Analysis of the intervention of an anti-fall device in Motorcycle Autonomous Emergency Braking (MAEB) experimental tests

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Abstract. Motorcycle Autonomous Emergency Braking (MAEB) is a rider assistance that may soon play a role for the improved safety for Powered-Two-Wheeler users. Several studies were carried out to investigate the feasibility of automatic braking (AB) events. In a recent experiment, tests were conducted with volunteer participants to assess AB intervention under different riding conditions. The prototype vehicles were equipped with an anti-fall device (outriggers), the main object of this study, to ensure participants’ safety. The outriggers limit the roll angle of the motorcycle, thus preventing accidental capsize. Data from the sensors installed on the side arms were analyzed to identify ground contact events, for which a correlation with the driving style adopted by the participants has emerged. There was one case in which MAEB activation was followed by outriggers intervention. However, detailed analysis indicated that this could not be assimilated to an incipient fall. Our results show that the simple sensor setup was able to gather useful information for the experimental tests.

1. Introduction
In recent years, road safety has been an important topic for many researchers from different fields, with the final goal of reducing the burden of deaths and serious injuries that every year occur due to road crashes all over the world [1]. Thanks to the research in the field of advanced technology, all road users have benefited from the introduction of various advanced driving assistance systems.

However, among the different categories, powered two-wheeler (PTW) users had the lowest reduction of fatalities. This happened also due to the continuous increase of users, as this type of vehicle is popular for its agility in city traffic and its cost-effectiveness. In contrast, the use of motorcycles and scooters was shown to have higher risks that that of four-wheeled vehicles. In addition, powered two-wheelers have less advanced riding aids currently available in the market.

Recent studies showed that one promising riding assistance system among those under development is Autonomous Emergency Braking (AEB). This technology, already spread in cars [2], is still in an experimental phase for PTWs, where it is known as Motorcycle Autonomous Emergency Braking (MAEB) [3]. In fact, two-wheeled vehicle dynamics is strongly connected to the rider’s behaviour and an unexpected braking events may lead to a loss of control. In the past years, a few studies investigated the feasibility of MAEB trough field testing, to assess the rider stability under Automatic Braking (AB).
These studies involving both professional and common riders and tested different PTW prototypes in various riding conditions [4–6]. The results of these studies suggested that the system could be applicable in the future on standard vehicles. However, further investigations are still required to assess in which riding conditions and with which working parameters MAEB is safely applicable.

In the context of a new experimental campaign regarding AB to assess the acceptability among end-users of MAEB with common riders as participants, a PTW was provided with outriggers to prevent the vehicle from lateral fall and therefore ensure participants’ safety. In particular, in the situation of a loss of control, a contact between the extremity of one of the lateral arms and the ground could be an important marker of an incipient fall caused by the AB system. However, a brief or even prolonged contact of the arms with the ground may also happen without any control loss by the rider, thus being linked with the riding style of the participants.

The main goal of this study was to assess whether the intervention of anti-fall outriggers mounted on an experimental PTW can be a robust marker for detecting the incipient loss of control during MAEB tests. Secondly, the contact events of the lateral arms were also assessed as a possible parameter characterising the different riding styles of the participants.

2. Methods
This section presents the test protocol, the instrumentation and the details of the riding manoeuvres involved in the AB tests. Further details are available in a previous work [7]. Then, a brief overview of the data analysis carried out to analyse the intervention of the outriggers will be presented.

This study was approved by the Ethics Committee of the University of Florence (Written opinion N. 46, 20/03/2019). The participants recruited for this study were selected among active riders characterized by a minimum of two years or 10,000 km of riding experience and age between 20 and 65 years. The participants were recruited through an online survey containing questions about demographic data and riding habits.

2.1. Test protocol
The test activity was carried out in an area closed to traffic. The circuit was designed to contain four manoeuvres, namely straight riding, curve, lane change and slalom manoeuvres, to be travelled in both directions (see Figure 1). Testing the AB in this configuration represents a step forward compared to previous tests, which focused on straight-line riding.

![Figure 1. Test circuit and manoeuvres](image_url)

The test procedure included three test sessions. In the first one, the participant familiarized with the motorcycle by riding along the circuit and following given instructions. A typical time of 15 minutes was given to the participants to familiarize with the test vehicle and the track. This warmup phase had a flexible duration to allow all the participants to obtain adequate confidence with all the manoeuvres.
the following test sessions, the participants were asked to ride freely along the test track and experienced automatic braking (AB) deceleration events performed via remote control by an operator. This study focused on the first of the two session, being the one that included AB events with cornering vehicle. The session included 10 laps in each direction. The nominal deceleration of the AB events was 0.3 g and the nominal duration of the intervention was 1 s.

To ensure participants safety, the motorcycle was equipped with outriggers configured to allow a maximum roll angle of 25 degrees. The manoeuvres included in the track and the corresponding speed limits were designed to complete the track without the need to exceed the roll limit, meaning that a contact between lateral arms and the ground was avoidable in ideal riding conditions. Participants were told that a brief contact of the outriggers with the ground (contact event) during the test ride has to be considered an indication that either the speed or the trajectory were deviating from the prescribed values. At the end of the test sessions, questions about the test execution and the intervention of AB were asked to the participants in the final questionnaire.

2.2. Curve manoeuvre
The main curve included in the test track was designed to be travelled at a speed of around 35 km/h and a roll angle not exceeding 25 degrees. Under the assumption of steady state cornering, the curve had a nominal constant radius of 15 m. The curve shape allowed the participants to negotiate it without any contact between lateral arms and ground. However, this occurred when speed and trajectories were close to the design values. A deviation from the prescribed riding parameters caused the intervention of the outriggers. For example, if a participant rode too fast while approaching the curve, the PTW would have required a roll angle higher than 25 degrees to complete the steady state manoeuvre. This would lead to the intervention of the outriggers and the resulting contact between the wheel of the lateral arm and the ground. The contact event occurs in two main different ways: a brief contact and a prolonged contact. This means that the wheel at the end of the outrigger can touch the ground one or more times. Under particular conditions, a rider could also lean on the lateral arm for the whole curved trajectory (see Figure 2). However, a contact between the lateral arms and ground can also be caused by a loss of vehicle control leading to an incipient “low-side” fall event of the PTW. Indeed, this condition is the critical situation that required the application of the outriggers in the tests, since the lateral arms are designed to prevent from a low side of the vehicle and the associated rider fall event. In this case, a sharp rebound on the wheel positioned at the extremity of the lateral arm results in a brief contact event, whereas a complete fall on the arm results in the extended contact.

![Figure 2. Curve manoeuvre with the lateral arm in contact with the ground](image)

2.3. Instrumentation
The motorcycle used in our tests was a Ducati Multistrada 1260S MY 2018 equipped by a remotely operable autonomous braking device (see Figure 3) based on a prototype presented in a previous work [8]. This sport-touring motorcycle vehicle has also electronic controlled suspensions, combined braking
and a four-stroke engine with a displacement of 1262 cm³. The PTW was provided with informative lights on the rear top case and on both sides of the vehicle to show the AB status to the investigators. Two GoPro cameras installed onboard recorded the video of the tests. The top case also contained the instrumentation used to control the autonomous braking system and the data acquisition system that recorded signals from the PTW CAN-Bus (including throttle, brake action, steering angle, vehicle tri-axis acceleration & gyro). Other recorded data were GPS position and steering angle. A display was positioned above the stock dashboard for quick diagnostics.

Figure 3. Fully equipped motorcycle

2.3.1. Outriggers
The test motorcycle was provided with outriggers, visible in Figure 3. This anti-fall device is constituted by two lateral arms mounted on custom metal plates, fixed on vehicle frame. Each arm has a small idle wheel with a diameter of 250 mm at its end, which allows a smooth contact with the ground. The reliability of the outrigger design was extensively tested by the outsourcer in many years of rider training activities.

Figure 4. Lateral arm of the anti-fall device

Figure 4 offers a view of the left-hand lateral arm. Considering a lateral arm and its plate, the mass is 25 kg for each side. The inertial properties were calculated with a multi body simulation (Table 1).

Table 1. Inertial properties of the outrigger (including both lateral arms and plates)

| Parameter | Value   |
|-----------|---------|
| I_xtot    | 5.32 kgm² |
| I_ytot    | 3.43 kgm² |
| I_ztot    | 9.3 kgm²  |
2.3.2. Hall sensor placed on lateral arms
An Arduino’s KY-024 additional module was placed on each lateral arm, housed in a specific 3D printed case. The module was provided with a linear magnetic Hall effect sensor, powered on a voltage of 5V, which reacts in the presence of a magnetic field. It provides both analogue and digital outputs and has a potentiometer to adjust its sensitivity. In this application, the digital output was used, working as a switch that turns on/off when a magnet is close to the sensor. A small magnet was placed on the wheel disc in order to obtain one signal rise per revolution of the wheel. With this set-up, the wheel spin frequency was used to estimate the wheel speed, which provided information regarding the contact events between the outriggers and the ground.

2.4. Data analysis
The analysis of the data collected during these tests was carried out using Matlab software. The Hall sensor outputted a tension value other than zero only when the magnet placed on the wheel passed close to it, meaning that the signal is constant when the wheel does not spin. This constant value was either 0 V or 5 V, depending on the location of the magnet. When the wheel started spinning the signal switched between the two values with a frequency proportional to rotational speed. Calculations were made following the scheme shown in Figure 5. We assumed a steady turning with the small wheel laying on the ground and a peripheral constant speed of 30 km/h, which was the average travelling speed of the participants along that curve.

![Figure 5. Curve manoeuvre calculation scheme](image)

Geometric distances l and r were measured directly on the bike and d is the diameter of idle wheels at the end of the arms. The value of curve radius R was estimated considering a steady turning manoeuvre with a speed of 30 km/h and a roll angle α of 25 degrees, equal to the setting value when the motorcycle is supported by the lateral arm. The geometric parameters used for calculations are listed in Table 2.

| Parameter | Value |
|-----------|-------|
| R         | 15 m  |
| r         | 1.38 m|
| l         | 1.25 m|
| α         | 25 deg|
| d         | 0.25 m|
Using these parameters and assuming pure rolling between the small wheel and the ground, the calculated turning frequency resulted as 9.2 revolutions per second. This means that the magnet passed next to the sensor approximately nine times per second, resulting in as many peaks in the sensor signal output.

A Matlab script was developed to automatically find events of contact between the lateral arm and the ground from sensor data. It analyzed the signal and searched for sets of close-up peaks. As can be seen in Figure 6, the signal amplitude never reached the nominal value of 5 V because saturation time was consistently larger than the passing time of the magnet on the sensor. The amplitude was also inversely proportional to speed and considering the test parameters, a local maximum was considered as a peak only if its amplitude was higher than 0.25 V. Lower values were attributed to signal noise. A group of more than 5 close peaks was assumed to be an intervention of lateral arms (contact event).

In order to validate this method, a pilot test session was carried out, executing repeated touches of the left-hand-side arm wheel with the ground in a parking lot (see Figure 6).

![Figure 6. Plot from the sensor validation test](image)

In Figure 6, the first peak identifies the beginning of contact between idle wheel at the end of the lateral arm and ground. At that time, the vehicle speed is about 25 km/h and idle wheel speed is 18 km/h. After that, the motorcycle accelerates, while the idle wheel decreases its velocity. This means that there is no more contact with the ground and the wheel is therefore decelerating. This method was also validated analysing the video recorded during the tests, which confirmed the brief contact in this time window. After this validation, this method was used to automatically search events in experiment data.

3. Results

3.1. Test participants

This study involved 14 common riders as volunteer participants (13 male and 1 female), selected among a sample of around 50 possible participants through an initial questionnaire. Age varied from 22 to 59 years, with an average value of 38.5 years. Three participants declared to use a scooter as their main powered-two-wheeler vehicle, while the remaining eleven used different types of motorcycle. One participant had already experienced a motorcycle equipped with outriggers. All the participants filled in a final questionnaire, in which they answered questions regarding the test. Nine out of 14 participants found it easy to get familiar with the outriggers, while four of them considered it not too difficult nor too easy. One person found it difficult to get familiar with the anti-fall system. All participants declared to be willing to repeat the same test protocol without the presence of this safety device.
3.2. Riding style
We analysed the data of 600 laps of the test track travelled in both directions in the first two test sessions, namely the warm-up and the first AB test session. Overall, 1048 contact events between the lateral arm and the ground were detected, ranging from a minimum of 15 (participant 01) to a maximum of 142 (participant 13). A video check was carried out considering two test sessions to confirm the number of events detected automatically by the algorithm. The discrepancy was 6.7%, deemed acceptable. No relationship was found between average riding speed and number of contact events.

Observing the self-declared riding styles, it was found that the number of events was higher for people who declared an aggressive riding style. In contrast, among the participants who declared a cautious riding style the number of contact events was smaller. The results are depicted in Figure 7.

![Figure 7](image_url). Correlation between contact events and riding aggressiveness

Concerning the analysis of the warm-up phase, we found that initially, the frequency of interventions of the outriggers increased with the number of laps. Then, in the last part of the warm-up session the frequency of intervention tended to stabilize and the value was similar to that observed in the following session.

3.3. Curve manoeuvre
This analysis focused on the first test session after the warm-up phase, and in particular on the interventions of AB system during the curve manoeuvre. Due to a technical problem, the data from one participant were incomplete and therefore excluded from this analysis.

In a total of 260 laps, the algorithm found 114 contact events. In average, a contact event took place in 43.8% of laps. In these laps the AB was deployed 44 times during the curve, in correspondence of which 19 contact events were identified. The incidence of the contacts between the lateral arm and the ground in correspondence of the AB was 43.2%, a value close to the one observed in the laps without AB intervention.

3.4. Intervention of outriggers in correspondence of AB
Among the 19 events in which the intervention of the outriggers was close in time with the AB event, in 16 cases the contact of idle wheel occurred before the deployment of the AB. An example is showed in Figure 8.
Figure 8. Contact between the lateral arm and the ground before AB intervention

The beginning of contact between idle wheel and ground was indicated by the first peak in the sensor output. In the example of Figure 8, the rider was travelling counter-clock wise and therefore the contact took place on the left-hand side. The Autonomous Braking intervention started when PCB Status signal switches from 1 to 2. As can be seen in Figure 8, the wheel is already touching the ground when the AB system is activated. In all the 16 cases, the motorcycle roll angle decreased after the braking event, meaning that the vehicle straightened and thus did not fall onto the lateral arm.

In the remaining 3 events, the contact event happened after the AB intervention, but only in one of these cases the AB deployment and the contact with the ground were close enough to suggest a correlation (see Figure 9).

Figure 9. Contact event after AB intervention

In this case the autonomous deceleration led to a rise of the roll angle, until the right arm touched on the ground. This happened with a roll angle slightly above 20 degrees, which was lower than the limit of 25 degrees allowed by the outriggers. This event was caused by a small slope of the road, which brought the ground closer in the right-hand side turns. Regardless of the numeric value, the important difference from the previous cases is that the roll angle increased instead of decreasing as a result of the AB. However, the analysis of other vehicle parameters such as steer angle did not provide any
additional information. An accurate analysis of the on-board videos recorded during the test (see Figure 10) supported the hypothesis that this event was not an incipient fall caused by AB.

![Video sequence of the possible incipient fall](image)

**Figure 10.** Video sequence of the possible incipient fall

4. Discussion
The goal of this study was to investigate whether the intervention of lateral anti-fall devices mounted on a prototyping vehicle could be a marker of incipient falls. Two simple Hall-effect sensors were placed on both lateral arms (one each side) and their output was interpreted to identify the interventions of the anti-fall device.

The number of contact events between the outriggers and the ground turned out to be linked to the riding style of the participants. Aggressive riders generally faced manoeuvres with higher roll angles, reaching the limit imposed by the outriggers more often compared to cautious riders. The correlation between the riding style and number of contact events was not strong though, and further analysis is required to assess other possible influencing factors.

However, the frequency of the contact events was found to be a candidate parameter to determine the confidence level reached by the participants during the warm-up phase. In fact, contacts per km ratio stabilized at the end of warm-up session and kept constant through the following sessions.

Since the highest number of events happened in the curve manoeuvre, the analysis of this study focused on it. Autonomous braking activations in curve were 44 and it was found that in 19 cases the intervention of the anti-fall device occurred close to AB intervention. The incidence of the contact events was almost the same for the free laps and for the laps where autonomous decelerations occurred. In 16 of these cases, the idle wheel was already in contact with the ground when AB activated. Further analysis showed that the roll angle always decreased after AB (straightening motorcycle), and thus not making it fall on the lateral arm. This result was in line with the theory, as the deceleration lowered vehicle speed and therefore it needed a smaller roll angle to negotiate the curve. However, the support provided by the lateral arm could have influenced motorcycle response and output from this simple sensor is not enough to completely understand the phenomenon.

In the three events in which the contact between the idle wheel and ground initiated after the activation of the AB, only in one case the two events were close enough to be possibly linked. The Autonomous Braking happened just before the idle wheel touched the ground. An in-depth video analysis showed though that the idle wheel was very close to the ground at the time of braking and a very small increase in roll angle caused a brief and smooth intervention of lateral arm.

The presence of the outriggers in some of the observed cases represented a potential confounder to determine the amplitude of destabilization induced by the autonomous braking, but the video analysis revealed that the rider would have been able to regain the vehicle control with a slightly larger roll angle. This is also supported by participant’s feedback via the questionnaire filled out at the end of test sessions. In fact, autonomous braking interventions in curve were considered “a little rough”, but the participant did not indicate that the specific event produced a loss of control.
5. Conclusions

The simple Hall-effect sensor put on the outrigger lateral arms allowed the researchers to obtain important information about the test. Riding styles were connected to the number of interventions of the anti-fall system and this information can be useful to assess the level of familiarization achieved by the rider with both the vehicle and the circuit. One critical situation was identified from the analysis of sensor output, but the measurements were not exhaustive to determine with certainty whether or not it was an incipient fall. To obtain a better understanding of critical cases found in this kind of analysis, a sensor capable of measuring the force with which the lateral arm supported the motorcycle may be used to identify possible rebounds on the small wheel of the outrigger. In fact, a lateral fall would cause a large reaction force compared to a slight contact caused by the reaching of limit roll angle by the rider while riding.

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