AUTONOMOUS EMERGENCY BRAKING FOR CORNERING MOTORCYCLE

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ABSTRACT

Research question
Autonomous emergency braking (AEB) has been indicated as a potential safety application not just for passenger cars and heavy goods vehicles, but also for motorcycles and powered two-wheelers (PTWs) at large. Motorcycle AEB (MAEB) was designed to produce autonomous deceleration of a host PTW in case of inevitable collision. Previous studies limited MAEB to the case of a PTW travelling along a straight, as the activation of AEB was considered hazardous for a leaning vehicle. This study aims to extend the applicability of MAEB to cornering scenarios.

Methods
A virtual PTW in a simulated environment was equipped with MAEB and Active Braking Control (ABC). MAEB consisted of a virtual obstacle detection device, triggering algorithms that identify inevitable collision states, and an automatic braking device. When an inevitable collision is detected for the host PTW and at the same time the rider is applying some braking force, MAEB deploys enhanced braking, which assists the rider reaching the maximum feasible deceleration. ABC consisted of control algorithms for the automatic braking device that stabilise the vehicle along the curved path. The complete system named MAEB+ was tested using detailed computer simulation reproducing real world crashes.

Data sources
The crash cases used for the simulations were selected from the in-depth crash dataset “InSAFE”, which collects severe road crashes in the metropolitan area of Florence. The selection criteria were the following: a) the PTW crashed into another vehicle; b) the PTW was travelling along a curved path with roll angle above 15 deg; c) the rider applied some braking force prior to impact; d) PTW loss of control was not the main contributing factor.

Results
In the simulation, MAEB+ was able to assist the rider in reducing the motorcycle speed prior to impact with higher deceleration compared to baseline MAEB and in maintaining the stability of the motorcycle.

Limitations
The potential benefits of the proposed system, expressed in terms of impact speed reduction or avoidance of fall events, cannot be directly correlated with actual benefits for the rider in terms of injury mitigation. In fact, risk curves expressing the level of injury for the rider as a function of kinematic quantities (such as impact speed) are not currently available for riders.

Significance of results
Previous studies showed that MAEB would typically apply to situations where the motorcycle is travelling along a straight path. However, this paper shows that MAEB associated to ABC can apply also to those cases where the PTW is leaning, thus contributing to prove and extend the robustness of MAEB.

INTRODUCTION

An advanced emergency braking system, often referred to as Autonomous Emergency Braking (AEB), indicates a system that detects imminent collisions and activates emergency braking to decelerate the vehicle with the purpose of avoiding or mitigating the crash [1]. The first patent disclosing this specific concept was published in 1992 [2]. In 2006 the first high-end passenger cars able to brake without input from the driver were released on the market by Volvo and Mercedes Benz. Only few years later the first city car model was fitted with AEB (Fiat Panda, 3rd generation). AEB is nowadays available for a range of passenger cars [3], whereas since the 1st November 2014 AEB has become mandatory in the European Union for buses, coaches and trucks.

The scientific literature of the last decade is rich in studies discussing triggering algorithms, system architectures, evaluations, human related aspects of AEB for passenger cars [1, 4-10]. More recently, in 2012, the authors presented a simple prototype of AEB for powered two-wheelers (PTWs) [11], after the concept being introduced independently in 2009 by two research projects funded by the European Commission, namely
PISa [12] and SiM [13]. The prototype of MAEB described in [11] applied to straight path scenarios with roll angles up to 10 deg. This limit was due to avoid the risks for the rider associated with an unexpected, automatic braking action produced by MAEB while the vehicle was leaning in a curve.

In previous studies the authors investigated the applicability of MAEB via case-by-case retrospective analysis based on in-depth crash datasets from different countries [14-16]. In most of the cases where automatic braking may have applied, the motorcycle was travelling along a straight path. However, the extension of MAEB applicability to larger roll angles would represent an important step of development. Firstly, this improvement would enhance the applicability of MAEB. For example, in the multinational datasets presented in [16] the percentage of cases where MAEB was considered ‘not applicable’ due to PTW roll angles greater than 10 deg ranged between 5% and 28% for the Italian and Swedish datasets, respectively. Secondly, the acceptability of MAEB among riders is expected to be higher if the system can safely deploy even when the PTW is cornering, due to increased usability (additional details on the indicators of acceptability can be found in [17]).

This paper introduces a system named MAEB+ combining the functionalities of MAEB with an Active Braking Control (ABC) that maintains vehicle stability during hard braking while cornering. An analysis of the effects of MAEB+ was performed via computer simulations reproducing three real world crashes selected from the in-depth motorcycle crash dataset InSAFE (In-depth Study of Accidents in Florence).

METHODS

From the InSAFE database, three suitable PTW-to-car crash cases were identified and reconstructed via numerical simulations. For each case, a baseline simulation was tuned in order to reflect the kinematics and the collision configuration identified by the original InSAFE crash reconstruction. Then, for each crash case two additional simulations were performed, assuming that MAEB and MAEB+ respectively were active on the PTW at the time of the crash. Finally, the baseline results and the results obtained with MAEB and MAEB+ were compared to analyse the possible effects of these crash mitigation systems.

SYSTEM DEFINITION

The MAEB+ system combined two subsystems: MAEB and ABC, presented by the authors respectively in [11, 18] and [19, 20]. MAEB was designed to monitor the vehicles around the host powered two-wheeler and to deploy automatic braking in case of inevitable collision with an opponent vehicle. ABC was designed to optimise the braking action of the rider while guaranteeing the capsize stability. ABC can potentially assist MAEB in safely achieving the desired emergency deceleration both in straight and, more importantly, in curved path. In this study MAEB and ABC were combined to assist the rider in case of imminent collision in a curve. In this situation both MAEB and ABC are engaged, thus enhancing rider’s braking action (MAEB) and keeping the vehicle stable along the curved trajectory (ABC). In the following paragraphs, each subsystem and their interaction will be described.

MAEB subsystem

MAEB monitored the vehicles in the frontal surroundings of the host PTW and when an inevitable collision was detected the automatic brake was deployed. A full prototype of MAEB was developed within PISa and implemented on a large-size scooter. The obstacle detection device was a compact, multi-layered laser scanner mounted in front of the vehicle. The triggering algorithm was designed for the simple scenario in which the host PTW approached a fixed obstacle moving along a straight path. The algorithm deployed autonomous braking as soon as the collision became inevitable – either by braking or swerving at the physical limits [11].

Recently, new triggering algorithms were developed by the authors to apply to a wider range of pre-crash scenarios, including intersection scenarios. These algorithms were based on the concept of Inevitable Collision State (ICS) defined by Fraichard and Asama [21]. Given the current state $s = (v_{PTW}, v_{car}, P_{car}, \theta_{car})$, where $v_{PTW}$ and $v_{car}$ represent the speed of the host PTW and opponent car, respectively, and $P_{car}$ and $\theta_{car}$ are respectively the relative position and relative heading of the opponent car with respect of the host PTW, $s$ is an inevitable collision state if, no matter what the future manoeuvres of host and opponent vehicles are, a collision will eventually take place. Inevitable collision states can be pre-computed and implemented via triggering look up tables, as described in detail in [18]. The analysis of these look up tables indicated that in typical pre-crash situations the ICS can be identified up to 0.5 s before collision. This study adopted the triggering algorithms computed for a case in which the PTW is initially travelling along a straight path [16]. Concerning the deployment of automatic braking once the collision becomes inevitable, two different modes were identified. The first one was a proper autonomous braking (AB) with moderate deceleration deployed by

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the system when the collision was inevitable and the rider was not braking. The second method was the enhanced braking (EB), deployed when the collision was inevitable and the rider applied some braking action. In this case, the system amplified the braking force up to the limit imposed by the road-tyre friction coefficient.

Previous studies recommended limitations for the deceleration level in AB mode. In fact, the unexpected autonomous deceleration may destabilise the rider with dangerous consequences. Symeonidis, Kavadarli, Shuller, Graw and Peldschus [22] performed experiments with volunteers in controlled conditions using a sled to produce different levels of decelerations simulating AB. Their results indicated that a deceleration of 0.35 g was acceptable for AB. The initial prototype vehicle equipped with MAEB was tested on the road by professional riders, confirming the feasibility of AB deceleration at 0.3 g [23]. However, in these tests the riders were aware of the imminent automatic deceleration produced while approaching foam obstacles. Other tests were conducted by the authors involving common riders in order to validate the feasibility of genuinely unexpected AB events along a straight path [24].

ABC subsystem

The aim of ABC was to provide the maximum deceleration and, in case of critical events, improve vehicle stability via longitudinal forces modulation. Similar concepts were described in the literature [25] and at present this technology is available on the market [26]. The basis of the ABC was a system integrating combined braking (CB) and antilock braking (ABS), indicated here as C-ABS. CB converted a braking input into reference braking pressures on front and rear wheels for a steady state optimal braking [27]. Force modulation downstream of the CB adjusted the braking pressures to avoid wheel lock and improve stability during unsteady braking and cornering.

Figure 1 depicts the layout of the ABC system, which included Combined Braking (CB, yellow), Antilock braking (AL, light blue), risk evaluation module (green) and Active Braking (or braking modulation) module (AB, white). The hierarchy of the functions is described hereafter: 1) combined braking applied to every manoeuvre, aiming to maximise vehicle deceleration in every braking scenario; 2) in case of wheel slip over a threshold, antilock braking unit was activated; 3) the vehicle state was constantly under control during every manoeuvre: as soon as a critical event was detected, the RISK unit sent a warning signal to the AB unit; 4) active braking unit was activated as soon as the RISK unit sent an alert; AB acted directly on the CB function.

The braking forces modulation was based on the application of the correction $\rho_c$ to the actual braking force distribution. The correction was computed so that the desired stability target was addressed maximizing the deceleration. The correction was a function of the total longitudinal force and therefore it was a function of the maximum acceleration/deceleration that the rider tried to achieve.

The factor $\rho_c$ was computed according to the following equation:

$$
\rho_c = \frac{-Izz \cdot \ddot{\psi}}{Fxt \cdot a \cdot \delta \cdot \cos(\phi)}
$$

Figure 1. General layout of the Active Braking Control: Combined Braking function (CB, yellow); Anti-Lock function (AL, light blue); RISK function (green); the Active Braking, or braking modulation, function (AB, white)
where $I_{zz}$ represents the yaw inertia of the PTW in the body-fixed system of reference, $\ddot{\psi}$ the yaw acceleration, $Fx_T$ is the total longitudinal tyre force, $a$ is the longitudinal distance between the CG and the centre of the front wheel, $\delta$ is the steering angle and $\phi$ is the vehicle roll angle.

The intervention of the braking modulation control unit applied to the original braking force distribution, $\rho$. The correction $\rho_c$ was subtracted from the original force distribution. When the AB unit deployed, the correction was computed, and the braking force distribution was modulated in order to produce the new braking balance.

The RISK unit detected a potential fall and activated the AB unit. The RISK function integrated in the risk unit was the implementation of the equations described in [20]. This unit was composed of a number of algorithms, named RISKi, able to detect potential fall events that are critical for PTW stability and safety. The parameters were designed to identify incipient fall events produced by braking intensity or heavy oscillations of vehicle body and steering bar.

The minimum working frequency adopted for the AL module was 10 Hz. It should be noted that current ABS working frequencies are typically lower (3-4 Hz).

**MAEB+ system**

MAEB+ was designed to extend the applicability of MAEB beyond the straight path scenario and cover situations in which the PTW is cornering by incorporating AB and EB functions with the braking control algorithms of ABC.

As previously described, the ABC received braking inputs and modulated them to produce optimally distributed braking and vehicle stability during the braking manoeuvre. In the MAEB+, the braking inputs of the ABC module were either the rider’s control actions or – in case of inevitable collision scenario – MAEB control actions.

As the aim of the present study was an overall evaluation of the influence of MAEB+ in real world crash circumstances, and not the development of the physical system, the system modelling was highly simplified as follows.

The rider action was modelled in BikeSim as an open loop force applied on the brake levers in order to produce the deceleration profile described in the crash reconstruction report. MAEB module received the triggering signal from the ICS module and front/rear braking signals from the rider. MAEB module provided the adjusted front/rear brake delivery pressures, which followed the states described in Table 1.

MAEB outputs were passed to the ABC module, together with vehicle state data. The outputs of ABC module were the modulated front/rear brake pressures provided to the BikeSim module as braking pressure inputs at the callipers. A scheme of MAEB+ is provided in Figure 2.

### Table 1.
**In&Out MAEB State Chart**

<table>
<thead>
<tr>
<th>MAEB inputs</th>
<th>MAEB outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front brake pressure @ master cylinder (from rider)</td>
<td>Rear brake pressure @ master cylinder (from rider)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>$\beta$</td>
</tr>
<tr>
<td>0</td>
<td>$\beta$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$\beta$</td>
</tr>
</tbody>
</table>
Figure 2. Scheme of MAEB+: bold lines indicate multiple signals; s is the current state of host motorcycle and opponent vehicle used to determine inevitable collision states; M/C is the master cylinder braking pressure; D is the braking pressure at delivery; W/C is the braking pressure at callipers; F and R indicate front and rear brakes, respectively.

CASE STUDIES

InSAFE crash database

The InSAFE study is conducted by the University of Florence with the Intensive Care Unit (ICU) of the Emergency Department of the Careggi Hospital. InSAFE has been collecting road accident data since 2009 in the cities of Florence and Prato and their surroundings [28, 29]. The data collection protocol of InSAFE complies with the guidelines defined by the European funded Project DaCoTA [30]. The selection criteria consist in urban and non-urban road crashes (not only with PTWs) involving at least one seriously injured person (Injury Severity Score, ISS ≥ 15) admitted to ICU. Investigators inspect vehicles involved in the crash to collect data on vehicular deformation, seat-belt usage, and protective garment including helmets and motorcycle clothing. Furthermore, for each case, retrospective site inspection and witness interviews are carried out in order to identify relevant pre-crash events. The ICU involved in the study alerts the InSAFE team providing information on injuries typologies and severities codified using the Abbreviated Injury Scale (AIS). A biomechanical correlation between injury and cause is conducted for each case by a panel of physicians and engineers. Through vehicular deformation, skid marks and witness accounts, collision speeds are computed and then validated using the accident simulation software Virtual Crash [31].

In the period 2009-2014, the InSAFE team has collected 206 serious road accidents of which 94 cases (45%) were fully reconstructed and studied (Table 1 reports the road accident typologies in the latter subset of records). Forty in-depth cases involved PTWs (Table 3 for details). The most frequent PTW crash configurations were head-on-side collisions (66%) followed by the head-on collisions (27%) (Table 4). Concerning the injury outcomes, the most severe configurations were head-on collisions, leading to a mean ISS of 22.0 and mean MAIS of 3.3.

For the present study, the selection criteria for the identification of the cases to be considered in the simulations were the following: a) the PTW collided with another vehicle; b) the PTW was travelling along a curved path with roll angle equal or above 15 deg; c) the rider applied some braking force prior to impact; d) PTW loss of control was not the main contributing factor. These criteria led to the identification of three crash cases, described in the following paragraphs. (Right hand side driving is in place in Italy, where these cases took place.)

Table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>N.</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Vehicle</td>
<td>9</td>
<td>9.5</td>
</tr>
<tr>
<td>Vehicle-to-Pedestrian</td>
<td>38</td>
<td>40.5</td>
</tr>
<tr>
<td>Vehicle-to-Bicycle</td>
<td>14</td>
<td>15.0</td>
</tr>
<tr>
<td>Vehicle-to-Vehicle</td>
<td>33</td>
<td>35.0</td>
</tr>
<tr>
<td>Total cases</td>
<td>94</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 3.
Accident types of events involving PTWs in the InSAFE database

<table>
<thead>
<tr>
<th>Type</th>
<th>N.</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Vehicle</td>
<td>5</td>
<td>12.0</td>
</tr>
<tr>
<td>PTW-to-Pedestrian</td>
<td>7</td>
<td>17.0</td>
</tr>
<tr>
<td>PTW-to-Bicycle</td>
<td>3</td>
<td>7.5</td>
</tr>
<tr>
<td>PTW-to-Car</td>
<td>23</td>
<td>56.0</td>
</tr>
<tr>
<td>PTW-to-Van</td>
<td>2</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Total cases</strong></td>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.
PTWs accident configurations (opponent vehicle: car or van)

<table>
<thead>
<tr>
<th>Type</th>
<th>N.</th>
<th>%</th>
<th>Mean impact speed (km/h)*</th>
<th>Mean MAIS*</th>
<th>Mean ISS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head-on crash</td>
<td>7</td>
<td>28.0</td>
<td>50.7</td>
<td>4.0</td>
<td>28.7</td>
</tr>
<tr>
<td>Head-on-side crash**</td>
<td>17</td>
<td>68.0</td>
<td>46.2</td>
<td>3.1</td>
<td>19.6</td>
</tr>
<tr>
<td>Sideswipe crash</td>
<td>1</td>
<td>4.0</td>
<td>53.0</td>
<td>3.0</td>
<td>14.0</td>
</tr>
<tr>
<td><strong>Total cases</strong></td>
<td>25</td>
<td>100</td>
<td>47.7</td>
<td>3.3</td>
<td>22.0</td>
</tr>
</tbody>
</table>

* Referred to PTW user
** PTW impacting on side of opponent vehicle

Case study 1 – ID-16

This case involved a 37-year-old male rider fatally injured in a head-on collision with a medium-sized car (Figure 3). The accident happened in a rainy winter night in low traffic conditions at signalised intersection with fully controlled cross-traffic light. A Mercedes E280 approached the crossroad with green light travelling straight at 65.8 km/h (±5 km/h). A Yamaha Cygnus scooter was approaching the same junction from opposite direction at 56.5 km/h (±5 km/h). The rider, eventually found to be positive to the alcohol test, did not stop at the red light and turned left. The roll angle of steady-state cornering was approximately 23 deg. Due to the weather conditions, the adherence was supposed to be in the range 0.55-0.60 (typical values from literature [32, 33]), leading to a maximum deceleration of 5.4-5.9 m/s². Skid marks were not reported. In the crash reconstruction both vehicles were assumed to start decelerating at 0.3 g (corresponding to 50% of the maximum braking force) one second before the crash (assuming typical reaction times). The impact speed was 55 km/h (±5 km/h) for the car and 50 km/h (±5 km/h) for the PTW. The rider suffered injuries with ISS of 36. The three most serious injuries were reported at the head and chest (MAIS 4), and face (MAIS 2). The accident took place on urban roads in residential area, where a 50 km/h speed limit was in place.

Figure 3. Case study 1, head-on collision at urban crossroad (ID-16)
Case study 2 – ID-10

In this accident, a 25-year-old male rider was seriously injured as result of head-on collision with a small-size car (Figure 4). The crash scenario was an S-curve in a dual lane, two ways, non-urban road with a speed limit of 60 km/h during a sunny day (no dazzling involved). A Suzuki GSX R750 was travelling at 94 km/h (+/-5 km/h). Before entering the first of the two curves, the motorcycle was in the opposite lane to negotiate the right hand side bend with a roll angle of approximately 40 deg. A FIAT Punto car was oncoming in the opposite direction at 57 km/h (+/-5 km/h). The rider started braking 0.5 s before the impact, with a peak deceleration of 0.7 g reached at impact. In addition, also the driver applied a braking action of 0.3 g at 0.5 s from the crash. The impact speed was 88 km/h (+/-5 km/h) for the PTW and 50 km/h (+/-5 km/h) for the car. The rider was subjected to multiple injuries (ISS of 29). The most severe ones were located in the chest (MAIS 4) and in the pelvic region (MAIS 3).

Case study 3 – ID-30

The third accident involved a 20-year-old male rider seriously injured in a sideswipe collision with a small-sized car. The accident happened in a sunny spring day with moderate traffic conditions. The accident scenario was a non-signalised crossroads (Figure 5). A Renault Clio car approached the intersection from right to left hand side of the rider path. The driver reached the crossing (signalised with STOP signal) slowing down the vehicle up to 17 km/h (+/-5 km/h) and then accelerating until the crash. A Honda SH300 scooter was traveling on the main road at 77 km/h (+/-5 km/h). The rider realised the driver’s intentions too late. One second before impact the rider applied a braking action resulting in a deceleration of 0.3 g and made an evasive manoeuvre towards the left hand side with a maximum roll angle of approximately 15 deg. The impact speeds were 65 km/h (+/-3 km/h) and 37 km/h (+/-3 km/h) for the PTW and for the car respectively. The rider was assigned an ISS of 19 with MAIS 3 injuries to head and thorax and MAIS 2 injuries to the spine. All the injuries were caused by the impact of the rider with the road environment (a post and the concrete shoulder).
SIMULATIONS

The three in-depth crash cases were reconstructed using the software tool PreScan (TASS International, Helmond, The Netherlands) [34]. Motorcycle dynamics was simulated using BikeSim software (Mechanical Simulations, Ann Arbor, MI, US). The algorithms of MAEB+ were modelled in Matlab Simulink software environment. The three software packages were interfaced with each other to run simulations that included road geometries, reconstructed trajectories of the opponent vehicles, detailed vehicle dynamics, and control algorithms for the safety system.

Baseline cases and variant cases were simulated. The baseline simulations aimed to obtain realistic reconstructions of the actual cases in last 2-3 seconds prior to crash. The simulation results were compared with the original reference cases as described in the crash reports, to check the agreement in terms of: initial position, path, and speed profile of the vehicles involved, driver and rider’s control actions (type, timing, and intensity), impact point, and relative heading at collision.

Variant simulations used the same conditions defined for the baseline cases, and included virtual MAEB and MAEB+ to evaluate the effects that these systems may have produced compared to the baseline cases. For each case (baseline and variants), a simplified reference trajectory was defined using the original crash reconstruction developed with Virtual Crash software. Reference trajectories were obtained assembling only straight and constant radius stretches for both car and motorcycle. The reference trajectory of the motorcycle was passed to BikeSim as a target path for the virtual rider. Details of the virtual rider are available elsewhere [35, 36].

Driver and rider inputs were defined based on the information available from the crash investigations and the Virtual Crash reconstructions. Open-loop throttle and brake controls were defined via step functions for host and opponent vehicles. Trial-error procedure was adopted to identify timing and intensity of the longitudinal controls.

The PTWs were modelled in BikeSim using the model of a scooter reproducing a Piaggio Beverly 300.

RESULTS

According to the simulations, in one case analysed (ID-10) MAEB and MAEB+ would have deployed in autonomous braking mode (AB) followed by enhanced braking mode (EB), as the rider started braking after reaching the ICS condition (inevitable collision state). In the remaining cases the simulations indicated that MAEB and MAEB+ would have deployed in EB mode only, as the riders applied the brakes before reaching the ICS condition.

Impact speed reductions were estimated in the range from 0.8 km/h to 3.0 km/h for MAEB, and from 1.3 km/h to 6.1 km/h for MAEB+. In all three cases the activation of MAEB and MAEB+ would have increased the mean deceleration in the time frame between the ICS detection and the collision.

Results showed higher decelerations for MAEB+ compared to simple MAEB. In two of the cases, the impact speed reduction was more than double with MAEB+ compared to MAEB. This outcome is mainly due to MAEB operating on the front disk only, with limitations compared to the combined braking operated by MAEB+, especially on damp and wet road conditions. Speed profiles, longitudinal accelerations, and brake pressure values for the three simulations are provided in Figure 7.

In addition, the simulations showed that the hard braking with braking modulation operated by MAEB+ obtained lower destabilisation of the vehicle with respect to MAEB deployment, as visible in the diagrams in Figure 8. With MAEB+, the absolute value of the roll angle tended to reduce while braking, as the vehicle tended to maintain the original path at decreasing speed.

In the following paragraphs, the main results for each case will be briefly presented. The results are also synthesised in Table 5.

Figure 6. Wheelbase and centre of gravity of the Piaggio Beverly 300. Experimental measurements with rider: a=925 mm; b=545 mm; h= 500 mm.
The benefits of autonomous emergency braking in terms of increased average deceleration and consequent impact speed reduction were noticeable in case ID-16 (PTW turning in front of opponent vehicle), in which the rider was reported to brake with low deceleration only. However, the deployment of MAEB produced a quick increase in the absolute roll angle, which was a sign of an incipient loss of control and subsequent fall. With MAEB+ the vehicle achieved similar decelerations without noticeable destabilisation.

The benefits of MAEB and MAEB+ were less tangible in case ID-10 (head on crash scenario). The impact speed reduction produced by autonomous emergency braking was moderate. The deployment of EB produced additional vibrations of the vehicle (less evident when using MAEB+), as a consequence of the large roll angle at triggering.
Also in this case (sideswipe scenario) the benefits of autonomous emergency braking in terms of impact speed reduction were moderate. However, the benefits of MAEB+ in terms of vehicle stabilisation were noticeable. In fact, in the initial phase of the curve the brake modulation reduced the braking force on the front wheel and built up braking pressure to the rear. In conclusion, the vehicle appeared to be stable while negotiating the curve even under hard braking conditions.

**DISCUSSION, LIMITATIONS AND FUTURE PERSPECTIVES**

The values of impact speed reduction obtained with MAEB in the simulations were in line with the values estimated in previous studies, although derived from different configurations (with roll angle smaller than 10 deg). The introduction of MAEB+ has allowed generalizing speed reduction benefits of MAEB to a larger set of accident configurations. In addition, the improved management of braking forces allowed higher decelerations in all the case studies, while the PTW stabilization, achieved with the ABC subsystem, prevented the vehicle capsizing prior to the impact in ID-16. In the latter case the deployment of the system in EB mode while the

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial speed (km/h)</th>
<th>Time to collision at ICS (s)</th>
<th>Configuration</th>
<th>Impact speed (km/h)</th>
<th>Impact speed reduction compared to baseline (km/h)</th>
<th>Average deceleration from ICS to collision (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID-16</td>
<td>56.5</td>
<td>0.26</td>
<td>Baseline</td>
<td>52.3</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB</td>
<td>49.3</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB+</td>
<td>46.2</td>
<td>6.1</td>
<td>7.8</td>
</tr>
<tr>
<td>ID-10</td>
<td>91.0</td>
<td>0.37</td>
<td>Baseline</td>
<td>84.5</td>
<td>-</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB</td>
<td>83.1</td>
<td>1.4</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB+</td>
<td>81.4</td>
<td>3.1</td>
<td>6.0</td>
</tr>
<tr>
<td>ID-30</td>
<td>85.0</td>
<td>0.38</td>
<td>Baseline</td>
<td>67.4</td>
<td>-</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB</td>
<td>66.5</td>
<td>0.8</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MAEB+</td>
<td>66.0</td>
<td>1.3</td>
<td>5.4</td>
</tr>
</tbody>
</table>

*Table 5. Synthesis of the results for the three simulated cases in baseline, MAEB, and MAEB+ configurations*

Figure 8. Diagrams showing roll angle and yaw rate of the PTW in the simulations: a) case ID-16; b) case ID-10; c) case ID-30.
rider was applying mild braking allowed to capitalize an impact speed reduction close to the theoretical values presented in previous studies, which turned in more than 20% of PTW kinetic energy reduction at impact. The analysis of case ID-16 showed the peculiar relevance of MAEB+ in situations where human factor failures are key elements and roll angles are not close to the limit. These results also suggest that autonomous emergency braking is likely to produce higher benefits when the rider is only able to achieve low deceleration prior to the collision, possibly due to lack of confidence in applying strong braking while turning, or as a result of panic, uncontrolled reaction in the imminence of a crash.

Despite the lower impact speed reduction obtained by the autonomous emergency braking, also in the other case studies MAEB+ outperformed MAEB. The limited speed reduction derived from higher braking forces applied by the riders in the simulations. (Maximum decelerations are similar in ID-10 and ID-16, but in the latter case a larger speed reduction was obtained.) It is worth noticing that the dynamical model of a scooter was used in case ID-10, despite the actual PTW involved was a sports motorcycle. Similar results would be expected when adopting a dynamical model of a sports motorcycle, in agreement with the similar results obtained with a scooter and a sports motorcycle in the computer simulations used for the assessment of the ABC system [19, 20].

In the proposed simulations, the position, the speed, and the heading of the opponent vehicle were assumed to be available for the MAEB and MAEB+ systems (as long as the obstacle was in the field of view of the PTW). Possible obstructions in the field of view, although not reported for the cases considered, could represent a strong limitation to a system that adopts an optical sensing device, especially in urban scenarios. In addition, the use of an optical sensing device to identify and track obstacles is particularly challenging when the roll angle is greater than 10 deg [11]. The adoption of V2X communication in order identify the triggering event will represent a fundamental step in the development of MAEB+.

In the simulations, the ABC subsystem provided enhanced stability to the PTW while hard braking along a curve, in the assumption that when EB deploys – thus abruptly increasing the deceleration of the vehicle – a real rider would be able to hold themselves firmly on the vehicle. Initial tests with professional riders experiencing EB deployment were conducted in the past [23], showing the feasibility of such system along a straight path with alerted rider. As far as the authors are aware, there are no other similar studies available in the literature. This important question regarding the feasibility of EB, and especially in emergency situations while negotiating a turn, should receive adequate attention in the future.

The braking stabilisation potential of ABC, when confirmed with larger set of simulations and with practical tests, would then enable MAEB deploying while negotiating a curve. But first and foremost, it would make MAEB deployment more reliable in a pre-crash scenario along a straight path, by compensating for possible second-last swerve avoidance manoeuvres operated by the rider in proximity of MAEB activation. In this context, such safer deployment of MAEB in the future may allow anticipating AB and EB intervention in time (higher TTC at triggering leading to higher effectivenes in impact speed reduction or even crash avoidance). In other words, MAEB+ has a potential to enable the application of MAEB to “avoidable impact conditions” and not just after the collision has become inevitable. However, the development of a MAEB+ for collision avoidance should be accompanied by the elaboration of appropriate overriding strategies. Best practice indicates human factor to be integrated since the initial design phase through extensive rider characterization and testing on volunteers.

As final limitation, the potential benefits of the proposed system expressed in terms of impact speed reduction or avoidance of fall events cannot be directly correlated with actual benefits for the rider in terms of injury mitigation. In fact, risk curves expressing the level of injury for the rider as a function of kinematic quantities (such as impact speed) are not currently available for riders.

CONCLUSIONS

MAEB+ was presented as an evolution of MAEB that incorporates optimal braking distribution and cornering stability. MAEB+ and baseline MAEB were tested in computer simulations reproducing three real world crash cases selected from the InSAFE database of crashes in the metropolitan area of Florence, Italy. The results showed that both MAEB and MAEB+ systems reduced the impact speed of the PTW compared to the cases in the actual configuration without braking assistance systems. In addition, MAEB+ was able to obtain higher decelerations and improved stability with respect to baseline MAEB, thanks to special algorithms of braking modulation. MAEB+ extends the applicability of autonomous emergency braking to a set of crash scenarios that so far were excluded from the evaluations of the potential benefits of MAEB. The results of this study also suggested that the effectiveness of MAEB+ is likely to be higher when the rider applies early, poor braking, and when roll angles are far from the limit, compared to cases in which the rider is able to apply late, nearly optimal braking, and in tight corners requiring high roll angles. When further validated, MAEB+ or similar systems could also enable the deployment of emergency braking when the collision between PTW and opponent vehicle
is still preventable. This concept is inspiring, especially considering that in the current literature such futuristic scenario of motorcycle autonomous emergency braking has not even been mentioned.

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REFERENCES