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## Defining suitable parameters for safe and effective deployment of a motorcycle Pre-Crash Braking system: findings from field testing and crash simulations

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**TITLE:** Defining suitable parameters for safe and effective deployment of a motorcycle Pre-Crash Braking system: findings from field testing and crash simulations

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**ABSTRACT**

***Research question / Starting point for investigation***

*Pre-Crash Braking (PCB) is a promising technology currently under development, aiming to improve motorcyclists' safety by providing automatic braking input and reducing impact speed in pre-crash conditions. However, the implementation of the PCB as a system that influences motorcycle control, remains controversial from the perspective of the users.*

*This study, conducted within the EC funded project PIONEERS, aims to define suitable parameters of intervention and technical requirements for obstacle detection for a safe and effective application of PCB.*

***Methods***

*First, a field test program involving 51 common riders as participants on two test vehicles was executed to assess the feasibility of different levels of autonomous braking intervention. The system was tested in the speed range of 30-50 km/h while performing typical manoeuvres including straight riding and lane change.*

*Second, 60 crash cases sourced from two different in-depth databases from Italy and France were reconstructed using two different 2D simulation software, to test various obstacle detection system requirements and evaluate the potential safety benefits of the PCB intervention.*

***Results***

*In both straight-line and lane change manoeuvres, autonomous braking intervention reaching decelerations up to 5 m/s<sup>2</sup> with fade-in jerk up to 20 m/s<sup>3</sup> for a duration of approx. 1 s were considered manageable on both test vehicles by participants. Overall, the system intervention was tested more than 900 times with no loss of control. The crash simulation analysis indicated that a field of view of 80° and a detection range of 30m or higher can be adequate to effectively identify obstacles and trigger PCB. Tangible safety benefits were found to be achievable with several combinations of the analysed design parameters.*

***Impacts / Effects / Consequences***

*Our latest findings show that PCB still has to be considered among the motorcycle safety countermeasures of the future. In fact, by employing design parameters within the up-to-date feasibility thresholds evaluated in this study, the PCB estimated effects had a relevant safety impact.*

# 1 Introduction

This study presents the results of the collaborative research performed within the framework of the European Commission-founded project PIONEERS, whose general objective was to improve the safety of Powered-Two-Wheelers (PTWs) users through an innovative integrated approach to rider protection, based on personal protective equipment and onboard active safety systems.

Within the project, one of the cores of research was Pre-Crash Braking (PCB), being one of the most promising technologies among onboard safety systems in development for PTWs [1]. PCB provides the functionalities of Motorcycle Autonomous Emergency Braking (MAEB) in pre-crash conditions, delivering an autonomous braking action intended to reduce the pre-crash speed of the host PTW immediately before the crash. Such technology showed a positive effect on other road vehicles such as trucks and passenger cars [2].

The working parameters of PCB, intended as braking parameters, which define the performance of the pre-crash autonomous braking action, and obstacle detection requirements, which define the performance of obstacle detection tools required for effectively detect opponent vehicles or objects and trigger the PCB at the proper timing, are the key for safe and effective implementation of PCB on PTWs. As indicated in studies on passengers' cars, different parameters can provide different results in terms of impact speed reduction and injury mitigation [3].

In order to explore suitable parameters for PCB intervention, early studies employed mainly two approaches: field tests to evaluate rider stability during the deployment of Automatic Braking (AB), and crash simulations to estimate PCB potential benefits for injury mitigation [4]. Studies focusing on field testing started in 2010 with professional riders and with a PTW equipped with a laser-scanner and producing automatic decelerations in correspondence with a target obstacle [5]. Further research was performed testing AB with common riders as participants and decelerations up to  $2 \text{ m/s}^2$  deployed unexpectedly via remote control [6], and again, with professional riders in lane-change riding scenarios [7]. Crash simulations were also employed to develop decision logic to trigger PCB interventions [8], and to explore its potential benefits on crashes [9], [10].

In order to make PCB a mature technology to be introduced on standard vehicles, further research is required to define safe and reliable working parameters. Some preliminary studies which analysed its effectiveness, suggested that the parameters of intervention field-tested so far may not be sufficient to reduce the likelihood of sustaining serious injuries in case of crashes [11]. In addition, the current technological development of obstacle recognition tools fostered by the introduction of Autonomous Emergency Braking for passenger cars and research for Autonomous Driving, offered in the last few years new reliable tools for obstacle detection, which could pave the way to an effective triggering of PCB.

The goal of this study is to identify suitable parameters of intervention and technical requirements for obstacle detection tools for a safe and effective application of PCB. We performed field tests with two prototype vehicles and participants to assess the acceptability of the PCB among end-users and the controllability of the vehicle with different sets of braking parameters, while computer simulations were used to evaluate PCB effects and its efficacy in reducing impact speed with a broader set of braking parameters and obstacle detection requirements.

## 2 Methods

This study combines two different methodologies -Field testing and Crash modelling- with the common goal of identifying suitable parameters for safe and effective deployment of Pre-Crash Braking system on Powered-Two-Wheelers (see Figure 1). In this section both the methodologies and the sets of PCB working parameters tested in field testing and simulations will be presented.

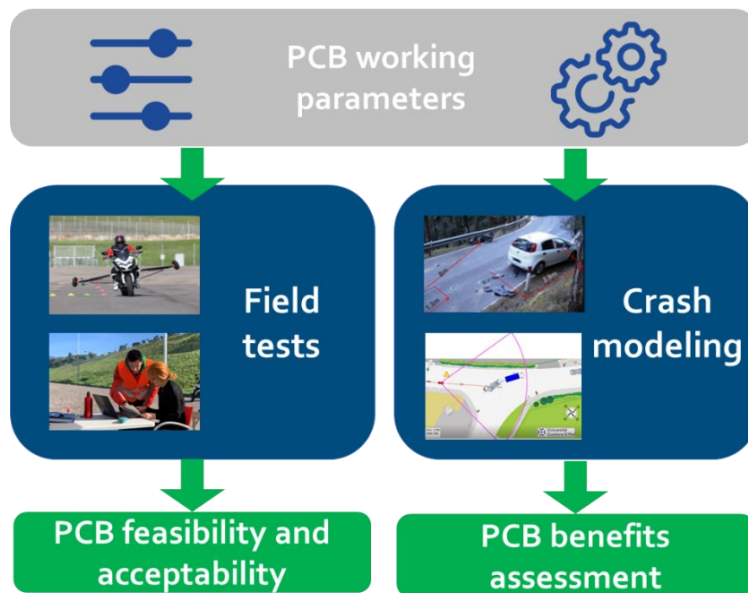


Figure 1 – Methodological approach employed for this study

## 2.1 Field test methods

Field tests were performed on two different test vehicles provided with Automatic Braking (AB) devices capable of activating braking without rider action. Both vehicles (a sport-touring motorcycle and a 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.

The AB test procedure was developed based on previous studies based on pilot testing and literature review carried out by the authors [12]. The AB interventions were tested at different velocities ranging from 30 km/h to 60 km/h (depending on the requested manoeuvres).

The participants were recruited among active riders with 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.

This study obtained ethical approval from the Ethics Committee of the University of Florence (Written opinion N. 46, 20/03/2019).

### 2.1.1 Test procedure and AB parameters

Participants tested the intervention of the AB system by riding with one of the two test vehicles along the test track: the AB activations were manually triggered by one investigator via remote control [13]. 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 deceleration of respectively  $3 \text{ m/s}^2$  and  $5 \text{ m/s}^2$  and fade-in jerk of  $15 \text{ m/s}^3$  tested in four manoeuvres (straight-line, lane-change, slalom, and curve). For the MP3, as for the Multistrada, the test included two phases with a nominal deceleration of respectively  $3 \text{ m/s}^2$  and  $5 \text{ m/s}^2$  and fade-in jerk of  $15 \text{ m/s}^3$ , tested in two manoeuvres (straight-line and lane-change). The test with MP3, after the above-mentioned phases, also included two other phases with fade-in jerk up to  $25 \text{ m/s}^3$ .

The participants were not aware of the timing of AB intervention nor the exact position within the test track: this aimed to obtain AB events that were as unexpected for the rider as possible while keeping a low learning effect. Overall, the AB was deployed in the different manoeuvres with an average frequency of one activation every 100 s of riding and with a pseudo-random order. Full details of the test procedure were presented in [14].

### 2.1.2 Test vehicles

The first test vehicle was a Ducati Multistrada 1260S, a sport-touring motorcycle equipped with Motorcycle Stability Control (MSC), combined braking and semi-active suspensions. The vehicle was provided with outriggers to prevent the vehicle from lateral fall (see Figure 2 - left), since the intervention of AB in lateral manoeuvres such as cornering and slalom was also tested with this vehicle, but it will not be presented in this paper. The second vehicle was a Piaggio MP3 500, a two-front-wheel scooter provided with Antilock Braking System (ABS) (see Figure 2 - right).



Figure 2 – Test vehicles: Ducati Multistrada 1260 (left) and Piaggio MP3 500 (right)

### 2.1.3 Data recording

A similar data acquisition system was employed on both vehicles to collect data from the PTWs' CAN-Bus (throttle, brake action, steering angle, vehicle tri-axis acceleration and gyro), from an Inertial Measurement Unit (IMU) attached to the back of the participants to record the chest movement during the tests, and from an internal tri-axes accelerometer and GPS receiver. Both test vehicles were also equipped with action cameras to record the driver's body and monitor his/her behaviour during the AB. In order to collect subjective data, questionnaires were adopted to ask participants their opinion on the test, the AB system tested and the controllability of the vehicle during the AB activation in the different manoeuvres.

## 2.2 Crash simulation methods

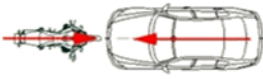
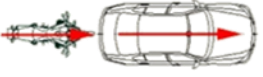

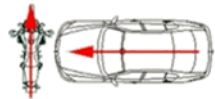
The second step of this study employed computer simulations to reconstruct real-world crashes and assess the potential benefits of PCB applied with different parameters of intervention. The simulations were designed to cover a broad range of PCB parameters, including those tested in the field test campaign. Also, different levels of performance for the obstacle recognition tools supposed to trigger PCB were analysed.

### 2.2.1 Crash data source

Crash cases for simulation were extracted from two different in-depth road crash databases: the InSAFE database from the University of Florence (UNIFI), which collects crashes from the Florence metropolitan area, Italy [15], and the EDA database from the University Gustave Eiffel (UGE), which collects crashes from both rural and urban roads in France [16]. In total sixty cases were employed, thirty from each database, extracted and reconstructed based on the detailed description of the crash collected in the database, including for example road configuration, marks documented in the crash scenario, damage to vehicles, injuries of riders, and police reports. Overall, crashes included in the study involved mainly L3 PTWs (77%) and 23% of L1 PTWs only. They occurred mainly at intersections (70%), while only 22% were in straight-line and 8% in curves. The distribution of the crash configuration among the two databases was slightly different: the InSAFE dataset collected more Head-to-side (T-bone) crashes (56%), while in the EDA database 50% of cases were Head-on crashes (see Table 1 – for the detailed definition of the crash configurations see [17]). A lower proportion of Head-to-rear and Sideswipe crashes were included in both databases.



Table 1 - Crash Configuration distribution of 60 cases among the two databases

Crash Configuration	InSAFE	EDA	Total
<b>Head-on</b> 	5 (16.7%)	15 (50.0%)	20 (33.3%)
<b>Head-to-rear</b> 	3 (10.0%)	2 (6.7%)	5 (8.3%)
<b>Head-to-side</b> 	17 (56.7%)	7 (23.3%)	24 (40.0%)
<b>Sideswipe</b> 	5 (16.7%)	6 (20.0%)	11 (18.3%)
<b>Total</b>	30 (100.0%)	30 (100.0%)	60 (100.0%)

### 2.2.2 Crash reconstruction tools

Crash reconstructions were performed on two different 2D simulation tools developed by UNIFI and UGE based on previous studies on PCB [9]. Among the 60 cases included in the study, 20 were simulated in both crash simulation tools (10 from each database), to compare results from the two different software. Each crash case was first reconstructed in the virtual environment and validated using all the information collected in the database (e.g., comparing the impact speed at the crash and the incidence of the two vehicles involved in simulations with detailed data from crash investigators). Then, the intervention of PCB with different parameters was simulated (see the following section). The effect of PCB was measured in terms of Impact Speed Reduction (ISR), as the difference between the impact speed without and with PCB.



Figure 3 – Crash simulation tools employed for the study by UNIFI (left) and UGE (right)

### 2.2.3 PCB tested parameters

Crash simulations were employed to assess the influence on PCB effectiveness of five parameters, three related to the automatic braking system (Triggering Strategy, Deceleration and Fade-in Jerk), and two related to the obstacle recognition system (Field of View and Range). See Table 2 for full details about the ranges and the incremental steps used for simulations.

The **Triggering Strategy** defines the timing of deploying PCB based on the detection of the inevitable collision state: the time in which the crash between the PTW and the opponent vehicle/object becomes unavoidable. Based on different thresholds of deceleration in longitudinal and lateral directions achievable by the PTW, it is possible to define different triggering strategies. These correspond to a different time to collision at which the PCB is triggered. Full details of the definition of triggering strategies are presented in [18]. For this study, three triggering strategies (called "Conservative", "Standard" and "Progressive") were simulated in both crash simulation software. In order to have a more realistic PCB behaviour, the software employed by UGE added to PCB simulation a constraint on times to collision with the realistic values of 0.6 s (Conservative), 0.8 s (Standard) and 1 s (Progressive).

Three values of PCB **Deceleration** were employed in crash simulations: two of these values (respectively, 3 m/s<sup>2</sup> and 5 m/s<sup>2</sup>) were devised by field tests performed with participants (see section 2.1.1), while the highest value of deceleration (7 m/s<sup>2</sup>) was tested to assess what could be the potential benefits of PCB with decelerations even higher than those currently field-tested with participants. Similarly to deceleration, the two levels of **Fade-in Jerk** tested with participants were also employed in simulations.

The **Field of View** represents half of the width in degrees of the detection zone of the obstacle recognition system. Combining its value with the **Range**, we can define the obstacle recognition cone in which an opponent vehicle or object can be recognised by the system (see Figure 3). This defines the timing when the other vehicle is detected by embedded sensors on the PTW and therefore PCB can be triggered. The Range is the maximum distance at which the PCB can detect an opponent vehicle/object. For both parameters, a wide range of values was tested in simulations, based on the state-of-the-art radar technology. It is evident that state-of-the-art sensor devices are capable to have a wider range. However, to limit simulation time, for PCB with progressive triggering strategy the range does not extend 90 m.

Table 2 - PCB Parameters variation

Parameter	Range	Incremental step
Triggering strategy	[conservative, standard, progressive]	-
Deceleration	[3 m/s <sup>2</sup> -7 m/s <sup>2</sup> ]	2 m/s <sup>2</sup>
Fade-in Jerk	[15 m/s <sup>3</sup> -25 m/s <sup>3</sup> ]	-
Field of View	+/- [10° - 70°]	15°
Range	[30 m - 90 m]	15 m

\* NOTE: this value represents half of the whole FOV of the detection cone

The wide number of parameters tested allowed us to assess the influence of each parameter on PCB performance (see section 3.2.1). However, 450 different combinations of PCB parameters tested did not allow us to obtain a realistic assessment of the expected benefits provided by the system. Three combinations of parameters were therefore selected to analyse the potential effectiveness of PCB considering a pessimistic (low efficiency), an average, and an optimistic (high efficiency) implementation of parameters. The sets of parameters selected for the three configurations are displayed in Table 3.

Based on results from field testing (see section 3.1.4), for the PCB deceleration, the more conservative setting (3 m/s<sup>2</sup>) was selected for the pessimistic configuration while for the average and progressive configurations

the deceleration of  $5 \text{ m/s}^2$  was chosen. Similarly, the fade-in jerk was set to  $15 \text{ m/s}^3$  for the pessimistic configuration and  $25 \text{ m/s}^3$  for both the average and optimistic configurations.

Table 3 - Sets of parameters for the three PCB realistic configurations

Parameter	Pessimistic	Average	Optimistic
Triggering strategy	Conservative	Standard	Progressive
Deceleration ( $\text{m/s}^2$ )	3	5	5
Fade-in jerk ( $\text{m/s}^3$ )	15	25	25
Range (m)	30	30	30
Field of View ( $^\circ$ )	+/-15	+/-45	+/-45

## 3 Results

### 3.1 Field test results

The results of the field-testing activity will be presented in this section: actual PCB working parameters field-tested for both test vehicles will be related to their feasibility in different riding conditions and acceptability among users.

#### 3.1.1 Test participants

Overall, 51 participants (10 women, 41 men) were included in this study, testing only one of the two vehicles. Thirty-one participants tested AB on the Multistrada, while 20 on the MP3. Participants were selected based on their main usage of PTWs: the majority of participants who tested AB on Multistrada were mainly leisure riders while participants selected to test the AB intervention on the MP3 were mostly commuters. 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. For further details on the sample of participants included in the study please see [14].

#### 3.1.2 Tested Automatic Braking intervention and manoeuvres

Table 4 reports a summary of the AB-tested intervention for the two test vehicles in the two manoeuvres considered in this study: straight-line riding and lane change reproducing an avoidance action (see Figure 4). 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 in the test protocol.

Overall, the AB was tested with the Multistrada almost 250 times in straight line and lane change, whereas considering also the trials in different conditions and manoeuvres more than 500 AB tested interventions were recorded. With the MP3 the AB intervention was tested approx. 290 times the same manoeuvres.

For the Multistrada, the AB was deployed at two different levels of nominal deceleration (respectively  $3 \text{ m/s}^2$  and  $5 \text{ m/s}^2$ ), and with a fade-in jerk level of  $15 \text{ m/s}^3$ . These nominal values were also measured after testing. Similarly, for the MP3 the two values of deceleration ( $3 \text{ m/s}^2$  and  $5 \text{ m/s}^2$ ) were measured in the trials, while the two levels of fade-in jerk (respectively  $15 \text{ m/s}^3$  and  $25 \text{ m/s}^3$ ) set for the test resulted in a wide distribution of values of fade-in jerk, with peaks reaching up to  $30 \text{ m/s}^3$ .

The AB duration for both vehicles was approx. 1 s (respectively, 1.08 s and 0.97 s for Multistrada and MP3), while the riding speed at AB trigger ranged from 37 to 45 km/h.



Table 4 – Summary of AB tested interventions

Test Vehicle	Participants	Manoeuvre	Nominal deceleration [m/s <sup>2</sup> ]	N° of PCB activations	Initial Speed [km/h]		Event duration [s]		Deceleration [m/s <sup>2</sup> ]		Fade-in jerk [m/s <sup>3</sup> ]	
					Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ducati Multistrada	31	Straight-line	3	63	47.6	4.7	1.07	0.03	2.9	0.3	15.0	4.0
		Lane change		65	41.7	6.0	1.05	0.11	3.0	0.4	12.6	4.1
		Straight-line	5	63	49.1	4.7	1.14	0.03	4.7	0.4	20.2	3.9
		Lane change		65	41.5	5.4	1.05	0.20	4.8	0.4	19.6	7.3
Piaggio MP3	20	Straight-line	3	42	40.7	3.8	0.97	0.12	3.1	0.3	15.3	3.4
		Lane change		34	38.8	3.2	0.96	0.13	3.6	0.3	17.2	3.9
		Straight-line	5	40	41.1	4.7	1.00	0.00	4.7	0.4	18.9	3.2
		Lane change		33	39.4	3.3	0.93	0.19	5.2	0.5	20.5	4.4

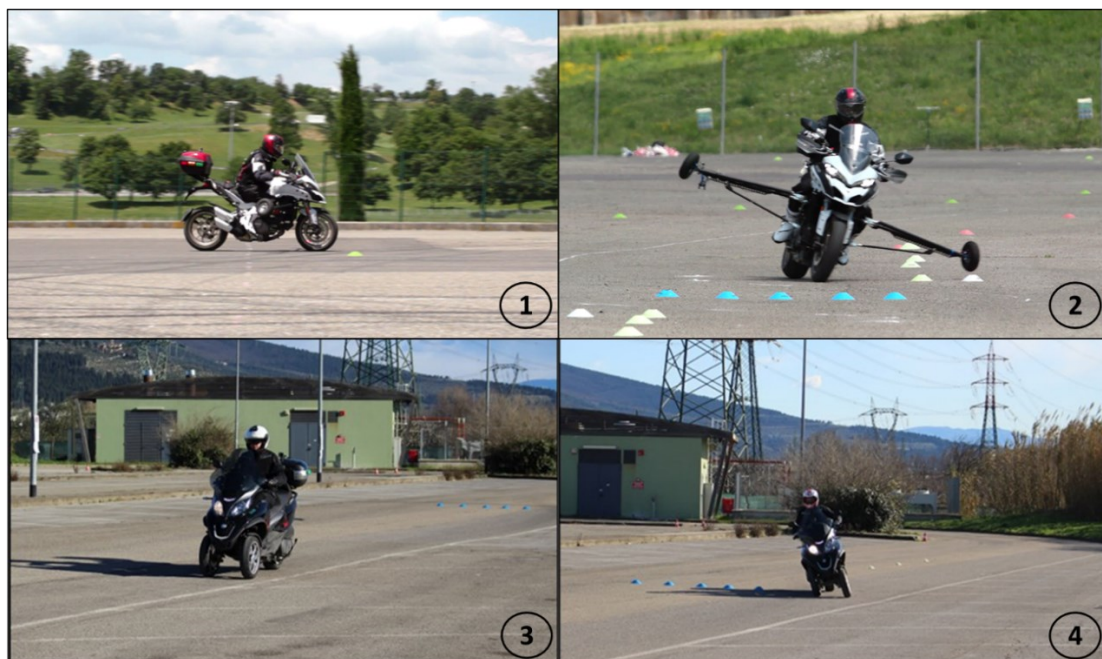


Figure 4 – AB activation in the two manoeuvres: 1) Multistrada in straight-line, 2) Multistrada in lane-change, 3) MP3 in straight-line, and 4) MP3 in lane-change.

### 3.1.3 PCB intervention during avoidance action

Being the feasibility of PCB intervention when the rider is performing lateral maneuvers one of the main open issues when assessing its safety and applicability, an in-depth analysis of PCB intervention during lane-change maneuver reproducing avoidance action was performed [19].

Vehicle dynamics in the lane change manoeuvre with and without automatic braking were compared (see Figure 5): minor effects were found on vehicle dynamics -except for those produced by the automatic braking- which never questioned the controllability of the vehicle. For both vehicles, participants were always able to manoeuvre the lane change by avoiding the virtual obstacle without executing other actions or braking. Due to the automatic deceleration and lower speed, minor differences in the vehicle lean were reported. No loss of control was reported by the participants in the questionnaire nor recorded by cameras.

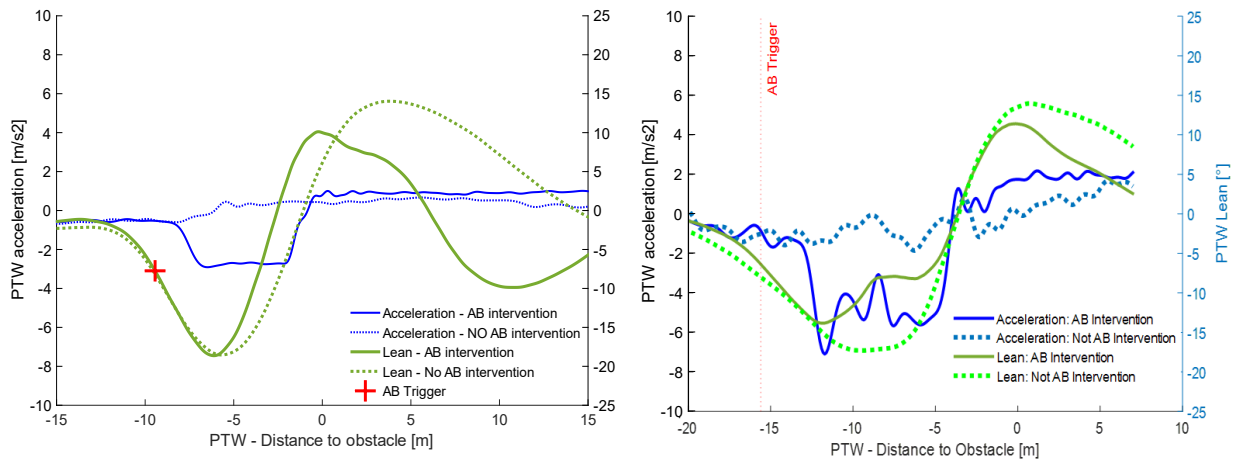


Figure 5 - Comparison of acceleration (blue) and vehicle lean (green) between a lane change with (solid) and without (dotted) AB. Left – 3 m/s<sup>2</sup> AB intervention on Multistrada; Right – 5 m/s<sup>2</sup> AB intervention on MP3

### 3.1.4 Users' acceptability of 5 m/s<sup>2</sup> PCB deceleration

At the end of the test, the participants assessed the Automatic Braking system based on the conditions they experimented. 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 or the participants' behaviour.

The perception of the intensity of AB intervention in terms of braking deceleration and fade-in jerk is displayed in Figure 6 for both test vehicles.

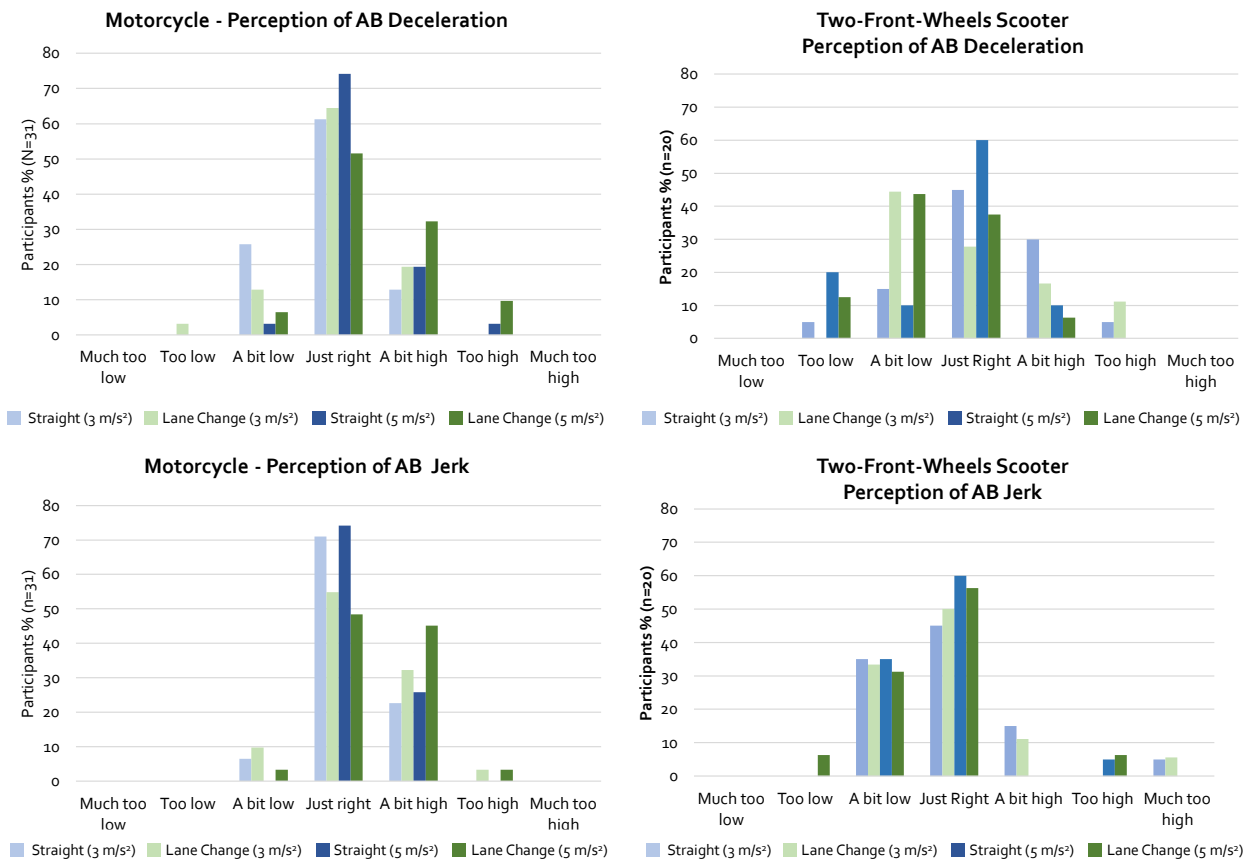


Figure 6 - Perception of AB intervention for Multistrada (left) and MP3 Scooter (right)

## 3.2 Crash simulation results

The results of the crash simulation activity will be presented in this section: first, the influence of different PCB working parameters on Impact speed Reduction will be presented, second, the effect of three different sets of PCB parameters (an optimistic, average, and pessimistic configuration) will be compared.

### 3.2.1 Influence of PCB parameters

A total of 60 crash cases (half from the InSafe database and half from the EDA database) were employed to assess the influence of PCB working parameters such as triggering timing, braking deceleration and the fade-in jerk. The same set of 60 cases was also used to simulate the effect of obstacle recognition parameters such as Field of View (FOV) and Range.

In order to assess the influence of each parameter, simulations were performed employing a standard set of parameters (Standard triggering, Deceleration = 5 m/s<sup>2</sup>, Fade-in jerk = 25 m/s<sup>3</sup>, Field of View = 40°, and Range = 30 m), and by varying only one parameter at a time.

#### Triggering

Setting all the other parameters to the standard value and varying only the triggering strategy, median reductions in impact speed of 5 km/h (conservative), 7.5 km/h (standard) and 12 km/h (progressive) were obtained (see Figure 7).

#### Deceleration

The PCB deceleration turn out to provide the highest influence on impact speed reduction: comparing ISR produced by 3, 5 and 7 m/s<sup>2</sup> PCB deceleration, the median speed reduction obtained by PCB intervention was, respectively, 2.5 km/h, 7.5 km/h and 9 km/h, using the standard setting for the other parameters (see Figure 8).

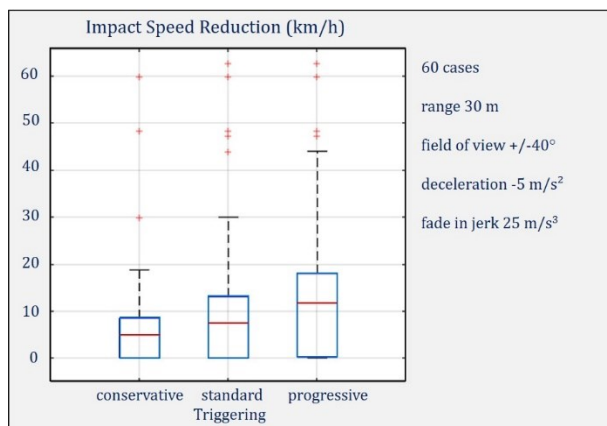


Figure 7 - Influence of the Triggering in PCB simulation

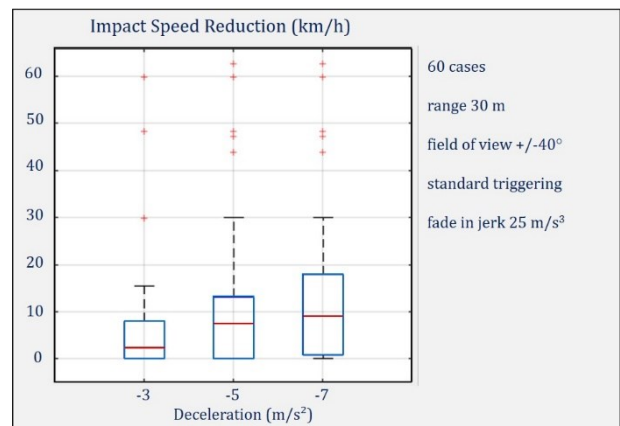


Figure 8 - Influence of the Deceleration in PCB simulation

#### Fade-in jerk

Regarding the fade-in jerk, its influence on ISR among the two levels tested in the simulations was found to be limited (about 1 km/h) among the 60 cases (Figure 9). A median impact speed reduction of 6 km/h was estimated for a Fade-in jerk of 15 m/s<sup>3</sup> using standard values for all the other parameters, while 7 km/h ISR was obtained for a Fade-in jerk of 25 m/s<sup>3</sup>.

#### Field of View

Figure 10 shows the influence of the Field of View employing the standard set of parameters. With a FOV of 10° (on either side of the longitudinal axis of the PTW, i.e., 20° of total aperture), the detection was zero in at least half the cases. At 25° FOV, the median impact speed reduction was 4 km/h, at 40° it was 7.5 km/h while beyond 40° the ISR gain was very limited.

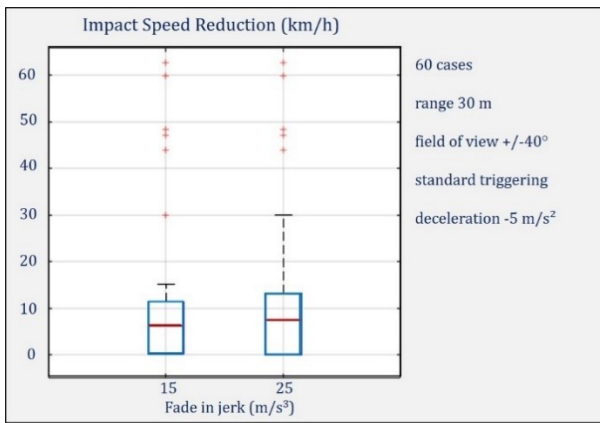


Figure 9 - Influence of the Fade-In Jerk in PCB

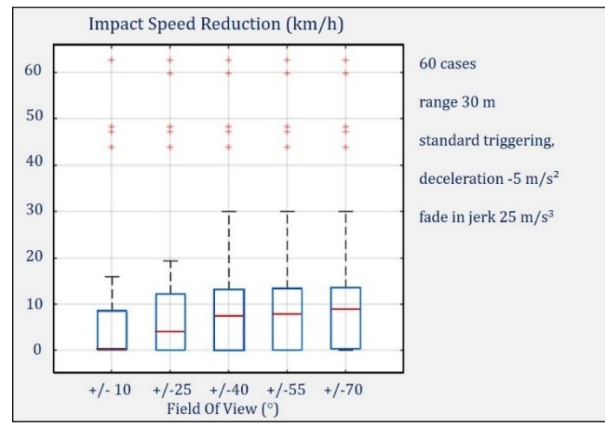


Figure 10 - Influence of the Field of View in PCB

**Range**

Due to limitations in the simulation tools, the influence of the Range on ISR was analyzed by employing only 40 cases simulated by Univ. Eiffel: 30 cases from EDA and 10 from InSafe. The influence of the Range was however very limited: using the standard set of parameters, only a small difference between a range of 30 m and a range of 45 m was found (ISR increase of 0.2 km/h), while beyond 45 no increase of ISR was measured. Also using a different set of parameters (defined as “optimistic” - see section 2.2.3), the difference between the Range of 30 m and 40 m was limited (an increase of the average ISR of 0.4 km/h).

**3.2.2 Realistic PCB configurations**

From the large number of parameters considered in this study for the analysis of PCB effects, three realistic combinations of parameters were selected to represent typical system effects assuming a pessimistic (low efficiency), average, and optimistic approach (high efficiency).

Considering all 60 simulated crashes in the three configurations, median reductions in impact speeds of 0.0 km/h, 7.4 km/h and 11.6 km/h were obtained (see Figure 11 - left). In 15 crash cases, the PCB was not triggered with any of the three configurations, or its intervention did not produce any effect (e.g., in cases in which the opposing vehicle was not detected in time, or the rider is manually braking with a higher deceleration than that produced by PCB). Excluding these cases, and therefore selecting crashes in which PCB is applied effectively, the median ISR was, respectively, 2.8 km/h, 10.7 km/h and 15.1 km/h for the three PCB parameter configurations (see Figure 11 - right). In 8 crash cases, at least one of the three configurations prevented the crash.

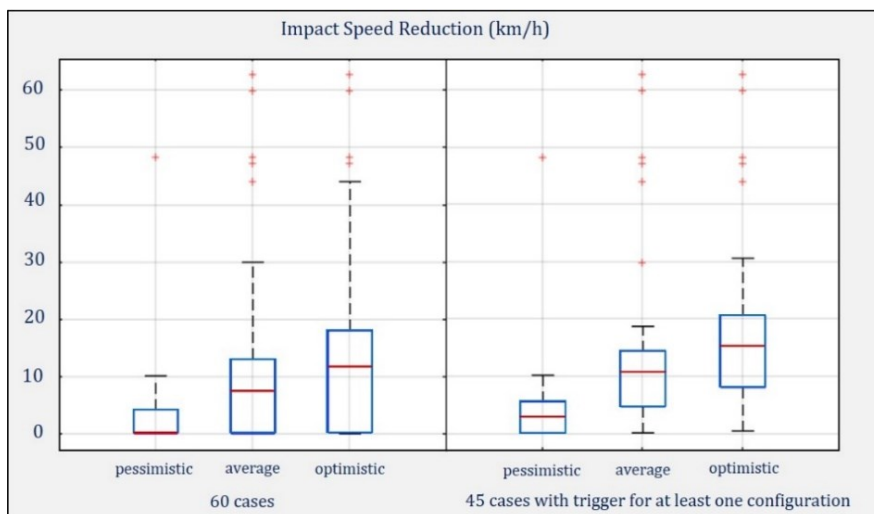


Figure 11 - Impact speed reductions for the three realistic PCB configurations considered (Left: all 60 cases – Right: 45 cases with PCB really triggered)

## 4 Discussion

The identification of suitable working parameters is the key to the future introduction of Pre-Crash Braking (PCB) on standard Powered-Two-Wheelers (PTWs). This study, results of the EC-founded PIONEERS project, merged two different approaches, field testing in the real world with common users as participants and crash simulations, to identify a set of appropriate parameters which can make PCB safe and effective in reducing injuries to PTW users.

The field tests campaign, which involved 51 participants and two different test vehicles, aimed to assess the feasibility and acceptability of PCB in the real world for a broad range of working conditions and parameters, which were never been tried before [22]. The sample size of participants employed for field testing was the widest so far in the field research concerning autonomous braking (PCB and MAEB). The system intervention was tested more than 1000 times on the two different types of vehicles with different parameters and manoeuvres. 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. The sample of participants was characterized by a wide range 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. They expressed generally a positive opinion about the system tested in both test vehicles, as the controllability of the PTWs was never at risk. Participants were always able to execute the avoidance manoeuvres, even with the highest level of PCB deceleration. The subjective assessment [21] and objective data analysis performed based on these tests [19]–[21], [23] indicated the applicability and feasibility of PCB with  $3 \text{ m/s}^2$  and  $5 \text{ m/s}^2$  of deceleration and up to  $20 \text{ m/s}^3$  of fade-in jerk, for interventions of up to 1 s duration.

The computer simulation approach was applied to sixty real-world crashes sourced from the InSafe and EDA databases, which were employed to estimate the effects of PCB and explore the influence of different sets of working parameters on its efficacy. Using two different simulation tools developed by the University of Florence and the University Gustave Eiffel, crashes were kinematically reconstructed and the PTW impact speed reduction provided by PCB was used as a reference for its efficacy, being strictly related to injury reduction [24]. A large number of parameters were considered in the analysis concerning the autonomous braking performance (deceleration, fade-in jerk, and triggering) and obstacle recognition tools performance (field of view and range). This allowed for a comprehensive assessment of the influence of each parameter on impact speed and the identification of three realistic combinations of PCB system settings. Deceleration and triggering were found to be the most important parameters to maximize the effects of PCB, while a Field of View of the obstacle detection system equal to or higher than  $45^\circ$  (so overall  $90^\circ$  of view) was found not to be beneficial to increase PCB capabilities to detect obstacles. The three realistic sets of parameters representing respectively, pessimistic, average and optimistic conditions for PCB parameters provided median impact speeds reductions of, respectively, 0 km/h, 7.4 km/h and 11.6 km/h. These values, which are affected by different riding conditions and manual braking actions of the rider, are in line with studies focusing on different traffic environments and are potentially capable to mitigate injuries and fatalities [25].

This study identified the influence of the key working parameters of Pre-Crash Braking, one of the most promising technologies to enhance the safety of PTW users, on its effectiveness in terms of braking action and obstacle recognition. These results can be employed by manufacturers and researchers to tune the braking intervention, design the detection system and develop the triggering algorithms and therefore further develop Autonomous Braking for PTWs, towards its introduction on standard vehicles. Also, the combined approach of field-testing computer simulation developed for this study can be a reference for future studies aiming at the development of new active safety systems for PTWs.

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