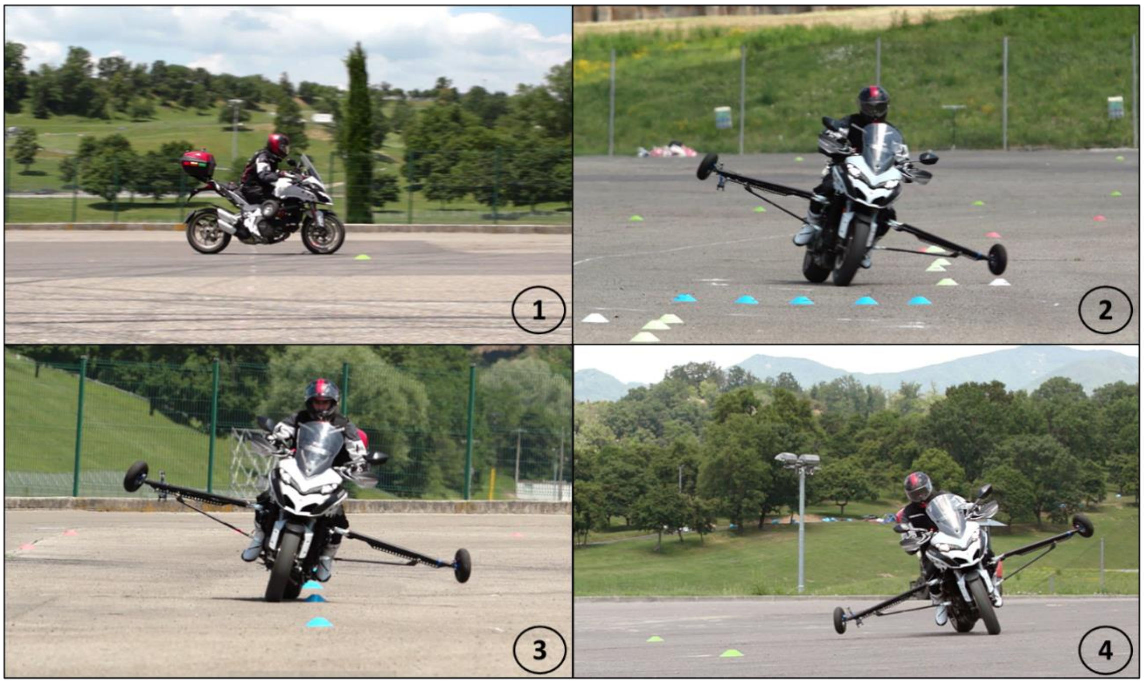

Figure 5 – AB activation on Multistrada in the four manoeuvres: 1) straight-line, 2) Lane-change, 3) Slalom, and 4) curve

Since the MP3 was not provided of outriggers, the participants involved in the test with the MP3 test vehicle tested the intervention of the AB in the two manoeuvres that involved a lower risk of lateral fall: straight line and lane-change (see Figure 6). As with the Multistrada test vehicle, the AB was deployed with two levels corresponding to the nominal deceleration of 0.3 g and 0.5 g. Two levels of nominal fade-in jerk were also tested, respectively 1.5 g/s and 2.5 g/s, each one in a separate test session. Overall, the AB was tested in four test session with different combinations of the two levels of decelerations and jerks. Due to weather conditions, not all the participants were involved in testing the AB in all the manoeuvres and with all the levels of intervention planned for this vehicle. The participants executed the manoeuvres at a nominal speed of 40 km/h with slight variations according to their natural feelings and skills. Overall, the AB was tested with the MP3 almost 400 times in the different conditions and manoeuvres defined by the test protocol for this vehicle.

Figure 6 – AB activation on MP3 in the two manoeuvres: 1) straight -line, and 2) Lane-change

Figure 7 shows a typical intervention of the AB system deployed in straight-line condition. In both test vehicles, the AB system produced a braking pressure profile able to decelerate the PTW following the parameters previously set up. The target level of deceleration was reached with a ramp of deceleration with a constant fade-in jerk, which was nominally 1.5 g/s for the Multistrada and 1.5 g/s and 2.5 g/s for the MP3. The nominal time of intervention in which the system reached the target value of deceleration and the time of intervention at constant deceleration, the so-called time of intervention, was around 1 s. After that, the system executed a reduction of deceleration up to reach the disengagement of the AB with a nominal fade-out jerk of 1.5 g/s. This profile of deceleration reproduced by the AB system, which is called ramp profile, was employed in both test vehicles with slight differences due to different construction of the AB devices.

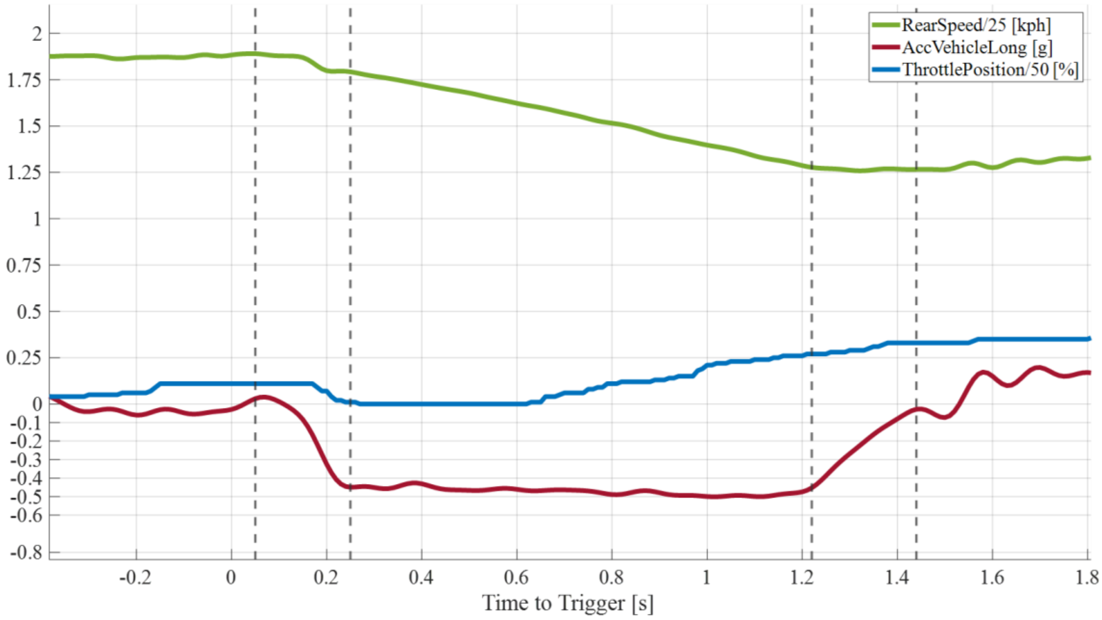

Figure 7 – Example of AB activation in straight-line conditions

3.3 Automatic Braking assessment

At the end of the test, the participants assessed the Automatic Braking system based on the conditions they experimented (see Figure 8). Among the 31 participants who tested the AB intervention with the Multistrada, a very high percentage of participants rated positively the system (excellent 23 %, very good 23 % and good 45 %). Just a very slight percentage of participants (6 %) had a fair opinion concerning the AB system and only one participant (3 %) gave a negative rating of it. Among the 20 participants who tested the AB intervention with the MP3, the trend of ratings was quite similar to the other vehicle. Again, most of the participants rated positively the system (excellent 15 %, very good 40 % and good 30 %) and just one participant (5 %) was indifferent to the AB. Two participants (10 %) gave a negative rating of AB.

Even if after testing the AB there were few negative opinions about it, for both test vehicles all the participants managed to complete the whole test without asking to interrupt the trials due to the intervention of the AB or other reasons. Moreover, no potentially dangerous situations were created by the intervention of the AB nor the participants' behaviour.

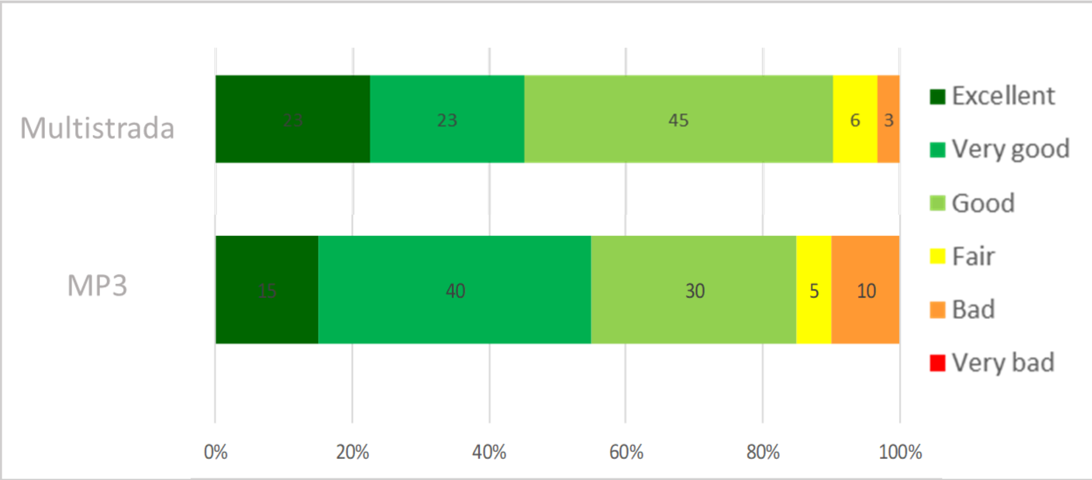

Figure 8 – Participants general assessment of tested AB system for the two test vehicles

4 Discussion

The field tests presented in this paper involved 51 common riders as participants to test pseudo-unexpected automatic decelerations on two different test vehicles, a sport-touring motorcycle and a two-front-wheels scooter. The Automatic Braking (AB) was deployed manually by investigators via remote control employing a similar approach to a previous study (Savino et al., 2016). The intervention of the AB was tested in different manoeuvres (straight-line motion, lane-change, slalom and curve), with two levels of deceleration and two levels of fade-in jerk. This allowed testing the AB in a broad range of working conditions and parameters, which were never tried before.

This study involved the largest sample size of participants (51) among the field research concerning the Motorcycle Autonomous Emergency Braking system (MAEB) so far. The two sub-samples of participants were characterized by wide ranges of ages, sex, riding experience and motivations for riding. However, despite this large sample and the wide variability, the participants involved in this study may not be completely representative of all PTW user populations.

The AB tested intervention was deployed with a ramp profile, which was previously shown to be effective and manageable by expert riders (Merkel et al., 2018). The parameters of nominal intervention (0.3 g and 0.5 g of deceleration and 1.5 g/s and 2.5 g/s of fade-in jerk) tested in this study allow assessing the feasibility of MAEB with common users with the most effective working parameters tested so far, which could be potentially effective in injury reduction in real-world crash conditions (Piantini et al., 2019). The final applicability and feasibility of MAEB with these working parameters will be the results of the analysis of the data collected in this study and will be presented in future papers. This will allow to understand which the optimal working parameters are to introduce the MAEB on standard vehicles. However, a first important result is that the Automatic Braking intervention was tested in these field tests more than 1000 times on two different types of vehicles and by 51 participants, with different levels of intervention and manoeuvres involved. All the participants completed the experiment and agreed to test the intervention of the AB unexpectedly in the conditions proposed by the investigators and no dangerous situation occurred in the context of the deployment of AB.

Concerning the acceptability among end-users of MAEB, the participants expressed generally a positive opinion about the tested system. For both the test vehicles, more than 80% of participants rated positively the Automatic Braking system and just a few of them (one out of 31 with Multistrada and two out of 20 with MP3) had a bad opinion concerning the system, mainly for discomfort reasons rather than for doubts about its safety or effectiveness. Moreover, during the tests, the controllability of the test vehicles by participants during AB interventions was never uncertain and participants were always able to execute the manoeuvres required by investigators. Another important indication that the AB system was positively accepted by participants it is that after testing declared interventions of AB, all the participants accepted to test it unexpectedly in the manoeuvres proposed by the investigators and only a few of them required to test them before as declared one.

Thanks to the contribution of this study and the field tests presented in this paper in the next future will be possible to have a comprehensive understanding on the limits of the feasibility and the acceptability of the Autonomous Emergency Braking system applied on powered-two-wheelers.

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