Analysis of the rider's body movement during the intervention of the Autonomous Emergency Braking system for Motorcycles (MAEB)

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Abstract. Among the rider assistance systems for powered-two-wheelers (PTWs) that are currently in the developing stage, autonomous emergency braking (identified by the acronym MAEB - Motorcycle Autonomous Emergency Braking) was shown to be promising to significantly improve the safety of such vehicles. This system, which is already available on passenger cars and trucks (known as AEB), reduces the vehicle speed in the event of a forthcoming collision. The lack of implementation of AEB on standard motorcycles is due to the characteristic capsize instability of PTWs and their complex dynamics, which is, strongly influenced by the motion of the rider. In a recent field-test campaign within the EU funded project “PIONEERS”, tests were conducted with common riders as participants to evaluate the intervention of MAEB in urban riding scenarios. A combined analysis of the data recorded from the vehicle, data related to the movement of the rider's body measured through an inertial measurement unit and videos recorded during the test, allowed characterizing the different behaviours of the rider's body in response to the activation of the automatic braking system in straight riding conditions. The results showed that body movement can be used as an indicator of the riders’ ability to control the vehicle under automatic braking conditions. In addition, in tests conducted with 0.5 g automatic decelerations, riders showed to be able to recover to natural riding position within the timeframe of the automatic braking activation event. This study defined an innovative method for evaluating the response of motorcyclists to the braking intervention and provides insights into the applicability of MAEB on standard vehicles.

1. Introduction
Powered-two-wheeler (PTW) users are globally increasing in recent years, due to the cost-effectiveness and flexibility in urban environments of this means of transport [1]. However, the increasing number of users is related to the increase of crashes and fatalities due to the lower stability of PTWs and high vulnerability suffered by PTW users [2]. In order to prevent and mitigate the negative outcome of crashes involving PTWs, researchers worked in recent years to introduce on PTWs some of the
Advanced Driver Assistance Systems (ADAS) already available on four-wheeled vehicles. Among the rider assistance systems derived from ADAS, the Motorcycle Autonomous Emergency Braking (MAEB), a technology which autonomously deploys a braking action in pre-crash condition to reduce PTW speed or even prevent crashes, has been indicated as one of the most promising technologies for improving PTW users’ safety [3]. In the past, some studies assessed the effectiveness of such a system [4] and its applicability in real-world conditions, mainly with expert riders [5,6] and straight-line riding conditions [7]. A further step in the development of MAEB was recently represented by a new field test campaign performed within the PIONEERS project [8]. In such experiment, extensive field testing involving two PTWs and common riders as participants was conducted to assess the applicability and the acceptability of Automatic Braking (AB) events reproducing unexpected MAEB interventions [9]. The first results of these field tests highlighted that safe MAEB interventions are feasible with decelerations up to 0.5 g [10] and in manoeuvres other than straight-line riding [11]. These important findings suggest that MAEB can be more effective in reducing speed before the crash and reducing injury risks for PTWs users then what was initially shown [12]. Even if the extensive field test campaign of PIONEERS provided evidence of the feasibility of safe MAEB interventions when adopting certain working parameters, concerns may still arise regarding the effect of MAEB intervention on the rider’s body, especially when the rider is not prepared for the intervention of the system.

During an unexpected automatic emergency braking event, the rider's body tends to move forward. Since unlike car occupants, the rider is not restrained by seat belts, such forward movement may lead to a loss of control. The understanding of the rider’s body response during MAEB intervention is, therefore, a key factor to assess MAEB safe applicability [13]. In addition, the body position and movement of the rider immediately before and during MAEB intervention could be used as indicators of rider capacity to handle MAEB intervention. Such indicators may be used to inform the system intervention regarding rider stability in real-time, in order to maximize the effect of the intervention while ensuring its safety. The objective of the present study is to characterize the body response of the rider during unexpected AB activations in straight-line riding conditions, to further validate the acceptability of MAEB among end-users and to enlarge its field of safe applicability in the future on standard powered-two-wheelers.

2. Methods
In this section, the test protocol employed to field test automatic braking (AB) interventions and the instrumentation used for the tests performed within the PIONEERS project [14] will be briefly described. Then, a summary of the data analysis performed to analyse the body movement in relation to the AB intervention will be presented.

2.1. Field test campaign
The participants for the AB tests were recruited among active riders having a minimum riding experience of two years or 10,000 km ridden and aged between 20 and 65 who volunteered for the tests based on an online survey. The test protocol for this study was approved by the Ethics Committee of the University of Florence (Written opinion N. 46, 20/03/2019). The test vehicle was a Ducati Multistrada 1260S, a sport-touring motorcycle equipped with Cornering ABS (Anti-lock Braking System), Combined braking and a four-stroke engine with a displacement of 1262 cm³. The motorcycle was also equipped with outriggers to prevent the motorcycle from lateral fall (Figure 1). The vehicle was provided with a remote-controlled AB system, set to decelerate the motorcycle at a nominal deceleration of 0.5 g for a duration of approximately 1s: this includes a fade-in time to reach the value of deceleration and a constant deceleration time.

During the tests, data from the CAN-bus of the motorcycle, data from external sensors, GPS position, and video from two Go-pro Hero4 cameras installed on the motorcycle were recorded. At the end of the test, subjective data including an adjusted controllability rating scale during the AB intervention was collected using questionnaires.
The test protocol, which was developed based on previous work [15,16], consisted of the following phases: a) a warm-up session to become familiar with the vehicle and the track; b) a familiarization with the AB system, consisting of deploying declared AB interventions in straight-line, c) two test sessions involving pseudo-unexpected AB activations during straight riding and manoeuvring using a nominal AB deceleration of 0.3 g and 0.5 g respectively, d) the completion of a final questionnaire. The AB intervention was deployed with a remote-controlled braking device which was activated by the investigator to produce unexpected automatic decelerations without intervention by the rider as the participants went through different spots of the test track. In the 0.5 g AB deceleration session, each participant tested the pseudo-unexpected AB intervention twice in the straight-line section, with an additional final AB intervention in a different spot of the track. The latter intervention was meant to get the rider less prepared than any other ordinary AB event; this was called “out of the blue” activation. The test protocol of this study was designed to test AB interventions with unprepared participants minimizing any learning effect in the participants. Further description of the test protocol and the field test campaign is available in previous papers [9,16].

3. Data analysis

The methodology used for the data analysis is presented in the scheme shown in Figure 2.
3.1. Data pre-processing

Every rider was equipped with an Inertial Measurement Unit (IMU) that measured accelerations and angles of the rider’s back on three axes. Data recorded by this sensor were used to describe the dynamics of the rider’s body during an AB activation. To give a complete description of the rider’s movements during AB events, videos acquired by a Go-Pro Hero4 camera installed on the outrigger at the right-hand side of the vehicle (to provide a side view of the rider's movements) were employed. The combined analysis of data recorded on the vehicle, data related to the rider's body movement and videos recorded during the test, allowed us to describe the different behaviours of the rider in response to the activation of the AB system in straight riding conditions. The analysis focused also on comparing the rider’s reactions in pseudo-unexpected AB activations with the “out of the blue” ones, which were assumed to be more difficult to control as completely unexpected [13].

The processing of data collected by the inertial platform unit (IMU) positioned on the back of the rider involved several steps (filtering, vector rotation, synchronisation). Data measured by accelerometer and gyroscopic sensors (accelerations, angular velocities, angles inclination) described the behaviour and the reactions of participants during AB interventions.

3.2. Video analysis and data validation

The first phase of the analysis was dedicated to the validation of the data. Using a specifically designed Matlab window displaying the data collected during the AB activation and the corresponding video recorded by the camera, videos and data were compared to have a qualitative validation of data and synchronization. This comparison also allowed us to a simple and intuitive analysis of the rider’s behaviour during AB activation from the video together with data in every timestep of the AB intervention. Further validation of the data was made employing the open-source software Kinovea, which was used to analyse the rider’s movements from the video. This allowed us to evaluate the accuracy of the data by comparing the participant's movements captured by the camera with the data acquired by the sensors. We chose the variation of the rider’s body pitch angle during the AB event as a measure of comparison between the measured data and the videos (see Figure 3). At the time of the AB trigger, the magnitude of the inclination of the rider was positioned to a reference value of 0° and then, for the duration of the automatic braking, the movement of the rider in terms of the angle of inclination of the body (pitch) was compared between videos and data.

![Figure 3. Example of video-validation process.](image-url)
The analysis of the videos also offered the possibility to make a first analysis of the AB effects on the rider. In this phase, the analysis was focused not only on the movements related to the rider’s torso, but also on the dynamics of the entire body of the rider during AB events. This allowed detecting patterns of behaviour during AB that were not detectable by the available sensors. Although there were no sensors to detect the movement of the head, the force exerted on the foot pegs or on the handlebars, this analysis allowed us to identify how riders reacted differently to the deceleration caused by AB. The analysis was carried out on 32 videos, each of which was rated from 1 to 3 by three experts (two of them made a first evaluation, while a third one independently assessed the evaluation agreement) depending on the rider’s perceived effort in managing the AB intervention. The videos were also viewed at slower playback speeds to focus more on details. To make these evaluations several elements were considered: the change in torso pitch angle during activation, head movement, stress on legs or arms, shoulder movements and any movement on the saddle. Scores were given related to the increasing difficulty level as reported in Table 1.

Table 1. Levels of disturbance of the rider due to AB determined by the video analysis.

| Levels  | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| Level 1 | The AB activation does not generate any destabilisation and the rider's reactions to deceleration were insignificant; the rider remains almost unmoved |
| Level 3 | The AB activation is notably destabilising the rider body movements are evident and involve, high body’s pitch angles, pelvis rising from the saddle, strain on arms and legs (detectable from video) |
| Level 2 | The AB activation has an influence on the rider that is in between the situations described in Level 1 and Level 3 |

3.3. Data analysis
After the video analysis and data validation, the final phase of the body movement analysis and characterization during AB intervention was performed based on all the data recorded from the vehicle and the IMU positioned on the rider’s back. The relevant signals were plotted and compared to perform a quantitative body movements analysis.

4. Results

4.1. Video analysis
In Table 2, the results of the qualitative analysis performed by three experts through videos collected during the tests are reported.

Table 2. Results of the video analysis.

| All AB activations | Pseudo-unexpected AB | Out of the blue AB |
|--------------------|----------------------|--------------------|
| n. %                | n. %                 | n. %               |
| Level 1            |                      |                    |
| 16 50.0            | 11 50.0              | 5 50.0             |
| Level 2            |                      |                    |
| 13 40.6            | 9 40.9               | 4 40.0             |
| Level 3            |                      |                    |
| 3 9.4             | 2 9.1               | 1 10.0             |
A first important result is that in any video major events of destabilization or imminent danger were found. Even in the three cases classified with the maximum level of disturbance, the rider was always able to control the PTW with ease, but body movements were more relevant compared with what was visible in the rest of the cases examined (see as example Figure 3). In 50% of the 32 AB activations evaluated, the rider did not show any unconventional movement and remained almost unperturbed during the AB intervention. Such events were classified with the lowest score of 1.

![Figure 4. Example of level 3 AB reaction.](image)

Separating the “pseudo-unexpected” AB activations from the “Out of the blue” cases (Table 2), the results are still in line with the overall distribution. Among the 22 pseudo-unexpected activations, 50% were classified with the lowest score (level 1), while only two cases were classified with the highest one (level 3). On the other hand, in the cases with the “Out of the blue” AB, the frequency of the level 3 score was slightly higher, even though the low number of activations available (10) has an influence on the variation.

4.2. Data analysis

4.2.1. Test participants. The test campaign involved 31 volunteer participants, non-professionals riders, characterized by different age, body size and riding experience (for further information regarding the sample of participants see [14]). Due to problems in data acquisition, only data from 12 out of 31 participants were considered for the analysis of the body movement in order to guarantee the best reliability. The following analysis is therefore based on data from 36 automatic braking activations in straight line riding conditions (three interventions per participant for a total of 24 pseudo-unexpected AB and 12 “out of the blue” AB).

4.2.2. Automatic Braking (AB) intervention. The Automatic Braking (AB) produced a longitudinal deceleration of the vehicle by acting on the throttle inhibition and the combined braking system. Figure 4 shows a typical deceleration profile (red curve): the trigger signal is followed by an increasing deceleration ramp and then, once a target value (approx. 0.5 g) is reached, there is a constant deceleration phase. The end of the intervention is characterised by an exit ramp, and it returns to the conditions prior to the trigger. The average duration of the event was 1.19s and the AB deceleration produced a mean speed reduction of 15.6 km/h. The longitudinal fade-in jerk of the vehicle during the AB activation phases reached peaks around 20 m/s² (see Table 3).
Table 3. AB intervention characterization.

|                          | Mean | SD  |
|--------------------------|------|-----|
| AB deceleration [m/s²]   | 4.50 | 0.42|
| Fade-in jerk [m/s³]      | 15.98| 2.61|
| AB duration [s]          | 1.19 | 0.02|
| Initial speed [km/h]     | 49.1 | 5.1 |
| AB Speed reduction [km/h]| 15.7 | 2.2 |

Figure 5. Example of an AB intervention: vehicle deceleration and speed reduction.

4.3. Body movement

The data analysis performed on the 36 AB interventions highlighted two types of typical behaviour of the rider's body during the AB events. Both these types were characterized by a similar initial phase while they differ in the second part of the AB intervention.

4.3.1. Convergent behaviour. As showed in Figure 5, the so-called “convergent behaviour” is characterized by a first phase in which the rider and the PTW decelerate with the same deceleration (red/blue curve). After the automatic braking has been activated and the deceleration of the AB increases with a constant fade-in jerk, there is no relative motion between the body of the rider and the vehicle. This phase starts at the AB trigger and ends when the target AB deceleration is reached. In the second phase, the deceleration of the body and the vehicle diverge: the deceleration of the rider's body continues to increase and registers a maximum peak, almost double the deceleration of the vehicle at the same time. This phenomenon is caused by a relative motion of the rider with respect to the vehicle, observable as an increase in the pitch angle of the torso, as a translation of the rider on the saddle or as a combination of these two movements. The rider at this stage does not assume his/her typical natural riding position.
and this phase represents the most critical (less stable) time during AB intervention for the vehicle control. In the final phase of the AB intervention, the rider regains his/her natural riding position (while the AB system is still active) and the body deceleration returns to follow the vehicle deceleration. With this type of behaviour, the final part of AB intervention is characterized by a stable condition, with the body of the rider moving with magnitude and trends of deceleration similar to those of the vehicle: this behaviour is therefore called "convergent".

**Figure 6.** Example of convergent behaviour in response to AB intervention.

4.3.2. *Non convergent behaviour.* The second type of behaviour detected by the analysis does not present the last phase within the AB event duration (Figure 6): after an initial deceleration peak, other peaks of the same intensity are reached by the body of the rider. The trend of the variation of the pitch angle of the body shows greater peaks than in the “convergent” behaviour and the body remains bent forward for the entire duration of the AB activation. The decelerations of the body and the vehicle reach similar values at the end of the AB activation. The rider never returns to a natural riding position within the duration of the AB intervention, but only when it is concluded. In this case, the two decelerations do not converge within the AB activation time frame, and therefore this type of behaviour was called "non convergent".

4.3.3. *Incidence of behaviours.* Among the 36 AB activations analysed, 16 (44.4%) recorded a non convergent behaviour: 10 pseudo-unexpected activations (41.7%) and 6 “out of the blue” ones (50%). The other AB interventions were characterized by a “convergent” behaviour of the rider’s body.
4.3.4. Timing of body movement. The first phase of the response to AB intervention in common to both behaviours, resulted in an average duration of 0.32 seconds: 0.29 seconds in the case of convergent behaviour and 0.36 seconds in the case of non convergent behaviour (Figure 7). If we consider only the activations that have shown a "convergent" behaviour, the least stable phase of the rider (phase 2) had an average value of 0.43 seconds: considering that the entire activation event has an average duration of 1.19 seconds, for about 36% of the activation the rider performed an oscillatory or translational motion with respect to the motorcycle. These times were slightly higher in “out of the blue” braking, with an average duration of 0.46 seconds, compared to the pseudo-unexpected ones with an average of 0.41 seconds.

4.4. Vehicle controllability

Further analysis was carried out by analysing parameters that characterize the lateral dynamics of the vehicle, such as roll angle and lateral acceleration (of both the body and the vehicle). Abnormalities of these parameters in straight riding conditions may have been indicative of instability and incipient loss of control. However, no peculiar deviation in such parameters was detected in any of the 36 activations analysed. This was also confirmed by the results emerging from the subjective questionnaires completed by the participants at the end of the session [10]: 100% of the participants included in the study rated the AB intervention with a controllability rating score lower than three, indicating good vehicle behaviour and easiness of control (for details regarding the controllability rating scale see [16]), with a limited compensation required by the rider to execute the desired trajectory during the automatic braking.

Figure 7. Example of non convergent behaviour in response to AB intervention.
5. Discussion

In this paper, further results of a field test campaign carried out within the PIONEERS project [14] were presented. This analysis focused on the rider body movement during the intervention of an Automatic Braking event representing an unexpected intervention of a Motorcycle Autonomous Emergency Braking (MAEB) system in straight-line riding conditions. A new approach was developed to analyse the movement of the body of the rider during the activation of the AB system, based on videos and data recorded during field testing. First, in-depth video analysis of the AB intervention recorded from lateral position made by three experts defined a qualitative classification of the AB intervention based on the effort of riders to cope with the vehicle during the AB intervention. Even if the results coming from this type of analysis are inevitably influenced by the subjective opinion of the experts, they allow an identification of the most relevant cases to be further investigated. At the end of the analysis, no potential loss of control events during the AB intervention were identified. After the video analysis, a quantitative analysis of data collected by vehicle sensors and an IMU positioned on the back of the rider was performed. This analysis allowed characterizing the body movement of the rider during the AB intervention: two types of behaviours defined by different timing required to regain the natural riding position of the body after the AB intervention were identified. These results confirmed the importance of measuring the motion of the rider’s torso to define rider state during AB, as highlighted in previous work [17]. Overall, our results were compatible with the limited prior research on this topic [18].

This study has also some limitations. First, due to some recording issues, not all the participants involved in the field test campaign were considered for the analysis. Those included in the study were however a heterogeneous subsample (about 30%) of the whole group, the selection of which was basically random. Also, in previous analyses, such sub-sample did not show any specific bias and analysis performed in other studies did not indicate any different behaviour between our subsample and the overall sample in terms of incipient loss of control [9,10]. A further limitation is represented by the challenge to collect reliable data regarding body movement with simple instrumentation. Several data processing and filtering were required to perform this analysis, for which video recordings collected during the tests were used as a reference in order to double-check the phenomena observed in the data analysis.

Despite these limitations, the analysis highlighted that in most of the cases riders were able to return to a natural riding position during the AB activation event, and also in those cases considered less stable (non convergent behaviour), where participants had more difficulty regaining a natural riding position,
any incipient loss of vehicle control was noted as shown in previous studies [9,10]. More critical conditions, such as those occurring in the unexpected activation, did not particularly affect the behaviour of the riders.

6. Conclusions
This paper presented an integrated methodology to characterize the movement of the body of riders in relation to the activation of an active safety system for PTWs such as MAEB, based on videos and quantitative data recorded during field testing. This methodology highlighted a good potential to characterize the response of the rider in case of the intervention of an automatic braking system, identifying different types of behaviours whereby in the specific case the rider reacts to unexpected braking actions. The results of the analysis highlighted two types of behaviour in response to the AB intervention, characterized by different timing required to regain the natural riding position of the body after the intervention. Even if these two behaviours were associated with different levels of disturbance of the rider due to AB intervention, no potential loss of control was detected. The results of this work confirmed, through rider’s body movement analysis, that MAEB is likely to be safely applied in real riding conditions, as emerged in previous studies.

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