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Feasibility study of motorcycle autonomous emergency braking system

Doctoral Candidate
Cosimo Lucci

Supervisors
Prof. Giovanni Savino
Prof. Marco Pierini

External Referees
Prof. Brian Fildes
Prof. Matteo Massaro
Dr. Shane McLaughlin

Dean of the Doctoral Programme
Prof. Giampaolo Manfrida

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Abstract

Over the last years, the development of new technologies and active safety systems for on-road vehicles contributed to mitigate the burden of road traffic crashes. This, unfortunately, did not fully apply to Powered Two-Wheelers (PTWs), for which the technological development was slowed down by their complex dynamics, smaller research interests and lower vehicle cost. Despite PTWs have one of the highest rates of crashes per kilometre travelled, their distribution is growing all over the world, thanks to their affordability and their agility in congested traffic environments, causing every year many crashes and fatalities. After the introduction of Antilock Braking System (ABS), which already showed its efficacy in preventing crashes, several studies indicated that Motorcycle Autonomous Emergency Braking (MAEB), which is the PTW derivative of the passenger car Autonomous Emergency Braking (AEB), is the most promising technology to mitigate PTW crashes among those currently in development. This technology, which deploys autonomously a braking action to reduce impact speed when an imminent collision is detected, was shown to be potentially effective and widely applicable in PTW crashes. However, to introduce such a system on standard PTWs, the riding conditions in which it can be applicable and its working parameters must be identified to maximise crash mitigation effects while not reducing PTW controllability and safety. This requires designing MAEB intervention in accordance with riders' capabilities to manage the vehicle in pre-crash conditions.

The present work aimed to investigate the real-world applicability of MAEB and its acceptability among end-users. The goal of this study was to identify pre-crash riding conditions and system intervention parameters which can make MAEB applicable in real-world crashes, accepted by end-users and effective in mitigating injuries. For this purpose, a field test campaign conducted within the EU founded PIONEERS project was carried out, involving 35 participants and two test vehicles provided with automatic braking devices able to simulate MAEB intervention in realistic riding conditions.

The results of this field test campaign, analysed through different publications, indicate the safe applicability of MAEB in conditions representative of real-world riding. The designed MAEB working parameters resulted capable to reduce vehicle speed while guaranteeing the controllability of the PTW with limited effort required to the rider. The end-users who tested the system indicated good acceptability of MAEB encouraging its final development and its implementation on standard vehicles. Finally, the potential benefits of MAEB application in real-world crashes have been estimated through real-world crashes simulations, highlighting the relevant impact of MAEB in terms of injury and fatality mitigation potential.

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List of Abbreviations and acronyms

Acronym	Definition
AB	Automatic Braking
ABC	Active Braking Control
ABS	Antilock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AIS	Abbreviated Injury Scale
ARAS	Advanced Rider Assistance Systems
BSD	Blind Spot Detection
CAN-bus	Controller Area Network Bus
CB	Combined Braking
ECU	Electronic Control Unit
ESC	Electronic Stability Control
EU	European Union
GPS	Global Positioning System
ISR	Impact Speed Reduction
ICS	Inevitable Collision State
IMU	Inertial Measurement Unit
LDW	Lane Departure Warning
LKA	Lane Keeping Assist
MAEB	Motorcycle Autonomous Emergency Braking
MAIS	Maximum Abbreviated Injury Scale
MSC	Motorcycle Stability Control
PCB	Pre-Crash Braking
PPE	Personal Protective Equipment
PTW	Powered-Two-Wheeler
OB	Out of the Blue
TC	Traction Control
VRU	Vulnerable Road User
WP	Work Package

1 Introduction

The constant burden of road crash injuries and fatalities that every year occurs all over the world, has fostered over the last few decades policy makers discussions and scientific research, with the common goal of improving the safety of future transportation systems. The discussion on road safety has contributed in many countries to the introduction of new road safety laws and to the development of a range of new driver assistance systems to reduce the number of crashes that every year cause fatalities and severe injuries. A key role to the increased relevance of road safety issues was played by the road safety philosophy known as "Vision Zero", which was introduced through a Road Traffic Safety Bill and approved in October 1997 by the Swedish parliament [1]. The Vision Zero is an expression of the ethical imperative that "*It can never be ethically acceptable that people are killed or seriously injured when moving within the road transport system*" and therefore put the target that "*eventually no one will be killed or seriously injured within the road transport system"*. The Vision Zero principles changed the approach to road safety: from the conventional cost-benefit assessment, the selection of strategies and measures for improving road safety is now based on the achievement of the optimum state of the road transport system, which allows obtaining the target of zero road fatalities and severe injuries [2]. This new approach to road safety since 1997 has spread among different countries, including the European Union, which in the European Commission's "Strategic Action Plan on Road Safety" set the ambitious road safety plan to reach zero road fatalities by 2050. In order to reach the goal by 2050, the European Commission implemented different strategies to improve road safety, working on "safer vehicles, safer infrastructure, better use of protective equipment, lower speeds and better post-crash care" [3].

For the decade 2021-2030, the EU has set the target of 50% reduction for fatalities and serious injuries by 2030 [4]. Worldwide, this goal was strengthened by the Stockholm Declaration [5], an agreement for further global political commitment in improving road safety published by the Global Ministerial Conference on Road Safety in February 2020.

Despite these efforts in reducing road fatalities and crashes in Europe, the progress is slow, and the burden of road crashes is still very high [3]. In 2019, 22,800 people died in road crashes and around 120,000 people suffered serious injuries with life-changing consequences. This had also a huge economic impact, which was estimated for 2019 to be around 280 billion euros, which mean around 2% of EU GDP. The burden of road crashes is even higher outside Europe, where road traffic injuries are the eight leading cause of death for people of all ages and the first one for children and young adults aged 5–29 [6].

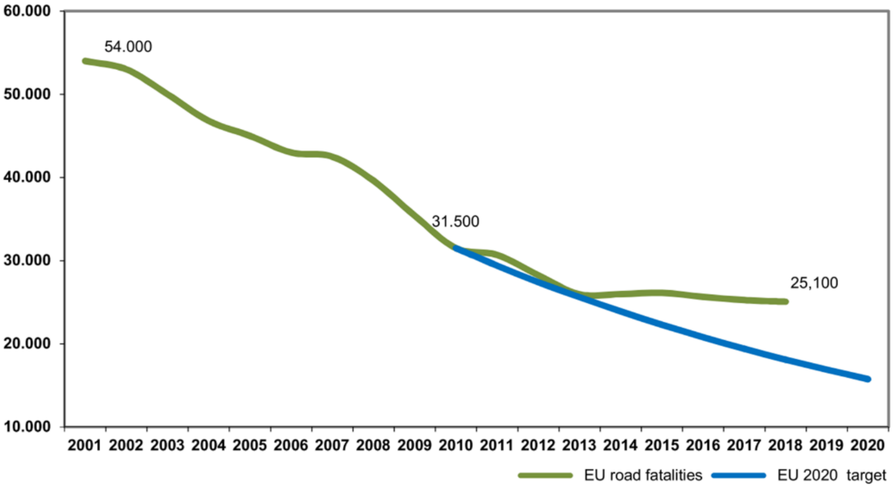


Figure 1 – Evolution of EU road fatalities and targets for 2001-2020 [7]
(Source: CARE - EU road accidents database)

The goals for 2020 in terms of road fatalities reduction will be probably missed (see Figure 1), and to reach the goals set for 2030 all the stakeholders involved in enhancing road safety (policymakers, manufacturers, researchers, and end-users), will have to make an extreme effort to innovate road safety measures and technologies. This is even more critical for motorcycle users, for whom the fatalities reduction in the last decade was smaller than those obtained for other types of road users (see Figure 2). The motorcyclists, and more generally all Powered-Two-Wheeler (PTWs) users, (which include all two- and three-wheeled motorized vehicles such as motorcycles, scooters and mopeds), are considered Vulnerable Road Users (VRUs) because of their high rate of fatalities compared with the number of circulating vehicles. In addition, even if motivations for riding are not the same in different countries [8], overall, PTWs have increased their diffusion year by year, thanks to their affordability compared to cars (reduced fuel consumption, maintenance, and insurance costs) and their ability to move in congested traffic environments and urban areas. Motorcycles are also employed by leisure riders for sport or entertainment. The diffusion of PTWs is even more important in mid- and low-income countries, where the adoption rates are very high (1 every 3 inhabitants in Malaysia and Vietnam [9]), but they are a fundamental means of transportation also in high-income countries, with a fleet of over 34 million vehicles in Europe and 8 million in the US [10] and with increasing trends of adoption (e.g. in Australia [11]).

However, despite the number of circulating PTWs in Europe has rapidly increased in the last decade, the required increase in the safety of this type of vehicle remained limited, and PTWs are consistently considered as a high-risk mode of transport, with a documented higher risk of death and severe injuries associated to crashes for their users compared to those of other vehicles [12].

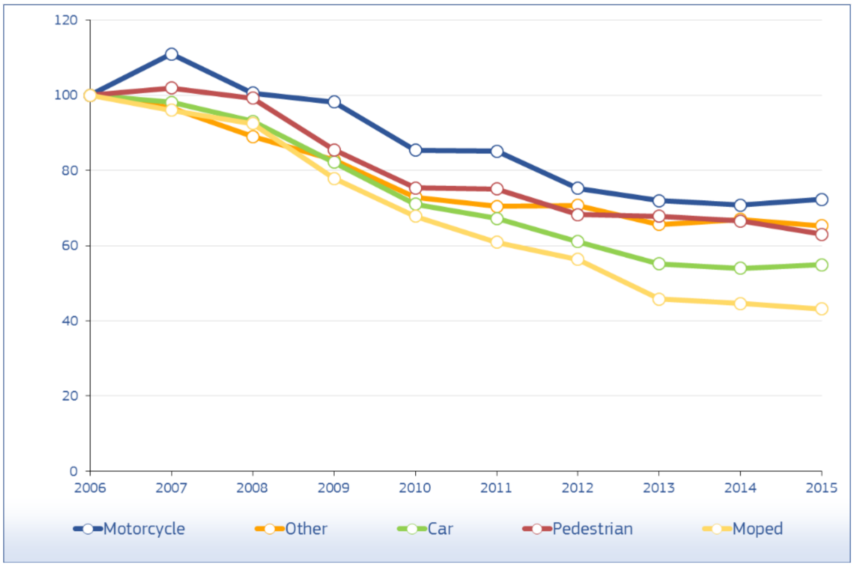


Figure 2 – Index of motorcycle and moped fatalities in Europe compared with other modes of transport [7] *(Source: CARE - EU road accidents database)*

There are several reasons why PTWs are more hazardous than other vehicles: the reduced size of PTWs and their ability to move in between lanes of cars make them less visible and their trajectories less predictable to car and truck drivers. Besides, just because they have only two wheels, PTWs are in some conditions less stable and very demanding for the rider to be controlled compared to cars, requiring the rider body coordination and skilled controls. This is even more relevant in emergency situations, where the ability of riders in swerving or braking can make big differences in avoiding crashes [13]. In fact, PTWs are more vulnerable to wheel sliding and less stable, and therefore the execution of an effective swerving manoeuvre or braking action in an emergency situation requires considerable skills. Furthermore, PTWs and especially motorcycles have powerful engines compared with their weight: this means that they are capable of high acceleration and velocities, which make them potentially more dangerous than other types of vehicles. In addition, PTWs have a smaller size and generally, their structure offers limited protection to the rider against adverse weather conditions or injuries in the case of crashes.

The most popular and sometimes sole protection for riders is the safety helmet [14],[15], which was proved to be an effective device in mitigating head injuries [16]. From a perspective of on-board safety systems, the strategy to mitigate this higher potential risk of crashes and injuries for PTWs is represented by Advanced Rider Assistance Systems: electro-mechanical systems that assist riders employing sensors and cameras to detect nearby obstacles or driver errors in riding and respond accordingly. Four-wheeled vehicles are nowadays provided with many validated Advanced Driver Assistance Systems (ADAS), such as Antilock Braking System (ABS), Electronic Stability Control (ESC), Autonomous Emergency Braking (AEB), Adaptive Cruise Control (ACC), Lane Keeping Assist (LKA), Lane Departure Warning (LDW) or Blind Spot Detection (BSD). Some of these systems showed already in real-world conditions good reliability and efficacy in avoiding or mitigating crashes [17]. Regarding PTWs, even if researchers and PTW manufacturers worked to introduce active [18] and passive [19], [20] safety technologies, the number of on-board safety systems already available is limited: only ABS, which is mandatory in Europe since 2016, and its version working also in a leaning condition called Motorcycle Stability Control (MSC) [21], have been successfully introduced on standard vehicles [22].

The main reason why safety systems for PTWs are less developed and common than in cars and trucks is that the design of an effective and reliable active safety system for PTWs is more complex than for cars. Due to the lower stability of the vehicle and the contribution required to the rider to maintain stability and upright position, the intervention of safety systems must cope also with rider reaction. Even if significant activities were carried out in past years on the development of new safety systems for PTWs, detailed and demanding investigations are required in order to provide standard vehicles with effective solutions for improving PTW users' safety.

Considering all the recent results of the research and the ongoing activities on the development of ARAS to increase PTWs safety, after the introduction of ABS, the most promising technology in mitigating PTW crashes is the Autonomous Emergency Braking (AEB). This system autonomously performs a braking action to reduce impact speed or even avoid crashes when the rider has no time to brake or misses to execute an appropriate braking action due to distraction, perception failures or panic. AEB was successfully implemented in passenger cars and trucks [17], and now it is mandatory in Europe for trucks and buses. The focus of this research project will be therefore the development of the so-called Motorcycle Autonomous Emergency Braking system (MAEB) in order to foster the implementation of the AEB also on PTWs.

1.1 Motivations and goals

After more than ten years of research and many research projects, the open questions are still on whether common PTW users may be able to manage the intervention of the MAEB if deployed with effective working parameters (i.e., high deceleration and fade-in jerk) and in the typical conditions of common pre-crash situations where such system may contribute to reducing the injuries.

The present work aims to investigate the feasibility of MAEB and its acceptability among end-users, assessing the implementation of the highest levels of jerk and deceleration which would allow achieving the largest speed reduction pre-crash conditions. This will allow understanding in which conditions the MAEB can be safely applicable without requiring excessive compensation by a potentially unaware rider and without causing excessive PTW destabilization. This is because, despite the potential benefits that MAEB may have for the improved safety of riders, its activation parameters must be defined in accordance with the rider's capabilities to manage the vehicle, to maximise pre-crash braking effect while not reducing PTW controllability.

The goals of this research project can be summarized as follows:

1) Identification of a range of pre-crash riding condition and system intervention parameters which can be managed by end-users in unexpected activations and therefore applicable for MAEB.
2) Evaluation of the riders' acceptance of the autonomous emergency braking for motorcycles and their reactions at system deployment.

Based on the results of the previous research questions, a further goal was defined during the third year of the project:

3) Assessment of the effectiveness and injury mitigation potential of MAEB

1.2 PIONEERS project

The study presented in this thesis was carried out within the PIONEERS research project, which was funded by the European Union's Horizon 2020 research and innovation programme under grant agreement N° 769054 [23].

The PIONEERS project aims to improve the safety of Powered Two Wheelers (PTWs) through an integrated approach to rider protection considering on-rider and on-board safety systems. Thanks to the improvement of the safety performances and the usage rate of personal protective equipment (PPE) for PTW users, and through the development of new onboard safety systems, the project aims to reduce the number of fatalities and injuries among PTWs users. PIONEERS involves different types of partners: seven universities and research institutes, two industrial partners, four protective equipment manufacturers, two motorcycle manufacturers and one automobile club.

The project, which started in May 2018 and will finish in November 2021, is expected to provide a higher understanding of how to prevent injuries to PTW users and better testing methods enabling better performance assessment for protective equipment. In addition, thanks to the involvement of European manufacturers, the project wants to develop better products (personal protective equipment and on-board systems) in order to achieve an increased safety level of PTW users and improving European competitiveness.

In order to achieve the general goal of improved safety for PTW users, the project was divided in the following six objectives [23]:

1) Prioritizing the most safety-critical accident scenarios and developing methods to identify relevant future safety issues.
2) Developing improved injury criteria to assess the injury risk on the most critical body regions.

3) Designing field-effectiveness driven test methods (virtual and physical) with a high degree of reliability and repeatability to assess current and future safety systems under realistic impact conditions and to provide input to the standardisation groups.
4) Defining the system requirements of the PPEs and on-board safety systems of the future for optimal rider protection.
5) Developing the new generation of PPEs and on-board safety systems (prototypes).
6) Developing advanced design tools and improved products by establishing minimum performance requirements to better inform the final user and to differentiate high-quality European products from products that offer a lower level of protection.

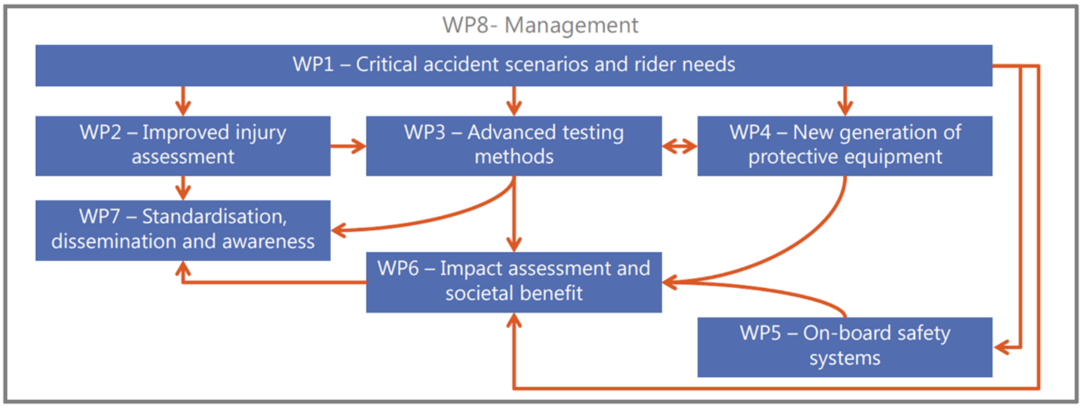


Figure 3 – PIONEERS organization and methodology [23]

In order to accomplish each objective of the project dedicated work packages (WP) were instituted involving a subset of the partners. The present PhD study was carried out within the fifth work package, which had the goal of developing new on-board safety systems, and in particular in the sub-task 5.2 which focused on the MAEB, known in the project as Pre-Crash Braking (PCB). This sub-task had the goal to assess the riders' acceptance of an automatic pre-crash braking system able to reduce PTW speed when the crash is unavoidable and assess their reactions at system deployment. For this reason, a field test campaign involving common riders as participants has been planned in order to investigate the optimal parameters, accepted and validated by riders, to maximise deceleration before impact. At the end of this part of the project, a benefit analysis will be performed in the sixth work package with the results of this task.

In task 5.2 of the PIONEERS project, two partners of the project were involved in the execution of field tests in two different test location: The University of Florence and the Technical University of Darmstadt. At the two sites, the research groups investigated specific features, but in both experiments, the functionality was tested by volunteer participants and a basic set of trials were performed at both test sites in order to allow an integrated data processing. At the University of Florence test site, the tests were planned to involve two test vehicles and a sample of common riders as participants, which required a large research team. For this reason, two researchers (the PhD candidate CL and a postdoctoral researcher) were entrusted with the two parts of the research activity, under the supervision of the scientific responsible. In order to execute all the research activities, the two researchers have been also provided by two groups of research assistants, composed of graduate researchers and undergraduate students.

In this thesis only the activities within the task of the project for which the candidate was responsible will be presented, together with the results obtained by his work and the work of the students whom he coordinated during the project. The candidate was responsible for performing all the preliminary activities including the pilot testing and the definition of the test protocol. Successively he was in charge of setting-up the first test vehicle employed in the field tests and to execute the related field tests with participants. After that, in order to accomplish the requirement of the project, he was responsible for performing the data analysis of the data collected in the field tests with the first vehicle and drafting the related part of the final documentation.

1.3 PhD organization

As mentioned in the previous section, the present work was carried out within the Task 5.2 of the PIONEERS project. The workflow of the research activity was therefore a compromise between the requirements of the research project and the constraints of the PIONEERS project. During the first year, a comprehensive literature review of the research concerning MAEB was carried out, and a first prototype of the test vehicle to be used for the field experiments was developed. During the second year, a pilot testing activity was performed in order to define the test protocol, which obtained the approval of the Ethics Committee of the University of Florence. After that, a second test vehicle was developed thanks to the collaboration with industrial stakeholders within the PIONEERS project, and a field test campaign was carried out involving 35 external participants on the two test vehicles. The third year of PhD was dedicated to the analysis of the data collected during the field test campaign and to drafting publications. In addition, a period of three months was spent at the Monash University Accident and Research Centre, and a further study based on an in-depth database of PTW crashes focusing on the assessment of the potential benefits of MAEB was performed. A diagram representing the workflow of the research activity in the three years of PhD is displayed in Figure 4.

This dissertation wants to present the research activity carried out by the candidate during his PhD. The document was organized as a hybrid paper-based thesis. Some sections will be presented as a conventional thesis, in some cases integrated with conference publications, while others will be composed mainly by peer-reviewed journal publications. Due to the time required for the review process and publication, not all the papers included in this thesis are already published.

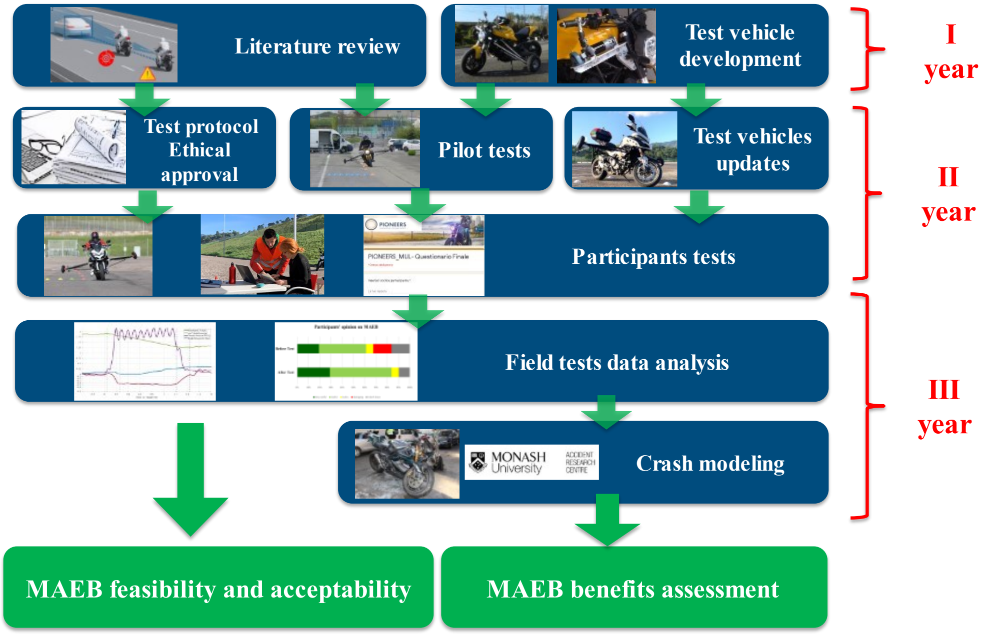


Figure 4 – PhD organization and workflow: the first year was employed to perform the literature review and to develop a first test vehicle; during the second year pilot tests were carried out to define the test protocol and to develop a second test vehicle which was then employed for the test with participants; the third year was dedicated to the field test data analysis to investigate MAEB feasibility and acceptability and to perform a further study to estimate MAEB benefits

The remainder of the document is organised as follows. After this introduction, in the second section of this thesis, the state of the art of the Autonomous Emergency Braking systems for PTWs will be presented. After an overview of the most promising Advanced Rider Assistance Systems (ARAS), a comprehensive summary of previous studies related to both MAEB field testing and MAEB benefits assessment will be presented, highlighting for each one the impact that they had on the following studies and on this research project. In the third section, the methods employed for this study will be described: details regarding the field test campaign carried out for this PhD will be presented, including the test design, the prototype vehicles development, the final test protocol and the recruitment of participants. In the fourth section, the main results of this work will be presented: after a brief description of the field test campaign with participants, two journal publications focusing on the applicability of MAEB in critical conditions will represent the main output of this study. In addition, further results on MAEB applicability and acceptability will be presented. In the fifth section of this thesis, an additional study focused on the assessment of MAEB benefits based on the results obtained in previous sections will be presented. The latter study, which will be presented through a journal publication, was carried out in collaboration with the Monash University Accident and Research Centre of Melbourne, Australia. Finally, the conclusions of the activity and future steps in the research regarding MAEB will be described.

2 Literature review

Active safety systems for PTWs have been in development for the last 40 years in order to improve riders' safety. Some technologies (e.g., ABS) derived from passenger cars or trucks, while others were specifically designed for single-track vehicles (e.g., *anti-wheelie* control). However, though numerous rider assistance systems are currently available on standard PTWs (see Figure 5), only a small number have been shown to have significant impact on riders' safety.

The most effective active safety system currently offered on PTWs is the Antilock Braking Systems (ABS). This technology, derived from four-wheel vehicles, was introduced in the late 1980s to prevent wheel locking during hard braking or in conditions of poor road adherence. ABS was shown to be able to reduce braking distances and allow the rider to maintain better control of the PTW [24], reducing also the chance of capsizing before the crash ('sliding' crashes) [25]. In addition, recent retrospective studies focusing on ABS benefits assessments, highlighted its capabilities to reduce the number and the severity of real-world crashes [22], [26]. Another safety system already available on standard PTWs is Traction Control (TC), which prevents the rear wheel from skidding when the rider increases the throttle of the PTW reducing electronically the torque transmitted by the engine to the rear wheel. In the first stages, TC was designed to improve riders' safety on slippery surfaces, whereas recent developments focused mainly on improving acceleration performances. Nowadays most of the main PTW manufacturers have their own TC system and TC is spread among high-end motorcycle, however, limited evidence is available in the literature highlighting its efficacy in improving safety [18].

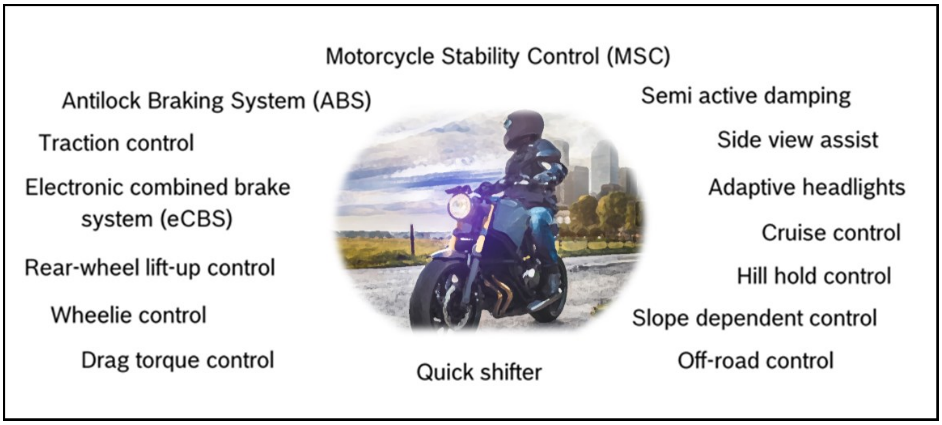


Figure 5 – Rider assistance systems already available

The Motorcycle Stability Control (MSC), which was introduced on standard vehicles in 2013, includes ABS to prevent the wheels from locking, traction control to prevent the rear wheel from spinning and Combined Braking (CB) to ensure optimum distribution of brake force. In addition, the capabilities of the three technologies are extended also in leaning conditions, using roll angle estimations. The MSC, which represents the highest level of safety system available nowadays for PTWs, is therefore able to control the stability of the vehicle by preventing roll and yaw instabilities and avoiding wheel locking. However, in order to obtain this level of safety, several sensors including IMU to obtain roll angle estimations are required [21] and therefore the cost of such system is preventing its diffusion among low-end PTWs. Further studies were carried out focusing on collision avoidance technologies and warning systems (e.g., curve warning), sometimes derived from other applications (passenger cars and trucks). However, most of them are in the early stages of development and it is not predictable when they will be ready for standard vehicles [18].

As mentioned in the introduction, the focus of this research project was the Motorcycle Autonomous Emergency Braking (MAEB) system, also known in the literature as Pre-Crash Braking (PCB). This technology, which is the PTW derivative of the AEB (Autonomous Emergency Braking) system already available and proved to be effective for four-wheels vehicles [17], [27], [28], was shown to be one of the most promising ARAS for improving PTW users' safety [18]. MAEB was shown to be applicable between 37 and 53 percent of the cases of in-depth databases of motorcycle crashes in developed countries [29] and in some conditions, it may achieve impact speed reductions that are likely to reduce motorcyclists' injuries. Concerning the acceptability of MAEB among end-users, an early study based on survey data involving 6297 respondents from over 10 countries [30], [31], highlighted that the overall acceptability of ARASs is lower compared to the equivalent acceptability of the systems installed on passenger cars (ADAS). The differences between riding a PTW and driving a car, both in terms of motivations and physical differences between the two types of vehicle, influence the feasibility, effectiveness and affordability of assistance systems. However, emergency braking assistance systems were considered (as early as in 2012) one of the most useful safety functions for PTWs.

This system reduces the PTW pre-crash speed applying autonomously a braking force when the impact with another vehicle, pedestrian or other obstacle encountered on the road is identified as forthcoming. If the system is designed to be deployed when the crash is unavoidable, it can only reduce impact speed (the so-called Pre-Crash Braking – PCB). On the contrary, if MAEB is triggered before the crash is unavoidable, it can bring greater benefits compared to the sole impact speed reduction. In summary, the primary aim of this system is to reduce the PTW speed to mitigate injuries sustained by the user, but in the future, this system may also be able to avoid crashes.

In the following subsections, the state of the art regarding MAEB relevant to the research questions of this project will be presented. Previous studies focused mainly on four aspects:

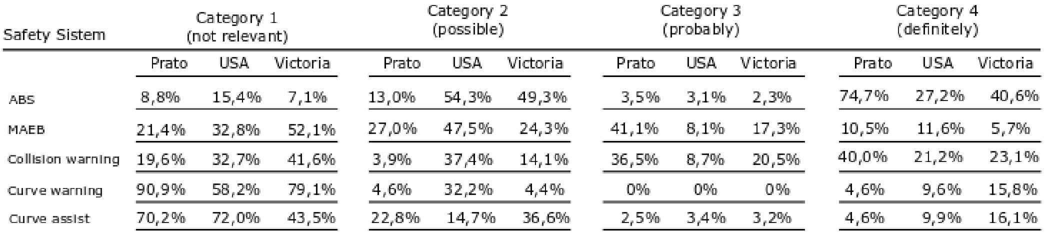
1. Assessing MAEB applicability in real-world crashes.
2. Defining MAEB triggering algorithms.
3. Field testing MAEB with volunteers to explore the rider stability and MAEB acceptability among end-users involving PTW prototype systems provided with Automatic Braking (AB) devices.
4. Investigating the potential benefits of MAEB via crash reconstructions and theoretical estimations.

2.1 MAEB applicability

Assessing the potential applicability of MAEB before its implementation on standard vehicles was a significant challenge for researchers. The absence of data recorded in crashes involving vehicles provided with MAEB makes retrospective assessments not possible. However, assessing its applicability in real-world crashes, represents a fundamental goal to be achieved to understand the potential impact of MAEB in real-world near-crash and crash situations. Within a study focusing on comparing the applicability of different PTW active safety systems (included MAEB) to identify the most promising ones, a group of experts assessed the expected applicability of five ARAS based on Australian crash configuration definition [32] and estimated the potential applicability of each ARAS based on crash data.

As a reference the ABS, which since 2016 is mandatory in UE for some types of PTWs, showed the highest rates of applicability in all the countries: ABS resulted to be not relevant only in between 7.1%-15.8% of all the crashes considered in this study and to be definitely applicable in 40.6%-62.8% of them [33]. Concerning the MAEB, it resulted to be applicable in a range of 5.7%-47.9% of Australian PTW crashes [34], 10.5%-78.4% of Italian PTW crashes and 11.6%-67.2% of US PTW crashes [33]. These estimations, which varied broadly among different countries and traffic environments, showed nevertheless that MAEB could intervene in a wide percentage of PTW crashes, revealing high potential applicability, especially in urban environments. Within each country, the wide ranges in MAEB applicability estimations represented different levels of applicability based on the classification provided in [34] (see Table 1).

Table 1 – MAEB estimated applicability in Italy (Prato), USA and Australia (Victoria) [33]



Safety Sistem	Category 1 (not relevant)			Category 2 (possible)			Category 3 (probably)			Category 4 (definitely)		
	Prato	USA	Victoria	Prato	USA	Victoria	Prato	USA	Victoria	Prato	USA	Victoria
ABS	8,8%	15,4%	7,1%	13,0%	54,3%	49,3%	3,5%	3,1%	2,3%	74,7%	27,2%	40,6%
MAEB	21,4%	32,8%	52,1%	27,0%	47,5%	24,3%	41,1%	8,1%	17,3%	10,5%	11,6%	5,7%
Collision warning	19,6%	32,7%	41,6%	3,9%	37,4%	14,1%	36,5%	8,7%	20,5%	40,0%	21,2%	23,1%
Curve warning	90,9%	58,2%	79,1%	4,6%	32,2%	4,4%	0%	0%	0%	4,6%	9,6%	15,8%
Curve assist	70,2%	72,0%	43,5%	22,8%	14,7%	36,6%	2,5%	3,4%	3,2%	4,6%	9,9%	16,1%

2.2 MAEB triggering algorithms

The selection of the decision logic and the triggering algorithms of an active braking system such as MAEB, is one of the key aspects that must be defined in the early stages of its development. For an autonomous braking system, the main issue is to define whether to allow the intervention of the system when the collision is still avoidable or only after the collision has become physically unavoidable. This influences the time available for the system to be active before the crash and therefore to produce its effects. In the first case, the intervention of the system could be more effective, but its acceptability for end-users could be much lower because of the unavoidable unnecessary interventions. On the other hand, if MAEB is designed to intervene only when the crash has become physically unavoidable, it would allow only a reduction of the crash impact speed.

When the system was at the first stages of its development, early-studies focusing in MAEB triggering algorithms assumed the system for intervening only when the crash between the host PTW and the opponent vehicle/object was estimated as unavoidable. The first studies focused on establishing when an obstacle is no longer avoidable by a PTW through a swerving manoeuvre. This was executed using a numerical model which was then validated by an experimental campaign involving 12 participant riders [35]. The following study, in order to develop the decision logic of the MAEB prototype installed on a PTW employed in the PISa project [36], defined the unavoidable-crash condition for a PTW based on its kinematics [37]. In this study, based on rear-end crash configuration, the full braking action and the swerve manoeuvre were schematised to identify the kinematic conditions for which a collision is physically unavoidable. The results of the study (see Figure 6) showed that based on the travel speed of the host PTW, the crash can be avoided through full braking action or swerve manoeuvre with different efficacy in relation to the PTW travel speed. Overall, at low PTW velocities, the most effective manoeuvre is the braking action, while at higher speeds the swerve manoeuvre is the most effective one. However, the main result of the study from MAEB perspective is that a combination of PTW speed and distance from the obstacle in which the collision is unavoidable was identified (Figure 6). This combination was therefore considered as the reference for MAEB deployment and decision logic of intervention.

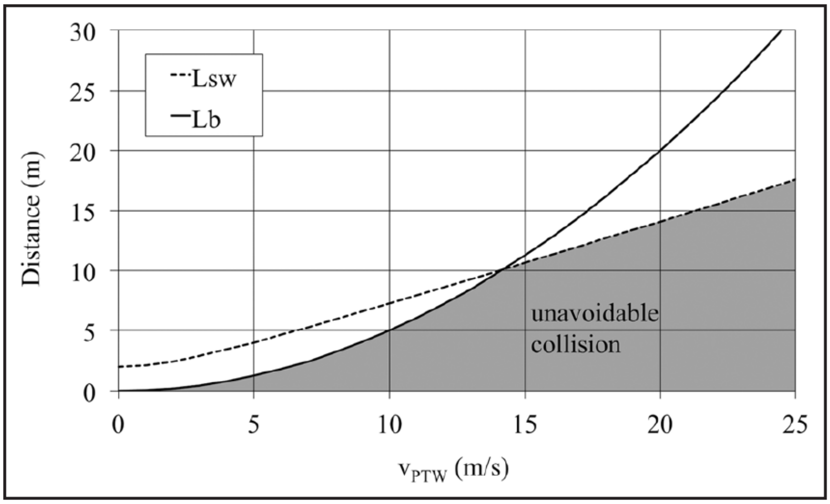


Figure 6 – Minimum distance to avoid a collision considering pure swerving (Lsw) and pure braking (Lb) [37]

An essential contribution in the research on MAEB triggering algorithms was given by Savino et al. in 2016, with a study focusing on identifying inevitable collision states (ICS) for PTWs [38]. A methodology to identify ICS for PTWs was proposed based on previous studies focusing on ICS for other applications and previous findings on swerving and braking distance for PTWs [35], [37]. The proposed method allowed therefore to extend the applicability of previous triggering algorithms to include any crash configuration involving a PTW and a passenger car in typical traffic scenarios (see Figure 7, which represent this strategy applied to car AEB). The ICS method, which was designed for MAEB, but which can be applied as a triggering criterion for other active safety systems, represents a reliable algorithm for triggering MAEB in all the crashes in which the PTW is travelling straight and the opponent vehicle is in the frontal surroundings of the PTW, the two vehicles eventually colliding with each other. In addition, the real-time implementation of the method was shown to be easily obtained based on look-up tables, making the method applicable in real-world applications. In other linked studies, the algorithm was tested through numerical simulations reconstructing real-world crashes coming from databases of different countries [29], [39]. The results of these studies confirmed that with the application of the ICS triggering algorithm, the MAEB would be able to mitigate multiple-vehicle PTW crashes across a wide range of impact configurations.

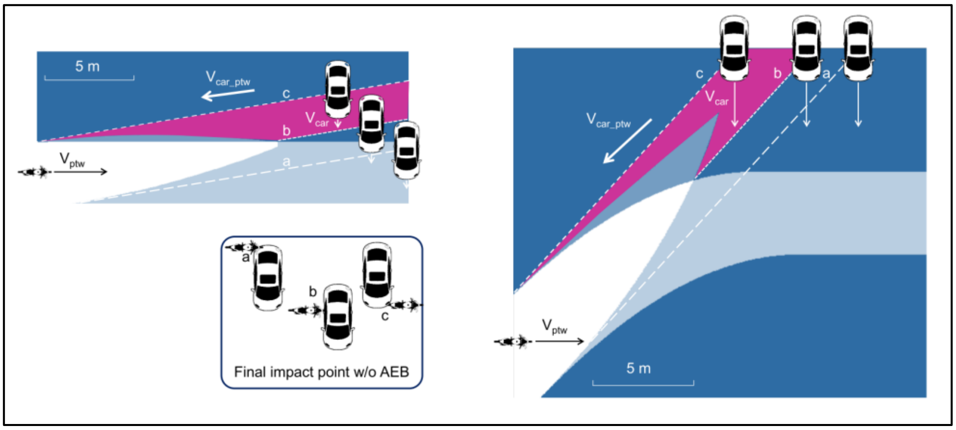


Figure 7 – Car AEB triggering zone: AEB is triggered when ordinary braking action is not enough to avoid collision (the passenger car is located between lines b and c) [39]

The algorithm presented in the previous paragraph was also employed to assess the applicability of MAEB in cornering conditions [40]. All the previous studies considered the MAEB applicable when the PTW is travelling in straight line conditions, and neither in numerical simulations, the applicability of MAEB to cornering scenarios was tested since it was considered hazardous for a leaning vehicle. A new algorithm for MAEB intervention in leaning conditions was proposed [40]: the standard MAEB was associated with an Active Braking Control (ABC), which consisted of a new control algorithm that stabilises the vehicle along the curved path. The ABC consisted of the integration of Combined Braking and ABS through a braking modulation module. Such system is similar to what is nowadays available for PTWs with the name of Motorcycle Stability Control (MSC). The combination of MAEB and ABC, the so called MAEB+ (see Figure 8), was tested in virtual environment with computer simulation reproducing real-world crashes, employing three cases selected from the in-depth crash database "InSAFE" (which collects severe road crashes in the metropolitan area of Florence). The results of the simulations showed that MAEB+ reduced the PTW speed prior to impact with higher deceleration compared to baseline MAEB, while maintaining the stability of the motorcycle. In conclusion, the results of this study showed that MAEB in combination with active braking assistance systems like MSC could be possible, but field test were recommended to assess the vehicle controllability in such conditions.

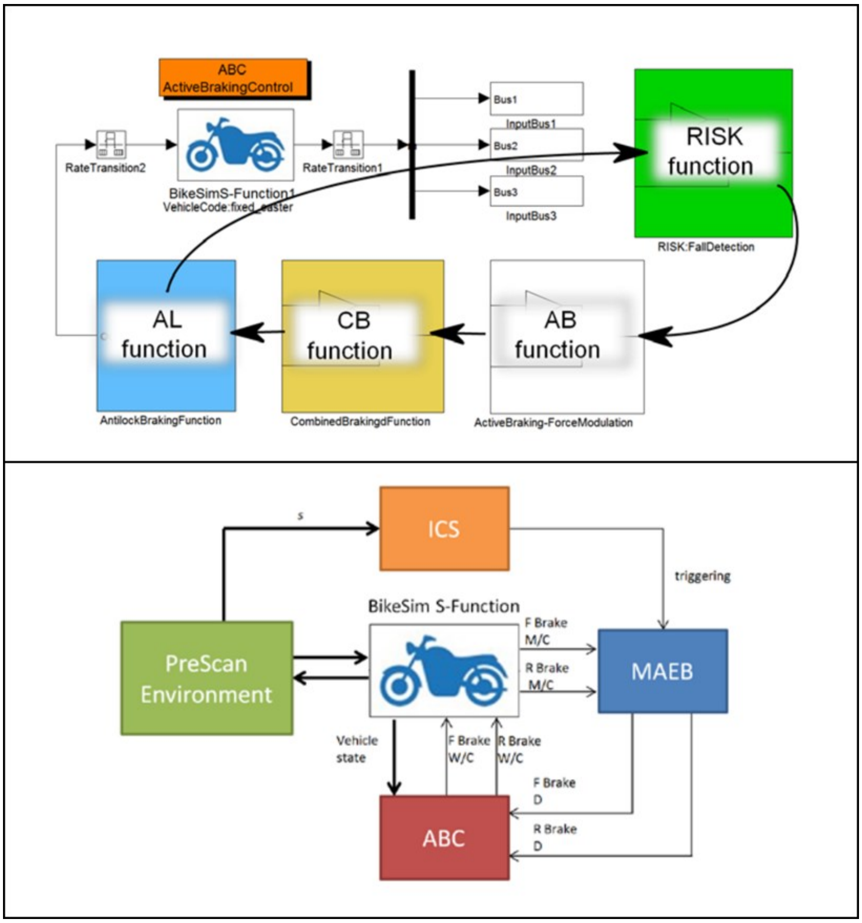


Figure 8 – Up: scheme of Active Braking Control (ABC), including Antilock Braking Function (AL), Combined Braking Function (CB), Active Braking force modulation (AB) and Risk function; Down: Scheme of MAEB control logic including Environment control, Inevitable Collision State (ICS) definition and ABC [40]

2.3 MAEB field tests

The first tests focusing on MAEB feasibility were carried out by Symeonidis et al. [41] in order to assess rider stability in case of autonomous braking events. The tests, involving eight participants with different riding skills, were performed in laboratory settings, analysing rider kinematics in correspondence of simulated activations of automatic braking. To simulate the inertial forces experienced by the rider during the braking action, a sledge with a motorcycle mock-up was employed to recreate the interface between the motorcycle and the rider (see Figure 9). The prototype was designed to recreate a touring vehicle and it was directed in the opposite direction of movement of the sled, thus allowing to recreate the acceleration profiles of a braking manoeuvre.

In order to simulate the braking manoeuvre, the sled performed an acceleration of 0.35g in rearward direction compared to that in which the participant was facing. Employing a system of high-frequency cameras, an accelerometer and an electromyography system device, data on the participants' reactions were recorded. Three braking scenarios were tested: i) the participants activated the sled by means of a brake lever on the handlebars of the prototype, reproducing a manual braking action. ii) the activation of the sled was carried out externally by the investigator providing a haptic warning to the participant before activation or iii) the deceleration was activated by the investigator without any warning.

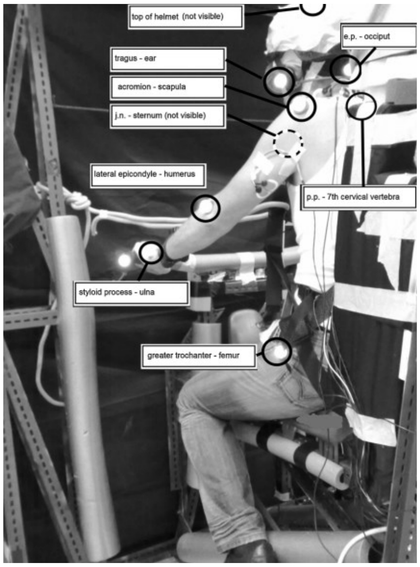


Figure 9 – Motorcycle mock-up and markers for body movement monitoring [41]

The results of this study highlighted that the movements obtained in the three scenarios with decelerations of 0.35g were not significantly different among the three tested scenarios. The authors concluded that with decelerations of up to 0.35g, MAEB should not create a greater instability to the rider compared to manual braking. This study, for the first time in literature, suggested that a 0.35g automatic deceleration in straight-line could be manageable by riders and paved the way to future field tests. Since rider instabilities induced by MAEB was considered one of the main issues for its application, the results of this study represented a fundamental milestone for the future development of the system.

The first field test of MAEB was carried out in 2010 within the European funded research project PISa (Powered two-wheeler Integrated Safety) [36]. This project, first of all, assessed the applicability of PTW safety functions through in-depth crash data analysis of 60 crashes representative of European crashes. After identifying the most promising safety functions, these were implemented on two different test PTWs, a scooter and a motorcycle. The scooter, a 500cc Malaguti Spidermax, was provided with the first autonomous braking system, allowing autonomous and enhanced braking functionalities. The vehicle was also equipped with a laser scanner for frontal obstacle detection, a vibrating seat to provide warning feedback to the driver and a semi-active front fork to improve stability during emergency braking. All the sensors and devices installed on the vehicle communicated via CAN bus with the dSpace control module. The first MAEB system was in place: the laser scanner was used to detect obstacles, while data from the inertial platform (Inertial Measurement Unit - IMU) and the GPS were used to assess the state of the vehicle; combining these signals, the decision-logic of the prototype system identified the presence of a possible crash scenario and decided whether MAEB should intervene based on data from the throttle, steering torque and braking pressure sensors. The system was designed to apply autonomously the braking action, which could be either in "autonomous" mode if the rider was not performing manual braking action, or "enhanced" mode if the rider was braking manually.

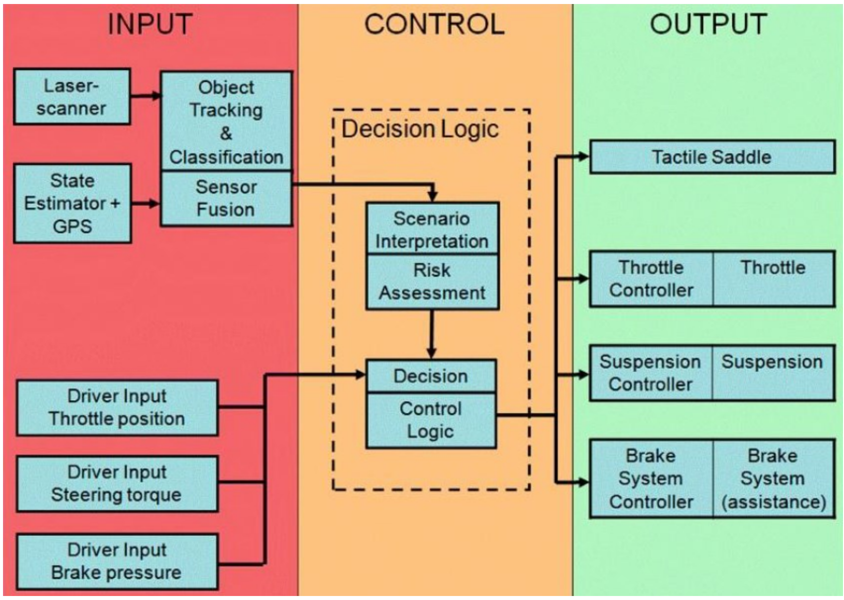


Figure 10 – Operating diagram of the first MAEB prototype vehicle [36]

The prototype vehicle was employed to carry out the first field tests, which were performed at the Transportation Research Laboratory (TRL) test track, to verify the MAEB technical feasibility and obtain subjective feedback from a set of riders [37]. The tests were carried out by seven professional riders, who rode the PTW at a speed of 45 km/h towards a stationary obstacle made of foam rubber which was passed sideways (see Figure 11); as the vehicle approached the obstacle, the MAEB system calculated the minimum deceleration required to avoid impact and when the threshold value, which varied between 0.5g and 0.9g, was passed, the automatic braking was deployed up to reach a target deceleration of 0.3g. Overall, the system was tested in 140 trials, in which it intervened regularly with no negative outcome for the riders. The participants declared that they were able to manage the deceleration with minor effort. The obstacle detection rate was of 98% with an average first detection distance of 58.3m. In a single case, the automatic braking did not take place due to an erroneous tracking of the obstacle by the laser scanner. The mean deceleration performed by MAEB (which was obtained without a closed control loop on braking deceleration) during the trials was around 0.28 g (SD 0.07 g). Even if some cases of false activation occurred due to spikes in object detection (11 out of 140 runs), the tests were performed without the occurrence of any dangerous event for participants. These tests represent a significant breakthrough in the estimation of the feasibility of the MAEB proving its technical feasibility and the possibility from professional riders to manage interventions with deceleration up to 0.3 g, also in the case of false triggering.

Figure 11 – Frist field tests involving MAEB [37]

The next step in MAEB field testing was carried out within the ABRAM project [42]: field tests were performed for the first time involving common riders (characterized by different age and riding skills) as participants. The tests had the goal to evaluate the acceptability of the MAEB system, recreating unexpected automatic braking events. The vehicle used for the experiment was a light sports motorcycle, which had been equipped with a remote-controlled braking system that allowed the investigator to produce an automatic deceleration of the vehicle by turning off the engine. This approach was chosen because it was low cost, reliable, repeatable, and safe; in this way, the deceleration was directly proportional to the speed of rotation of the engine so it was not possible to achieve values that could compromise the safety of the participants. The achievable deceleration ranged from 0.1g and 0.3g. The experimental vehicle was also equipped with two video cameras and a data logger recorded the vehicle position, speed and acceleration. The test consisted of some straight runs (see Figure 12) at a speed of 40 km/h in which the investigator could turn off the motorcycle engine decelerating the motorbike. The activations were performed at pseudo-random times reproducing pseudo-unexpected decelerations for the riders. Besides, in order to assess how unexpected the activation really was, a further activation was performed after these trials to surprise the participant and test a "genuinely unexpected" deceleration. The average decelerations during activation were 0.15 g with peaks that could reach 0.3 g.

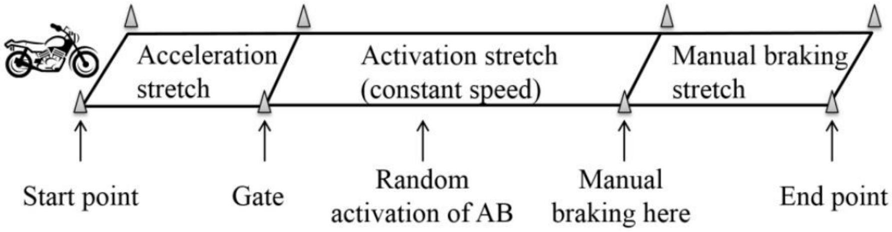


Figure 12 – Test track and procedure employed in [42]

This study allowed to understand that field tests involving pseudo-unexpected decelerations of a prototype PTW is a feasible way to investigate the influence of MAEB on common users, from both functional and safety perspectives. In addition, this study provided the first assessment of rider acceptability of MAEB intervention, confirming that MAEB activation with average decelerations of 0.15g can be easily managed by common riders. The test protocol presented in this article, approved by the Monash University Human Research Ethics Committee, also represents a reference for a future definition of MAEB field tests.

Within a following study of a different research team, focusing on investigating the tolerability of unexpected autonomous emergency braking manoeuvres [43], further field tests were carried out involving five expert and professional riders as participants [44]. These field tests were carried out with the specific goal of identifying the limits of deceleration and jerk achievable with the MAEB without compromising rider's stability. The tests were part of a larger research project (which started some months before the present PhD) which was supposed to perform test also with common riders as participants. To date, the results of the participants' test have not been published yet. The published study presented the results of the tests involving experts in the field, i.e. driving instructors, who were asked to provide feedback regarding decelerations that they felt could be easily managed by a normal user. The motorcycle used for the tests (Honda NC700X) was equipped with a remote-controlled automatic braking system which, by means of an electric motor, activated the rear brake pedal and disengaged the clutch by means of another actuator. Since the motorcycle was equipped with combined braking, the braking pressure was also applied on the front brake. Three different deceleration profiles were tested: the so-called impulse, the increasing ramp, and the constant deceleration (see Figure 13).

Participants were required to travel on a straight path at speeds of 45, 70 and 90 km/h and unexpected system activations occurred with different deceleration profiles. After each test, the experts provided feedback on the activation indicating whether they considered the tested level of intervention reasonable or unacceptable for ordinary users. At 70 km/h the experts considered automatic and unexpected decelerations manageable for ordinary users with values of 0.5g with the constant deceleration profile, 0.5g with the impulse deceleration profile. The jerk (rate of increase of deceleration) of 0.9g/s was considered applicable with common riders for the increasing ramp profile. The results of this study provide relevant recommendations for the working parameters and deceleration profiles applicable to MAEB. However, due to the limited sample and the experience of riders, the parameters indicated by the experts must be verified through field tests involving common riders.

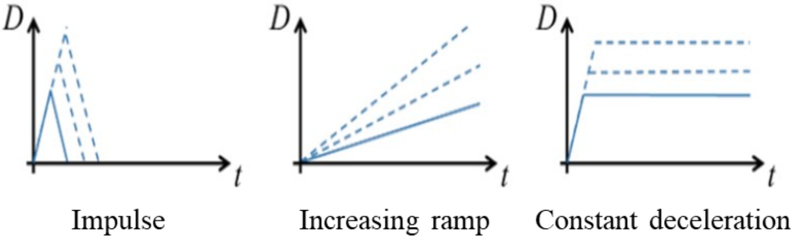


Figure 13 – AB deceleration profiles tested by Merkel et al. [44]

In addition, further analysis was carried out by the authors on the data collected in these field test campaign, in order to analyse the body movement to evaluate the adaption of the rider to autonomous braking. The results showed that it is possible to measure riders' adaptation to the automatic deceleration through monitoring head and body movement [45]. The findings showed also that the physical reactions of riders to unexpected automatic braking have a high degree of homogeneity [46]. This suggests that the results of studies focusing on rider's controllability of automatic braking intervention, even if performed with a relatively small number of participants, can predict the response of a large number of riders.

A small field test carried out in 2018 assessed the possibility of estimating the disadvantageous position of one-handed riding based only on available motorcycle dynamics sensors, in order to adapt the braking strategy in case of activation of MAEB [47]. A set of parameters able to detect one-handed riding in straight-line riding were identified: during automatic braking, the prototype system was able to identify one-handed riding before the achievement of the 50% final deceleration. The results of this study represent a relevant achievement for the control of the rider position on the handlebar to fully deploy MAEB only in safe conditions.

2.4 MAEB benefits estimation

Assessing the potential benefits of technologies that are yet to be introduced or are in pre-release stages, is a significant challenge for researchers. For some technologies, the estimations can be obtained through forecasting models or simulations, but greater is the challenge when we want to assess the impact of safety systems for road vehicles like ADAS/ARAS. This is because, before the introduction of such systems in standard vehicles, it is impossible to have data recorded in crashes involving vehicles provided with these technologies, and therefore any retrospective assessment is not possible. However, it is essential to estimate the benefits and the disadvantages of active safety systems before such systems are introduced on standard vehicles. For this reason, in the past, some studies focused on assessing MAEB benefits based on crash modelling and simulations.

One of the first studies was conducted in 2013 by Savino et al. [48] based on 58 PTW crashes, in which 43% of riders sustained at least MAIS2+ (moderate) injuries (Maximum value of Abbreviate Injury Scale [49]), representing European crash configurations. The study was executed by an expert team who analysed the in-depth material of the 58 crashes and defined a posteriori which could be the effect of MAEB in each crash. In addition, in the crashes in which MAEB was considered applicable, a further quantitative evaluation of MAEB benefits was conducted based on a set of possible rider reactions. The results showed that in 67% of cases, the application of MAEB could have mitigated the crash outcome reducing pre-crash speed. Besides, among the 19 cases in which experts considered that neither an expert rider would not have been able to avoid the crash, it was estimated that in 14 cases (74%) MAEB would have contributed in mitigating the crash. Further analysis clearly highlighted that the MAEB could potentially improve safety not only for novice riders but also for more experienced riders [50]. This study represents the first assessment of MAEB benefits based on crash data including a wide number of crashes representative of European crashes. The results suggested that MAEB could have relevant crash outcome mitigation potential if applied in car-following and crossing crash scenarios.

Table 2 – Estimated MAEB effects by crash scenario [50]

Scenario	N. cases/N. cases MAEB applicable	Mean speed reduction
Car following	9/8	1.9 m/s
Crossing	28/24	3.0 m/s
Single vehicle	7/0	-

A second study was carried out in the same period focusing on estimating quantitative potential benefits of MAEB via crash reconstruction [51]. In this study, seven fatal rear-end crash cases from the Swedish Transport Administration in-depth database were selected and reconstructed in a virtual environment. All the relevant characteristics of the crashes were reconstructed, including the road scenario, the vehicles involved and their precrash trajectories, and the presence of ABS and MAEB were simulated. A range of boundary conditions (compatible with the uncertainty of the in-depth data) was applied to each simulation and a range of possible rider behaviours was simulated. The working parameters for MAEB application were those defined within the PISa (Powered Two-Wheeler Integrated Safety) project (in particular, MAEB target deceleration was set to 0.3 g) [36]. The results of the application of MAEB in the crash simulations showed that in the cases in which MAEB resulted to be applicable its benefits turned out to be comparable to what was designed, while in the cases in which MAEB was not applicable "there was no clear evidence of an increased risk for the rider due to the system". This study estimated firstly the potential effects of MAEB evaluating impact speed reduction in seven fatal crashes: its consequences are doubly important. First, a confirmation that impact speed reduction previously field-tested can be obtained in real-world crashes was obtained using crash simulations and, second, important indications about the fact that MAEB do not provoke adverse effects on the rider safety were obtained.

A further step in the assessment of MAEB benefits was carried out in 2016 with a multicentric study [29]. Crashes collected in in-depth databases from three different countries (Australia - Neuroscience Research Australia (NeuRA) database, Italy - InSAFE (In-depth Study of road Accidents in Florence) database, and Sweden - Swedish Transport Administration (STA) database) were selected from a wider sample of cases up to obtain 91 cases in which MAEB was considered applicable. To extend the potential applicability of MAEB also to crossing scenarios and crashes involving stationary objects, a new triggering algorithm was established.

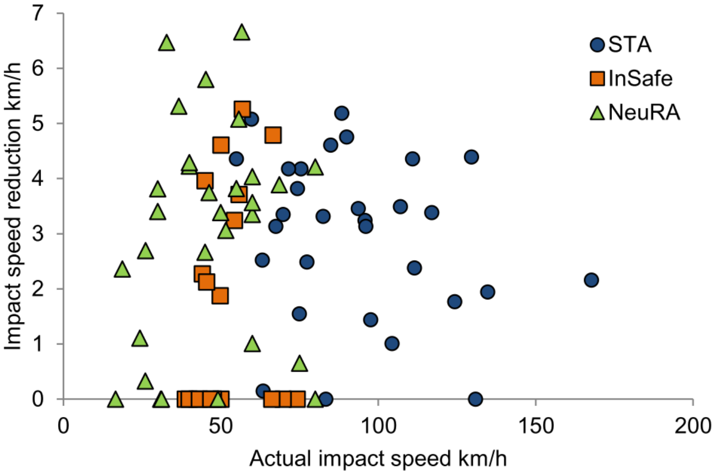


Figure 14 – Impact speed reduction due to MAEB distributed by In-depth database: STA (Sweden), InSafe (Italy), and NeuRA (Australia) [29]

Based on the crash reconstructions made through numerical 2D computer simulations and employing the new triggering algorithm, the potential benefits of MAEB were estimated in terms of impact speed reduction due to MAEB (see Figure 14). The results of this study revealed that MAEB can have potential in mitigating multiple-vehicle motorcycle crashes in a wider set of crash configurations compared to those tested until then. In addition, the MAEB was overall able to reduce the impact speed up to approximately 10% of pre-crash speed, depending on the crash scenario and the initial vehicle pre-impact speeds. This study allowed to estimate through crash simulations MAEB benefits in crashes coming from different countries and with different crash configurations, confirming the promising potential of MAEB in mitigating PTW crashes.

The following study was conducted by Savino et al. in 2016 with the goal of evaluating the sensitivity of the simulations to variations in reconstructed crash cases [52]: this allowed to perform a more robust estimation of MAEB effects and validate the results of previous studies. First, a set of crash configurations where MAEB was considered as potentially applicable based on the crash configuration definition employed in Victoria, Australia [32], were identified. Second, a set of 36 crashes coming from three Australian databases (MICIMS - Monash University Accident Research Centre, Victoria; Neuroscience Research Australia (NeuRA) database - New South Wales; and Centre for Automotive Safety Research (CASR) database - South Australia) were reconstructed through computer simulations. For each reconstructed case, a set of 100 variant cases were generated from the baseline simulation by randomly altering the initial conditions. These variant cases were employed to test the influence of different variables coming from crash investigations and therefore containing a certain level of uncertainty, to the effectiveness of MAEB. Finally, the effects of MAEB were evaluated in terms of impact speed reduction of the host PTW, and the influence of variant cases was assessed.

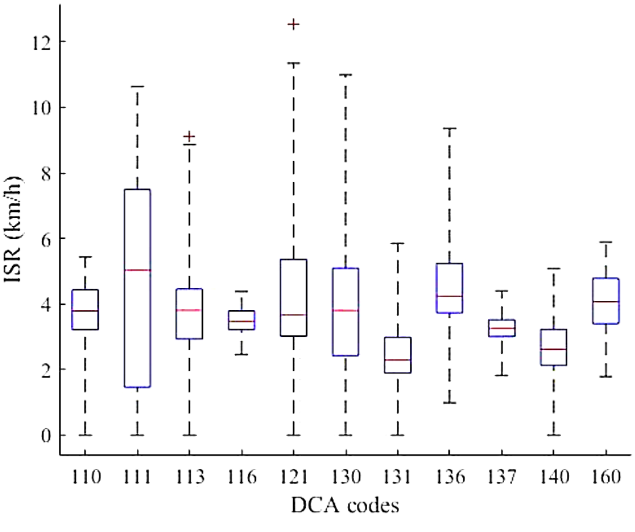


Figure 15 – Impact speed reduction distribution by crash configuration (DCA) produced by MAEB in the simulated variant cases [52]

The results of this study revealed that compared to the baseline cases, the cases in which the variables were over- or underestimated influenced the mean impact speed reduction by up to 20% (see results in Figure 15). In addition, further estimations of impact speed reduction achievable using MAEB were provided. This study suggests that the potential benefits of MAEB estimated through cases described in in-depth crash reports can be considered a robust estimation of the real benefits of the system, validating previous and following studies carried out with this method.

The latest study which attempted to estimate MAEB benefits focused on head injuries [53]. Employing a set of 13 motorcycle crashes coming from the Italian in-depth database of serious road crashes in Florence (InSAFE), the effectiveness of MAEB in reducing the head injury severity of a helmeted rider was assessed. Multibody simulations of the vehicles involved in the crash and the riders' body were employed to identify the impact conditions of the head against the colliding object. Regarding the MAEB intervention, an ideal system able to achieve two levels on Impact Speed Reduction of, respectively, 4 km/h and 8 km/h was considered. The results showed that MAEB allowed reaching a mean head impact velocity ranging from 10% to 18%. However, the authors highlighted that "non-identified parameters may have had a role in the head injury mitigation effects", and therefore, head injuries mitigation estimations are not highly reliable. In conclusion, this study showed that MAEB can reduce the impact speed of both the vehicle and the body (head) of the rider, but that impact speed reduction of 4 km/h appeared to be not enough to substantially mitigate head injuries: higher levels of ISR (equal or greater than 8 km/h) are required to make MAEB effective in reducing head injuries.

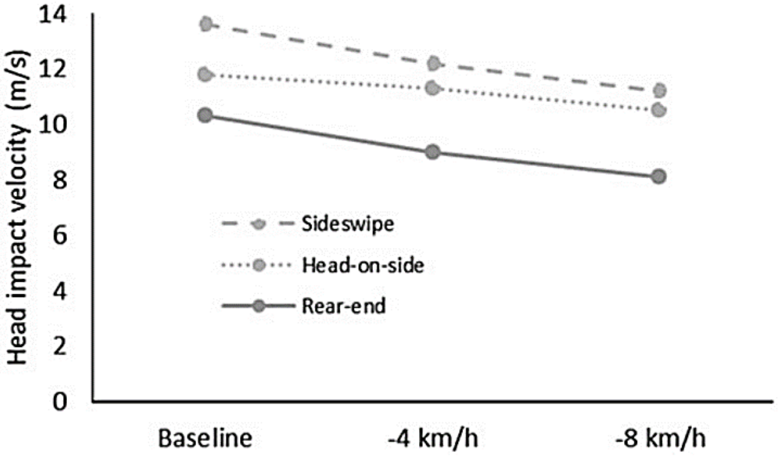


Figure 16 – Mean head impact speed by crash configuration in the baseline cases and with MAEB intervention (4 and 8 km/h ISR) [53]

A single-case study was also carried out in 2019 to assess MAEB effects using in-depth crash and drive-through data [54]. The study showed that, in order to improve the MAEB effectiveness discussed in previous studies, an early intervention could be an effective strategy as improving the MAEB target deceleration. Moreover, if it would be possible to combine the higher levels of deceleration with the early intervention, the MAEB may achieve an impact speed reduction even greater than what was previously estimated. The results of this preliminary estimations were employed as a reference in the study reported in the fifth section of this thesis.

3 MAEB test methods

Once the open issues of MAEB were identified through the literature review of prior studies concerning MAEB and more generally studies focusing on ARAS, the first step of the research activity was to identify the research methods and strategies to fill the gap in the knowledge regarding MAEB highlighted by the literature review process.

Based on literature review, the goals of this research project were identified in: i) assessing MAEB feasibility in a range of riding conditions representative of pre-crash situations and ii) assessing which levels of MAEB intervention parameters can be managed by end-users in unexpected activations. The evaluation of MAEB feasibility will be based on the riders' acceptance of the intervention of an automatic braking device and their reactions at system deployment. For this reason, the research strategy identified for this study was to field test the intervention of MAEB with participants. This indeed represents the most effective and reliable strategy to assess the applicability of MAEB and its acceptability among end-users. In this section, the methods employed in this study will be presented: by means of a journal publication the field test design criteria will be presented first. After that, the work carried out to set up and develop the two Automatic Braking (AB) prototype systems and the test vehicles will be presented. The last two sections will contain the details of the test protocol employed for this study and the procedure used to perform the recruitment of participants and their selection.

3.1 Test design criteria

The test design criteria were defined through two linked phases: a literature review and several sessions of pilot testing. First, a literature review of the previous studies on MAEB was carried out to determine more realistic intervention setting for MAEB and new working parameters to be tested. Studies concerning field testing were analysed to find out which working parameters for the MAEB intervention were considered feasible so far, whereas works on MAEB benefits assessment and crash investigations were reviewed to identify the relevant conditions of intervention for MAEB. After the literature review, using a test vehicle provided with an Automatic Braking (AB) device previously developed (see section 3.2.1), an intense activity of pilot testing was conducted involving members of the research group with extensive experience in PTW riding. The results of this work, which provided the test design criteria employed for this study, will be presented in this thesis through the following publication.

I) JOURNAL PAPER: Investigating the feasibility of Motorcycle Autonomous Emergency Braking (MAEB): design criteria for new experiments to field test automatic braking [55]

This manuscript was submitted for publication in September 2020 to MethodsX journal, it was accepted after receiving minor revisions and published online in January 2021. MethodsX is an open-access journal which publishes test protocols and methods for scientific research coming from all research areas. Since the journal aims to publish procedures and technical aspects of research, the manuscript has an unconventional format without detailed background and contextual information. The paper presents the test design criteria devised from the joint research activity of pilot testing and literature review carried out in the first year of PhD. The manuscript provides comprehensive support for the design of field tests to investigate the feasibility of MAEB and can be employed as a reference for designing tests for other advanced rider assistance systems. The guidelines and criteria presented in this paper were employed as a reference for the definition of the methods employed for this study and in the arrangements of the test protocol (which are presented in detail in section 3.3 and 3.4).

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Method Article

Investigating the feasibility of motorcycle autonomous emergency braking (MAEB): Design criteria for new experiments to field test automatic braking

Cosimo Lucci[a,*], Mirko Marra[a], Pedro Huertas-Leyva[a],
Niccolò Baldanzini[a], Giovanni Savino[a,b]

[a] *Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy*
[b] *Monash University Accident Research Centre, 21 Alliance Ln, Clayton, VIC 3800, Australia*

abstract

Autonomous Emergency Braking (AEB) was proved to be an effective and reliable technology in reducing serious consequences of road vehicles crashes. However, the feasibility in terms of end-users' acceptability for the AEB for motorcycles (MAEB) still has to be evaluated. So far, only Automatic Braking (AB) activations in straight-line motion and decelerations up to 2 m/s^2 were tested with common riders.

This paper presents a procedure which provides comprehensive support for the design of new experiments to further investigate the feasibility of MAEB among end-users. Additionally, this method can be used as a reference for designing tests for other advanced rider assistance systems.

- A comprehensive literature review was carried out to investigate previous findings related to MAEB. After that, a series of pilot tests using an automatic braking device on an instrumented motorcycle were performed.
- The specifications for new AB experiments were defined (in terms of test conditions, participants requirements, safety measures, test vehicles and instrumentation).
- A test protocol was defined to test the system in different riding conditions and with different AB working parameters. A proposal for the data analysis was presented.

article info

Method name: Field test autonomous emergency braking for powered-two-wheelers with participants
Keywords: Motorcycle, Active safety, Autonomous emergency braking, Field testing, Test protocol
Article history: Received 28 September 2020; Accepted 7 January 2021; Available online 10 January 2021

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[*] Corresponding author.
E-mail address: cosimo.lucci@unifi.it (C. Lucci).

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Specifications table

Subject Area:	Engineering
More specific subject area:	*Road safety*
Method name:	Field test autonomous emergency braking for powered-two-wheelers with participants
Name and reference of original method:	*The method proposed in this paper is an advancement of test protocol proposed in a previous study: G. Savino, M. Pierini, J. Thompson, M. Fitzharris, M.G. Lenné, Exploratory field trial of motorcycle autonomous emergency braking (MAEB): Considerations on the acceptability of unexpected automatic decelerations, Traffic Inj. Prev. 17 (2016) 1–12.* https://doi.org/10.1080/15389588.2016.1155210.
Resource availability:	*N.A.*

Method details

Method goal

To extend the tests to new conditions that are relevant for Motorcycle Autonomous Emergency Braking (MAEB), especially for the vehicle dynamics, while granting safety of participants and a good approximation of real-world conditions, to test the acceptability of new deceleration values.

Test methods

The guidelines and the test protocol presented in the following sections were developed through a process of literature review and pilot testing (see the section "Process employed to define the proposed test method" in the "Additional information" of this paper).

For this study, all subjects gave their informed consent for inclusion before they participated. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Florence (Decision N. 46, 20/03/2019).

MAEB test specifications

In order to field-test the Motorcycle Autonomous Emergency Braking system, in previous studies [1–3] Automatic Braking (AB) events were studied. Participants were exposed to an automatic deceleration through an automatic braking action executed by the motorcycle without a braking action of the rider. Therefore, the first step for field-testing MAEB interventions with participants, is the definition of the riding conditions to be reproduced and the necessary AB functions and performance. Subsequently, the test protocol can be developed observing the safety limitations required to safeguard participants involved in the tests.

Riding conditions

As found in the literature, the intervention of MAEB was tested as unexpected activation without an obstacle [2,3], in order to reproduce a false activation or an intervention that gets unprepared the rider. This is indeed one of the most challenging working condition related to safe controllability of the vehicle and rider acceptability of the system. Therefore, the test protocol is arranged to make AB interventions unexpected for the rider, triggering AB pseudo-randomly without the presence of obstacles. To reduce the predictability, the interventions are not excessively repetitive and frequent (i.e. they are spread in time and in different spots along the test track; as reference value is one AB intervention every 100 s of riding). The overall number of AB intervention is as limited as possible, in order to reduce the learning effect, while ensuring a repetition of the assessment: for each maneuver tested and level of deceleration, the number of repetitions is very low (2–3). These values derived from the trade-off between different opposing requirements: the maximum duration of the trial and the number of different activation conditions.

The AB is deployed in a set of representative conditions for real-world applications, including also conditions where MAEB could be less efficient or even present issues. According to the results of previous studies, such conditions are common in an urban environment, characterized by low velocities (up to 50 km/h) and mixed maneuvers (e.g. short straight lines, curves, lane changes and traffic filtering). Since MAEB is a pre-crash braking system, which could be triggered less than one 1 s before the impact [4], the AB is tested for a similar duration without stopping the vehicle.

Automatic braking

According to the literature, the deceleration profile so-called “Block profile”, which is a constant deceleration time achieved through a constant jerk, is the best one among the few profiles tested so far [3]. This simple profile combines good acceptance by riders and easiness of implementation. In order to maximize the efficacy of MAEB, the constant fade-in jerk is as high as possible, but always under levels previously showed as significant thresholds for the controllability of Powered Two-Wheelers (PTWs) (□ 25 m/s^3) [5]. At the end of the constant deceleration, a fade-out ramp with constant jerk is added to conclude the intervention; again, a maximum jerk of 25 m/s^3 is adopted to avoid risks of destabilization and possible high-side events when the lateral dynamic is involved. The AB device is also provided with safety controls, in order to guarantee the highest level of safety to the participants. The safety controls include limitations to the conditions for the intervention of AB (e.g. in terms of speed of the vehicle, deceleration and roll angle) and a latency time (e.g. 5 s) between two consecutive activations to avoid multiple interventions.

Safety limitations

During the execution of the tests, the investigators observe the participant and monitor the appropriateness of the riding style and conditions before the activation of AB. If the test protocol consists of testing the intervention of the system in lateral maneuvers, such as curve, the test vehicle needs to be provided with outriggers, to prevent participants from low side fall. Nevertheless, AB field testing is related with residual risks (e.g.: person struck by test vehicle, fall from the vehicle due to loss of control, vehicle collision with obstacles, failure of the AB system, failure of test vehicle).

Scenarios and maneuvers

A crucial point in the design of the field test is the definition of the test track employed to simulate an urban scenario. The track is intended to reproduce riding situations in which the speed and the performed maneuvers are similar to those observed in accidents in urban areas [6,7] and, more generally, in urban riding situations relevant for MAEB activation. Previous studies have focused on modeling the behavior of motorcycles in the urban scenario [8]. Aiming to reproduce this behavior on a test track, it is possible to simulate urban riding through four major maneuvers: straight-line riding, lane change, cornering and a slalom reproducing a complex vehicle dynamic condition such as traffic filtering.

Straight-line section

The sector of the test track emulating straight-line riding is constructed with a straight stretch suitably sized. The length of this section is chosen to allow the speed range typical of urban scenario (40–50 km/h) to be achieved (see Table 1). This section is sufficiently extended to obtain the first zone of acceleration and a second zone at constant speed where the AB is triggered. This is the maneuver where MAEB intervention could be easily applicable since AEB showed good benefits in rear-end and head-on crash scenarios [9], and it is the most tested maneuver in previous field studies [1–3].

Lane change section

The lane change maneuver in urban areas can be related to overtaking or swerving, both situations where MAEB is still untested. Even if overtaking is a common behavior among PTWs' riders, the swerve maneuver is much more relevant in pre-crash situations [7] and therefore it is the maneuver in which MAEB needs to be tested. According to the literature [10–12], single-lane change was reproduced by placing markers capable of simulating the three phases of the maneuver: i) ‘entry lane’ where the rider drives at a constant speed along a straight path; ii) ‘offset’, a section where the motorcycle is forced to move sideways to change the lane; iii) ‘exit lane’ where the vehicle again

Table 1
Maneuvers descriptive parameters.

Maneuver	Descriptive parameters	Notes
Straight	**Geometric parameters:**	
	Straight-line minimum length: 80 m	
	Kinematic parameters:	
	Speed range: 30–60 km/h	
	Roll range: < +/- 5°	
Lane change	**Geometric parameters:**	Reference [11]
	Obstacle width: 1.8 m	
	Cross-lane section: 7 m	
	Lanes width: 3 m	
	Kinematic parameters:	
	Speed range: 30–50 km/h	
	Roll range: +/- 15–25°	Max value of roll to be reached during the maneuver
	Roll rate: 30–40°/s	Max value of roll rate to be reached during the maneuver
	Yaw rate: 25–30°/s	Max value of yaw rate to be reached during the maneuver
Slalom	**Geometric parameters:**	Reference [10]
	Number of markers 4	
	Markers distance 7 m	
	Kinematic parameters:	
	Speed range: 25–40 km/h	
	Roll range: +/- 15–25°	Max value of roll to be reached during the maneuver
	Roll rate: 30–40°/s	Max value of roll rate to be reached during the maneuver
	Yaw rate: 30–40°/s	Max value of yaw rate to be reached during the maneuver
Curve	**Geometric parameters:**	Defined by speed and maximum roll
	Curve radius: 15–20 m	
	Kinematic parameters:	
	Speed range: 25–40 km/h	
	Roll range: 20–30°	

follows a straight-line trajectory. As the geometrical parameters of the vehicle (e.g.: wheelbase, trail, caster angle) influence its maneuverability, in this paper both geometrical measures of the lane change section and a set of ranges of the vehicle's dynamic parameters during the maneuver are reported as a reference (see Table 1). The corridor after the maneuver is delimitated to reduce the variability inter-subject and intra-subject during lane change (with and without AB activation) and to position markers orthogonal to the direction of travel in the 'offset' area to simulate an obstacle. In Fig. 1 the geometry of the maneuver and measured vehicle parameters are reported as an example. The AB triggering is performed at the entrance of the transition zone to evaluate its interaction with the execution of the swerve maneuver. In Fig. 3 a picture of a test vehicle during the execution of the maneuver and the set-up of the markers is displayed.

Slalom section

During normal urban riding, it is common to have situations in which the vehicle dynamic is complex, for example during traffic filtering. Although in many states it is declared illegal and in others it is subject to strict regulation [13], traffic filtering is a common behavior among PTW riders to reduce time spent in traffic and to gain the head of queues. Even if these conditions are not those where MAEB could bring clear benefits, it is necessary to test it in this dynamic maneuver, where the rider is moving continuously and therefore less prepared to a reactive action. This is necessary to assess its safety and riders' reactions (caused by a possible false activation) in such a complex maneuver. In order to reproduce these conditions, a slalom maneuver guided through some markers is included in the test track. Indeed, this path allows reproducing the vehicle's lateral movements and actions on the handlebars made by riders. Slalom is reproduced placing markers with a distance in a range of 7–14 m [10] from each other on a straight line depending on desired travel speed. The distance between markers and the travel speed is selected according to the maneuverability and dynamic behavior of the experimental vehicle (see Table 1). In Fig. 2 the geometry of the maneuver

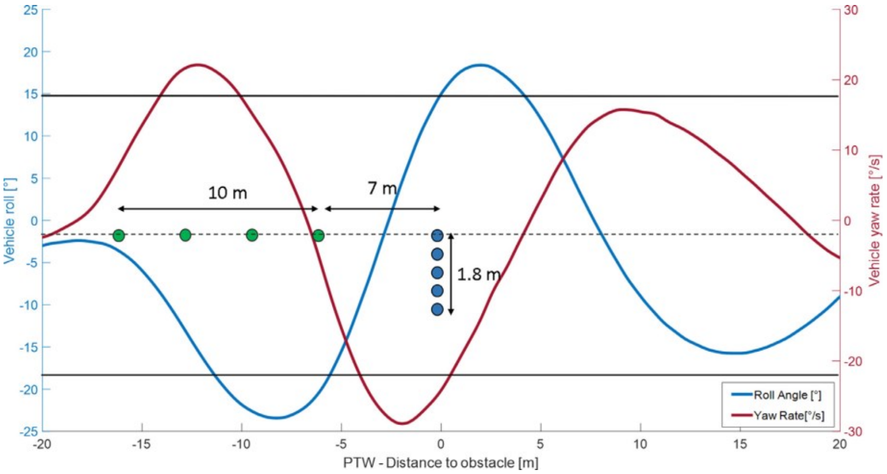


Fig. 1. Lane change maneuver.

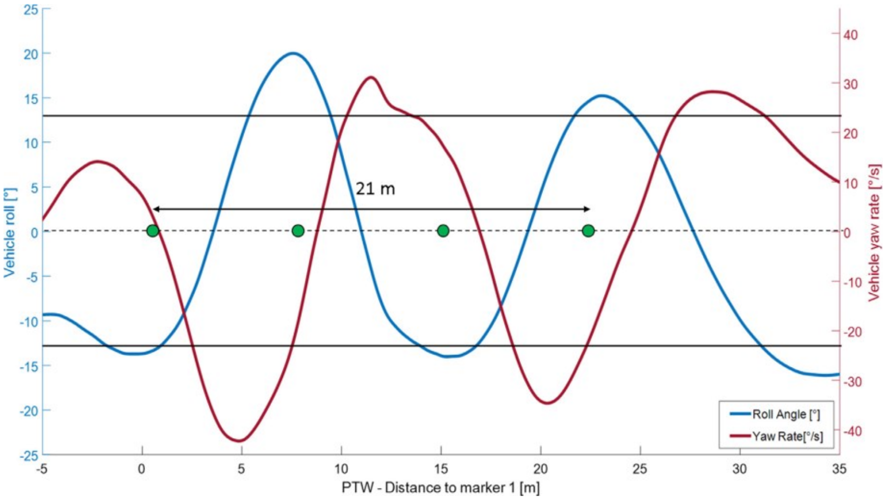


Fig. 2. Slalom maneuver.

and measured vehicle parameters are reported as an example. In Fig. 3 a picture of a test vehicle during the execution of the maneuver and the set-up of the markers is displayed.

Cornering section

A simple way to reproduce a curve is to use markers to define a curved path with a constant radius of curvature. Assuming a steady turning, from the equation of the motorcycle dynamics the necessary radius of curvature can be found according to the target roll and speed to be achieved. To reproduce

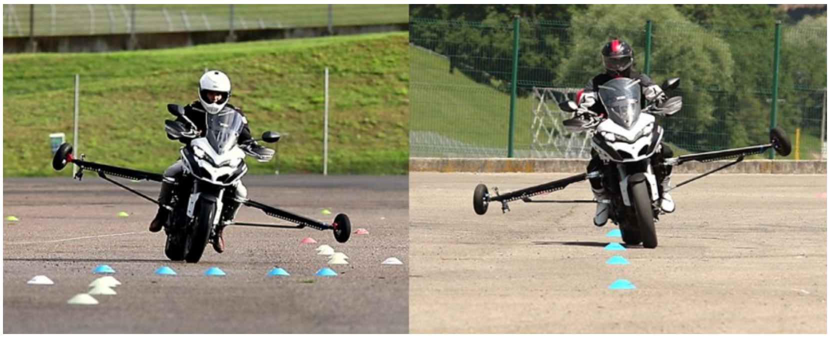


Fig. 3. Test vehicle during Lane-change (left) and Slalom (right) maneuvers.

urban scenarios, the AB is tested in curves with low velocities (25–40 km/h) and small lean angles (20–30°) (see Table 1). Nowadays there are no field experiments with AB activation in curves, although some applications in curves on real accidents have been studied via numerical simulations [14]. However, even if the potential benefits of MAEB in cornering are few and still not clear, it is nevertheless important to study the behavior of riders in the event AB activation during leaning.

Finally, before starting tests with participants both the test vehicle with the AB device and test track are intensely tested to guarantee high safety and reproducibility of the test. The AB device is tested under different environmental (temperature, wind, humidity) and asphalt adherence conditions. Preliminary tests are also useful to assess if the track was correctly designed and if the escape routes were adequate for the implemented maneuvers. Finally, the test protocol is thoroughly tested by several researchers and professional riders, in order to identify critical details of the test such as excessive physical or mental effort.

Participants recruitment and selection

Before starting with the participant's recruitment, the whole study obtains the approval of an ethical committee, since it is mandatory involving participants in testing active safety system such as MAEB [15,16]. After that, to proceed with participants' recruitment, a database of potential participants is created collecting information, such as demographics and general opinions on motorcycle safety systems, useful to select a representative sample. This is done through a recruitment questionnaire, which was digitalized and shared with motorcycle clubs, social networks, etc.

The selection phase leads to a sample wide enough to have statistical power and with high representativeness compared to PTW users in urban areas including males and females with different ranges of age. Due to the lack of normative data on which to base an accurate power calculation a convenience sample size of at least 20 participants is used, consistently with the literature examining driving performance [17], driver kinematics [18] or response time [19]. In the previous studies, tests were conducted with professional riders [1,3] and with common riders [2,3]. In order to assess the acceptability of the MAEB for the common users, it is required to continue testing it with this kind of participants. Since with non-professional riders the MAEB assessment could be strongly influenced by the selection of the sample of participants, participants with comparable profiles and riding experience are selected. Due to the limited development of the MAEB, novice riders are excluded and participants with a minimum riding experience are selected (2 years of riding or 10,000 km travelled). Moreover, the selected participants are those who ride weekly a motorcycle comparable to the test vehicle, in order to reduce bias due to different PTW styles.

Test vehicles

The appropriate test vehicles for these tests are the ones most used in the urban environment (example: moped, scooter and light motorcycle). However, it is easy to presume that the first MAEB systems that will be installed on high-end motorcycles, such as sports style or touring motorcycles. Consequently, such vehicles are also adequate for the experiments. The experimental motorcycle is a standard production vehicle with add-on of minimal non-invasive equipment and instrumentation, to ensure a relaxed and natural ride for the participants during the tests. Moreover, in order to increase the safety of participants during tests, the experimental PTW is equipped with standard ABS or better with Motorcycle Stability Control (MSC) and Traction Control (TC), since it is presumed that MAEB will be implemented on PTWs equipped with these systems.

Data collection and instrumentation

To measure the effect of AB interventions on riding stability, different procedures can be applied, which can be classified into performance, physiological and subjective measures. They differ in their degree of effectiveness and reliability and the resources required for their implementation [20].

Performance measures

The effect of the AB interventions is assessed measuring the performance in the riding tasks or maneuvers. Standard performance measures are the Mean Deviation (MD) from a nominal model, or the MD from a participant's baseline [20]. Additionally, kinematic thresholds defined in previous studies as reference for vehicles [21,22] and rider [23,24] are applied to measure the controllability and the stability of the vehicle during the maneuvers.

Vehicle data. Vehicle 3-axis accelerations and 3-axis gyro, brake pressures, throttle and steering position, clutch usage, speed and AB diagnostics signals are the basic variables to monitor if the response of the system corresponds to the designed one and to assess the riding behavior. To assess the performance of the system, the longitudinal acceleration is measured in two different ways to have a backup measure.

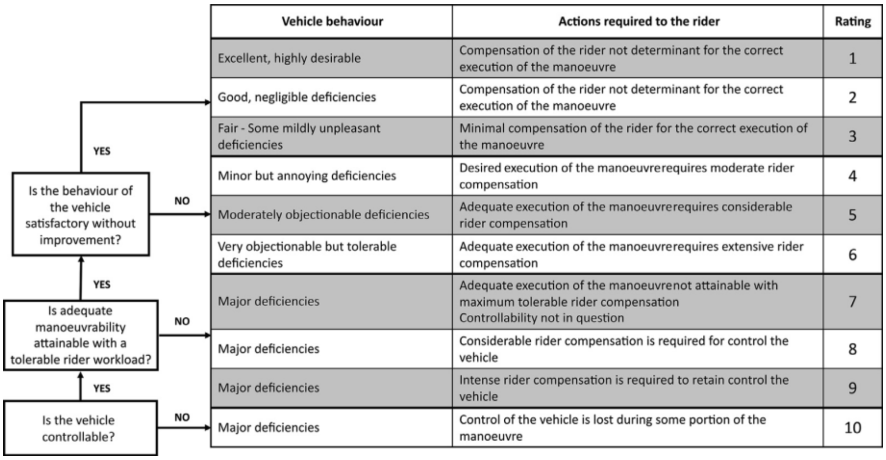
Rider position and kinematic data. The movement of the rider's body is registered with an Inertial Measurement Unit to investigate the interaction between the pilot and the vehicle during the activation of the system. The main variables collected are angle hip-chest, position (attitude), velocity and accelerations (linear and angular) of the rider's chest. Body position and movements are also recorded by video-cameras using anatomical landmarks of interest on segments of the body. An extra camera on a tripod out of the circuit records the maneuvers for qualitative analysis.

Physiological measures

The galvanic skin response (GSR) and the electromyography (EMG) may be employed to assess how demanding is for the rider to maintain the control of the vehicle [5]. Temperature and heart rate are also used to assess the responses of the body with physiological indicators [2].

Subjective measures/self-report measures

Subjective measures with questionnaires are a good solution to obtain additional data of interest related to the perception of participants. By means of clear and concise questions, questionnaires gather information related to the demands imposed on the subject (mental, physical, and temporal demands) and information related to the perception of the AB interventions and the effort required to control the PTW (compensate the AB action). To evaluate the physical and mental effort the Borg scale [25] is used, since it was widely adopted as an indicator to monitor exercise intensity. In order to have a comparable valuation of the controllability of the system, an adapted Cooper-Harper rating scale is employed [26,27]. This scale, which is a rating scale that is widely adopted to assess the controllability of aircrafts, was adjusted to assess the controllability of a PTW. As reported in Fig. 4, the rating in the scale is from one to ten, where one means an excellent behavior of the vehicle (the rider



Vehicle behaviour	Actions required to the rider	Rating
Excellent, highly desirable	Compensation of the rider not determinant for the correct execution of the manoeuvre	1
Good, negligible deficiencies	Compensation of the rider not determinant for the correct execution of the manoeuvre	2
Fair - Some mildly unpleasant deficiencies	Minimal compensation of the rider for the correct execution of the manoeuvre	3
Minor but annoying deficiencies	Desired execution of the manoeuvrerequires moderate rider compensation	4
Moderately objectionable deficiencies	Adequate execution of the manoeuvrerequires considerable rider compensation	5
Very objectionable but tolerable deficiencies	Adequate execution of the manoeuvrerequires extensive rider compensation	6
Major deficiencies	Adequate execution of the manoeuvrenot attainable with maximum tolerable rider compensation Controllability not in question	7
Major deficiencies	Considerable rider compensation is required for control the vehicle	8
Major deficiencies	Intense rider compensation is required to retain control the vehicle	9
Major deficiencies	Control of the vehicle is lost during some portion of the manoeuvre	10

Fig. 4. PTW-adjusted Cooper-Harper rating scale.

is not required to compensate the intervention of the system to maintain the desired trajectory), and ten means a loss of control. Additionally, a brief interview after the tests provides extra information about the participant’s impressions.

Test protocol specifications

The test protocol starts with a brief explanation of the test vehicle and its special controls. A short warm-up is also required to enable the participant to be familiar with the vehicle and the track before testing the intervention of AB. To evaluate participant control skills, the participants are asked to perform a set of manual hard braking until stopping the vehicle [5]. The measures of the response of the rider during the manual braking were useful to be compared with those taken during the AB interventions.

Since grating participants’ safety is the main concern and an ethical duty in research involving human beings [15,16], the design of the experiment in the approach of the participant to the intervention of AB must find a compromise between the optimal design [20] and safety. Therefore, before testing an unexpected intervention of AB the participant experiences expected interventions with levels of deceleration considered safe in the literature (at present, up to 2 m/s^2 [2,3]). Even if it could be a source of bias due to learning effects, this lets the participant have a safe familiarization with AB before testing new decelerations and maneuvers. Furthermore, measures of these declared AB interventions can be used to compare the rider’s response with those responses during the unexpected interventions of the test.

Activations of the system in unexpected conditions are anticipated by an explanation of the investigator, who introduces the intervention in terms of deceleration, jerk and maneuvers with possible system activation. The information is necessary to allow the rider to exclude from the trial activation of AB any of the maneuvers, if reputed not adequate to her/his riding level. Afterwards, the activations of the system in unexpected conditions are tested, triggering the AB in the different maneuvers according to a pseudorandom time scheme and starting with the lowest level of deceleration and jerk. At the end of each trial, the investigator asks some feedback from the participant before to proceed to test higher levels of deceleration or jerk.

Table 2
Example of the test protocol.

Test phase	Description	Duration [min]
Informing Participant	The participant receives all the information about the test, all the forms needed to take part in the test being checked by the researcher. After inspecting all the protective equipment and showing to the participant the test track, the researcher shows the test vehicle and its special commands. A demonstration of riding in the test track, performed by a team member, can be included to show how to approach the track and the maneuvers.	10
Familiarization	The participant has a limited time to warm-up and becomes familiar with the test vehicle, the track and all the maneuvers that are included in the test.	10–15
Base-line braking measures	The participant performs, at an initial speed of 40–45 km/h, manual stop maneuvers braking at three different levels of deceleration: corresponding approximately to the 30%, 50% and 90% of the maximum deceleration that he/she can achieve with the test vehicle.	10
AB Familiarization	The participant tests declared activation of the AB system at the different levels of deceleration planned to be tested in straight-line at a speed of 40–50 km/h.	5
First AB test session	The participant tests the unexpected activations of the system at the lowest level of deceleration. The interventions are defined at different points of the track in a pseudorandom way along the defined number of laps to reduce predictability. The researcher explains the maneuvers and where the system can be activated and asks the rider whether he/she wants to exclude in the trial the activation in any of the maneuvers. Eventually, the participant may ask to test one declared activation to include/exclude any of the maneuvers before the session with unexpected activations.	Number of Activations x 100 s
Break	The participant has some time to rest and completes a brief questionnaire about demands related to interaction with the system.	10
Further AB test sessions	The participant tests the activation of the system with higher levels of deceleration or jerk, following the same procedure of the first session. Again, the participant may ask to test one declared activation to include/exclude any of the maneuvers. The session ends with a break and a brief questionnaire.	Number of Activations x 100 s
Overall Questionnaire	The participant fills in a final questionnaire about the entire test and the MAEB system. A recorded interview can also be included.	15

The overall duration of the test is no longer than two hours, in order to avoid excessive fatigue and psychological overload of the participant. This time also includes some breaks to let the participant rest between different riding sessions.

The guidelines and principles proposed in this section were applied as an example in the test protocol contained in Table 2. The protocol is divided into different parts, one for each test phase; the AB test sessions can be repeated for each level of deceleration or jerk included in the test.

Test method validation

The procedure and the design criteria presented in this paper were employed to define a test protocol which was applied to further investigate the feasibility of MAEB [28,29]. Field tests were conducted involving 55 participants testing Automatic Braking intervention on three different PTWs. Field tests executed with the procedure presented in this paper were carried out [28,29]. The results coming from the analysis of these tests will provide a comprehensive understanding of the feasibility and the acceptability of the Autonomous Emergency Braking system applied to PTWs. In this section results from the final questionnaire filled-in by participants concerning the execution of the test are displayed, in order to validate the methods proposed in this paper.

A first validation of the proposed test procedure is that all the 55 participants completed the full test protocol and no potentially dangerous situations occurred for them nor the research team. This test campaign allowed to test the effects of automatic braking events deployed in different maneuvers and riding condition and different AB working parameters.

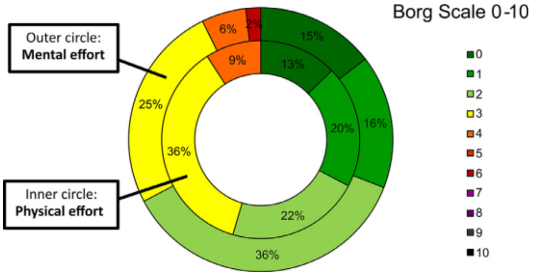


Fig. 5. Participants' rating of Physical and Mental effort - Borg scale (0= No effort – 10= Maximal effort).

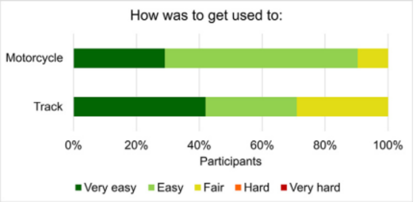


Fig. 6. Participants' rating of the warm-up phase.

Fig. 5 shows the distribution of the participants' rating regarding the mental and the physical effort required to complete the test. The complete test was considered generally easy manageable from both mental and physical point of view. Employing the Borg rating scale, participants gave an average score of 2.1 (SD = 1.2) to the physical effort and 2.0 (SD = 1.3) to the mental effort, both scores represent a light effort required to the participants to perform the test.

Concerning the warm-up test phase, all the participants rated the time given for the familiarization with the test vehicle and the track as enough (49%) or abundant (47% abundant, 4% very abundant). In Fig. 6 is displayed the participants' rating of the warm-up test phase session. For 90% and 70% of participants, becoming familiar with respectively the motorcycle and the test track with the included maneuvers, turn out to be easy or very easy. Nevertheless, no excessive strains to obtain an acceptable familiarization were reported by the remaining participants.

Planned data analysis

Field testing the intervention of an active safety system such as MAEB is a mandatory process before its introduction on standard vehicles (see for example what was done for AEB [30,31]. This is because it is required to prove its real feasibility and acceptability among end-users, ensuring MAEB safety in real-world scenarios. Therefore, after testing the intervention of MAEB following the guidelines and principles proposed in previous paragraphs, accurate data analysis is required to prove its acceptability and feasibility. The questionnaires and the feedback obtained from the participants during the final interview provide important hints on the acceptability of the systems for end-users and its working parameters. From questionnaires, information can be also acquired about the execution of the test and the tested AB device reproducing the effects of the MAEB system. The riders' movements are analyzed to investigate the effects of MAEB, monitoring their body reactions during the different phases of the automatic decelerations. This information is compared with data from questionnaires and with the movements of the body during normal riding and manual braking. Data from the vehicle is analyzed to have a complete characterization of the intervention of MAEB and the behavior of the riders during its interventions, focusing on PTW controls (throttle, clutch, brakes, steering angle) and PTW stability parameters. This analysis verifies or questions the subjective results coming from questionnaires with objective data. The data analysis also highlights if the intervention of MAEB can cause some hazards for the rider or reduce his/her ability to maneuver in pre-crash situations. These can be done using the fall detection models available in the literature for PTWs [21–23,32].

Conclusion

This paper describes a procedure to field test the intervention of an active safety system for motorcycles as MAEB (Motorcycle Autonomous Emergency Braking). Field test specifications concerning testing conditions, maneuvers, participants requirements, vehicles and instrumentation requirements are provided in order to support its design and robust execution. Lastly, an outline of data analysis is included.

The proposed guidelines and principles provide complete support to design a test protocol to further investigate the intervention and the feasibility of advanced assistance systems for motorcycles such as MAEB. Furthermore, this approach can be used as a reference for designing a field test for other active safety systems for PTW.

Additional information

Background of motorcycle autonomous emergency braking testing

A powered two-wheeler (PTW) colliding a stationary or slowly moving vehicle was found to be a common crash scenario in developed traffic contexts such as Europe and Australia [33,34]. In these situations, an automated braking response of the motorcycle was indicated as a plausible solution to reduce injury outcomes for the riders [35], assuming that such intervention should be deployed when the collision has become inevitable.

Researchers have considered whether common riders may be able to handle their vehicle under automated braking and what are the parameters of such intervention. The first documented experiment was conducted in the lab using a backward accelerating sledge, putting effort to produce unexpected events with equivalent decelerations of up to 3 m/s^2 [24]. The first on-road tests were conducted involving professional riders approaching a target obstacle with a test PTW equipped with a laser-scanner and producing automatic decelerations up to 7 m/s^2. A limitation of such tests was that participants were not presented with genuine unexpected events [1,36]. In an attempt to reduce the level of predictability of the automated braking events, the following experiment was conducted without obstacles and involving common user participants. The so-called “Wizard of Oz” approach was in place, in which the investigator activated the automated decelerations (up to 2 m/s^2) of the test vehicle via remote control [2]. New experiments were then conducted with professional riders testing undeclared automatic braking events at speeds up to 80 km/h, with decelerations up to 7 m/s^2 and jerk up to 12 m/s^3 [3]. These tests involved a moving target obstacle (a car mock-up trailer) reproducing a medium speed car-following test scenario. This study suggested that automatic decelerations greater than 3 m/s^2 can be controlled by common riders in straight-line motion.

In summary, previous research findings based on activation along a straight trajectory support the autonomous emergency braking for motorcycles (MAEB), but new tests are required to assess the feasibility of MAEB interventions for common riders when adopting decelerations greater than 2 m/s^2.

As regards the intensity of the automatic braking event, early studies that analyzed the effectiveness of MAEB suggested that decelerations of 3 m/s^2 may not be sufficient to reduce the likelihood of sustaining serious injuries [37]. If confirmed, the feasibility of higher decelerations becomes a critical factor for future development and implementation of MAEB.

As concerns the intervention scenarios to be considered, the activation in straight-line motion is certainly important, since in-depth crash investigations showed that in most pre-crash phases the motorcycle is not in a turn. However, in typical riding conditions, including pre-crash conditions where MAEB may apply, the motorcycle moves along trajectories that involve tilting oscillations (see for example [37]). Also, a lateral avoidance maneuver is often attempted by the rider during the pre-crash phase [7]. For these reasons, test scenarios other than the simple straight-line motion are warranted for a better understanding of the possible risks and possible applications of MAEB deployment before a crash in the real world.

Process employed to define the proposed test method

The guidelines and design criteria proposed in this paper were obtained through two linked phases: a literature review and a pilot test. First, to determine more realistic intervention setting for MAEB and new working parameters to be tested, a comprehensive literature review of the previous studies on MAEB was carried out. Researches concerning field testing were analyzed to find out which working parameters of MAEB were tested and recommended by literature so far, and which scenarios and maneuvers were already tested and considered safe. Works on benefits assessment and simulations were also analyzed to identify which conditions of intervention are more relevant or critical for MAEB. Moreover, in order to define new realistic intervention settings, a literature review of previous studies concerning PTWs maneuvers definition and testing was carried out.

After the literature review, using a vehicle provided with an Automatic Braking (AB) device previously developed by authors [38], a series of intensive pilot testing was conducted involving four researchers and expert riders. Tests included riding conditions relevant for MAEB activation in a real-world setting. The riders were aware of the test scope, but they performed an objective judgement on the activation for defining conditions viable for participants with any expertise level and unaware of the activation timing of the system. Specific AB activation parameters were defined for each tested maneuver. Finally, a test protocol based on guidelines coming from both literature review and field testing was defined and intensively tested in following sessions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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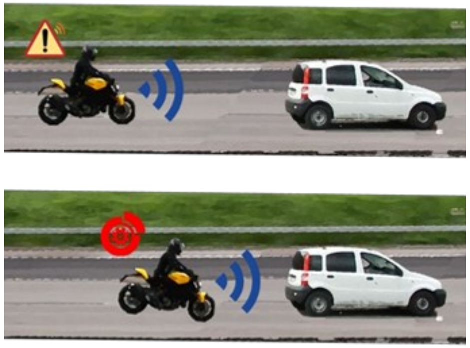
Motorcycle Autonomous Emergency Braking (M-AEB)



Test conditions

MAEB test specifications
- Riding conditions
- Automatic Braking
- Safety limitations

Riding scenarios
- Straight-line
- Lane change
- Slalom
- Cornering

Participants
- Demographics
- Type of user
- Opinion on Automatic Braking

Instrumentation
- Data collection
- Test vehicles

Test protocol

1. **Preparation** of the participant
2. **Warm-up** and **participant's skills**
3. Automatic braking **test sessions**
4. **Questionnaire** and interview

3.2 Test vehicles development

In the present work, two test vehicles were developed and employed. A first vehicle was a Ducati Monster 821, a naked sports bike motorcycle, which in the preliminary phases of the research activity was provided with an AB device and successively it was employed to pilot testing and to define the test protocol. After the pilot-testing phase, all the specifications for the AB system were defined and employed to develop a second test vehicle. The second vehicle, a Ducati Multistrada 1260 S (sport-touring style motorcycle), was developed and instrumented in collaboration with the PIONEERS project partners. This vehicle was employed to test the AB with the majority of participants since it was provided with a more reliable AB device.

3.2.1 Pilot tests vehicle

The pilot-test vehicle was a Ducati Monster 821 MY 2018, a naked sports bike popular in Italy, provided with 821cc four-stroke engine, Bosch ABS and Ducati Traction Control system. This bike was available thanks to a collaboration with the manufacturer. During the first year of PhD the motorcycle was provided with the following instrumentation developed to be employed in the pilot testing phase (see Figure 17):

- ***AB device:*** The automatic braking device was realized employing an electric gearmotor which operates the front brake lever producing autonomously a braking action by means of a dedicated mechanism.
- ***AB control unit:*** A special control system has been developed to control the prototype automatic braking device in order to use the experimental vehicle in pilot tests of the test protocol. An Arduino electronic board was employed to control the motor driver for the control of the electric motor and to integrate it with a remote activation control unit.
- ***AB diagnostic system:*** The diagnostic system installed on the motorbike consists of two LEDs to be positioned in an area visible to the action camera. These two LEDs are used to indicate which deceleration level has been activated so that the correct functioning of the system can be verified during the field tests and the post-test analysis.
- ***Data acquisition unit:*** The data acquisition unit chosen was a DL1 Club data logger from Race Technology. Although this device is designed for passenger car use, it was chosen because of the limited dimensions that make it suitable to be installed on a PTW and because of it's suite of internal sensors. The datalogger includes 3-axis accelerometers, 1-axes gyroscope, analogue inputs, GPS positioning working at 20Hz and small size. The vehicle was also provided with a GoPro HERO3 action camera to evaluate the behaviour of the driver when the braking system is activated, as well as to verify the correct functioning of the prototype device.
- ***Safety system:*** The motorcycle was provided with a pair of extension arms installed on special plates and secured to the motorcycle frame to prevent the motorcycle from falling sideways. The system was built and installed by a specialised company.

Figure 17 – Ducati Monster 821

The test vehicle setup and the implementation of the remote-controlled AB system developed for this study were published in the following publication.

II) CONFERENCE PAPER: Remote controlled braking actuation for motorcycle safety system development [56]

This publication, which was presented at the IEEE 5th International Forum on Research and Technology for Society and Industry (RTSI) in September 2019, presents the results of the work carried out to build the laboratory motorcycle to be used in the MAEB pilot testing research activity. The publication focuses on the realization of a remote-activated braking device and its control unit. The results section reports the system validation, including a brief characterization of the existing braking system, a description of the calibration method and the discussion of data obtained during real-world testing. The results displayed in this paper were fundamental to obtain a reliable prototype of the test vehicle, which was employed in the pilot testing phase and to define the test protocol.

Remote controlled braking actuation for motorcycle safety system development

Cosimo Lucci, Lorenzo Berzi, Niccolò Baldanzini
Dept. of Industrial Engineering - DIEF
Florence, Italy
Lorenzo.berzi@unifi.it

Giovanni Savino
Dept. of Industrial Engineering - DIEF
Florence, Italy
Monash University Accident Research Centre,
Melbourne, Australia

***Abstract*—Amongst various initiatives in the last 20 years for the improvement of the safety of any road vehicles, Autonomous emergency braking for Motorcycles (MAEB) could provide a significant reduction in the number of crashes or the mitigation of crash injury outcomes. User acceptance of this system, however, is still subjected to a number of uncertainties due to the peculiar needs of two-wheel riding. The activity proposed in this paper is inspired by the need to build a laboratory motorcycle to be used in teaching, research and learning activities. A braking device to be used for testing of remote-activated braking events in real-world conditions is presented. The device was conceived in order to be low-cost, removable and not invasive in the vehicle, since it would act on existing levers. A simple control system based on commercial components is introduced; the device targeted a deceleration of 5 m/s^2 (expected to be a safe value for most riding conditions); the system would be tested within not-professional riders. Our results include a brief characterization of existing braking system, a description of calibration method and the discussion of data obtained during real-world testing.**

Keywords—Motorcycle; Autonomous braking; Riders safety; Active safety; Vehicle integration.

I. INTRODUCTION

The ambitious goals targeted by the European Commission, aiming at cutting the road toll by 50% in the period 2020-30, require that effective countermeasures are identified and implemented for all modes of transport, including vulnerable road users such as powered two wheelers (PTWs). According to previous research, autonomous emergency braking (AEB) is one active system that may contribute to a mitigation of PTW crashes. Two main research topics can be identified in literature. The first one investigates the potential benefit for two wheeler riders (motorbikes, bicycles) due to the adoption of AEB or other active systems by four wheel vehicles (the *less vulnerable counterpart* in the circulating fleet, see [1][2]). The second one is focused on adoption of active safety systems directly on two-wheel vehicles. In case of autonomous braking needs, the system is usually designed to detect imminent collision situations and deploy an automatic braking event even without the input of the rider. Retrospective studies showed that autonomous emergency braking applied to PTWs (also known as motorcycle AEB, or MAEB), may influence about one third of all PTW crashes in traffic contexts such as Italy, Sweden and Australia [3][4]. An encouraging fact on this technology is that AEB is currently fully operative and already on the market for passenger cars and other vehicles [5], [6]. Much more than for AEB, one critical issue to the introduction of MAEB on series vehicles is related to the acceptance of the system by end-users. In the last ten years, both lab [7] and field tests were conducted to determine the appropriate working conditions of MAEB. Field tests involving participants focused on expert riders [8][9], or low unexpected decelerations in straight line [10]. Recently, test were conducted also with higher deceleration [11]. However, the feasibility of automatic braking and in general of advanced safety systems [12] on single track vehicles has not been thoroughly confirmed yet, and it is therefore necessary that before introducing such a system on the PTW market, further feasibility tests involving participants should be conducted. The following activities are essential: (i) assess if normal riders would easily manage unexpected decelerations; (ii) identify the limits of intervention in terms of deceleration and jerk; and (iii) identify the possible scenarios of intervention. To complete these tasks, new field tests are required and a test vehicle able to perform remote-controlled deceleration and data acquisition has to be developed.

II. REMOTE BRAKING SYSTEM: GOALS AND ACTIVITIES

A. *Scope of the activity*

In this paper, we present the development and initial testing of an automatic braking device that can be easily installed on test PTWs to conduct early stage experiments in the field for the investigation of the feasibility and acceptance of automatic decelerations on motorcycles. The automatic braking device should brake a motorcycle without the intervention of the ride via remote control activation.

Since autonomous emergency braking has the purpose of mitigating inevitable impacts, the related braking device must fulfil strict constraints in terms of braking actuation and performances. Moreover, since the device will be employed in field tests with common riders, it must guarantee high safety standards.

The braking device is designed to work in urban scenarios, with speeds up to 50 km/h. This means that it must be able to perform braking force not only in a straight line but also during lateral manoeuvres and curve. To investigate the feasibility of automatic decelerations, it is necessary to achieve decelerations greater than those tested so far [8] [10] [11]. For this reason, the braking device must apply enough braking force so that the motorcycle reaches decelerations up to 6 m/s^2. To reach a deceleration of 6 m/s^2 without the availability of a combined braking systems, it is necessary to brake the front wheel. For this reason, the braking device presented in this paper was applied to the front brake only. Given the fact that the device will be employed in pilot tests to evaluate the acceptability of automatic decelerations on motorcycles, it is essential that the braking device has a wide capability to be adjusted in terms of resulting deceleration and jerk. The device will be used to identify suitable working parameters for MAEB application. In addition, the device must be removable, and it must not modify permanently the motorcycle. To ensure the safety of the rider during the tests, the braking device must be easily disengaged by the rider also during an automatic braking event.

Such braking device will enable performing pilot tests to identify suitable working parameters for MAEB, and to define a test protocol for the analsysis of rider acceptance to unexpected deceleration events through field testing involving participants.

B. Instrumented vehicle characteristics

The test vehicle where the device is installed is a Ducati Monster 821 MY2018, a conventional street style motorcycle equipped with an 821 cc double cylinder engine. The test vehicle is equipped with a special safety outriggers device to prevent any fall or impact of the vehicle with the ground. The effectiveness of these safety outriggers is guaranteed by extensive testing with motorcyclists carried out before application in this project: they are designed to intervene at adjustable roll angles and work smoothly to minimize the risk of the driver falling because of the intervention.

The instrumentation installed on the vehicle includes a GoPro camera mounted on the left outrigger, facing the motorcycle. It provides a lateral view of the motorcycle including the braking device and the rider.

A data logger is installed (Race Technology DL1 Club) performing data collection at a sample rate of 100 Hz. It provides vehicle speed, gear number, engine RPM, clutch usage, front and rear brake activation, front brake pressure, and throttle. The data are logged directly from the motorcycle's CAN Bus. The data logger provides also data from internal sensors: measures of longitudinal and lateral accelerations, roll rate and position with 20 Hz Global Positioning System (GPS). To record the device operation condition, custom analog signals are also logged.

C. Implementation of the system: mechanical devices

The braking device that we present was designed with the purpose to be simple and easily adjustable to different testing conditions, safe for the rider in every circumstances and based on standard components, to guarantee high affordability and fast assembly. The device actuated automatic braking by acting directly on the front brake lever via electromechanical system, without direct intervention on the hydraulic brake circuit. This device allows the rider to use the front brake during the tests. The braking device is external, easily removable from the motorcycle so that the vehicle can be completely reconfigured as original. Once the braking device is removed, the motorcycle returns as original and no intervention is required to restore the standard brakes. The braking device is designed to give to the rider the chance to disengage mechanically the actuator in every condition.

The braking device was installed on the motorbike using a frame attached to the right fork. The main T crossbeam placed under the brake lever composes this frame; there are also two brackets for additional structure stiffness and resistance. The motor and the transmission are housed in the upper part of the frame; the support brackets and the connection to the fork are linked in the lower part of the frame. The structure of the frame enables several possible configurations for setting up the device on the fork and adjusting its position compared to the handlebar and brake pump. This makes the device adaptable to other motorcycles and flexible to different layouts. A 12 V epicyclic gearbox motor characterized by a reduction ratio of 100:1 actuates the braking device. The gearbox motor is installed on the frame of the braking device through two brackets.

The transmission of the power from the electric motor to the brake lever is made up of several standard components. A joint, provided with elastic pins, connected the crankshaft to the driven shaft and the brake actuator. A ball bearing was added to support the crankshaft and the joint. A shaft connecting the crankshaft joint and a knuckle joint, a knuckle joint that allows the rotation of the second part of the actuator, and a spherical joint, composed the brake actuator. The spherical joint was then linked to the brake lever through a pivot, which allows the mechanical disengagement of the actuator.

Due to the inclination between the rotation axis of the actuator and the brake lever, during the rotation of the brake lever the point of contact executes a trajectory that cannot be covered by a rigid mechanism. For this reason, the connection between the brake lever and the actuator was obtained using a spherical joint, which is free to slide alongside the brake lever. The kinematic mechanism is therefore able to rotate the brake lever following its trajectory. To reduce stress on the brake cylinder the original brake lever was replaced with one using a spherical joint.

To ensure that the movement of the actuator is limited in a safe range, a limit switch made of an aluminum block was introduced, made integral with the driven shaft through elastic pins. Two screws settled on the frame limited the rotation of the block. Tuning the position of the screws produced the tuning of the desired range of movement of the brake lever. A tunable tension spring was also installed to ensure that the brake lever returned in the initial position after any automatic braking event. The full system is shown in Fig. 1.

Fig. 1. Mechanical braking system installed on the motorcycle.

D. *Implementation of the system: control and electronic devices*

After the definition of the specifications of the mechanical brake actuator, the characteristics of its electric drive and control system were defined accordingly. The required features were the following: (i) modulation and control of target vehicle deceleration through electric motor current control; (ii) communication enabling remote control input; (iii) ability to actuate the motor-epicyclic reducer group in both directions.

The electronic control unit of the system was programmed via Matlab\Simulink “C” compilation. This solution had a reduced development time and high compatibility with other existing codes (already developed for similar applications within the working group). It also enables the use of high-level libraries for future development of control capabilities, and guarantees portability of the software in case of system upgrades.

The automatic braking device was built using low-cost, on-the-shelf components, resulting in a modular system in which each part can be substituted or modified for possible needs derived from future field testing. The main electronic control unit was an Arduino UNO device (installed microcontroller: ATmega328P), which resulted satisfactory for the current needs, while future upgrades using different microcontrollers (e.g. ATmega2560, installed on Arduino MEGA devices) are possible. Such microcontrollers are compatible with CANbus devices (e.g. MCP2515 controller) to read/write signals if interfaced with vehicle on-board network. The final size of the system is compatible with the installation on the motorcycle since it can be contained on a compact tank bag (see Fig.2).

The selected motor was a PM – DC type. To obtain actuation on both directions, an H-bridge electric drive was installed; an integrated driver and Mosfet unit was in place. The final components selected for the application and its functional layout are depicted in Fig. 2 and Fig. 3.

Fig. 2. Complete system installed on the vehicle.

TABLE I. COMPONENTS FOR SYSTEM CONTROL AND ACTUATION.

Feature	**Device**	**Component description**
Electronic control unit	Arduino UNO	Microcontroller based on ATmega328P
Electric drive	Full bridge motor drive based on VHN5019A-E	Current up to 30A (12A continuous) Current control through PWM signal Current sensing through Analog voltage signal
Remote control	RF remote command (Pushbutton – relay).	433Mhz transmission Output through STSP NO relay. 150m working distance.
Lever actuation	DC Motor 100:1 gearbox	Nominal voltage: 12V Torque-to-current constant (motor shaft): 0.0156 Nm/A Rated torque (gearbox output shaft): 9.8 Nm

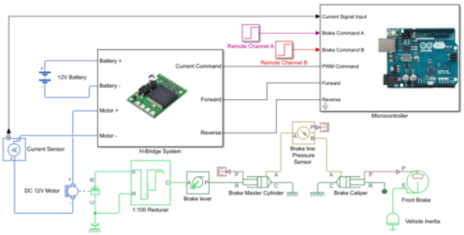


Fig. 3. Functional layout of electric system including: Microcontroller; H-bridge system; Drive and braking system. Symbols and colors are selected within standard Simulink physical libraries, lines and blocks corresponding to a different physical domain: electric devices (light blue); mechanical rotational devices (light green); mechanical translational devices (green); Hydraulics (yellow).

E. *Activation logic and control*

The software implemented in the microcontroller included a feedback control of the motor current. The current amplitude is proportional to the motor torque and, therefore, to the pressure generated in the braking system. The reference current is compared with the current circulating in the motor, measured by the the motor driver integrated unit; a PID system provides error compensation through the generation of a 0 to 100%

signal, directly used to feed the H-bridge driver with a PWM control signal.

After receiving a triggering signal from the external remote control unit, the microcontroller program starts a control loop: a target current is set, the motor direction is set to ‘forward’, and - after controlling the motor current for a predefined period - motor rotation is reversed in order to release the system actuation on the brake lever. Two different triggers were defined. The first one (Command A in Fig.4) corresponds to a certain vehicle deceleration, the second one to a higher value (Command B). The program runs at 10ms time step using an ODE1 fixed step solver.

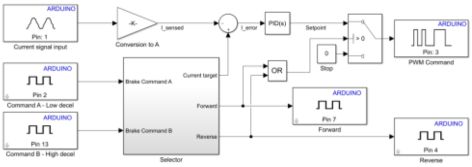


Fig. 4. Simulink program deployed as a compiled C code on the microcontroller.

III. CALIBRATION AND TESTING OF THE SYSTEM.

A. *Preliminary calibration*

An initial set up of the system was performed, which provided a preliminary calibration of the gain of each component based on predefined motor current values and front brake pressure targets (see Table II). Then, a few tests were performed to assess the overall system performance. As depicted in Fig. 3, the system reacted as expected, since the effective measured current in the motor was proportional to the target (expressed as a variable voltage), while the pressure output on front brake system was close to the target values; pressure outputs in a series of repetitions also satisfactory repeatability.

TABLE II. DATA FOR SYSTEM CALIBRATION AND TARGET ACHIEVEMENT

Item	Limits	Value
Current command (reference voltage to request a certain current)	Max value: 20A @5V	4 A/V
Current measured (sensor output)	Min value: 0V @0A	0.140 A/V
PID Gain	Max PID output value: 255 (corresponding to 100% PWM duty cycle)	P = 15 I = 1 D = 0
Target for motor current and front brake pressure	Target Max value: 6 A Fuse: 7.5 A	Brake front pressure: 15-20bar
Brake lever stroke	Measured with maximum force (by rider): 55mm	Measured stroke at target: about 30-40mm depending on value
Deceleration target	-0.6g	0.5g

For the measured time frame, a number of samples at which the current was considered stable (i.e. I/dt< 2 A/s) were used to assess the linearity between current and pressure (see Fig. 6). The dispersion of the measured points was within the expected threshold. Such dispersion, considering the braking system, was clearly related to: (I) the time needed for the actuator to reach lever stroke (approximately 30-40 mm, a value which was not accurately measured during datalogging); (ii) the delay between brake cylinder displacement and pressure increase.

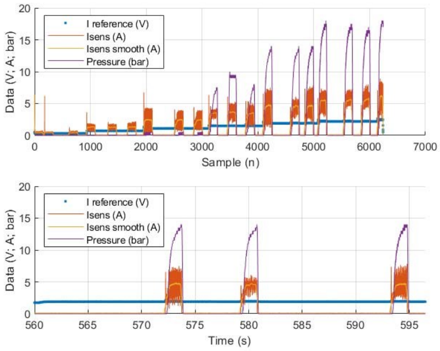


Fig. 5. Testing of the system results. I reference is a variable voltage corresponding to a current request; Isens is the output of the current sensor; for better readability, it has been smoothed using a 10 points moving average (100ms time frame); front brake pressure is also plot. Upper plot: results on various I reference values. Lower plot: focus on three repetition.

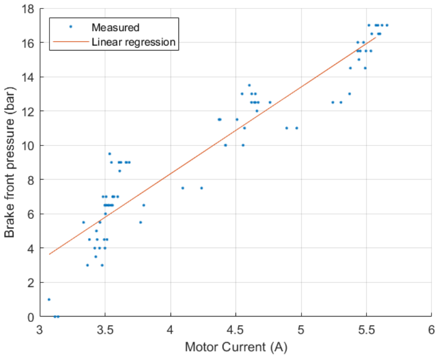


Fig. 6. Comparison with measured data and their linear regression. R-squared is 0.885.

B. Calibration based on vehicle testing

The second phase of the calibration of the system aimed at reducing the time needed to achieve the target pressure and at improving the final brake lever release. This phase started with the definition of target decelerations, the corresponding target pressures and finally the related control inputs for the prototype braking system. Fig.7 shows the results of a set of tests aimed at identifying a relationship between vehicle deceleration and hydraulic pressure on the front brake circuit. The analysis of the field tests showed that even if the R-squared value was low (approx. 0.6), in practice the relationship obtained was strong enough for our use case. The possible reason for the small correlation value is that the points used for the regression included the whole transient phase of each manoeuvre. In conclusion, the target pressure for a target average deceleration of 5m/s^2 was set to 12 bar.

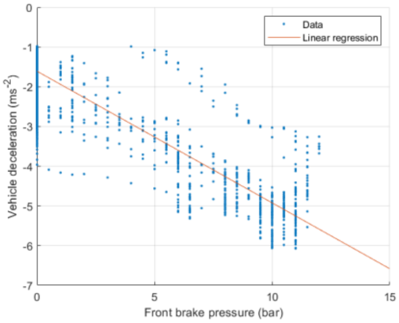


Fig. 7. Results of vehicle measurements on early testing. Relation between Front brake pressure and overall deceleration.

C. Final calibration and results

The tests highlighted the need to reduce the duration of the transient phase. Since a detailed model of the braking system was not available, a tabulated voltage-current value (the latter being the input to the motor current feedback system) was built on the basis of experimental data, considering the freeplay of the brake lever and the typical response of a full braking system. A high value for the initial reference current was chosen to to reduce the time needed to reach the target steady state value; this phase was called "pull-in" and its duration was initially set to 100 ms. However, we observed that with higher reference current values, such time can be reduced significantly. After the pull-in phase, the reference current is abruptly reduced and then it follows a ramp up to a predefined value, selected on the basis of the preliminary characterization, to maintain the desired braking pressure. Following that, the reference current is reduced to produce the brake pressure release and the final reverse motion of the motor. Details of the control sequence are depicted in Fig.8.

The typical current-pressure and deceleration trends obtained with the final application of the system after calibration are depicted in in Fig. 9. Table III shows that the brake pressure obtained in subsequent tests in various riding situations was adequate for achieving the desiderd deceleration in more than 90% of the cases. Such result is satisfactory for the system under development and could be further improved by modifying the system, for example including a control feedback on the braking pressure, or directly on the vehicle deceleration.

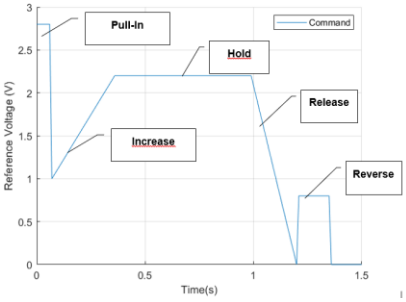


Fig. 8. Command signal built up for the application and its main phases.

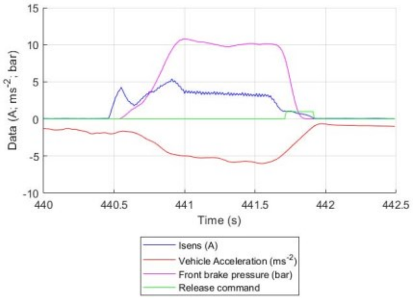


Fig. 9. Example of pressure application. Left: full data. Right: motor current and deceleration of the vehicle.

TABLE III. SUMMARY OF RESULTS AFTER EXECUTION OF ACTIVATION EVENTS WITH A RIDER IN REAL-USE CONDITIONS.

Vehicle road test						
Total activations of the system	**Straight**	**Slalom**	**Lane change**	**Curve**	**Events with unsufficient pressure**	**Critical events for the rider**
22	12	4	4	2	2	0

IV. CONCLUSIONS

The remote-controlled braking device presented in this paper enabled pilot tests to further develop MAEB system and to define new test protocols for the evaluation of the feasibility of automatic decelerations on PTWs. The proposed constructive solution fulfilled the testing requirements with a simple architecture based on standard components. Moreover, the placement of the braking device on the front assembly of the motorcycle allowed to embed all the components without being invasive for the rider. This solution enables many adjustments and easy fitting to other motorcycles. The construction of the device using standard components ensures a fast and easy assembly and great modularity: each part of the system can be easily replaced.

The prototype braking device was able to obtain the required performances of repeatability and accuracy for reaching the target current, pressure and vehicle decelerations; in typical interventions, peak decelerations of – 5 m/s^2 were achieved in 0.25 seconds from the remote triggering, with average deceleration rates not exceeding the conservative threshold of 20 m/s^3. In conclusion, the goals of the present activities were fully achieved. Future developments include the definition of a more “aggressive” calibration with shorter activation times, and the integration of the actuation logic in the CANbus system of the vehicle, in order to provide feedback according to the effective vehicle state.

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3.2.2 Automatic Braking (AB) function specifications

Based on the results of pilot testing with the Ducati Monster vehicle, the Automatic Braking (AB) function specifications were defined in order to develop a second test vehicle in collaboration with the partners of the PIONEERS project. The AB device was designed to be able to operate the braking independently when the electronic control unit (ECU) received an external signal. This signal was a surrogate signal for activation by the complete system in the event of imminent impact recognition. During tests with participants, the signal was sent by a researcher via a radio remote control.

Figure 18 shows a block diagram of the implementation of the AB system. The control unit receives input signals from sensors on the vehicle and other signals from the control system, all transmitted via CAN-bus. The block related to the detection of the imminent impact is replaced by a surrogate block consisting in the radio control managed by the researcher. If the safety limits are respected, when the trigger is sent from the remote control there is the intervention of the system, which allows the automatic deceleration of the motorcycle. The braking is activated through some parameters sent via the CAN-bus, which define the required deceleration profile. The system implemented by Bosch also communicated with the traction control unit, inhibiting the throttle control for the entire duration of the intervention. The ABS was active even during autonomous braking, so that it could intervene if required by the riding conditions.

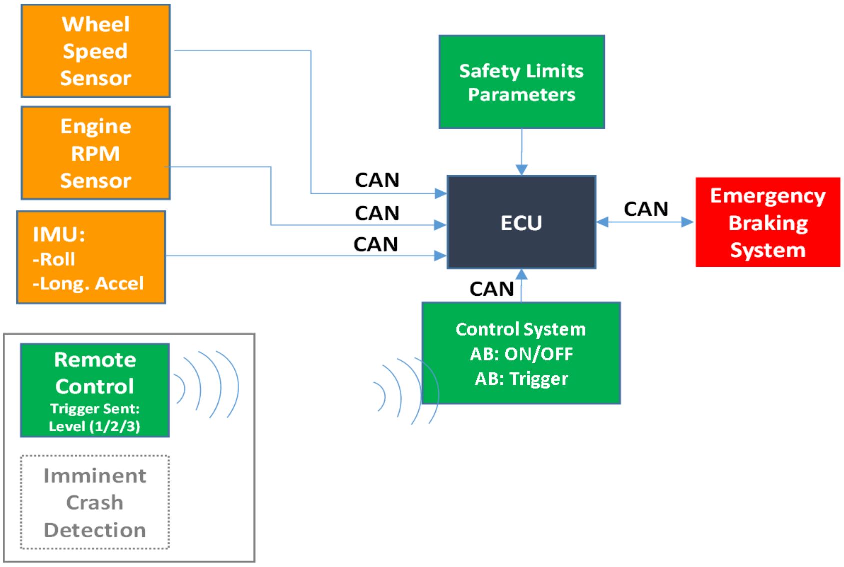


Figure 18 – AB system block diagram

3.2.2.1 *AB braking parameters*

The activation of the AB was controlled via a single CAN message. This message was composed of braking parameters that defined the characteristics of the automatic braking intervention, and the triggering input (Figure 19).

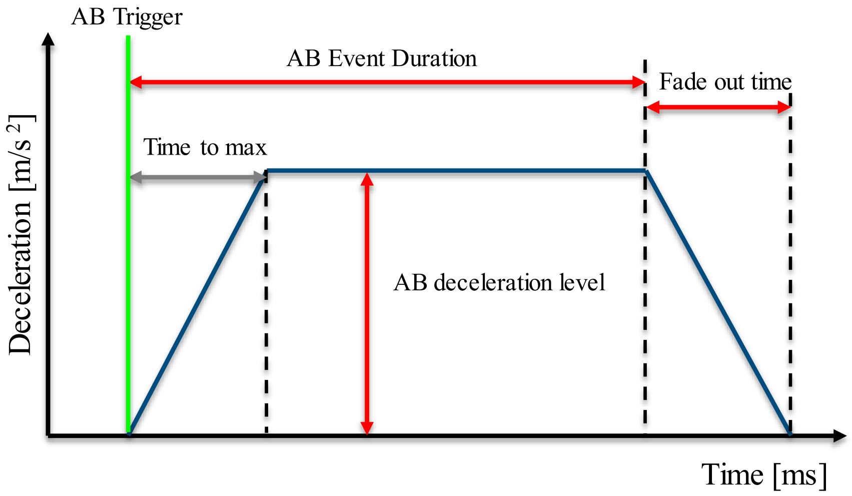


Figure 19 – Parameters to define the deceleration profile of the AB intervention

The braking parameters that characterized the automatic braking intervention of the AB were:

- **AB Trigger:** activation of AB.
- **AB deceleration level:** level of deceleration achieved by the vehicle.
- **AB event duration:** duration of the deceleration except for the fade-out time.
- **Time to max deceleration**: time to reach the peak of deceleration of the AB intervention – (defined as fade-in jerk).
- **Fade out time:** exit duration from the constant deceleration phase.

3.2.2.2 *Safety limits of the AB intervention*

The AB system was provided of some safety limits which were implemented to allow the activation of the AB only under safe riding conditions (Table 3). In addition, during the execution of the tests, the researchers observed the participant, and they checked the appropriateness of the riding style and conditions before any AB activation.

The AB system provided also some diagnostic signals to the ECU (ready to brake, active, disabled – AB out of the safety limits) verifying that the system was working correctly and transmitting whether the AB was activated or not.

Table 3 – AB safety limits

Safety Limits	
Vehicle Speed	Max 80 km/h Min 15 km/h
Engine RPM	Min 1800
Roll Angle	Within +/- 25°
Longitudinal Deceleration	Max 0.8 g
Latency time between consecutive activations	4 s

3.2.3 Participants tests vehicle

Thanks to the collaboration within the PIONEERS project, a second test vehicle was equipped with an advanced AB device realized by a partner of the project. The basic motorcycle was a Ducati Multistrada 1260 S MY 2018 (Figure 20), a sport-touring motorcycle made available by the manufacturer through a specific agreement signed as part of the PIONEERS project. The vehicle was equipped with a Brembo braking system fitted with a Bosch cornering ABS with PIONEERS specific software, combined braking, a four-stroke engine with a displacement of 1262 cm^3 and semi-active suspensions. The motorcycle was equipped with a top case to install all the AB control and data recording instrumentation and a lowered seat (825 mm), in order to give to all the participants a comfortable seat and control of the motorcycle.

Figure 20 – Ducati Multistrada 1260 S

3.2.3.1 AB remote control unit

The AB control unit (Figure 21) was composed of a remote-control unit which received the AB operating parameters via remote control and then wrote them to the AB ECU via CAN-bus line. The control unit was based on a microprocessor Arduino Mega 2560 coupled to a CAN-BUS shield, which adopts an MCP2515 controller for the CAN and a MCP2551 transceiver. This module allowed the microcontroller to communicate with the CAN-bus of the motorcycle through an RS232 port. The microcontroller was remotely controlled using a Futaba T6L Sport radio control, which works at 2.4 GHz and has a range of several hundreds of meters. The remote control sent to the microcontroller, through the receiver, three signals for the activation of the AB system. The control algorithm implemented into the microcontroller and able to transmit the operating parameters of the AB was developed in Matlab-Simulink environment and it was "deployed" on the microcontroller, to operate independently from any external computer. The microcontroller also took care of the additional features of the control box, such as the switching on/off the information lights, and the communication of instructions to the participant through dedicated lights.

Figure 21 – DL1 Club and AB remote control unit

3.2.3.2 Data acquisition

A DL1 CLUB device by Race Technology was used to record data of the tests. This datalogger was used to record data from the motorcycle CAN-bus (including the AB system and its remote-control unit), from the analogue sensors and from the IMU, for monitoring the participant's body movement, on a single support and with a sampling rate of 100 Hz. The device was placed in the rear case above the AB control box (Figure 21). The datalogger, powered directly by the motorcycle battery, had also an integrated 20 Hz GPS receiver without interpolation and a triaxial accelerometer with 0.005 g resolution.

3.2.3.3 Outriggers

The device used to prevent the motorcycle from falling sideways was composed of a pair of extension arms installed on special plates, secured to the motorcycle frame. The system was built and installed on special plates linked to the motorcycle frame by a specialized company. The arms consisted of three tubular steel bars, at the end of which there was an idle wheel mounted on a joint. The latter had the function of absorbing a possible impact with a small obstacle or with a discontinuity of the asphalt, while the tyre allowed continuing the manoeuvre also in case of contact of the wheel with the ground. The device allowed the adjustment of the maximum roll angle of the vehicle, corresponding to the condition in which the wheel of one of the supports was touching the ground. During tests with participants, the maximum roll angle was set at 25° (Figure 22). A validation of the usage of the outriggers for MAEB field testing was presented at the AIAS conference in September 2020 [57], but was not included in this thesis because it was not within the core activities of this research.

Figure 22 – Ducati Multistrada 1260 S with outriggers

3.2.3.4 Kill-switch

An additional device, called kill-switch, was installed on the vehicle and fixed to the handlebar near the throttle. The device consisted of a button connected upstream of the vehicle's electrical system, so that the power supply of all components could be cut off and thus stop the motorcycle. The button was kept closed by a removable element, which was connected to the driver's right arm by means of a flexible cable (Figure 23). If the rider had been thrown off the vehicle due to a fall, the element, pulled by the cable, would have been removed in order to stop the engine and avoid possible dangerous behaviour of the motorcycle. During the tests with participants, no event involved the intervention of this safety device.

Figure 23 – Kill-Switch with elastic cord secured around the rider's wrist

3.2.3.5 Information lights

In order to properly monitor the AB system, the motorcycle was equipped with visible information lights during the test. These systems included lights with three different colours to indicate the intervention levels of the AB (green indicated deceleration level 0.3 g, yellow 0.5 g and red 0.6 g), and two other lights, positioned on the outriggers support plates, indicating AB activation and the system inhibition (see Figure 24).

Figure 24 – Information lights: Level of AB intervention (SX), Status of the AB system (DX)

3.2.3.6 Rider movement

An Xsens MTi-G Inertial Measurement Unit (IMU) was attached on the back of the participants to record the body movement during the tests (Figure 25). The IMU registered the movement of the riders' body (Acceleration, Gyro and Orientation) relative to the vehicle, with a sampling frequency of 100 Hz. To compare the data obtained from the IMU with the video footage taken, 5 markers (2 on the lateral side and three on the back) were attached to the airbag vest (Figure 25).

Figure 25 – Xsens MTi-G IMU position (orange in the back) and markers on the back of the rider

3.2.3.7 Action cameras

The motorcycle was equipped with two "GoPro Hero 4 black" action cameras, set to record at 720p and 50 fps and continuously powered by the vehicle. The first action camera was 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 second action camera was placed in a lateral position, using a tubular support fixed to the right-side extension arm. This camera allowed to record the rider from the right side and monitor his/her behaviour during the AB intervention (Figure 26).

Figure 26 – Action camera view: Back position (SX), Right side position (DX)

3.3 Test protocol

Based on the test design criteria presented in section 3.1, a detailed test protocol was designed to field test AB with common riders as participants. In this section the test protocol is presented, including the details of the AB levels and manoeuvres to be tested. This test protocol obtained the approval of the University of Florence Ethics Committee (Decision N. 46, 20/03/2019 – see in the appendix section 8.1).

The events of AB intervention were carried out via remote control by one of the investigators. The activation took place only when the motorcycle was in specific areas of the track and while the participant performed one of the required manoeuvres. As such, the investigator could ensure that the following safety criteria for activation were met:

1) the participant at the time of intervention was neither too close to any obstacles nor too close to the limits of the test track;
2) the participant's riding behaviour fully complied with the instructions provided during the introductory phase. These included for example keeping the speed and lean angle within the indicated limits or keeping both hands on the handlebar.

Each test session consisted of a series of AB activations with decelerations between 20% and 60% of the maximum manually achievable with the motorcycle braking system. The AB system was designed to decelerate the motorcycle automatically, i.e. via remote control input and without rider intervention, with nominal decelerations ranging from 0.2 g to 0.6 g.

The tests took place in a flat area closed to traffic. The tests were conducted only during daytime hours. AB activations took place at different velocities ranging from 30 km/h to 60 km/h (depending on the requested manoeuvres) in conditions that included the following: straight driving, lane change, slalom, cornering. The AB system for Ducati Multistrada was designed to achieve decelerations that can be easily managed by riders in all the above conditions. The definition of the operating parameters of the system was validated through specific experimental activities carried out by the investigators for the development of the system and the test protocol.

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. The road conditions were checked with braking tests performed at the adherence limit (with ABS intervention) carried out by a member of the research team before starting each test session. Once the road conditions were assessed, the set of AB interventions to be tested was defined by the principal investigator or a delegate, taking into account the riding skills exhibited by the participant during the familiarization with the test vehicle and the warm-up phase. Before starting each test session, the set of interventions (type of manoeuvres with AB intervention, level of AB intervention) were disclosed to the participant, with higher emphasis when the asphalt was not dry. Each participant was given the opportunity to choose whether and under which of these conditions to test the system. In case of heavily wet road, tests could only include straight riding activation of AB in the presence of the outriggers. Decelerations were obtained via remote activation of a combined front and rear brake action.

The test track was divided into two parts: one part was dedicated to manual braking during the familiarization phase and the other to the AB activations during pre-established manoeuvres. The participant was not aware of the exact sequence of activations nor the exact timing. However, due to the characteristics of the track and an inevitable learning effect, the more the test session went on, the more the participants may become (consciously or unconsciously) aware of the probability of AB activation in certain spots of the track and at a certain time. For this reason, the activations cannot be considered completely unexpected. These events of AB activation are addressed as 'pseudo unexpected' events. In order to obtain at least one activation at higher level of unexpectedness per participant (a reference genuine unexpected activation), a wide and straight stretch of the track was identified to execute one single, final AB intervention. For this AB activation, named as ‘Out of the Blue’ (OB) event, AB parameters were the same of those previously tested and it did take place with the test vehicle in upright position (small lean angle), thus with equal or higher safety level compared to those applied in the pseudo unexpected events. The out of the blue event was consistently performed at the end of the experiment, when the ability of each participant to manage AB interventions was well confirmed.

The test protocol for this study included seven different phases, as described in the following paragraphs.

3.3.1 Description of the test phases

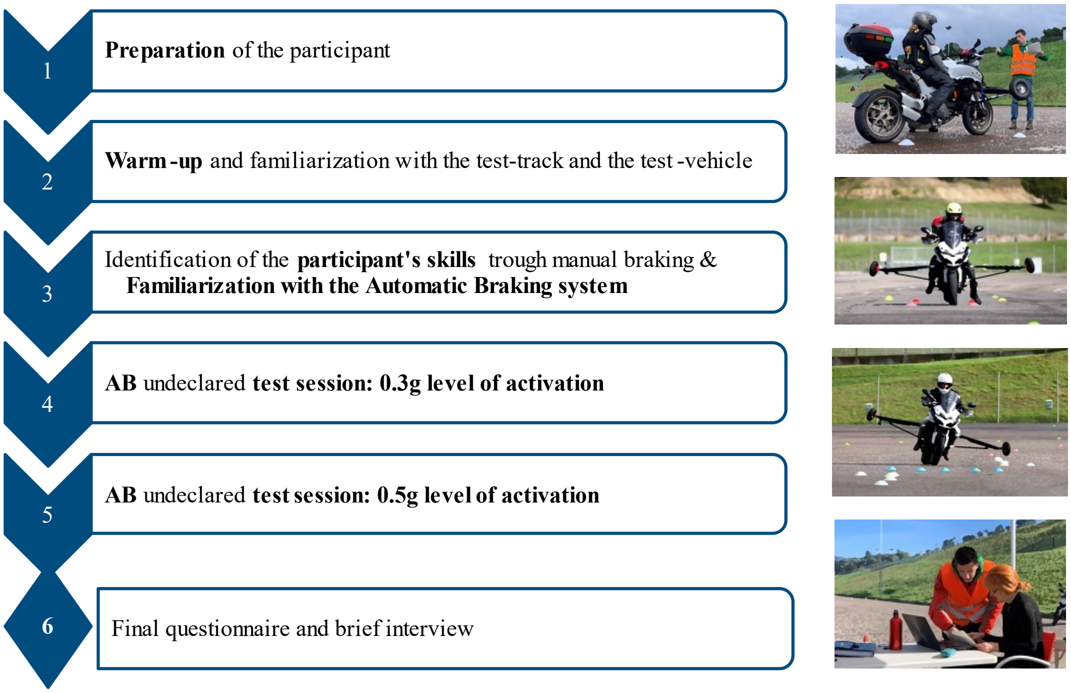


Figure 27 – Test phases

In this section a detailed description of the six phases which composed the field test procedure with participants is presented. The flow diagram of the test procedure is reported in Figure 27.

Participant preparation

Informed consent and documents: before starting with any activity, one investigator verified that the participant had read and understood the study information sheet. The participant was required to show his/her valid driving licence. The investigator then summarized the key elements of the test activity and reminded the participant that there was no obligation to continue: the participant was free to ask for a pause or to stop the experiment at any time. The participant and the investigator would sign two copies of the informed consent form. During this phase, one research team member performed some laps with the test vehicle in order to let the participant see how the test takes place, including all required the manoeuvres in the test track.

Protective equipment: the participant was required to wear a complete set of motorcycle protective equipment, which included full-face helmet, motorcycle jacket and trousers with internal protections, back protector, gloves, boots and airbag jacket. The research team provided the cord-type airbag jacket followed by brief description on the operating principles and safety-related aspects. The participant was provided also with any missing piece of the required protective equipment.

Inertial sensor: the back of the airbag jacket was equipped with a non-invasive sensor (approx. 30x24x10mm, and a weight of 100g) for measuring rider body movements.

Motorcycle outriggers: the vehicle used to test the AB system during manoeuvres requiring outriggers was equipped with a special engine-shutdown system (the so-called kill switch). This was composed of a wrist bracelet to be worn by the rider, connected by a rubber cord to an engine turn off switch that activates in case of a fall followed by separation of the rider from the vehicle.

Warm-up and familiarisation with track and vehicle

A warm-up phase allowed the participant to get familiar with the test vehicle in a progressive and safe way. The warm-up included the following steps:

a. One investigator provided an introduction to the use of the motorcycle, the outriggers, and the special controls (e.g. kill switch).
b. The participant first sat on the test motorcycle and from standstill, he/she weighed the vehicle for inertia and steering operation. At this stage, the participant was asked to sit and hold firmly while the investigators gently capsized the vehicle in order to let the rider experience the contact of the outriggers with the ground (both in terms of lean angle and system stiffness).
c. The participant started the engine, tested all the controls and then started the vehicle for a first ride consisting of a single lap of the track at very low speed (target speed 15 km/h). Then stopped at the starting point for a quick general check with the investigators.

d. The participant rode the test vehicle for two more laps along the track at low speed (target speed 30 km/h) and then stopped at the starting point. During this phase, the investigators checked whether the participant was able to adequately balance and control the vehicle.
e. The participant rode the test vehicle at higher speeds (within the given speed limit of 50 km/h), performing several laps of the track including the execution of the predefined set of manoeuvres for about 10 minutes. Additional time (up to extra 15 minutes) was given to participants until they reached an adequate level of familiarization with the track and the manoeuvres.

At the end of this phase, the participant was asked if he/she wanted to proceed with the next test phase.

In case the participant did not observe the indications and speed limits imposed, the investigator could interrupt the test and ask the participant to comply with the instructions. The participant could be warned that in case of improper or dangerous behaviour the test would have been interrupted.

Manual braking and familiarisation with AB system

This phase was designed to let the participant familiarize with the intervention of the AB system and included the following steps.

a. The participant performed three straight line, manual braking manoeuvres, respectively at 30, 60, and 90% of his/her maximum performance. These trials provided qualitative indications and quantitative data for an initial assessment of the level of riding ability of the participant.
b. The participant was asked to ride along a straight path and get prepared to declared activations of the AB at a predefined location. One investigator was in charge of remotely activating the AB system. A total of up to three declared activations were performed, with increasing decelerations ranging from 0.3 g up to 0.6 g. After each activation the participant returned to the starting position, where he/she were asked whether the control of the vehicle during AB intervention was operated with ease. Then, the participant was asked whether he/she felt comfortable in moving on to the higher level of deceleration.
c. Before starting with the proper test, the participant was offered the opportunity to experience one or more declared interventions of the AB system in one or more manoeuvres, in the case he/she felt the need to increase the confidence with the system and with the test protocol. If the participant requested any declared activations, such activity was performed at the beginning of the next phase.

AB test session: low level of activation

This phase involved the deployment of the AB system with the low deceleration level, with pseudo-random activation sequence and pseudo unexpected interventions. This part was divided into the following steps:

a. Facultative: the participant was informed about the AB interventions included in the test session and he/she had the chance to execute this facultative and preliminary familiarization with one or more specific AB activations – In such cases, the participant rode the test vehicle along single laps and experienced declared AB activations at low level of deceleration, while executing the manoeuvres requested at the end of the previous phase (if any). The participant was then asked whether to confirm or not the inclusion of such manoeuvres in the following test sessions.
b. A maximum of 10 low-level AB activations per session were remotely deployed by one investigator, following a predefined pseudo-random sequence. The first AB intervention was always activated during the simplest manoeuvre, namely the straight-line activation. Then, more demanding activations would follow. These may have included the lane change activation, the slalom activation, and the cornering activation. Such progression was specifically designed to have a progression in the required task in order to minimise the risks of a loss of control during the AB intervention. The participant was not informed about the predefined sequence of activations.

Short break

The participant was asked his/her consent to proceed with the following sessions, with increased jerk/deceleration levels for the AB interventions. The steps for this phase were the following:

a. The participant got off the bike for a break of about 5 minutes.
b. The participant filled in a short questionnaire including a controllability rating for each manoeuvre tested (employing the adjusted Cooper-Harper rating scale displayed in 8.2).
c. The next test session was introduced to the participant: pseudo unexpected interventions would take place at the higher level of intervention, while executing the same manoeuvres of the previous session. Again, the participant was offered the opportunity to test the intervention of the AB system in one or more manoeuvres, to increase the confidence with the system and with the test protocol. At the end of this phase, the participant may have asked to remove some of the manoeuvres from the next part. Alternatively, he or she may have asked to move on to the next part, with pseudo unexpected activations at high level of intervention in the proposed manoeuvres, or either skip the next session and move to the final questionnaire.

AB test session: high level of activation

This phase involved the deployment of the AB system with the higher deceleration level, with pseudo-causal activation sequence and pseudo unexpected interventions. In addition, an attempt to obtain a genuinely unexpected activation was carried out. This phase was divided in the following steps:

a. Facultative: the participant was informed about the AB interventions included in the test session and he/she had the chance to execute this facultative and preliminary familiarization with one or more specific AB activations – In such cases, the participant rode the test vehicle along single laps and experienced declared AB activations at high level of deceleration, while executing the manoeuvres requested at the end of the previous phase (if any). The participant was then asked whether to confirm or not the inclusion of such manoeuvres in the following test sessions.

b. A maximum of 10 high-level AB activations per session were remotely deployed by one investigator, following a predefined pseudo-random sequence. The first AB intervention was always activated during the simplest manoeuvre, namely the straight-line activation. Then, more demanding activations would follow. These may have included the lane change activation and the slalom activation. Such progression was specifically designed to have a progression in the required task in order to minimise the risks of a loss of control during the AB intervention. The participant was not informed about the predefined sequence of activations.
c. At the end of the last session, once the set of pseudo-random activations was carried out, an additional activation (‘out of the blue’ activation) was performed in correspondence of the dedicated straight segment of the track. This activation was applied only if the participant had shown high confidence with the AB intervention, if the speed limit was respected and if the participant was in full control of the vehicle.

Final questionnaire

In this final phase, the participant got off the bike and took off the protective equipment. Then, the participant was asked to fill in a short questionnaire to gather information about his/her personal experience during the test, in particular during the activation of the AB, and his/her general opinion about the AB system after experiencing the AB interventions. The questionnaire included also the controllability rating for each manoeuvre tested with the highest level of AB intervention.

3.3.2 Test track and manoeuvres

The presence of outriggers required a large test area, flat and free from obstacles (including impediments such as traffic islands). An aerial view of the test area is provided in Figure 28.

The activations of the AB were performed along a straight path, while performing a lane change, during a slalom and during steady-state cornering. Each activation took place four times per each level of intervention. In consideration of the number of manoeuvres involved and the number of repetitions, and in consideration also of the time needed to ride a complete lap of the large test track, two levels of intervention were tested during a total of two sessions: a) low deceleration; b) high deceleration. The single out-of-the-blue AB intervention was executed along a straight, with high deceleration level of 0.5 g. In case of wet asphalt during a test, AB intervention during cornering and during slalom may have been excluded, for safety reasons. In Figure 29 is shown the test track designed for the tests.

Figure 28 – Test area

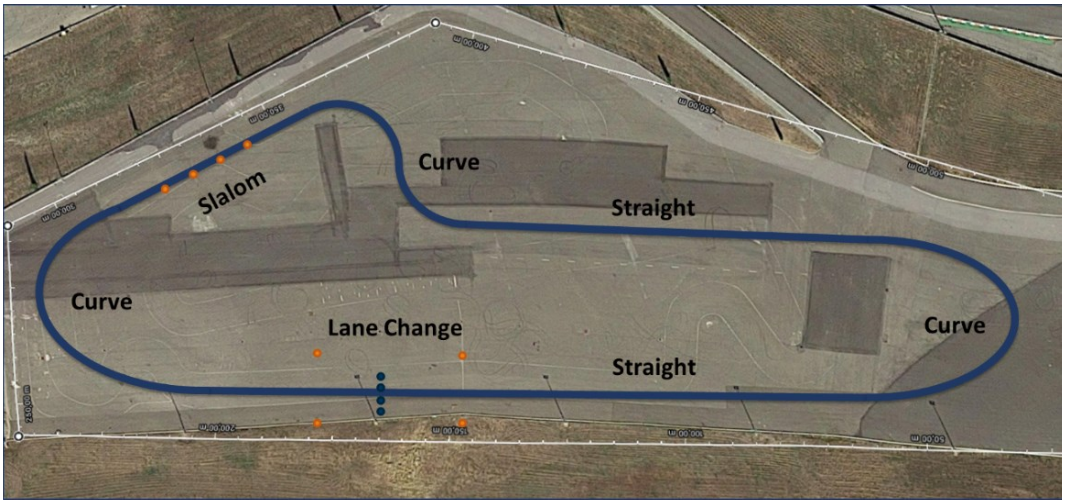


Figure 29 – Test track

The test protocol included a total of 17 (nominal number) activations per participant during 35 (nominal number) laps. The test protocol and AB activations are summarised in Table 4.

Table 4 – Test protocol in brief

Manoeuvre	**Nominal deceleration [g]**	**Nominal Jerk [g/s]**	**N° of AB activations**	**Direction**
Straight-line	0.3	1.5	2	Both sense of rotation: clockwise & counter clockwise
Lane change			2	
Slalom			2	
Curve			4	
Straight-line	0.5	1.5	2	Single sense of rotation
Lane change			2	
Slalom			2	
Straight-line – OB			1	

Figure 30 shows an example (participant n° 28) of the chronological order of the activations performed to the participants. The first ten activations belong to the first test session where the AB target deceleration was 0.3g, whereas the last seven activations are made in the second session and the final one is the so-called “out of the blue”.

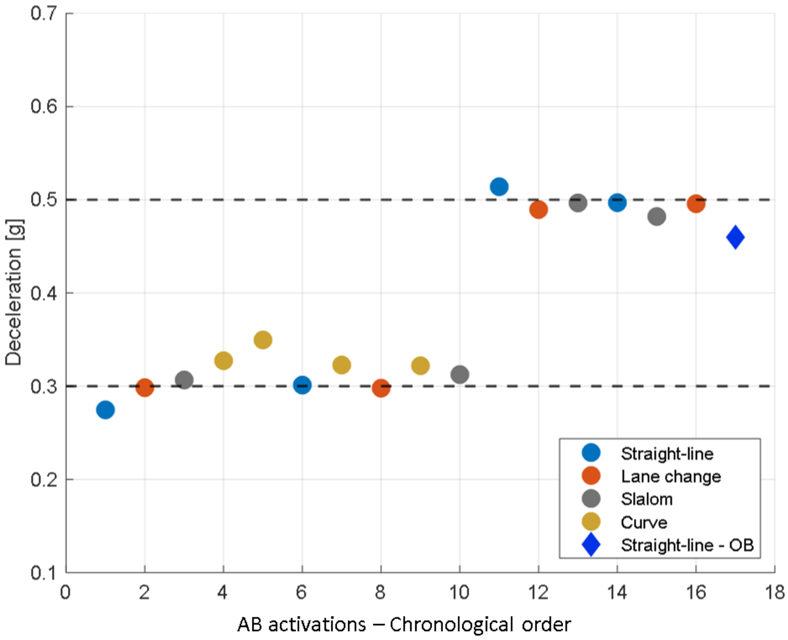


Figure 30 – Order of tested AB activations

3.4 Participants recruitment and selection

The experimental activity performed for this study was based on common riders as volunteer participants. In order to guarantee the rights of the participants and adequate procedures, the study was conducted in accordance with the Declaration of Helsinki, and the whole test protocol and procedures were submitted to the approval of the University of Florence Ethics Committee. The research project was approved (Decision N. 46, 20/03/2019) two months before the beginning of the experimental activities, and before they participated, all subjects gave their informed consent for inclusion in the study. The approval communication by the Ethics Committee is available in the appendix (section 8.1).

3.4.1 Recruitment

Being the goal of the recruitment phase to collect the highest number of volunteer riders as potential participants, a web page (see Figure 31) and short video advertising the field test activity (without details regarding MAEB) was arranged. The invitation to participate to the tests was then advertised through the following media:

- Web pages of the University of Florence and the Moving research group
- Social media
- Flyers in motorcycle accessory store and pubs frequently visited by motorcyclists
- Biker groups

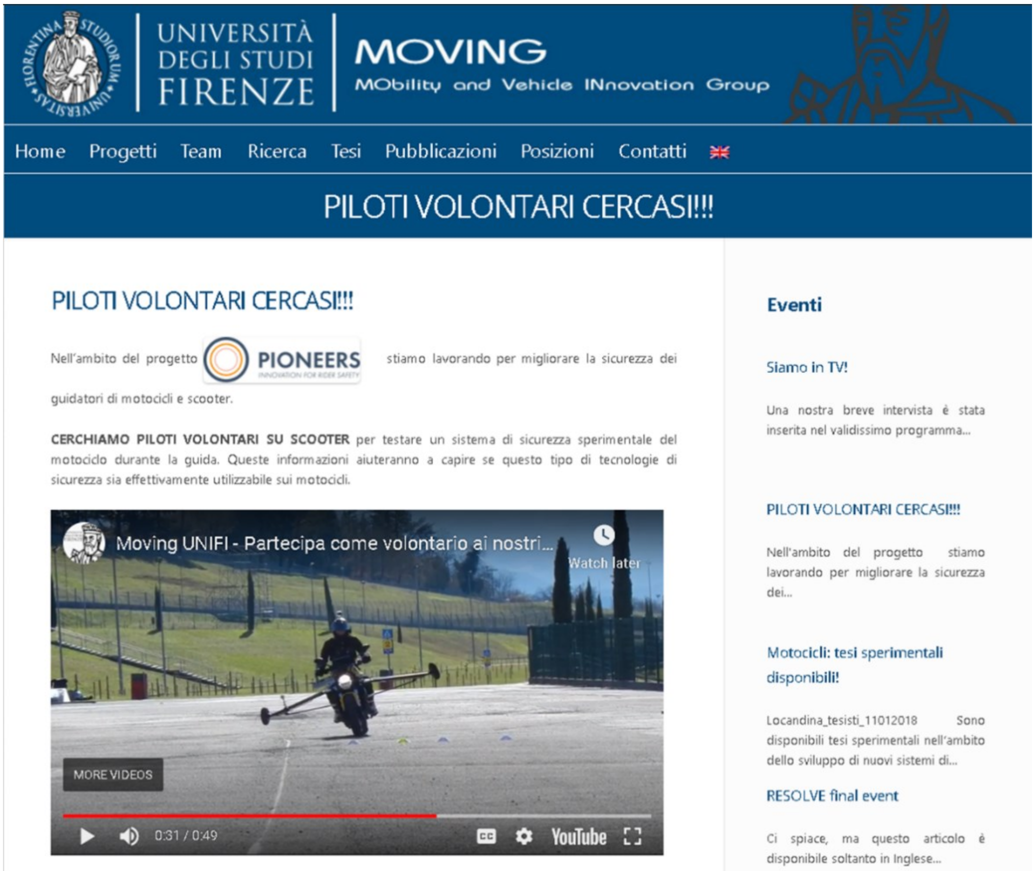
The rules and inclusion criteria were stated in the application page. Only adults over 18 years of age and able to express their consent were considered eligible for this study. The consent to participate was given freely, as stated in the informed consent. The participants involved did not include any of the members of the research team of the University of Florence. Furthermore, participants had the option to stop the test at any time. There was no form of economic incentive to take part in the study. PTW riders were expected to join for the sake of supporting the development of innovative safety functionalities for the benefit of future generations of riders.

Inclusion Criteria

- To own a full motorcycle licence (unrestricted) for more than 2 years, or with at least 10,000 km travelled.
- To use a motorcycle of the same type to the test vehicle (e.g., similar engine size or sport-touring type), with at least weekly frequency of use.
- Suitability for driving a standard motorcycle without special controls.

Exclusion criteria

- Height less than 160 cm (limit imposed by the seat of the test vehicles).
- Disabilities that preclude from riding a motorcycle.
- Neurological problems.



PILOTI VOLONTARI CERCASI!!!

PILOTI VOLONTARI CERCASI!!!

Nell'ambito del progetto PIONEERS stiamo lavorando per migliorare la sicurezza dei guidatori di motocicli e scooter.

CERCHIAMO PILOTI VOLONTARI SU SCOOTER per testare un sistema di sicurezza sperimentale del motociclo durante la guida. Queste informazioni aiuteranno a capire se questo tipo di tecnologie di sicurezza sia effettivamente utilizzabile sui motocicli.

Eventi

Siamo in TV!

Una nostra breve intervista è stata inserita nel validissimo programma...

PILOTI VOLONTARI CERCASI!!!

Nell'ambito del progetto stiamo lavorando per migliorare la sicurezza dei...

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RESOLVE final event

Ci spiace, ma questo articolo è disponibile soltanto in Inglese...

Figure 31 – Recruitment webpage (in Italian, as participants were mainly recruited in the area of the test track located approx. 40 km from Florence, Italy)

The potential participants who meet the inclusion criteria were required to register themselves on the database specifically created for this study. After that, they filled in a questionnaire on the following topics: demographic information, riding habits and general opinion on motorcycle safety systems. Thanks to this procedure approximately 110 candidate participants applied to join the test; 35 participants were then selected to be included in the test presented in this study, whereas other 20 participants were selected for testing MAEB with another test vehicle (scooter style), which was part of task 5.2 of the PIONEERS project.

3.4.2 Selection for the test

The selection of participants was performed using the information given by the potential participants through the questionnaire filled after the registration, based on the following characteristics: age, gender, level of education, type of user and opinion on MAEB. All this information were asked in the questionnaire before the potential participants knew about the test focused on MAEB. Since the goal of the study was to test the AB with a number of participants representing the potential users of MAEB system, the selection of riders to be included in the study was carried out to obtain a sample as much as possible heterogeneous of PTW users. However, the first participants within the sample of those included in the study were those characterized by a higher level of experience and estimated riding skills, and possibly owners of the same PTW or a PTW of the same category (sport-touring) of that used in the test. After that, less experienced riders participated in the study once the positive feedback of experienced riders confirmed the safety of the test. This allowed having a gradual approach for testing the AB in new working conditions with common riders.

All participants were contacted via e-mail and then called to give additional information about the test (i.e., information on the test vehicle and test procedure, time required, location of the test track). If the participants agreed to join the test, a date was scheduled, and contact data of the test supervisor was provided to the participant. The participants were also asked to bring their motorcycle garments if equipped, otherwise the equipment was provided by the research team.

4 Field tests results

In this section, the results of field tests performed with participants and the data analysis carried out in the third year of PhD will be presented. The results presented in this section have the goal of answering the two first research questions of this project: the riding conditions and the MAEB working parameters which can be feasible in real-world condition will be identified, and the riders' acceptance of the autonomous emergency braking for motorcycles will be evaluated. These results will be presented through four different publications, with the inclusion of further results which are still unpublished. First, an overview of the whole field test campaign carried out within the task 5.2 of the PIONEERS project will be presented through a conference paper. A first journal paper will then focus on the applicability of MAEB when the rider is performing a lane-change manoeuvre. A second journal paper will evaluate the applicability with new higher levels of intervention (0.5g of deceleration and 2g/s fade-in jerk). The fourth subsection will focus on the acceptance of MAEB by end-users through a conference publication. Finally, the last subsection will present some further results focusing on MAEB applicability which are still unpublished.

4.1 Field test overview

III) CONFERENCE PAPER: Autonomous Emergency Braking system for Powered-Two-Wheelers: testing end-user acceptability of unexpected, automated braking events deployed in typical pre-crash trajectories [58]

This publication, which was presented by the candidate at the 13th International Motorcycle Conference (IFZ) in September 2020[1]*, presents the field test campaign carried out in 2019 with the two test vehicles developed within the PIONEERS project. The paper focuses on the description of the field test campaign in which the Automatic Braking (AB) was tested 900 times in different riding conditions and with a total of 51 participants on the two vehicles. The results section reports a description of the test executed with the two vehicles in terms of MAEB working parameters and riding conditions. In addition, it reports the first results concerning participants' assessment of the tested AB interventions.*

This paper includes also the description of the field test campaign carried out with a Piaggio MP3 vehicle for which the candidate was not in charge and had a role of supporting the

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[1] The video presentation is available at the following link (Session 3): https://www.ifz.de/imc-2020-sessions/

field tests activities. However, this publication gives a comprehensive overview of the field tests carried with participants which allowed the analysis on MAEB feasibility presented in the following sections. A further description of the field test campaign including also the test carried out with the pilot test vehicle (the Ducati Monster 821) was presented at the AIAS conference in September 2020 [59]*, but was not included in this thesis because the candidate was not the first author of the publication.*

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

AUTHORS: Cosimo Lucci[1], Pedro Huertas-Leyva[1], Mirko Marra[1], Marco Pierini[1], Giovanni Savino[1,2], and Niccolò Baldanzini[1]

PRESENTER: Cosimo Lucci cosimo.lucci@unifi.it

AFFILIATIONS:

1) Dept. of Industrial Engineering, University of Florence, Via di Santa Marta 3, 0139 Florence, Italy
2) Monash University Accident Research Centre, 21 Alliance Ln, Clayton VIC 3800, Australia

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.

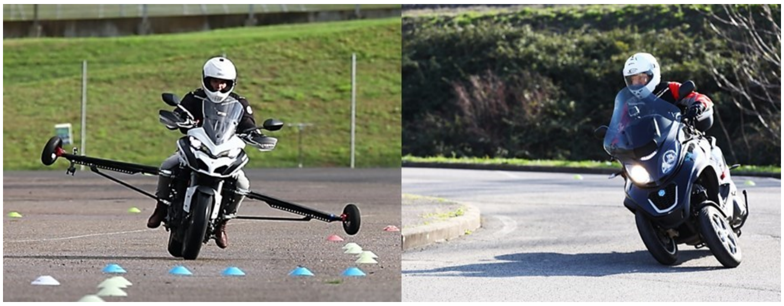

Figure 1 – Test vehicles: Ducati Multistrada 1260 (left) and Piaggio MP3 500 (right)

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 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 and 2.5 g/s), 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.

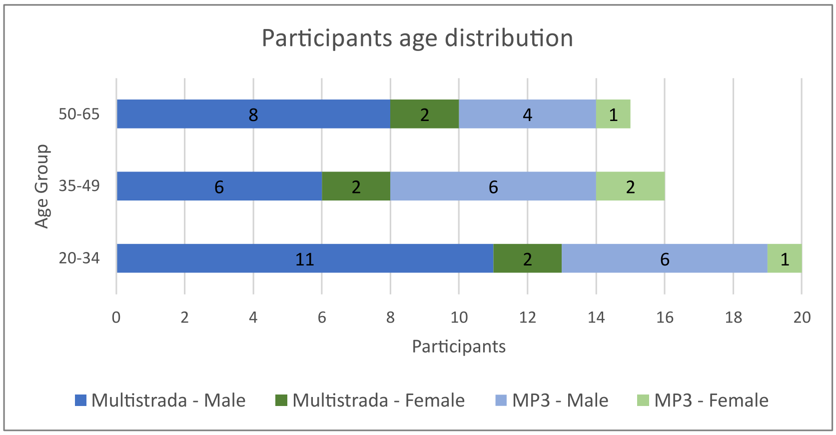

Figure 4 – Participants age and gender distribution for Multistrada and MP3 tests

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 speec [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.

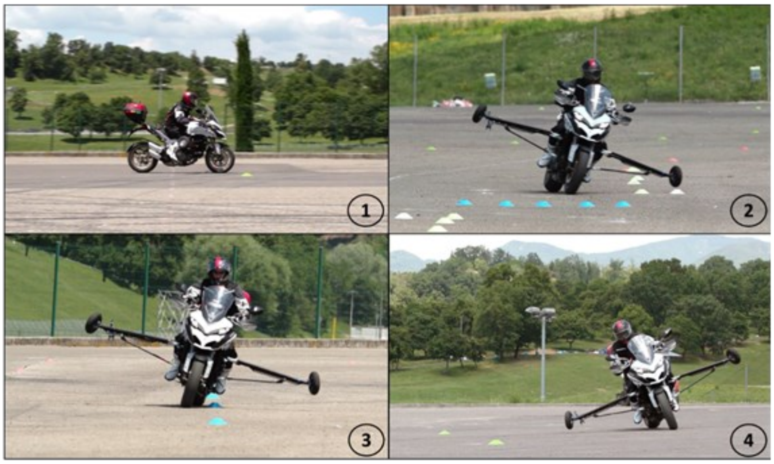

Figure 5 – AB activation on Multistrada in the four manoeuvres: 1) straight-line, 2) Lane-change, 3) Slalom, and 4) curve

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.

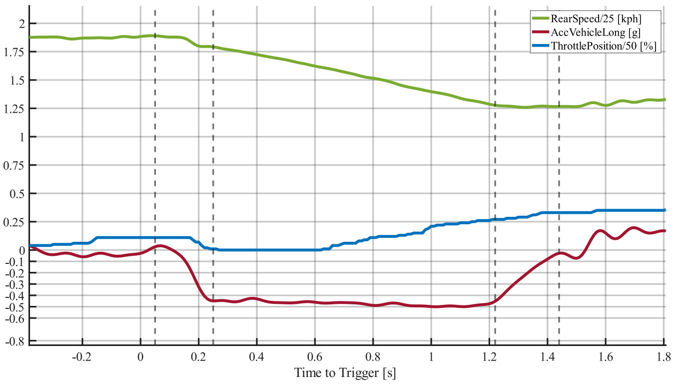

Figure 7 – Example of AB activation in straight-line conditions

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.

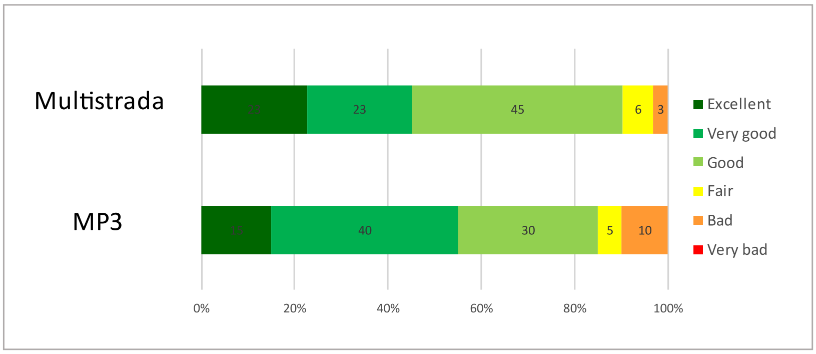

Figure 8 – Participants general assessment of tested AB system for the two test vehicles

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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4.2 MAEB applicability in lane-change manoeuvre

IV) JOURNAL PAPER: Field testing the applicability of motorcycle autonomous emergency braking (MAEB) during pre-crash avoidance manoeuvre [60]

This manuscript was submitted for publication in September 2020 to Traffic Injury Prevention journal and it was accepted for publication in January 2021. Traffic Injury Prevention is a multidisciplinary journal which publishes short-format papers (max 3500 words-length and six figures or tables) to support the scientific research concerning traffic injury prevention. The manuscript presents the results of field-testing Automatic Braking events in lane-change manoeuvres designed to reproduce pre-crash avoidance manoeuvres. The results of this paper highlight that participants were consistently able to control the vehicle during the automatic braking and to complete the avoidance action of the virtual obstacle. In addition, the speed reduction obtained with the AB interventions during lane change resulted to be very similar to that obtained in straight-line. The results of this paper allow extending the feasibility and safe applicability of MAEB not only in straight line condition as shown in previous studies, but also in a lateral manoeuvre and particularly in a typical pre-crash avoidance action like lane-change. This represents an important achievement for this project and a relevant contribution to the state of the art concerning MAEB in the process of being introduced on standard vehicles.

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Field testing the applicability of motorcycle autonomous emergency braking (MAEB) during pre-crash avoidance maneuver

Cosimo Lucci[a], Niccolò Baldanzini[a], and Giovanni Savino[a,b]

[a]Department of Industrial Engineering, University of Florence, Florence, Italy; [b]Monash University Accident Research Centre, Monash University, Victoria, Australia

ABSTRACT
Objective: Autonomous Emergency Braking (AEB) is a promising technology for crash avoidance or pre-crash impact speed reduction through the automatic application of braking force. Implementation of AEB technology on motorcycles (MAEB) is still problematic as its interaction with the rider may compromise the safety. In previous studies, MAEB interventions at low decelerations were shown to be easily manageable by common riders in straight line condition, but they were not previously tested in lateral maneuvers such as lane change and swerving, which are common in pre-crash situations. The objective of this paper is to assess the applicability of MAEB activation during lateral avoidance maneuver and to estimate its benefits in this scenario.
Methods: Field tests were carried out involving common riders as participants, using a test protocol developed on the experience of previous studies. The test vehicle was a sport-touring motorcycle equipped with an automatic braking system that could be activated remotely by researchers to simulate MAEB intervention. The motorcycle was equipped with outriggers to prevent capsizing. The Automatic Braking (AB) interventions using a nominal deceleration of 0.3 g were deployed at pseudo-random times in conditions of straight-line travel and a sharp lane-change maneuver emulating a pre-crash avoidance action. The straight-line trials were used as the reference condition for analysis.
Results: Thirty-one participants experienced AB interventions in straight-line and lane-change at an average speed of 44.5 km/h. The automatic braking was deployed in all the key phases of the avoidance maneuver. The system reached a deceleration of 0.3 g for a time of intervention of approximately 1 s. The participants were consistently able to control the vehicle during the automatic braking interventions and were always able to complete the lane-change maneuver. The speed reductions obtained with the AB interventions during lane change were very similar to those obtained in the straight-line conditions.
Conclusions: MAEB interventions with decelerations up to 0.3 g can be easily managed by motorcycle riders not only in straight-line conditions but also during an avoidance maneuver. Further investigations using higher deceleration values are now possible.

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Motorcycle; active safety; autonomous emergency braking; lane-change maneuver; avoidance maneuver

Introduction

In recent years, the diffusion of Powered-Two-Wheelers (PTW) has increased due to their affordability and ease of mobility in congested urban traffic environments compared with passenger cars. However, the increasing usage of PTWs has brought more PTW crashes (WHO 2018). From the automotive engineering side, in order to mitigate injuries and reduce deaths among this group of vulnerable road users, researchers and PTW manufacturers worked to introduce active (Savino et al. 2020) and passive (Pallacci et al. 2019; Willinger et al. 2019) safety technologies not yet applied to these vehicles. Among active safety system for motorcycles, a promising technology is Motorcycle Autonomous Emergency Braking. This system is designed to identify obstacles and autonomously apply a braking force to reduce the impact speed in a pre-crash situation: a lower impact speed and reduced energy transfer mean lower injury risks for motorcyclists (Ding et al. 2019). This technology has been widely implemented in passenger cars and trucks (for which it is mandatory since 2015 (European Commission 2016)). Regarding the application of AEB to PTWs, concerns are related to its interactions with the rider, which could compromise the safety of its intervention. The interaction with the rider poses a possible limit to achievable decelerations and in turn to the benefits of this technology in mitigating real-world crashes.

Previous studies have focused on two aspects: investigating MAEB benefits via crash reconstruction and theoretical estimations, and field testing of prototype systems by volunteers to explore rider stability under Automatic Braking (AB) (Savino et al. 2020).

MAEB has been shown to be applicable in 37 to 53% of the cases of in-depth databases of motorcycle crashes in

CONTACT Cosimo Lucci cosimo.lucci@unifi.it Department of Industrial Engineering, University of Florence, Florence, Italy.
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developed countries (Savino et al. 2014) and in some conditions, it may achieve impact speed reductions that are likely to reduce motorcyclists' injuries. Despite preliminary studies and field tests confirming that low decelerations by the system are applicable and easily manageable by common riders in straight line condition (Savino et al. 2012, 2016; Merkel et al. 2018), question remained concerning the applicability and safety of MAEB on standard vehicles when the rider is performing lateral maneuvers. In fact, studies focusing on in-depth crash analysis (Penumaka et al. 2014), revealed that during the pre-crash phases PTW users often attempt an avoidance maneuver. Therefore, it is necessary to determine whether MAEB activation can jeopardize safety when applied before or during an avoidance maneuver. Specifically, the open question is whether MAEB activation may prevent the rider to execute the desired avoidance actions in the pre-crash scenarios or provoke rider destabilization and loss of vehicle control.

The goal of this paper is twofold: first to field test the safe deployment of AB during an avoidance maneuver on motorcycle-style PTW, and, second, to assess if such intervention can obtain the same speed reduction compared to AB deployment during straight riding.

Methods

Field tests

The participants were recruited from among active riders having a minimum of two years or 10,000 km of riding experience and aged between 20 and 65. The invitation to participate in the tests was advertised through the web pages, social media, flyers and biker groups. In the recruiting phase, riders who volunteered for the tests were aware that they would be testing an advanced safety system for PTWs, but not specifically MAEB.

All subjects gave their informed written consent for inclusion before participating. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Florence (Decision N. 46, 20/03/2019).

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 cm^3 and semi-active suspensions. The vehicle was provided with a remote-controlled Automatic Braking (AB) system, set to decelerate the motorcycle at a nominal deceleration of 0.3 g and a fade in-jerk of 1.5 g/s. The nominal duration of the AB intervention was set to be approximately 1.2 s: this includes a fade-in time to reach the preset value of deceleration and a constant deceleration time. The test vehicle was also provided with outriggers to prevent the motorcycle from lateral fall. During the field tests, data from the CAN-Bus of the motorcycle (throttle, brake action, steering angle, vehicle tri-axis acceleration and gyro), GPS position and video from two Go-pro Hero4 cameras installed on the motorcycle were recorded. Subjective data about participants experience of the AB events was collected from questionnaires. This included an adjusted controllability rating scale employed in previous studies (Cooper and Harper 1969; Savino et al. 2016). In particular, participants were asked to rate the effort required to complete the desired trajectory when the AB was deployed during or immediately before the execution of the maneuver. For this task, we employed an adaptation of the Cooper-Harper rating scale. This scale offered a tool for a subjective assessment of the vehicle behavior through the effort required to maintain the desired trajectory when the vehicle stability was perturbed by AB intervention. Being the rating referred to the execution of the maneuver planned by the rider before AB intervention, the rating is by definition a comparative measure to the same maneuver without AB. The rating scale ranged from one (very easy to control, no effort required to maintain the desired trajectory) to ten (impossible to control).

The field test procedure was developed based on previous work (Lucci et al. 2019, 2021), following the test protocol of a previous study (Savino et al. 2016): the vehicle was equipped with a remote-controlled braking device which was activated by the investigator to produce unexpected automatic decelerations without intervention by the rider. The participants were free to ride along a closed circuit for about 15 minutes (20 laps), while the automatic braking (AB) was manually deployed at pseudo-random times when the participants went through different spots of the test track that included straight line sections, curves and maneuvers including lane-change. 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 lane change maneuver was always executed swerving to the left side of the obstacle. The test session included also testing AB intervention in maneuvers other than straight-line riding or lane-change: overall, the AB interventions were triggered on average once every 100 s of riding. The test protocol of this study was specifically designed to test AB interventions in different maneuvers with unprepared participants (Huertas-Leyva et al. n.d.). For this aim, and also to minimize any learning effect in the participants, the following strategies were in place: (i) the number of AB interventions deployed in each maneuver was limited to two; (ii) the participants were not aware of the number of AB activations; (iii) each deployment was separated in time by several passages through the same track section without any AB intervention; (iv) the layout of the markers used to indicate the lane change maneuvers was devised to allow a natural variance of the trajectories followed by each participant, and consequently the associated vehicle dynamics; v) the different maneuvers in which AB was tested were characterized by different trajectories and control actions, minimizing global learning effects across maneuvers. These AB events were thus considered "pseudo-unexpected" interventions. The test protocol included the following phases: a) a warm-up session to become familiar with the vehicle and the track; b) familiarization with the AB system, consisting of deploying declared AB interventions in straight-line; and c) two test sessions involving pseudo-unexpected interventions, followed by completion of a questionnaire. The test session included two AB activations during straight riding and two activations during lane change using a nominal deceleration of 0.3 g. The complete test included a second session, the details of which will be presented in a future paper.

The data collected during the tests were analyzed to evaluate the actual parameters of the intervention of the system. The exact intervention timing in relation to the maneuvers was identified using both GPS data and vehicle IMU data. The results of the participants' questionnaires were analyzed to obtain a subjective assessment of the tested AB.

Definition of the straight-line maneuver

The AB activation along a straight line occurred in a 40 m long straight stretch of the test track, in which the nominal traveling speed was 50 km/h. The AB activation stretch was located in a longer straight section (with a length of approx. 120 m) of the track connecting the lane-change area and a bend. Neither the exact AB activation location nor the exact timing of activation were declared to the rider; the same applied also to the lane-change activations.

Definition of the lane-change maneuver

Being the lane change maneuver the main focus of this paper, in this section details of the lane change design and lane change execution by participants during the test will be provided. Lane change can be related to both overtaking or swerving action, but considering a pre-crash condition, swerving (i.e., obstacle avoidance) is the relevant maneuver on which MAEB ought to be tested. For this reason, the design of the lane-change aimed to safely reproduce the maneuver performed by a rider to avoid an obstacle in pre-crash conditions. In line with previous field experiments (Cossalter and Sadauckas 2006), a single-lane change can be obtained by placing road markers that identify three phases: an entry lane, (riding at constant speed along a straight path), a section where the rider is forced to move sideways with a minimum offset, and an exit lane where the motorcycle returns to straight-line motion. The maneuvering space was defined by placing four markers as the entry lane and five markers orthogonal to the direction of travel to set the reference for the obstacle. Figure 1 provides a schematic of the lane change setup. An example of the vehicle roll and yaw rate in relation to the distance from the obstacle in a reference lane-change maneuver without AB intervention is also displayed in Figure 1. The participants were asked to travel through the lane-change maneuver at a speed of approx. 40 km/h and to perform a sharp swerve in front of the transverse markers, as though they represented a fixed obstacle. The lean angle required to execute the lane change at the required speed was approximately 20 degrees, reaching a yaw rate of 25 deg/s. The instruction for the investigator was to manually trigger the AB intervention while the test vehicle was traveling along the 10-m entry lane before the cross-line section. These instructions produced a spontaneous distribution of the intervention timing at different points along the entry lane.

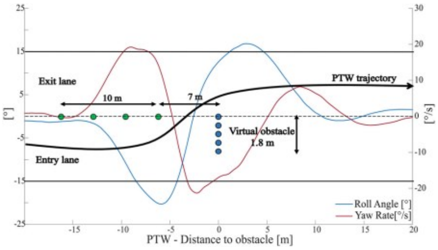

Figure 1. Lane-change maneuver definition, vehicle state signals and trajectory during a typical trial without AB.

Results

Test participants

Thirty-one participants (6 female, 25 male) were included in this study. The age of participants ranged from 21 to 59 years (mean age 39.8 years, SD 12.2). They were characterized by different levels of education (10% lower secondary, 45% upper secondary, and 45% university degree or higher) and riding experience (mean value 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.

AB intervention

Table 1 shows the values for the initial speed of the vehicle at AB intervention, the parameters characterizing the intervention of the automatic braking (event duration, level of deceleration and fade-in jerk), and subjective assessment of vehicle controllability.

For the lane-change maneuver, 60 AB activations instead of 62 were analyzed, as two interventions were excluded from the analysis due to triggering errors.

Mean motorcycle speed at AB activation was 47.2 km/h and 41.7 km/h, respectively for straight-line and lane-change maneuvers. The variability of the speed was due to the different riding styles and behaviors of the participants.

By design, the duration of the automatic braking was one second in both the maneuvers. The mean deceleration reached after the ramp was almost the same in straight line and lane change maneuver (respectively 0.30 g and 0.31 g). The variability in the decelerations was due to the automatic braking system, which did not perform closed-loop control of either the deceleration or braking pressure. Deceleration was affected by such factors as body mass and aerodynamic drag. The main difference between the intervention of the automatic braking in the two maneuvers was in the fade-in jerk, which was 1.53 g/s in the straight line and 1.28 g/s in the lane change.

For the controllability rating, the adjusted Cooper-Harper ratings of the automatic braking by participants were 1.5 in the straight line and 2.2 in the lane-change maneuver. These scores indicated as a very good vehicle behavior and

Table 1. AB tested intervention.

	Maneuver			
	Straight-line		Lane-change	
Participants	31		31	
Nominal deceleration [g]	0.30		0.30	
N° of activations	62		60	
	Mean	**SD**	**Mean**	**SD**
Initial Speed [km/h]	47.6	4.74	41.7	5.95
Event duration [s]	1.07	0.03	1.05	0.11
Deceleration [g]	0.30	0.034	0.31	0.037
Fade-in jerk [g/s]	1.53	0.407	1.28	0.423
Cooper-Harper rating *	1.55	0.71	2.19	1.03

* (range: 1 easy to control – 10 impossible to control)

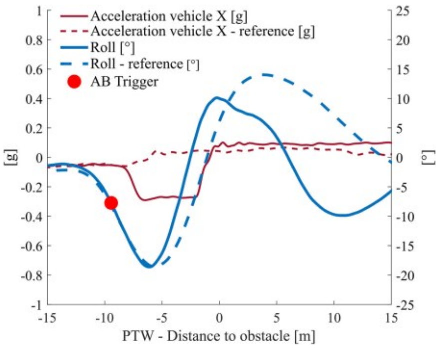

Figure 2. Comparison of deceleration (red) and vehicle roll (blue) between a lane change with (solid) and without (dotted) automatic braking.

controllability, with negligible deficiencies and a very limited compensation required by the rider to execute the lane-change maneuver during the automatic braking.

In comparing vehicle dynamics in the lane change maneuver with and without automatic braking, no significant effects were found except for those produced by the longitudinal deceleration of the vehicle. The participants were 100% successful in completing the lane-change maneuver with no contact with the markers representing the virtual obstacle. In addition, no braking action was executed by riders during the lane-change. Slight differences in the vehicle roll motion and in the steering angle required for the execution of the maneuver were reported (see Figure 2 as a representative example of a typical run). The researcher in charge of the test session and AB activation monitored the maneuvers and reported any loss of control in the test notes. No loss of control was reported by the participants in the questionnaire. Two participants (4/60 AB interventions in lane-change) touched the ground with the outrigger wheels, but this, consistent with what was stated by participants, did not result in any loss of control. An in-depth analysis trough videos and vehicle data revealed that these touches were part of their riding styles.

Phases of intervention

The activations of AB were triggered via remote control when the motorcycle was at a distance of on average 13.5 m (SD 2.7 m) from the markers representing the obstacle. Concerning the timing of the AB activations, the system was triggered with time to obstacle of on average 1.17 s (SD 0.23 s). Due to the duration of the automatic braking (1.05 s SD 0.11 s), this resulted in an average time to obstacle of 0.08 s (SD 0.36 s) at the end of the automatic braking.

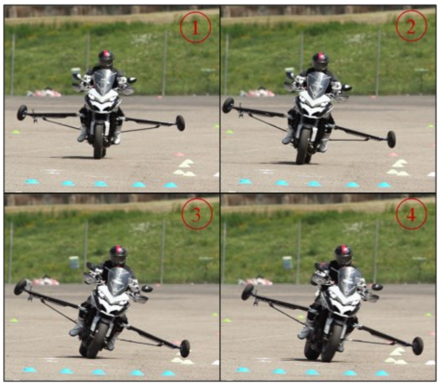

Figure 3. Pictures of four phases of lane-change maneuver: 1) straight-line motion; 2) Vehicle roll increasing; 3) neighborhood of vehicle roll peak; 4) Vehicle roll decreasing.

Concerning the phases of maneuver of the lane-change (Figure 3), this timing resulted in triggering the automatic braking mainly in the first two phases, 35% in the straight-line motion (vehicle roll $< 5°$), and 50% in the second phase (increasing vehicle roll $> 5°$), respectively. Only 13% of activations were triggered in the third phase, namely when the motorcycle was near to the roll peak, and just 2% in the fourth phase, with a decreasing roll. The Cooper-Harper ratings by participants who tested AB activations during the third and fourth phase of the lane-change maneuver were slightly lower (mean 1.67, SD 0.82) compared to the rating of those tested AB only in the first and second phase (mean 2.15, SD 0.68).

Effectiveness of MAEB

The automatic braking prototype tested in this study allowed to produce a speed reduction of 9.87 km/h (SD 1.65 km/h) in the straight-line and 9.94 km/h (SD 1.69 km/h) in the lane-change maneuver. These values were reached thanks to the nominal deceleration and the duration of the intervention set in the automatic braking control unit. Even though there were slight differences in the initial speed and steering input for the straight-line and the lane change, the speed reductions achieved by the automatic braking and variability were very similar in the two riding tasks (see Table 1).

Discussion

In the field tests involving 31 participants, pseudo-unexpected automatic decelerations deployed via remote control on a sport-touring motorcycle were tested in straight-line and lane-change maneuvers, employing an approach comparable to that from a previous study (Savino et al. 2016). Consistently with the earlier study testing pseudo-unexpected decelerations, the results confirm that in straight-line motion automatic decelerations up to 0.3 g can be easily managed by common riders. As in a previous study, the effort needed to control the vehicle during straight-line AB was rated as "almost no effort" on a scale from "absolutely no effort" to "extreme effort" (Savino et al. 2016), in these tests the ratings given by participants for both straight-line and lane-change AB can be interpreted as negligible compensation required by the rider to execute the maneuver during the automatic braking. Moreover, the same level of deceleration turned out to be managed with similar ease if applied in the lane-change maneuver emulating a pre-crash swerve.

The Automatic Braking (AB) was deployed with the same intervention parameters (nominal deceleration, fade-in jerk, duration of intervention) and initial speed in the straight-line and in the lane-change, similar to previous studies in straight-line conditions (Savino et al. 2016; Merkel et al. 2018). As previously shown for straight line, the same AB parameters applied in the lane change, resulted in no destabilization of the vehicle and the participants were consistently able to complete the maneuver avoiding the virtual obstacle. The subjective evaluations showed that limited extra effort compared with straight-line was required to control the vehicle during the intervention of the system. Also consistent with previous studies, no remarkable discomfort was reported by participants (Savino et al. 2012; Symeonidis et al. 2012; Savino et al. 2016). Importantly, the system was deployed in all the key phases of the lane change maneuver before reaching the obstacle, when the rider may attempt a lateral maneuver to avoid a collision. No different behavior of the riders nor of the vehicle was noted for AB triggering in the different phases of the maneuver. In addition, when AB was deployed along the straight just before the beginning of the maneuver (first phase), the participants were consistently able to begin and successfully complete the avoidance action. Furthermore, the participants who received an AB event in the third or fourth phase of the maneuver, reported on average lower effort to control the vehicle and to execute the maneuver compared with participants who received the AB also in the first two phases. Thus, triggering AB in the final part of the lane-change maneuver seemed to require similar effort to the rider to control the vehicle compared to the effort required in the case of early AB triggering. It should be pointed out that the aforementioned difference in self-reported effort was slight and the subsample was small, thus warranting further investigation. Notwithstanding these limitations, such result was unexpected in the design phase, as late interventions were expected to be more challenging for the rider than early interventions.

This study involved the largest sample size of participants in the field of Motorcycle Autonomous Emergency Braking (MAEB) testing so far (Lucci et al. 2020; Marra et al. 2021). Despite a wide range in terms of age, riding experience and motivations for riding, the participants involved in this study may not be representative of the general motorcycle rider population. Even if the sample was composed appositely to include different type of users, in order to mitigate possible biases, and specifically it did include participants with an initial negative opinion on MAEB (when surveyed before the test), a residual bias toward a positive opinion on the system may still have affected the results. In fact, recruited motorcyclists may be more technology-oriented than the average rider population. The limited range of speed at which the system was tested in both lane-change and straight-line is a limitation of this study. Testing speeds were selected as representative of the urban scenario and thus the test results aimed to provide information for the validation of benefits in such environment. Nonetheless, with higher velocities, the effort on the handlebar required to perform the swerve maneuver is higher and therefore the effort to control the vehicle during an automatic deceleration could be higher.

The AB interventions tested in this study cannot be considered as genuinely unexpected as MAEB interventions in real-world conditions would be. However, previous studies (Huertas-Leyva et al. n.d.; Savino et al. 2016), showed that AB interventions applied "out of the blue" had very similar effects compared to pseudo-unexpected interventions. As our test protocol was an advancement of that proposed by (Savino et al. 2016), our results are likely to be representative of the effects of real-world MAEB that may be observed in unexpected activation conditions.

The lane change maneuver was reproduced with no 3-dimensional obstacle but with five fixed markers as a reference constraint in the trajectory. Even if this configuration does not authentically reproduce the emergency situation and may not induce in the rider the same emotional state as in a real-world pre-crash situation, the maneuver was designed to require the same high values of roll-rate of a typical avoidance maneuver. The AB activation was thus tested with vehicle dynamics comparable with those of pre-crash avoidance actions. Therefore, assuming that a common rider in a real-world pre-crash setting may correctly operate the vehicle to complete the avoidance maneuver (in analogy with what we observed in our test settings), our findings suggest that AB interventions are not expected to require efforts so high as to prevent the successful completion of the emergency maneuver.

The speed reduction in the straight-line and in the lane-change was achieved using a nominal deceleration of 0.3 g and a duration of the intervention of about 1 s. Although a considerable speed reduction of around 10 km/h was obtained, similar values could not be reached in real-world crash scenarios, where the MAEB time of intervention was shown to be considerably shorter (Savino et al. 2016). Therefore, as was highlighted in previous studies for the straight-line conditions (Piantini et al. 2019; Savino and Piantini 2019), acceptability of higher decelerations in the lane change maneuver must also be confirmed in order to obtain significant injury reduction in real-world crashes.

The present paper expands the field of safe applicability of MAEB during straight-line riding, as previous studies suggested, to the lane change maneuver representing a realistic pre-crash avoidance action. The application of the automatic braking with a deceleration of 0.3 g at typical urban velocities, on a sports-touring motorcycle, did not to produce instability of the vehicle or rider. However, since these deceleration values were shown to be borderline for effectively reducing severity in real-world crashes, the feasibility of applying higher levels of intervention must be evaluated to assess the potential effectiveness and applicability of MAEB. Also, it would be desirable to repeat similar tests with a different Powered-Two-Wheeler style, in order to assess the possible influence of the riding position. Based on our findings, further investigations are now possible to assess the safe applicability of MAEB with higher values of deceleration not only in straight-line but also during lane-change maneuvers.

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ORCID

Cosimo Lucci http://orcid.org/0000-0002-7226-0501
Niccolò Baldanzini http://orcid.org/0000-0002-7467-4361
Giovanni Savino http://orcid.org/0000-0003-0949-0811

Data availability statement

The data that support the findings of this study are available from the corresponding author, [CL], upon reasonable request.

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4.3 MAEB applicability with 0.5g deceleration

V) JOURNAL PAPER: Does Motorcycle Autonomous Emergency Braking (MAEB) mitigate rider injuries and fatalities? Design of effective working parameters and field test validation of their acceptability [61]

This manuscript was prepared for publication to Transportation Research Part C journal and at the time of the submission of this thesis is still under review. Transportation Research Part C is a multidisciplinary journal which focuses on the different aspects of transportation research, with a special focus on the impact of emerging technologies on transportation system performance. The topics within the scope of the journal include studies concerning the development of intelligent transportation systems for increasing traffic safety and preventing crashes. The paper was prepared to be published in the journal as a research article: no specific layout limitations are required by the Journal.

The manuscript aims to identify MAEB working parameters for effective mitigation of injuries and, presenting the results of field tests carried out within the PhD project, validate their real-world applicability. These working parameters include 0.5g of MAEB target deceleration and 2g/s of fade-in jerk. The results of this paper highlight that 0.5g as MAEB target deceleration is capable to produce impact speed reductions up to 15 km/h, which are estimated to be able to reduce serious injuries by 15%. Field tests showed that participants were always able to control the vehicle and were consistently capable to manoeuvre and execute avoidance actions. The acceptance among participants of such levels of interventions was high indicating the possible applicability of the system with such working parameters in real-world conditions. The results of this paper represent one of the most relevant achievements within this research project and in the development of Motorcycle Autonomous Emergency Braking system, defining and validating a new set of working parameters capable of significantly reduce impact speed in pre-crash conditions and expected to be able to mitigate PTW users' injuries.

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

AUTHORS: Cosimo Lucci[1], Giovanni Savino[1,2] and Niccolò Baldanzini[1]

AFFILIATIONS:

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

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

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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.

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*

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 declaration 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., 2020). 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., 2021a) 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.

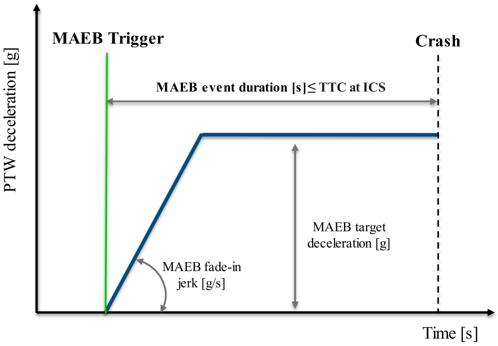

Figure 1 – Block profile for MAEB deceleration

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:

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

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-word 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., Forthcoming) (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.

	Reference crashes		**Real-world crashes (16)**	
Crash configuration (DCA)	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., 2021a). 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.

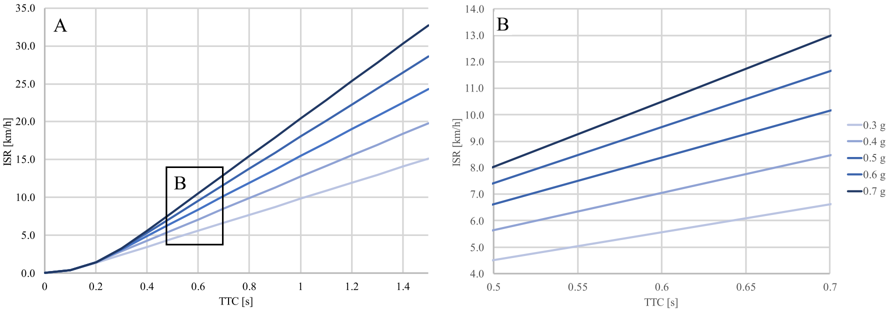

Figure 2 – Theoretical Impact Speed Reduction (ISR) achieved due to MAEB intervention, expressed as a function of Time To Collision (TTC) at triggering, computed for a range of values of target deceleration. Image B shows a close up of image A in the range of TTC 0.5 s - 0.7 s.

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., 2021a). 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 injures 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., forthcoming). 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.

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.

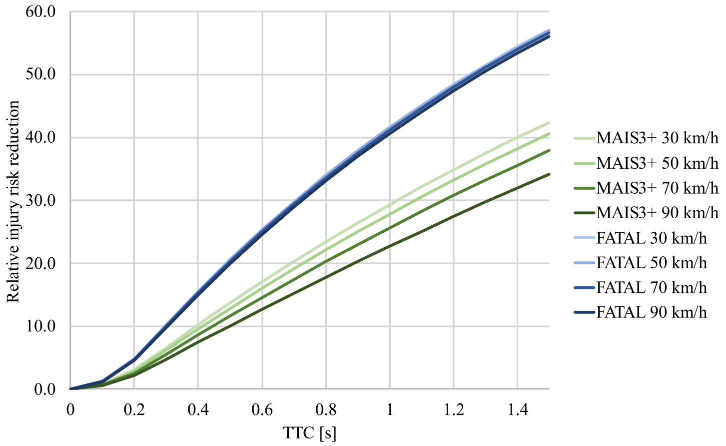

Figure 3 – Relative injury risk reduction for MAIS3+ and Fatal injuries by Time To Collision (TTC) at different crash speed, computed from the injury risk functions provided by (Ding et al., 2019) assuming 0.5 g MAEB target deceleration, 2 g/s fade-in jerk, and rear-end crash configuration.

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., 2021b, 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 cm^3 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 questionaries were developed based on those employed in previous studies focusing MAEB and standardized questionaries, 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., 2021a). 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., 2021b, 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., 2021b). 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., 2021b). 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., 2021a)) . 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., forthcoming; Lucci et al., 2021b). 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.

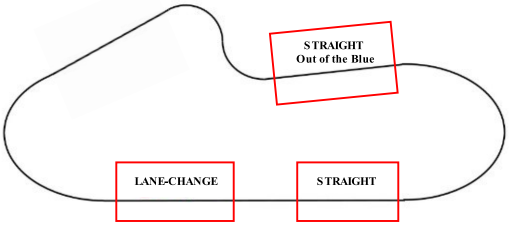

Figure 5 – Test track and AB triggering areas

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.

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., 2021a). 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., 2021a), 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.

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

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.

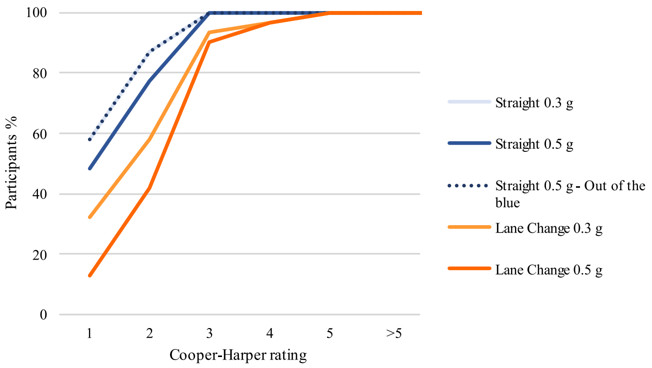

Figure 6 – Cumulative Cooper-Harper rating

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.

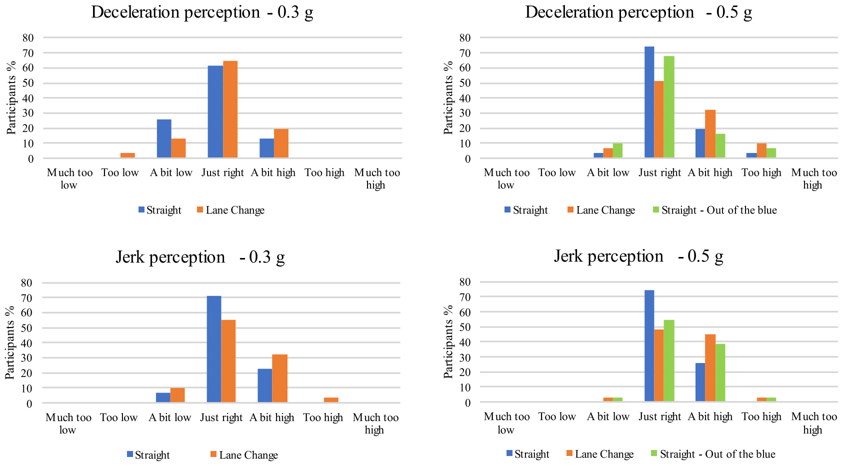

Figure 7 – Participants ratings of tested AB deceleration and fade-in jerk

Regarding the predictability of the tested AB interventions (the method employed was validated in a linked study by (Huertas-Leyva et al., Forthcoming)), 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.

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.

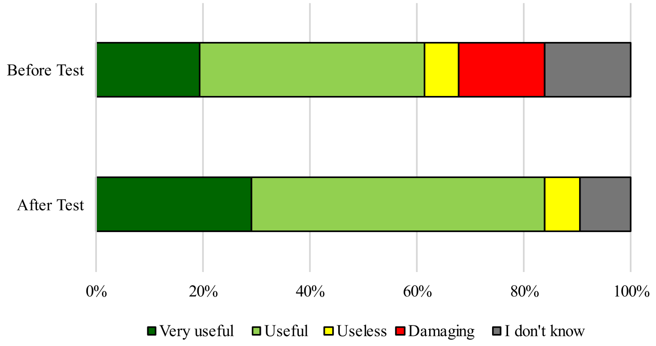

Figure 8 - Participants' opinion on MAEB before and after testing AB

Participant 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 participant declared to be available to spend up to 500€ for MAEB, with 10 % of the participant 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

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).

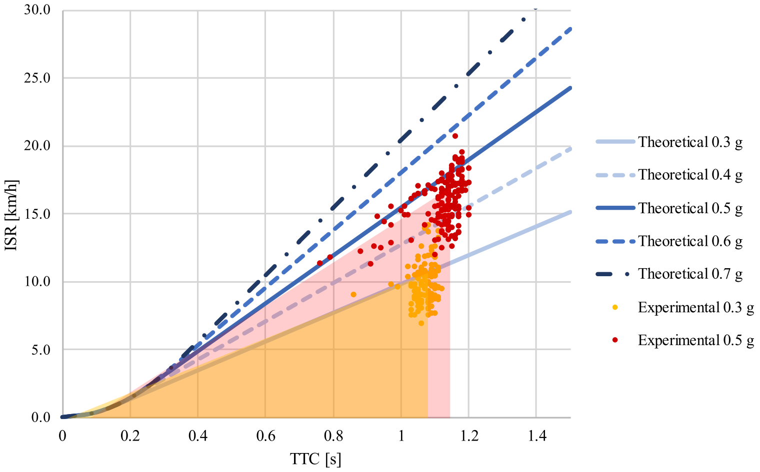

Figure 9 – Tested AB intervention (experimental data) and MAEB feasibility regions (coloured area)

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 a 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.

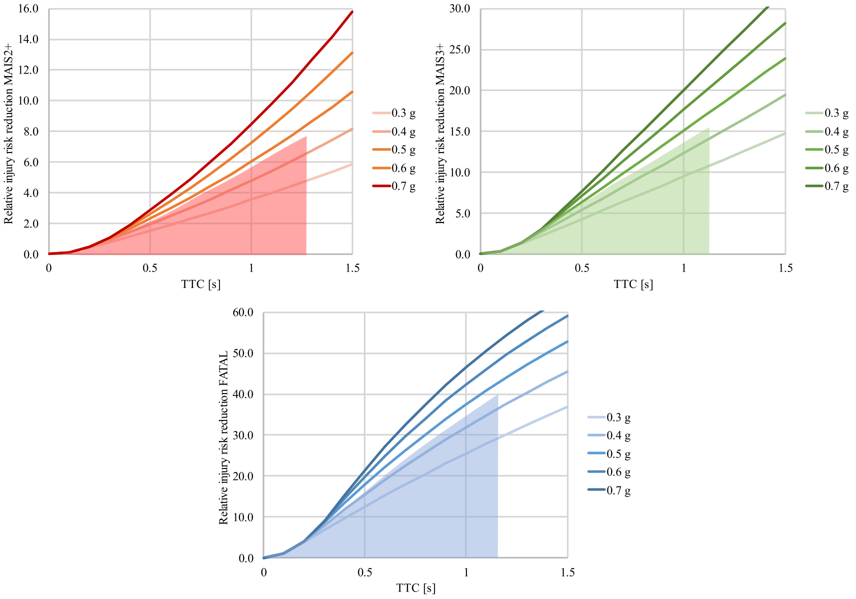

Figure 10 – Relative Injury Risk reduction curves and MAEB feasibility regions (coloured area) for MAIS2+, MAIS3+ and Fatal injuries

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., 2021a; 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., 2021a), 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., 2021b; 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., forthcoming). 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 MAEB effective for PTW users injury mitigation. Once a target injury or fatality reduction are set, MAEB parameters are derived accordingly. We identified the working parameters representing 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. Our results, supporting that a substantial autonomous braking is feasible even during the execution of avoidance manoeuvres, pave the way to future testing of MAEB in real-world emergency scenario towards its implementation on standard vehicles.

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DATA AVAILABILITY STATEMENT: The data that support the findings of this study are available from the corresponding author, [CL], upon reasonable request.

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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
	2	Maybe the manual braking could be more effective
Bad	1	The MAEB is very helpful in straight lane, in the other manoeuvres reduce the handling of the vehicle

4.4 Acceptance of MAEB

VI) CONFERENCE PAPER: The acceptance of Autonomous Emergency Braking System for Motorcycle: results before and after testing

This publication was accepted for presentation at the 2020 Australasian Road Safety Conference (ARSC), which was supposed to be in September 2020 in Melbourne, Australia, but was postponed to September 2021. This brief paper, which has the format of an extended abstract as required for the conference, focuses on a very relevant issue for MAEB: the acceptance among end-users. The result section shows that before testing AB, PTW users overall consider MAEB as the less useful riding assistance systems compared with other safety systems for PTWs, but that after testing AB events their consideration of MAEB increase and nobody consider it damaging. The findings provided through this publication constitute a relevant achievement of this project, clarifying the potential acceptability among end-users of MAEB and their possible willingness to have it on their own vehicles.

The acceptance of Autonomous Emergency Braking System for Motorcycles: results before and after testing

Cosimo Lucci[a], Giovanni Savino[a,b], Niccolò Baldanzini[a], Marco Pierini[a]

[a] Dept. of Industrial Engineering – DIEF, University of Florence, Florence, Italy.
[b] Monash University Accident Research Centre, Melbourne, Australia.

Abstract

Autonomous Emergency Braking (AEB) is a promising technology in the future of motorcycle safety, since it could be effective in reducing the consequences of crashes. To evaluate whether a personal experience of the intervention may influence the acceptance of such a system, an analysis of the results of a field study conducted in realistic pre-crash manoeuvres and involving 31 participants was carried out. Among users who applied for volunteering in field tests with motorcycle safety systems, the pre-test acceptability of AEB was generally lower compared to that of safety system already installed on standard vehicles. After field-testing automatic braking interventions, the participants' opinion about the potential effectiveness and reliability of the system was more positive; none of the participants considered the system damaging anymore. Field testing motorcycle autonomous emergency braking in realistic pre-crash manoeuvres turned out to have a positive influence on the acceptability of the system among our participants.

Background

Autonomous Emergency Braking (AEB) automatically applies a braking force to reduce impact speed or prevent crashes. Previous studies showed that AEB for motorcycles (MAEB), could be effective in reducing serious consequences of powered-two-wheeler (PTW) crashes (Savino et al., 2020). Even if AEB systems are widely considered effective for passenger cars by researchers and designers, they may be reluctantly accepted by PTWs' end-users. This is because riders tend to dislike automated systems that interfere with the riding task (Beanland et al., 2013). We hypothesised that a direct experience of MAEB intervention and the linked feeling that the vehicle is still under rider control, may positively influence MAEB acceptability among end-users.

The goal of this paper is to evaluate the influence on acceptability among end-users of field testing MAEB interventions.

Method

Field tests were carried out involving 31 participants selected among a sample of 115 subjects who volunteered for the test: they were selected to obtain a heterogeneous sample in terms of age, gender, riding experience, type of PTW user, and attitude towards rider assistance systems. Tests were performed with a motorcycle provided with an automatic braking system triggered via remote control (Lucci et al., 2020). The participants were instructed to ride along a track including a set of manoeuvres (straight path, lane change, slalom simulating traffic filtering, curves) (Lucci et al., 2021). Undeclared interventions of MAEB were deployed by the investigators at predefined locations, with nominal speeds of 35-50 km/h. Nominal decelerations of 3 and 5 m/s^2 were adopted, where the latter is currently considered a limit for a safe intervention (Merkel et al., 2018; Savino et al., 2016). Questionnaires were administered before and after testing MAEB; an adjusted Cooper-Harper rating scale was adopted (Cooper & Harper, 1969) to rate vehicle controllability during

MAEB interventions. This scale allowed a subjective assessment of the vehicle behaviour through the effort required to maintain the desired trajectory when the vehicle stability was perturbed by MAEB intervention (the CH scale ranges from one -very easy to control-, to ten -impossible to control-).

Results

When asked about 11 advanced assistance systems for PTW (e.g. ABS, Traction Control(TC), Active Cruise Control(ACC), MAEB, etc.), the sample end-users generally expressed a good opinion (Figure 1a) on the assistance systems; those which are already available on production PTWs (ABS, TC) were generally better rated. MAEB was considered as the least effective system: 12.8% of participants indicated it as damaging. A considerable percentage of the sample end-users were completely unaware of some safety systems (ABS-10.1%, TC-7.3%, ACC-24.8%, MAEB-22.9%).

Considering the 31 participants who field-tested MAEB, the intervention turn out to be easily manageable on straight line (Cooper-Harper rating $5 m/s^2$ deceleration: <4 100%, 4-6 0%, >6 0%); lateral manoeuvres required a higher effort to control the vehicle but the intervention was still considered manageable (Cooper-harper rating $5 m/s^2$ deceleration: Lane change: <4 90%, 4-6 10%, >6 0%; Slalom: <4 71%, 4-6 23%, >6 0%) (see Figure 1c). The opinion regarding the system improved after testing the intervention: about 85% of the participants stated that MAEB is useful/very-useful and nobody considered it damaging (Figure 1b).

Conclusions

This paper shows that field testing MAEB in realistic pre-crash manoeuvres and with realistic working parameters has a positive effect on the participants' opinion about the system. This is expected to have a positive influence on users' acceptability of the system and on willingness to have it installed on their vehicles.

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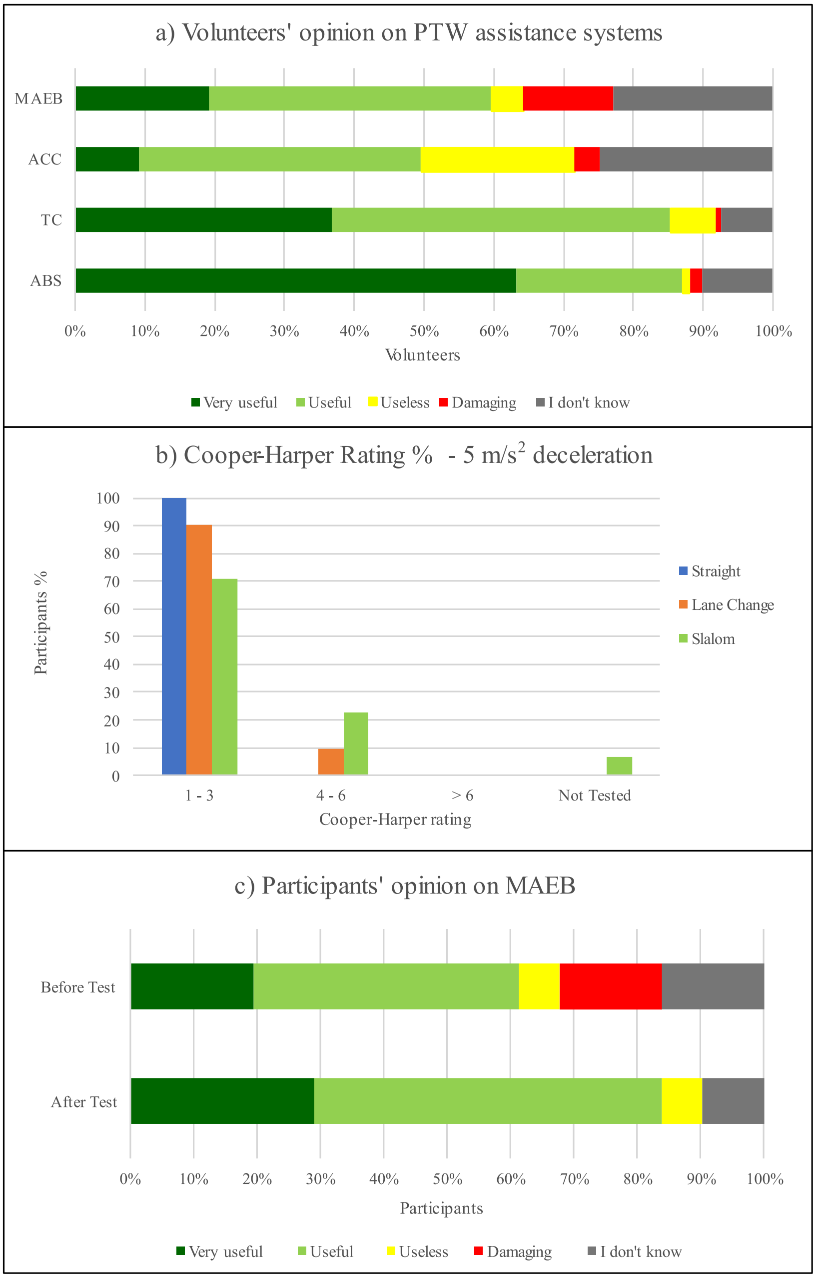

Figure 1. Questionnaires and tests results

4.5 Further results

This section contains further results coming from the field tests data analysis which, due to time constraints, are still unpublished. The analysis and the results presented in this section are therefore not as refined as those presented in the previous papers but were included in this thesis because they represent a relevant outcome of this work and, if published in the near future, an important contribution for the development of MAEB.

4.5.1 AB interventions

As reported in section 4.1, the field test performed within this study included also testing AB interventions in riding conditions other than straight-line and lane-change. Participants experienced the intervention of AB during slalom manoeuvre, which was intended to reproduce a condition in which the rider is required to manoeuvre the vehicle with a complex dynamic, and in the curve, with lean angles up to 25°. The AB tested in slalom and curve are summarized in Table 5 (the AB interventions in straight-line were added as reference), classified according to the manoeuvre and nominal AB deceleration.

At least two AB interventions were tested in slalom in each test session (respectively, 0.3g and 0.5g AB nominal deceleration) except for participants who rode in wet conditions (2 out of 31). Instead, only four activations in the 0.3g test session for each participant (except for those who rode in wet conditions) were performed in curve (see Table 5).

Table 5 – Slalom and Curve AB interventions

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
Slalom		62	32.1	3.3	0.89	0.25	0.32	0.033	1.40	0.414
Curve		115	28.7	2.0	0.59	0.25	0.33	0.028	1.73	0.504
Straight-line	0.5	62	49.1	4.7	1.14	0.03	0.48	0.035	2.06	0.402
Slalom		59	34.1	4.0	0.88	0.26	0.50	0.035	2.21	0.557

In curve and slalom AB interventions, the PTW travel speed at AB trigger was on average around 30km/h, a lower value compared with AB activations tested in straight and lane-change (on average 48km/h and 41km/h). These velocities, which were constrained by the size of the test area and by the maximum roll angle permitted by the outriggers, are however coherent with the urban riding scenario (20-50 km/h). The duration of AB interventions, on average, was shorter than in straight-line due to the inhibition of the system. However, the duration of the AB interventions in slalom and curve were higher or similar to the Time To Collision (TTC) at which MAEB is expected to be triggered in real-world crashes (which was estimated around 0.60s [38]). Even if the time of intervention was shorter than in straight-line, in both curve and slalom manoeuvre the AB system performed fade-in jerk and AB decelerations consistent with the set nominal values, and slightly higher than those performed in straight-line.

Regarding the roll angle in cornering activations, lean angles at the time of AB trigger have been identified for all activations, according to the direction of rotation in the test track (CW=clockwise, CCW=counter clockwise). The mean roll in CW was 18.0° (SD 2.5°), while in the CCW mean value was 22.2° (SD 2.3°). This difference was due to a slight inclination of the track in that section.

The cornering manoeuvre was divided into the following phases according to the roll angle and the roll rate (see Figure 32):

- Phase 1 - Cornering approach: roll angle < 5°
- Phase 2 - Increasing roll: roll angle > 5° and roll rate > 5°/s
- Phase 3 - Constant roll: roll angle > 5° and roll rate < 5°/s
- Phase 4 - Decreasing roll: roll angle > 5° and roll rate > 5°/s

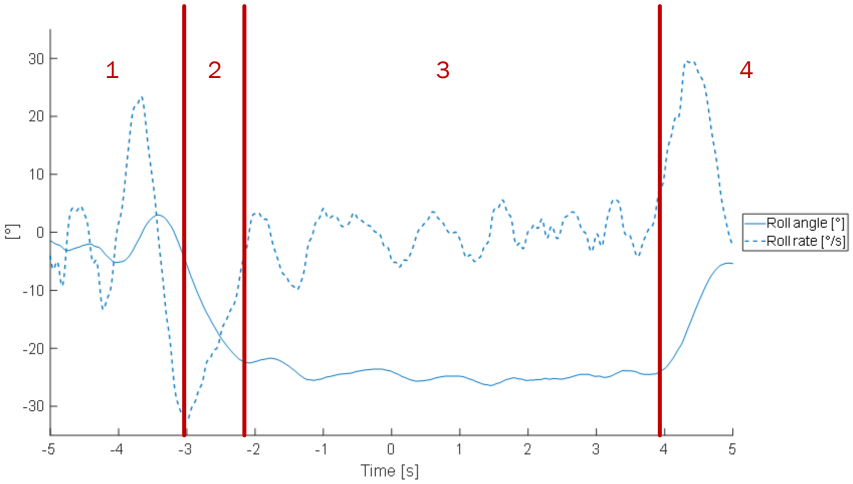

Figure 32 – Curve manoeuvre phases definition

In both directions, the AB tested interventions were deployed mainly (around 90%) in the constant roll phase, while a small proportion (less than 5%) is in the increasing or decreasing roll phases. Any AB activation was deployed during the cornering approach (straight-line riding).

4.5.2 Participants assessment

The AB intervention deployed during slalom and curve riding were managed by participants with a slightly higher effort compared to the other manoeuvres at the same level of AB target deceleration. The cumulative distribution of adjusted Cooper-Harper ratings (see as reference the scale displayed in 8.2) is displayed in Figure 33.

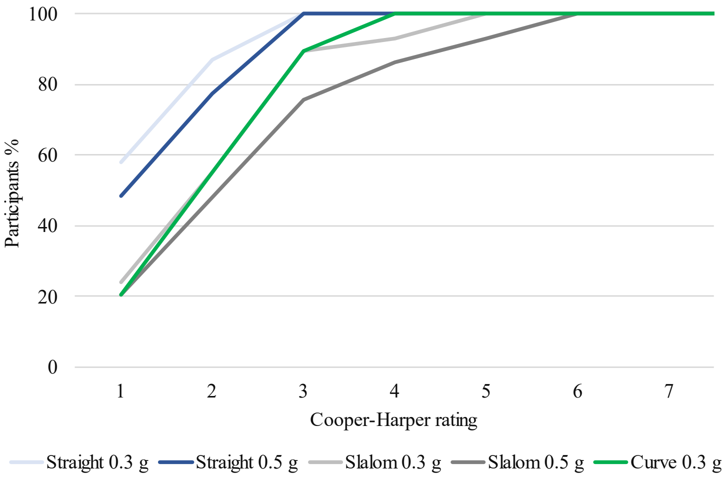

Figure 33 – Cumulative distribution of adjusted Cooper-Harper rating

A difference can be observed between the compensation required to the participants in straight line conditions and that required in curve and slalom. The two curves associated with straight-line manoeuvre, reach the 100% of participants with the rating of three. All the other curves associated with the intervention of AB in the other manoeuvres reach the 100% of participants' ratings with the rating of 4 or higher, and the curve associated to the slalom manoeuvre with 0.5g AB deceleration reaches the 100% level at the rating of six, which indicated a high compensation required to the rider to execute the manoeuvre.

As indicated in Table 6, with 0.3g AB deceleration, the controllability rating indicated a similar effort required to the participants to manoeuvre in curve and slalom compared to lane-change. Interestingly, the controllability rating given by participants in constant leaning conditions, which was previously considered one of the most demanding riding conditions for AB intervention, did not indicate higher effort required to participants to control the vehicle compared to the other manoeuvres (lane-change and slalom).

In the 0.5g deceleration session, the lane-change and slalom obtained comparable mean controllability ratings. However, the higher ratings given by a few participants in slalom, indicated that for some participants the AB intervention can be more demanding to be controlled when deployed in such vehicle dynamic conditions.

Table 6 – Adjusted Cooper-Harper rating comparison

Manoeuvre	**Deceleration**	**Cooper-Harper rating**	
		Mean	**SD**
Straight	0.3 g	1.5	0.7
Lane Change		2.2	1.0
Slalom		2.2	1.1
Curve		2.2	0.9
Straight	0.5g	1.7	0.8
Lane Change		2.6	0.9
Slalom		2.8	1.4
Straight - Out of the blue		1.5	0.7

The results provided in this section are intended to integrate the understanding of MAEB feasibility and acceptability among end-users offered by the publications presented in the previous sections. These results, which hopefully will be presented in a publication after a further data analysis, contribute to the understanding of the limits of MAEB applicability.

Even if the riding conditions which the slalom and curve manoeuvre were intended to reproduce are not those more relevant for PTW crashes and MAEB application, assessing the safe applicability of MAEB in such condition ensure its safety and vehicle controllability in case of unnecessary activation, which for such system, especially in the early stages of development, can be a real risk. The results provided by this preliminary analysis indicated that AB intervention with declarations up to 0.3g can be easily managed by end-users also in conditions of constant leaning (up to 20°) and with complex vehicle dynamics. With higher decelerations (0.5g), AB intervention required higher compensation to be managed by riders with complex vehicle dynamics, but the results of the tests indicated that it still can be manageable with reasonable effort.

The specific subjective assessment of AB intervention in such conditions and the overall assessment of tested AB interventions and MAEB system by participants (presented in the sections 4.3 and 4.4), indicated that the tested AB interventions in curve and slalom are acceptable by end-users and can be managed with limited effort.

These results can be employed to define a set of vehicle state parameters (e.g., in terms of roll and roll-rate) which can define the conditions in which MAEB deployment can be considered safely applicable and therefore inhibit MAEB trigger if these conditions are not matched.

5 MAEB benefits assessment

In this section, an additional study addressing the third research question of this project will be presented through a journal publication. This study was carried out in collaboration with the Monash University Accident and Research Centre of Melbourne, Australia, where the candidate spent three months (between February and May 2020) during his PhD . Based on the results of the field tests presented in the previous sections, the goal of this additional study was to assess the potential benefits of MAEB and its effectiveness for injury mitigation in PTWs crashes. The potential benefits of MAEB were estimated assessing both, the Impact Speed Reduction (ISR) produced by MAEB (as previously done in literature), and the injury risk reduction using injury risk functions recently published in the literature [62]. The MAEB benefits were evaluated using retrospective data from real-world crash investigation of PTWs crashes that occurred on public roads in Australia, based on MICIMS database [63], [64]. This allowed answering the third research question of this project regarding the effectiveness and injury mitigation potential of MAEB. In addition, further exploratory tests aiming at improving MAEB effectiveness when the rider is already manually braking before the crash were carried out within this study and presented in the paper. This allowed proposing new strategies to improve MAEB effectiveness working as enhanced braking system which pave the way for future studies and developments on MAEB after this PhD project.

VII) JOURNAL PAPER: Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: estimating the potential for injury reduction using real-world crash modelling [65]

The abstract (plus two figures) of this manuscript was accepted for presenting full-length papers at the 65th AAAM Annual Conference (Association for the Advancement of Automotive Medicine), which will be held October 2021 in Indianapolis, USA. In addition, the paper was submitted and accepted for publication on a Special Issue of Traffic Injury Prevention journal, which was the final goal for this paper. The paper was therefore structured following the journal template (max 3500 words-length and six figures or tables).

The paper presented in this section represents the final stage of this PhD, which allowed to estimate the benefits of the new working parameters and riding conditions field-tested and considered feasible for MAEB. In addition, further estimations to test MAEB as an enhanced braking system applied in circumstances where the rider is braking before a crash were carried out. The results of this paper highlight that MAEB could lead to relevant impact speed and injury risk reductions in cases without manual braking before the crash, whereas, in cases in which the rider is already manually braking, the benefits of MAEB are limited.

However, thanks to the new modes of intervention proposed in this paper for the MAEB working as enhanced braking, MAEB can reach such effectiveness in reducing pre-crash speed and injury risk comparable to that obtained in cases without manual braking. The results of this paper represent the completion of this PhD estimating MAEB benefits based on the outcomes of the first part of the research project. In addition, the new strategies to improve MAEB effectiveness proposed in this paper will be a reference for future developments of MAEB.

TRAFFIC INJURY PREVENTION
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Motorcycle Autonomous Emergency Braking (MAEB) employed as enhanced braking: Estimating the potential for injury reduction using real-world crash modeling

Cosimo Lucci[a], Trevor Allen[b], Marco Pierini[a], and Giovanni Savino[a,b]

[a]Department of Industrial Engineering, University of Florence, Florence, Italy; [b]Monash University Accident Research Centre, Monash University, Victoria, Australia

ABSTRACT

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

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

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

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

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Introduction

Assessing the potential benefits of technologies that are yet to be introduced or are in prerelease stages is a significant challenge for researchers. While estimations can be executed by employing forecasting models or simulations, the challenge is greater when we want to assess the impact of safety systems for road vehicles. This is due to a lack of data recorded in crashes involving vehicles provided with the technology, making retrospective assessments not possible. Assessing the benefits and disadvantages of active safety systems such as Motorcycle Autonomous Emergency Braking (MAEB) is crucial before such systems can be considered for introducing into new vehicles. This includes identifying the types of crashes in which the system is intended to intervene and assessing the outcome of those crashes with the technology implemented. As for Autonomous Emergency Braking (AEB) for cars (Fildes et al. 2015), MAEB is a technology capable of reducing pre-crash speed by applying autonomously a braking force on Powered-Two-Wheelers (PTW). The effect of autonomous braking can also be evaluated through a reduction in the severity of crashes rather than the total elimination of the crash. The intervention of MAEB has been field-tested in straight-line riding conditions and with low decelerations deployed as an

CONTACT Cosimo Lucci cosimo.lucci@unifi.it Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy.

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unexpected intervention with common riders (Savino et al. 2020). More recently, new field tests suggested that MAEB could be applicable with higher levels of braking intervention and not only in straight-line riding (Merkel et al. 2018; Lucci et al. 2020, 2021). These identified improvements in the applicability of MAEB, mean that its benefits could be higher than those estimated in previous simulation studies (Savino et al. 2016; Piantini et al. 2019; Savino and Piantini 2019). Moreover, studies focusing on crash investigations highlighted that only half of the riders are able to brake before a crash (Penumaka et al. 2014). MAEB was designed in the past to perform a fixed level of deceleration to be handled by a rider that is unaware of the automatic intervention. Such level of deceleration was identified regardless of the amount of manual braking by the rider. In manual braking conditions, the rider's action may produce a deceleration that is close to or even higher than that produced by the automatic action. In such cases MAEB efficacy may be much lower. A second consideration is that excessive automatic braking action applied by MAEB during a manual braking could introduce unintentional hazards for the rider. Therefore, a strategy to optimize MAEB effectiveness when the rider brakes manually in pre-crash conditions would improve its potential benefits in these conditions. These conditions however remain untested in terms of rider's acceptability.

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

Methods

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

Crash configurations and data source

Based on the results of previous studies (Savino et al. 2019; Terranova et al. 2020) a set of crash configurations were identified (using DCA codes). MAEB was recently tested in lateral maneuvers including lane-change reproducing a swerve before a crash (Lucci et al. 2021), and identified as "possibly applicable." For each crash configuration in which MAEB was considered applicable, a minimum of two cases (when available) were extracted from a database of motorcycle crashes in Australia. The database includes 235 cases involving a non-fatal motorcycle injury crash occurring on a public road in Victoria, Australia, between 2012 and 2014 (Day et al. 2013; Allen et al. 2016). The following criteria were used to achieve a representative sample of crashes where MAEB was considered possibly applicable: i) all crash configurations in the database identified as "possibly applicable" to MAEB (as defined by previously published studies) should be represented in the reconstructions; ii) the number of cases reconstructed for each crash configuration (DCA) should be matched as close as possible to their prevalence/proportion in crash database. For rare crash configurations, this meant only one case reconstruction (and often only one available crash of that configuration); and iii) PTW speeds of cases included in the reconstructions should be representative of speeds seen for each configuration (see Table 1). Cases involving the following crash configuration types were identified as possibly applicable: vehicles from adjacent directions (DCA 110, 111, and 113), vehicles from opposing directions (DCA 120 and 121), vehicles from same direction—rear-end (DCA 130, 132, 134, and 137), maneuvering (DCA 140, 147, and 148), overtaking (DCA 150 and 151) and on path crashes involving parked vehicle or animal (160 and 167). While the intention was to analyze at least two cases per crash configuration, only one case was available for some configurations (n = 7) due to either a low prevalence of that crash type or insufficient cases with required detail about travel speed. The list of cases by crash configurations is displayed in Table 1, while in the Online Appendix the representation by VicRoads (VicRoads 2013) of the included crash configurations is displayed. For each crash configuration, the cases were controlled to have mean crash speed and ISS score close to the mean values within

Table 1. Summary table of cases by crash configuration; refer to Table A1 in the Online Appendix A for detailed classification separated by DCA.

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

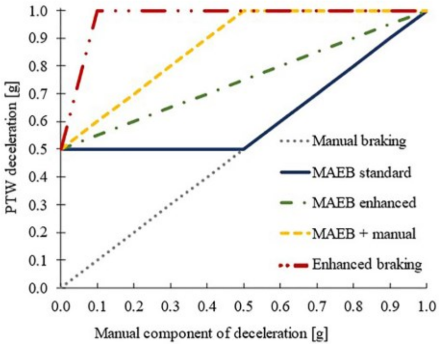

Figure 1. Correlations to define MAEB target deceleration as used in modelling MAEB intervention. (Example for 0.5 g MAEB target deceleration).

the database. In addition, the cases were controlled to have a similar proportion between cases with manual braking and cases without manual braking before the crash compared with the proportion in MICIMS database, which was respectively, 50.5% and 49.5%.

Crash reconstruction model

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

MAEB function definitions

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

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

Injury risk assessment

Once the crash speed was calculated with the different MAEB modes, the potential effects in reducing injuries were estimated using injury risk functions published in the literature (Ding et al. 2019). These functions allowed us to evaluate the injury risk for each type of injury reported in the literature (MAIS 2+, MAIS 3+ and FATAL). The injury risk was evaluated based on relative crash speed for crashes against passenger cars or fixed obstacles and based on the crash speed in ground-impact crashes. For each test case, four parameters were required to assess the injury risk: i) point of impact (if PTW frontal or lateral impact with opponent vehicle); ii) crash opponent: (if crash opponent was passenger car or ground); iii) driver impact (if motorcyclist impacted the opponent with directional change or

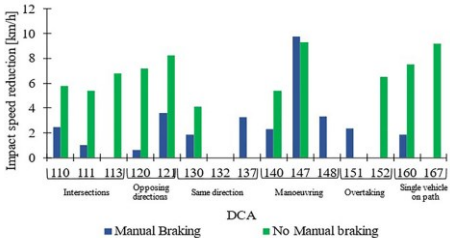

Figure 2. Mean impact speed reduction achieved by MAEB standard mode: distributed by crash configuration. Crashes separated by the presence of manual braking (blue/left bars) and no manual braking (green/right bars).

not; and vi) stability conditions (whether PTW was stable or not before the crash).

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

Results

MAEB applicability

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

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

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

MAEB standard mode

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

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

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

MAEB enhanced mode

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

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

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

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

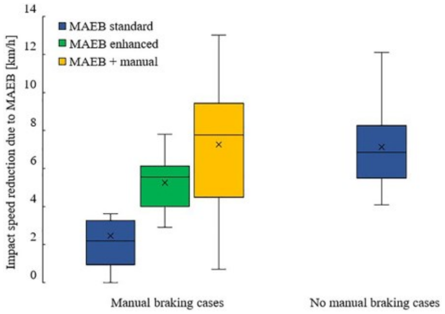

Figure 3. Comparison of impact speed reduction due to MAEB by intervention mode.

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

Injury reduction

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

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

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

Discussion

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

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

With the hypothesis that all the variables influence a crash in the same way (with or without the presence of MAEB), we supposed that for a specific crash an injury risk curve could be applied based on relative speed (i.e., the change in speed would not significantly change the crash configuration). This allowed us to estimate the injury risk reduction based on the estimated ISR produced by MAEB. The results highlight that standard MAEB in cases involving

Table 3. Injury risk reduction.

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

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

no-manual braking could bring a reduction from 10% to 22% of the relative risk to sustain, respectively, MAIS2+ to fatal injuries. This suggests that MAEB could prevent around 20% of the fatalities in the cases in which the system is applicable. However, this represents a smaller reduction in terms of absolute injury risk (ranging from 4.4% for MAIS2+ to 0.5% for fatal injuries). For this reason, we must consider that if MAEB interferes with undesired side effects eventually leading to a fatal crash in 0.5% of the cases in which it intervenes, all its benefits are nullified. MAEB intervention must be proved to be safe in at least 99.95% of cases in which it is triggered. In a recent field test campaign, MAEB did not provoke any loss of control in more than 1000 activations (Marra et al. 2021). More details regarding the relationship between relative injury risk reduction and impact speed reduction are provided in the Online Appendix A.

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

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

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

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Data availability statement

Data available on request from the authors.

Disclosure statement

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

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ORCID

Cosimo Lucci http://orcid.org/0000-0002-7226-0501
Trevor Allen http://orcid.org/0000-0002-3911-7914
Marco Pierini http://orcid.org/0000-0003-3648-5567
Giovanni Savino http://orcid.org/0000-0003-0949-0811

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

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

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

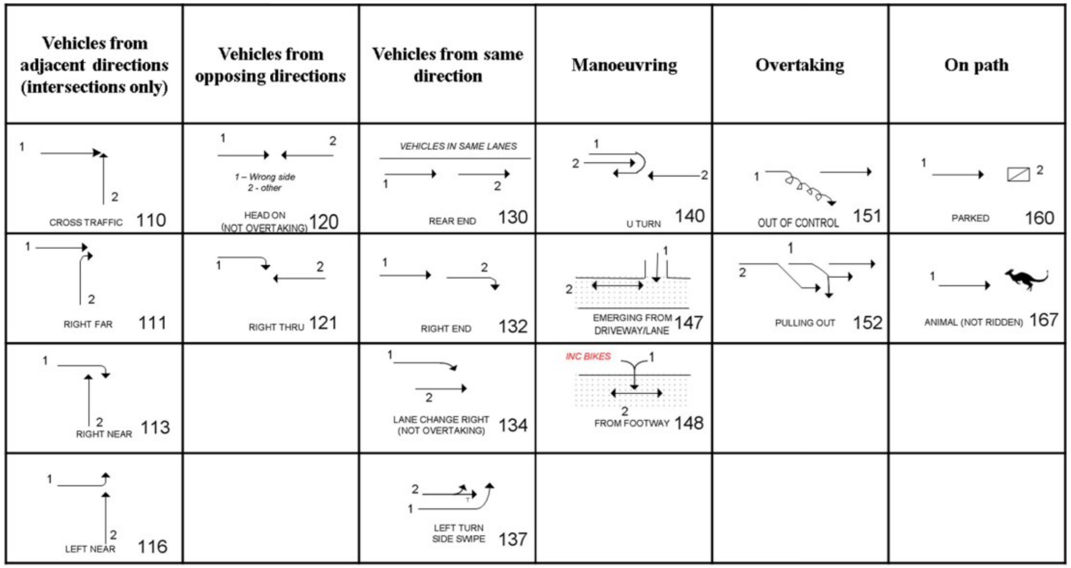
CORRESPONDING AUTHOR: Cosimo Lucci – cosimo.lucci@unifi.it

Appendix

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

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

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



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

Table A3 – List of MICIMS cases included in the study

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

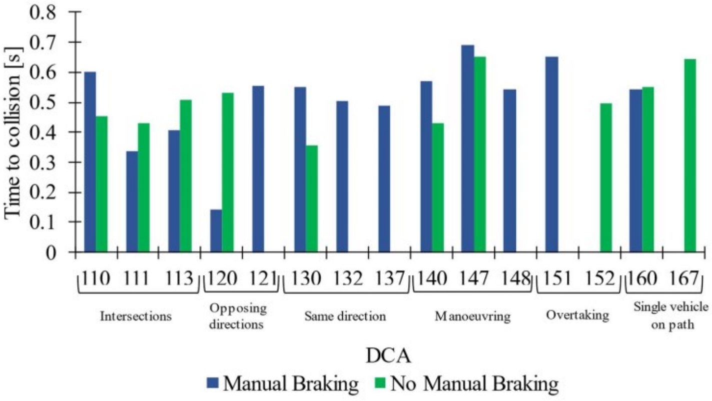


Figure A1 - *Mean time to collision at MAEB trigger distributed by crash configuration. Crashes separated by the presence of manual braking (blue) and no manual braking (green)*

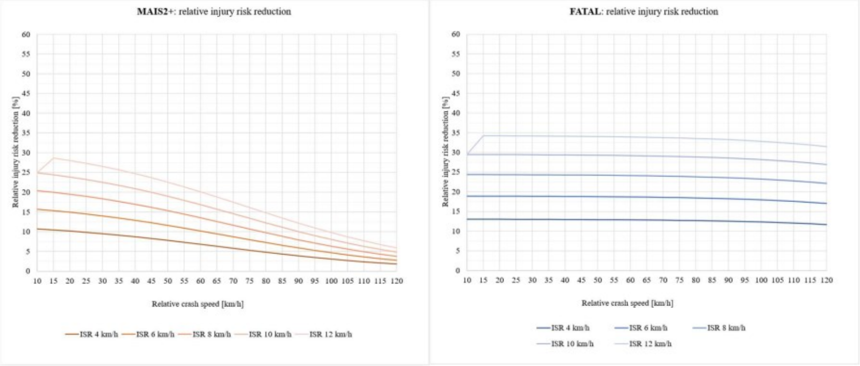


Figure A2 – Relative injury risk reduction for MAIS2+ (left) and FATAL (right) injuries: influence of Impact Speed Reduction (ISR)

6 Conclusions

The present work investigated the feasibility of MAEB and its acceptability among end-users through a field test campaign involving 35 participants. Two test vehicles provided with automatic braking devices were employed to reproduce unexpected MAEB intervention in realistic riding scenarios. The ultimate goal was the identification of the pre-crash riding conditions and system intervention parameters potentially effective in mitigating injuries which can make MAEB applicable and acceptable in real-world crashes. The results of this study highlighted that MAEB can be applicable in pre-crash conditions and it can be effective in reducing impact speed. The set of working parameters identified in this study resulted to guarantee the controllability of the PTW and were positively accepted by end-users. In addition, the estimations based on real-world crash simulations highlighted that MAEB has a promising potential in reducing injuries and fatalities among PTW users.

This dissertation was based mainly on four journal papers, integrated by three conference papers. Each paper represents a contribution to the development of MAEB towards its introduction on standard vehicles.

The first journal paper [55] provided the guidelines for the definition of the procedure to field test the intervention of MAEB. This paper, which was used as a reference to define the test protocol employed in the field test with participants, gather all the relevant information required to define the test protocol derived from literature review and pilot testing activities. A comprehensive description of the field test requirements in terms of testing conditions, manoeuvres, participants requirements, vehicles and instrumentation requirements is provided. An example of a test protocol and an outline of data analysis is also included. The contribution of this paper is twofold: first, it provides complete support to design a test protocol to further investigate the MAEB, and second, it set a reference for the design of field tests for other active safety systems for PTWs.

The second paper [60] discussed the manoeuvrability of the PTW during the intervention of MAEB. In the publication, the applicability of MAEB during a lane change manoeuvre representing a realistic pre-crash avoidance action was discussed, employing a deceleration of 0.3g at typical urban velocities. The deceleration of 0.3g, which is approximately the double of the typical coast-down deceleration of the motorcycle used in the field tests, represented a first step towards higher decelerations effective in reducing PTWs speed. The results highlighted that with such level of intervention, the automatic braking does not produce instability of the vehicle nor the rider, and the latter is constantly able to perform the avoidance action. Before this study, MAEB was considered for straight-riding application only and its intervention was supposed to prevent riders to manoeuvre. This paper showed that MAEB intervention do not prevent riders to execute avoidance actions, paving the way to further investigations focusing on higher values of deceleration.

The main contribution of this work is represented by the third journal paper included in this dissertation [61]. This paper, based on the results of previous studies and motorcyclist injury risk functions, proposed a methodology to define the working parameters (0.5g of target deceleration and 2g/s as fade-in jerk) required to make MAEB effective to mitigate injuries. The proposed parameters were validated through field test involving common riders as participants to analyse MAEB feasibility and the end-users' acceptability in realistic riding conditions. Similarly with the results of the previous study, the proposed parameters resulted to be suitable for MAEB interventions and allowed the rider manoeuvring the vehicle to execute an avoidance action. However, the application of MAEB intervention with such working parameters must be limited by checking that the rider has his/her hands positioned on the handlebar, in order to avoid potential loss of control. This paper contributes to MAEB development validating its application with common riders of the highest working parameters tested so far, expected to be capable to mitigate PTW user injuries.

The final contribution of this work is represented by the last paper presented, focusing on MAEB benefits estimation [65]. In this work, carried out in collaboration with the Monash University Accident Research Centre (MUARC) where the candidate spent three months of his PhD, MAEB intervention was simulated in real-world reconstructed crashes to assess its quantitative kinematics effects. The potential benefits of MAEB in terms of injury risk reduction were estimated employing the highest levels of intervention that underwent field-testing (refer to journal paper n.3), thus highlighting how much promising this technology actually is in mitigating rider injuries in PTW crashes. This paper provided a robust estimation of the benefits of MAEB, showing the impact in terms of injury risk reduction achievable through its introduction on standard vehicles. The paper focused also on the application of MAEB as an enhanced braking system, proposing and testing two new strategies of intervention. This provides a recommendation for the future research and development of MAEB function to be applied in the cases in which the rider does apply a manual braking action prior to collision.

The contribution to the current body of knowledge of this research project (in the form of four journal papers integrated by three the conference papers), constitutes a relevant enhancement on the development of MAEB towards its application on standard vehicles. As showed in previous studies, the technology to implement such system on standard PTWs is substantially ready: obstacle detection systems and electronic control units are already installed on PTW, as confirmed by the recent introduction of the Adaptive Cruise Control on production high-end motorcycles [66]. What is restraining MAEB implementation is mainly the incomplete understanding of its interaction with the rider when deployed in real-world riding conditions. Despite the relevant contribution provided by this study, further research is recommended to evaluate the applicability of MAEB on standard vehicles.

In fact, even if the tested riding scenarios are those most relevant for MAEB applications, further validation in other riding conditions, such as leaning, must be tested to ensure its safety and vehicle controllability in case of unnecessary activation. In addition, further studies focusing on the combination of MAEB intervention with manual braking are required: this would allow developing MAEB to be applied concurrently to manual braking, validating on real-world PTW the strategies to enhance its effectiveness proposed in this dissertation and tested via numerical simulation. Further validations of MAEB application should include emergency conditions with obstacles: even if the test presented in this study attempted to reproduce the unexpected activation (since it is considered one of the worst working conditions of such system), the reaction of the rider in relation to a hazard might modify its response to MAEB intervention. Further validation should include higher velocities, which highly influence the dynamics of the vehicle, and different Powered-Two-Wheeler style vehicles, in order to assess the possible influence of the riding position.

This study demonstrated that the application of Autonomous Emergency Braking technologies to motorcycles is feasible under certain conditions, and it may provide relevant benefits in terms of reduction of fatalities and injuries for motorcyclists: a final research and development effort to make it ready for standard vehicle application is now required to make the motorcyclists of all the world safer.

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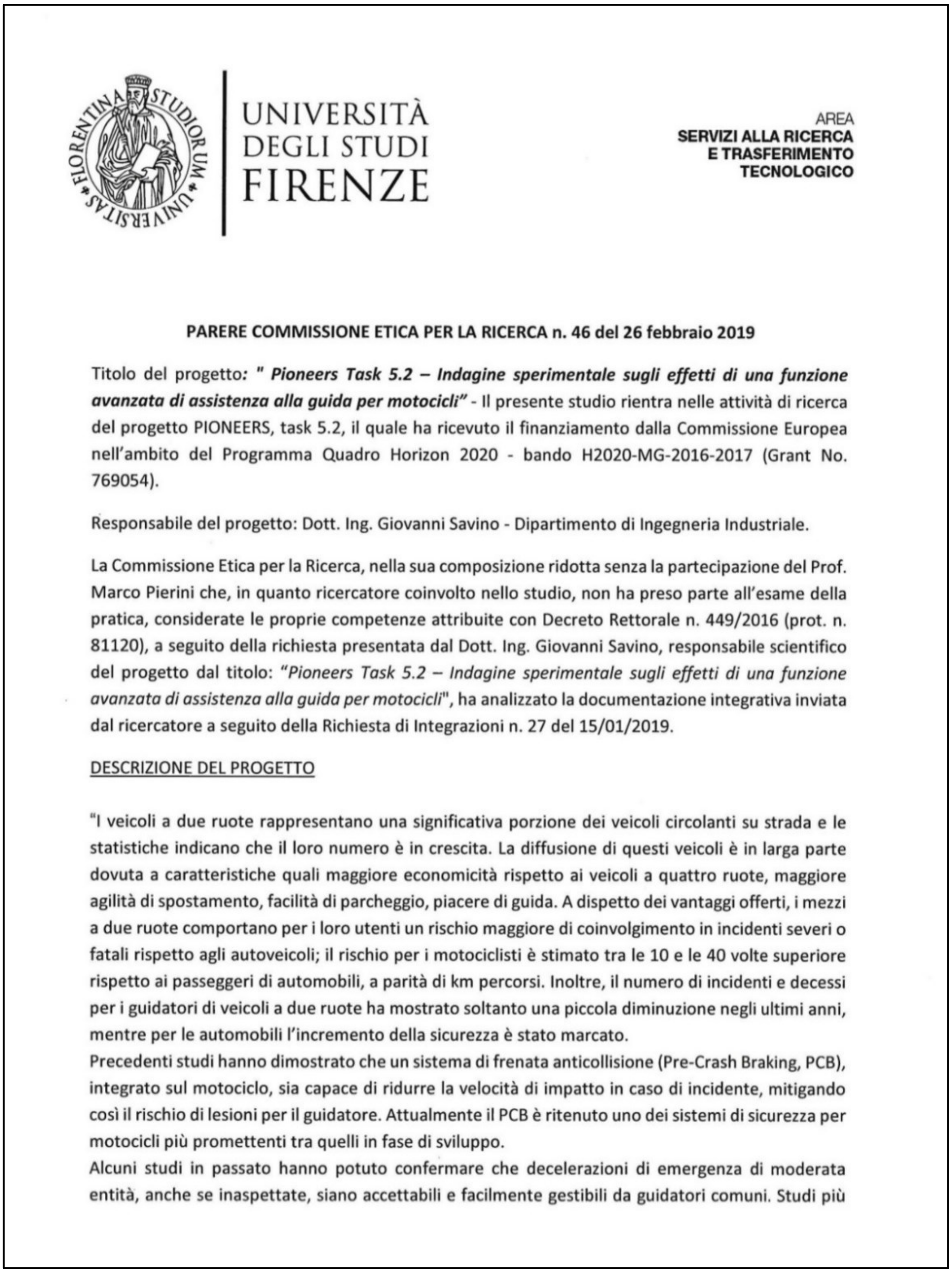
8 Appendix

8.1 Ethical approval communication



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PARERE COMMISSIONE ETICA PER LA RICERCA n. 46 del 26 febbraio 2019

Titolo del progetto***: " Pioneers Task 5.2 – Indagine sperimentale sugli effetti di una funzione avanzata di assistenza alla guida per motocicli"*** - Il presente studio rientra nelle attività di ricerca del progetto PIONEERS, task 5.2, il quale ha ricevuto il finanziamento dalla Commissione Europea nell'ambito del Programma Quadro Horizon 2020 - bando H2020-MG-2016-2017 (Grant No. 769054).

Responsabile del progetto: Dott. Ing. Giovanni Savino - Dipartimento di Ingegneria Industriale.

La Commissione Etica per la Ricerca, nella sua composizione ridotta senza la partecipazione del Prof. Marco Pierini che, in quanto ricercatore coinvolto nello studio, non ha preso parte all'esame della pratica, considerate le proprie competenze attribuite con Decreto Rettorale n. 449/2016 (prot. n. 81120), a seguito della richiesta presentata dal Dott. Ing. Giovanni Savino, responsabile scientifico del progetto dal titolo: "*Pioneers Task 5.2 – Indagine sperimentale sugli effetti di una funzione avanzata di assistenza alla guida per motocicli*", ha analizzato la documentazione integrativa inviata dal ricercatore a seguito della Richiesta di Integrazioni n. 27 del 15/01/2019.

DESCRIZIONE DEL PROGETTO

"I veicoli a due ruote rappresentano una significativa porzione dei veicoli circolanti su strada e le statistiche indicano che il loro numero è in crescita. La diffusione di questi veicoli è in larga parte dovuta a caratteristiche quali maggiore economicità rispetto ai veicoli a quattro ruote, maggiore agilità di spostamento, facilità di parcheggio, piacere di guida. A dispetto dei vantaggi offerti, i mezzi a due ruote comportano per i loro utenti un rischio maggiore di coinvolgimento in incidenti severi o fatali rispetto agli autoveicoli; il rischio per i motociclisti è stimato tra le 10 e le 40 volte superiore rispetto ai passeggeri di automobili, a parità di km percorsi. Inoltre, il numero di incidenti e decessi per i guidatori di veicoli a due ruote ha mostrato soltanto una piccola diminuzione negli ultimi anni, mentre per le automobili l'incremento della sicurezza è stato marcato.
Precedenti studi hanno dimostrato che un sistema di frenata anticollisione (Pre-Crash Braking, PCB), integrato sul motociclo, sia capace di ridurre la velocità di impatto in caso di incidente, mitigando così il rischio di lesioni per il guidatore. Attualmente il PCB è ritenuto uno dei sistemi di sicurezza per motocicli più promettenti tra quelli in fase di sviluppo.
Alcuni studi in passato hanno potuto confermare che decelerazioni di emergenza di moderata entità, anche se inaspettate, siano accettabili e facilmente gestibili da guidatori comuni. Studi più

recenti suggeriscono che anche decelerazioni automatiche di entità superiore possano essere ben sopportate da un guidatore medio. Ciò richiede ulteriori conferme sperimentali.

Questo studio è focalizzato sullo sviluppo dei sistemi PCB. L'obiettivo specifico consiste nel fornire nuova conoscenza riguardo ai parametri di attivazione del PCB ed in particolare, i profili di decelerazione opportuni per condizioni di guida realistica ed il grado di accettabilità di questa funzione di sicurezza da parte degli utenti. In aggiunta, valuteremo l'utilità di sottoporre gli utenti ad un processo di familiarizzazione con il sistema e cercheremo di stabilire se esiste una correlazione tra il profilo del guidatore ed i parametri di accettabilità del sistema.

L'impatto atteso per questo studio è un fondamentale contributo per comprendere se il sistema PCB sia effettivamente utilizzabile sui motocicli con parametri compatibili a garantirne una reale efficacia ai fini della mitigazione dei traumi stradali.

Inoltre, la valutazione dell'accettabilità del sistema PCB per motocicli permetterà di produrre stime sulla rapidità di penetrazione di questo sistema e di sistemi analoghi sul mercato; ciò è significativo sia per realizzare stime realistiche sui benefici di questa tecnologia che per guidare lo sviluppo ulteriore del sistema."

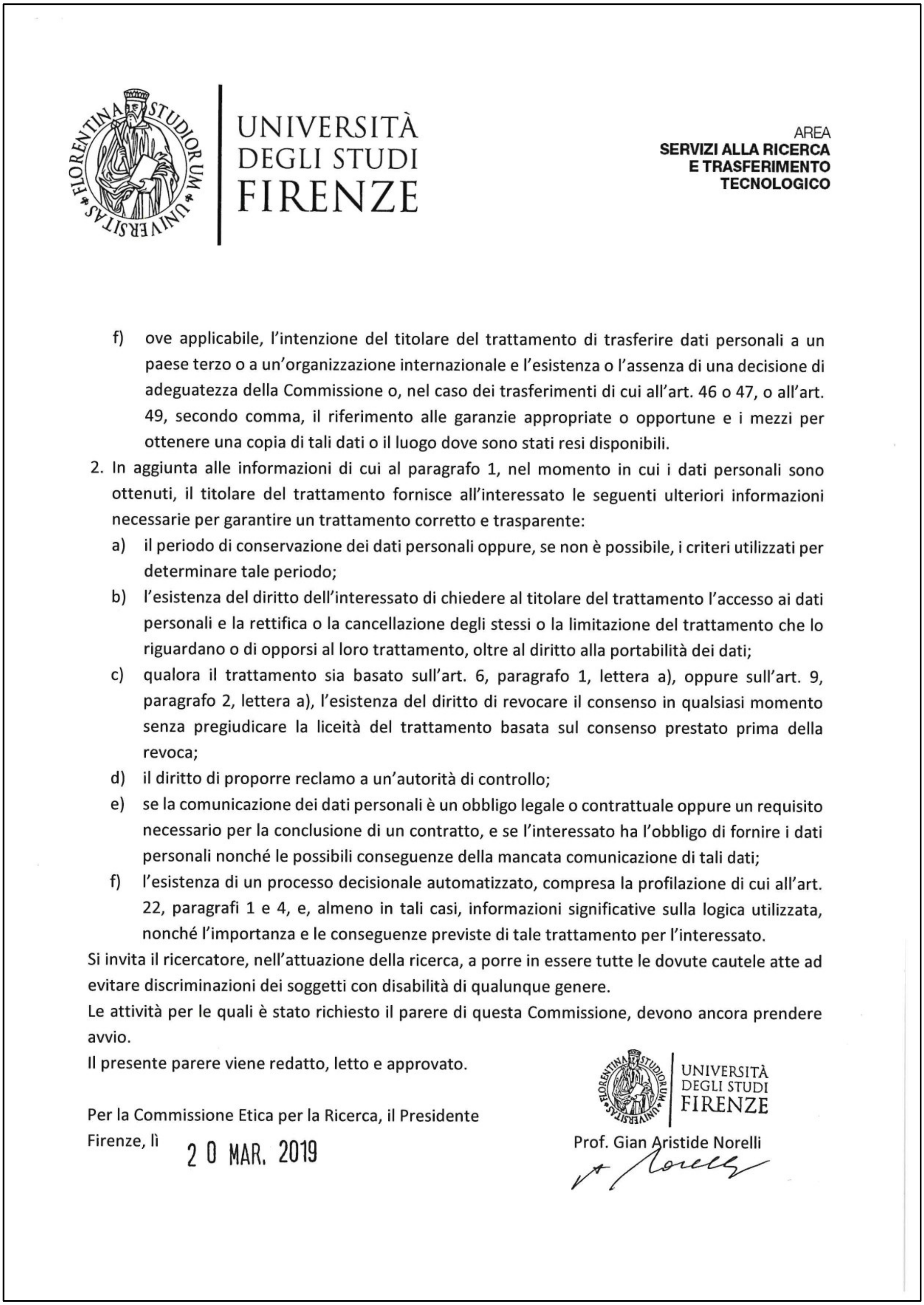
La Commissione Etica per la Ricerca

esaminata attentamente la documentazione integrativa pervenuta, approva la struttura generale del progetto e le modalità di esecuzione dello stesso così come illustrate dal responsabile scientifico ed accorda dunque parere positivo.

Si raccomanda tuttavia di eliminare l'ultimo capoverso del punto 9 dell'Informativa e di mantenere come unica mail di contatto quella del responsabile scientifico.

Si ricorda che, ai sensi dell'Articolo 13 EU RGPD, il titolare del trattamento dovrà fornire all'interessato, nel momento in cui i dati personali sono ottenuti, le seguenti informazioni:

a) l'identità e i dati di contatto del titolare del trattamento e, ove applicabile, del suo rappresentante;
b) i dati di contatto del responsabile della protezione dei dati, ove applicabile;
c) le finalità del trattamento cui sono destinati i dati personali nonché la base giuridica del trattamento;
d) qualora il trattamento si basi sull'art. 6, paragrafo 1, lettera f), i legittimi interessi perseguiti dal titolare del trattamento o da terzi;
e) gli eventuali destinatari o le eventuali categorie di destinatari dei dati personali;



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- f) ove applicabile, l'intenzione del titolare del trattamento di trasferire dati personali a un paese terzo o a un'organizzazione internazionale e l'esistenza o l'assenza di una decisione di adeguatezza della Commissione o, nel caso dei trasferimenti di cui all'art. 46 o 47, o all'art. 49, secondo comma, il riferimento alle garanzie appropriate o opportune e i mezzi per ottenere una copia di tali dati o il luogo dove sono stati resi disponibili.

2. In aggiunta alle informazioni di cui al paragrafo 1, nel momento in cui i dati personali sono ottenuti, il titolare del trattamento fornisce all'interessato le seguenti ulteriori informazioni necessarie per garantire un trattamento corretto e trasparente:
   - a) il periodo di conservazione dei dati personali oppure, se non è possibile, i criteri utilizzati per determinare tale periodo;
   - b) l'esistenza del diritto dell'interessato di chiedere al titolare del trattamento l'accesso ai dati personali e la rettifica o la cancellazione degli stessi o la limitazione del trattamento che lo riguardano o di opporsi al loro trattamento, oltre al diritto alla portabilità dei dati;
   - c) qualora il trattamento sia basato sull'art. 6, paragrafo 1, lettera a), oppure sull'art. 9, paragrafo 2, lettera a), l'esistenza del diritto di revocare il consenso in qualsiasi momento senza pregiudicare la liceità del trattamento basata sul consenso prestato prima della revoca;
   - d) il diritto di proporre reclamo a un'autorità di controllo;
   - e) se la comunicazione dei dati personali è un obbligo legale o contrattuale oppure un requisito necessario per la conclusione di un contratto, e se l'interessato ha l'obbligo di fornire i dati personali nonché le possibili conseguenze della mancata comunicazione di tali dati;
   - f) l'esistenza di un processo decisionale automatizzato, compresa la profilazione di cui all'art. 22, paragrafi 1 e 4, e, almeno in tali casi, informazioni significative sulla logica utilizzata, nonché l'importanza e le conseguenze previste di tale trattamento per l'interessato.

Si invita il ricercatore, nell'attuazione della ricerca, a porre in essere tutte le dovute cautele atte ad evitare discriminazioni dei soggetti con disabilità di qualunque genere.

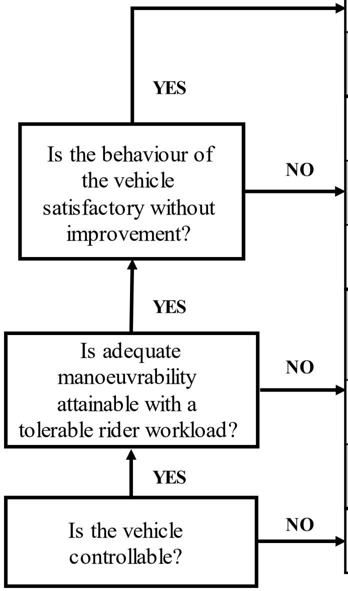
Le attività per le quali è stato richiesto il parere di questa Commissione, devono ancora prendere avvio.

Il presente parere viene redatto, letto e approvato.

Per la Commissione Etica per la Ricerca, il Presidente
Firenze, lì 20 MAR. 2019

Prof. Gian Aristide Norelli

8.2 Adjusted Cooper-Harper rating scale



Vehicle behaviour	Actions required to the rider	Rating
Excellent, highly desirable	Compensation of the rider not determinant for the correct execution of the manoeuvre	1
Good, negligible deficiencies	Compensation of the rider not determinant for the correct execution of the manoeuvre	2
Fair - Some mildly unpleasant deficiencies	Minimal compensation of the rider for the correct execution of the manoeuvre	3
Minor but annoying deficiencies	Desired execution of the manoeuvre requires moderate rider compensation	4
Moderately objectionable deficiencies	Adequate execution of the manoeuvre requires considerable rider compensation	5
Very objectionable but tolerable deficiencies	Adequate execution of the manoeuvre requires extensive rider compensation	6
Major deficiencies	Adequate execution of the manoeuvre not attainable with maximum tolerable rider compensation Controllability not in question	7
Major deficiencies	Considerable rider compensation is required for control the vehicle	8
Major deficiencies	Intense rider compensation is required to retain control the vehicle	9
Major deficiencies	Control of the vehicle is lost during some portion of the manoeuvre	10