FURTHER DEVELOPMENT OF MOTORCYCLE AUTONOMOUS EMERGENCY BRAKING (MAEB), WHAT CAN IN-DEPTH STUDIES TELL US? A MULTINATIONAL STUDY

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ABSTRACT

Objective: In 2006, Motorcycle Autonomous Emergency Braking (MAEB) was developed by a European Consortium (PISa) as a crash severity countermeasure for riders. This system can detect an obstacle through sensors in the front of the motorcycle and brakes automatically to achieve a 0.3 g deceleration if the collision is inevitable and the rider does not react. However, if the rider does brake, full braking force is applied automatically. Previous research into the potential benefits of MAEB has shown encouraging results. However, this was based on MAEB triggering algorithms designed for motorcycle crashes involving impacts with fixed objects and rear-end crashes. To estimate the full potential benefit of MAEB there is a need to understand the full spectrum of motorcycle crashes and further develop triggering algorithms that apply to a wider spectrum of crash scenarios.

Methods: In-depth crash data from three different countries were used: 80 hospital-admittance cases collected during 2012-2013 within a 3 hour driving range of Sydney (Australia), 40 crashes with ISS>15 collected in the metropolitan area of Florence (Italy) during 2009-2012 and 92 fatal crashes that occurred in Sweden during 2008-2009. In the first step, the potential applicability of MAEB among the crashes was assessed using a decision-tree method. To achieve this, a new triggering algorithm for MAEB was developed to address crossing scenarios as well as crashes involving stationary objects.

In the second step, the potential benefit of MAEB across the applicable crashes was examined by using numerical computer simulations. Each crash was reconstructed twice – once with, and once without MAEB deployed.

Results: The principal finding is that using the new triggering algorithm, MAEB is seen to be a value mitigating multiple vehicle motorcycle crashes across a broader range of crashes than previously was seen to be the case. Crash mitigation was achieved through reductions in impact speed of up to approximately 10%, depending on the crash scenario and the initial vehicle pre-impact speeds.

Conclusions: This research is the first attempt to evaluate MAEB with simulations on a broad range of crash scenarios using in-depth data. The results give further insights into the feasibility of MAEB in different speed ranges. It is clear then that MAEB is a promising technology that warrants further attention by researchers, manufacturers and regulators.

KEYWORDS

Autonomous emergency braking, motorcycle, evaluation, in-depth crash investigation, collision mitigation

INTRODUCTION

Motorcycles are the most rapidly growing form of transport globally (Joint OECD/ITF Transport Research Committee 2008). Over the last decade the number of motorcycles in the Australian fleet has increased by 56% (Australia Bureau Statistics 2010). Similarly, motorcycles in the Swedish fleet doubled between the late 1990s and 2008 (Swedish Transport Administration 2010) and in Italy the composition of the fleet has shifted with a 30% increase in motorcycles between 2005 and 2012 (ACEM - Motorcycle Industry in Europe 2013). This increase has benefits for mobility as motorcycles reduce urban congestion and are an affordable form of transport (European Transport Safety Council 2013). However, motorcycle riders represent an increasing proportion of the road traffic crashes casualties internationally. In Australia, motorcyclists represent 27% of serious transport injury and 4% of registered vehicles (Henley and Harrison 2009). Across European Union countries, riders represent 16% of road death fatalities while accounting for only 2% of total kilometres driven (European Transport Safety Council 2013). Furthermore, the fatality rate of motorcycle riders is not declining at the same rate as that of car occupants (Henley and Harrison 2009). While road death numbers are generally declining, the deaths among motorcyclists have increased over the last decade in the European Union (Yannis *et al.* 2012). Similarly in Australia, fatalities among motorcyclists increased by 3.4% between 1998 and 2007 while deaths among all other road user have declined (Johnson *et al.* 2008).

The ETSC has also noted a distinct difference in vehicle safety improvements between cars and motorcyclists over the last 20 years. While there have been substantial improvements in the design and construction of cars that have contributed to reductions in deaths and injuries to drivers and passengers, this has not been the case for motorcycles (European Transport Safety Council 2007). Motorcyclists are generally regarded as vulnerable road users due to the absence of a protective frame. The typical absence of external structure and restraints in motorcycles present a major challenge for designing injury prevention countermeasures (Barbani *et al.* 2014). However, there is potential for primary safety technologies to help avoid and reduce the severity of crashes. Enhanced braking systems may be particularly beneficial for motorcycles (Sporner and Kramlich 2001, Roll *et al.* 2009). Anti-lock braking system (ABS) is one such technology that has been available on some motorcycles since the 1980's. With increasing evidence of ABS effectiveness in improving motorcycle stability under braking (Vavryn and Winkelbauer 2004) and reducing the likelihood and severity of collisions (Rizzi *et al.* 2009), this technology is becoming more common (European Transport Safety Council 2013). However there is scope to improve on ABS. ABS is not effective unless a rider attempts to brake, and even when a rider does brake, ABS cannot amplify braking. Autonomous braking and enhanced braking technologies could address these limitations (Roll *et al.* 2009) and have recently been highlighted as technologies requiring further investigation by the ETSC.

In 2006, a European Consortium (PISa) began identifying, developing and testing new technologies to help motorcycle riders avoid crashes and mitigate the consequences of others to reduce the overall burden of injury due to motorcycle crashes (Savino *et al.* 2010). A result of this work was the development of a Motorcycle Autonomous Emergency Braking (MAEB) system. The MAEB system can detect an obstacle through sensors in the front of the motorcycle and brakes automatically if the collision is inevitable and the rider does not react (AB). However, if the rider brakes, full braking force is applied automatically (EB).

Previous research into potential benefits of MAEB has shown encouraging results (Savino *et al.* 2013a, Savino *et al.* 2013b). A study investigating MAEB applied to virtual reconstructions of 7 fatal motorcycle crashes that occurred in Sweden demonstrated the potential effectiveness of MAEB in motorcycle-to-car rear-end crash scenarios. However, as this work was based on MAEB sensor triggering algorithms designed for a limited number of crash scenarios, there is a need for further enhancement of the algorithms to address a greater range of crash scenarios. Furthermore, to estimate the full potential benefit of MAEB there is a need to understand the full spectrum of motorcycle crashes, and to examine the potential effectiveness of MAEB over a greater range of real world crashes.

METHOD

The triggering algorithms in the MAEB system used in previous works were enhanced to allow the MAEB to apply to a greater range of crash scenarios. Motorcycle crash data collected during in-depth investigation studies in three countries were then reviewed to identify cases where MAEB may be applicable. The selected cases were then simulated with and without the MAEB system to investigate the applicability and potential benefits of the enhanced MAEB system. This approach is similar to the one proposed by Kusano and Gabler (2012) for forward collision avoidance systems for passenger cars.

MAEB System Description

The MAEB system used here has been described previously (Savino *et al.* 2010, Savino *et al.* 2012, Savino *et al.* 2013b). It has been tested on road via a full demonstrator vehicle and the capability of riders to control the vehicle during automatic braking has also been described previously (Savino *et al.* 2012). In brief, the system comprises sensors mounted on the host motorcycle, an automatic braking device, and a control unit. Obstacle detection occurs via a laser scanner and dedicated control unit providing real time obstacle classification and tracking. The detection device has a horizontal field of view of 100 degrees and compensates via software for pitch and roll (Roessler and Kauvo 2009). An inertial measurement unit provides feedback on the dynamic state of the host motorcycle and a reference for determining the absolute position and speed of obstacles. Pressure sensors mounted on the hydraulic braking system, a throttle sensor and a steering sensor measure control inputs from the rider. In the prototype vehicle, autonomous deceleration is produced via a hydraulic unit modified to actuate a dedicated calliper-disk system mounted on the front wheel of the vehicle. The MAEB system also incorporates standard ABS, which also operates when the AB is not triggered.

MAEB Decision Logic (Activation, Inhibition and Triggering)

Upon detection of an inevitable collision the control unit uses a set of rules to decide whether or not to activate the automatic deceleration of the vehicle. If the rider does not apply any brake, the system performs a mild deceleration (autonomous braking, AB) up to 3 m/s^2. If the rider brakes prior or after activation of MAEB, the system performs full braking up to 90% of the adherence limit (enhanced braking, EB). This typically produces a deceleration of 9 m/s^2 in dry asphalt conditions. For EB, it is assumed that the automatic braking system is able to perform an optimal braking (Corno *et al.* 2008) by increasing the braking force produced by the rider and correctly distributing the braking force between front and rear brakes. The possible MAEB intervention modes are therefore: a) pure AB; b) pure EB; c) AB followed by EB. Automatic braking is not triggered when the motorcycle travels along a curve with roll angle greater than 10 degrees (due to risks for vehicle destabilisation) or when facing narrow obstacles (less than 1 m, due to technical challenges with obstacle localization). The rider can inhibit or disengage the automatic braking by operating a swerve manoeuvre or accelerating. The deceleration values have been validated using volunteer riders in a controlled environment (Symeonidis *et al.* 2012).

MAEB Algorithm enhancements

The decision logic of the MAEB system described previously was designed to identify inevitable collision situations in rear-end crash scenarios or with fixed obstacles. Triggering decisions were based on comparisons between computed minimum distance to avoid collision by swerving or braking and actual distance of the obstacle, as described in Kiefer *et al.* (2005). A new triggering algorithm has been developed based on the theory proposed by Fraichard and Asama (2004). This algorithm applies to a wide range of motorcycle-to-vehicle collision scenarios, including those at intersections and with curving opponent vehicles. Given the current speed of the host motorcycle and opponent vehicle, and the current relative heading of the opponent vehicle, the new algorithm computes the locus of current positions *A* that lead the opponent vehicle to inevitable collision. If the current position of the opponent vehicle is in the region *A* of inevitable collision, the current state will be considered as inevitable collision state (ICS). This algorithm is similar to the ICS checker algorithm presented by Martinez-Gomez and Fraichard (2008). We specifically redesigned it for a host motorcycle incorporating the results of field tests presented by Giovannini *et al.* (2013), and with the addition of heading and rectangular shape of the vehicles. An example of typical values for the time to collision (TTC) at ICS detection is shown in Figure A 1. The description of the algorithm and its validation are detailed in a separate paper (Savino *et al.* Forthcoming).

Database description

The present study includes data from three studies, described briefly below.

Australia: The Neuroscience Research Australia (NeuRA) dataset was collected during an in-depth case control study of motorcycle crashes in New South Wales between 2012 and 2014. Crashed riders are recruited after they have been admitted to hospital. In-depth interviews with the rider and medical record reviews are undertaken. Engineers then inspect the crash scene and vehicles and protective equipment involved. Police data are also collected if participants give permission to access these records. Crash scene and motorcycle inspections are retrospective but are usually completed within two weeks from the crash. Collected data are presented to a multi-disciplinary panel consisting of mechanical engineers, traffic engineers, motorcycle safety specialists, behavioural scientists, trauma clinicians and crash investigation experts. Crash circumstances are largely based on witness statements and verified by evidence within the data collected and agreed to by the expert panel.

Italy: The Department of Industrial Engineering (DIEF) at the University of Florence and the Intensive Care Unit (ICU) of the Emergency Department at Florence Careggi Teaching Hospital have been carrying out in-depth studies of serious road accidents since 2009 (Piantini *et al.* 2013). The investigated crashes must have occurred in the metropolitan area of Florence and have involved at least one seriously injured. The InSAFE (In-depth Study of road Accidents in Florence) team mainly conducts a retrospective investigation. Investigators inspect vehicles involved in the crash to gather data on vehicular deformation, airbag deployment, seat belts usage, helmets, etc. Detailed information regarding injuries is also collected from hospital and correlated with the accident dynamics. These data in conjunction with police records, witness statements and the InSAFE on-scene inspections are used in the reconstruction phase to estimate collision and initial driving speeds.

Sweden: The Swedish Transport Administration (STA) has been carrying out in-depth studies for each fatal road crash in the country since 1997. Crash investigators systematically inspect vehicles involved in fatal crashes and record direction of impact, vehicular deformation, airbag deployment, tire conditions, etc. The crash site is also inspected. Further information about injuries and use of protective equipment is provided by forensic examinations, questioning and witness statements from the police and reports from the emergency services. Collision speeds are generally derived by vehicular deformation, while initial driving speed is mostly based on witness accounts, brake skids, etc.

Step 1 – Sampling criteria - Applicability Rating

To ensure consistency, cases selected for econstruction were selected using a decision-tree method, as shown in Figure 2. A scale from 1 to 3 was used to rank the likely applicability of MAEB in each crash, as done in previous studies (Sferco 2001, Savino *et al.* 2013b). The decision-tree scale was defined as follows:

Score 1: MAEB would definitely not have triggered in the crash

Score 2: MAEB would probably not have triggered in the crash

Score 3: MAEB would probably have triggered in the crash

Step 2 – Simulations

Score 3 cases were then simulated in a virtual environment using MATLAB Simulink software to quantitatively estimate the applicability of MAEB. The simulations recreated simplified, 2D (planar) kinematics of the vehicles expressed in terms of relative position of centre of gravity (COG), speed, acceleration and heading at every step of simulation. A simple dynamic model validated for passenger cars was used for both the motorcycle and opponent vehicle (Althoff and Mergel 2011). The bank angle of the motorcycle was obtained assuming steady state cornering at every step of simulation. The primary purpose of the simulations was to compute the relative positions and speeds of the vehicles involved in the crash, so no further details of motorcycle dynamics were included. An assumption that the motorcycle would preserve stability and the rider maintain control when the roll angle remained below 10 degrees was incorporated in the modelling based on computer simulations described in (Savino *et al.* 2013b). Since typical values of time to collision at ICS detection are below 1 (see Figure A 1), only trajectories in the last second before collision were used to evaluate MAEB triggering behaviour and to estimate new trajectories when AB or EB activated.

Trajectories consisted of straight or curvilinear paths with fixed radius and given initial speed and acceleration, and possible braking or swerving actions performed by the rider/driver prior to collision. Initial speed and trajectory, braking deceleration and/or swerving events and impact speed were defined from the in-depth investigation data for each selected case. The simulation software synchronised the trajectories to obtain a collision of the COGs. Finally, the initial position of the host motorcycle was fine tuned to obtain the correct impact point and impact angle, in accordance with in-depth data.

Collision detections between vehicles during simulation were obtained by schematising the vehicles assuming their geometrical centre coincident with the COG of the vehicles. An example of simulated crash trajectories is presented in Figure A 2. The simulations assumed that MAEB intervention did not modify the rider's actions. Specific parameters used in the simulations are presented in Table A 1.

Each identified case was simulated twice, with and without MAEB. Simulations were used to examine: i) capability of MAEB to predict an inevitable collision state (ICS) prior to the actual collision; ii) timing of detection with respect to time to collision at triggering (TTC) without MAEB; iii) type of intervention (AB, EB, or AB+EB); iv) absolute and relative impact speed reduction due to MAEB intervention, by comparing impact speed with and without MAEB

RESULTS

Dataset description

Table 1 contains details of the combined dataset. The proportion of urban crashes ranged from 93% in the Italian database to 32% in Sweden. The type of PTW involved also varied across databases: the involvement of scooters was between 4% in the Swedish and Australian databases and 41% in the Italian database. While sports motorcycle accounted for 50% and 56% of the Swedish and Australian crashes respectively, they were not as common in the Italian dataset. The distributions of rider age were similar, although riders in the Italian database were generally younger.

Table 2 shows the distribution of crash types across the three databases. Single-vehicle crashes were common in the Australian and Swedish databases, while intersection crashes were common in all three dataset. In the Italian dataset, intersection crashes accounted for more than 50% of cases. Most single vehicle crashes in Sweden involved road barriers or ditches. However in Australia, most single vehicle crashes did not involve another object (13/21). In Italy, curbs were dominant, although the material was limited (n=4).

Among the remaining crashes (‘others’ in Table 2), the most common type in the Australian database involved motorcycles and cars merging into each other while travelling in the same direction and motorcycles colliding with cars that had pulled out into the traffic from a parked position.

In the Italian data, pedestrians or cyclists struck by the PTW were the most common, while collisions with animals accounted for most ’other’ crashes in Sweden.

Mean impact speeds ranged from 45 km/h in the Australian database to approximately 85 km/h in Sweden. Helmet use was common across datasets, although 8% of Swedish crashes involved riders without a helmet. Injury outcomes ranged from 100% fatal in Sweden to no fatalities in the Australian database, while ISS>15 ranged from 32% to 68% in Australia and Italy respectively (see Table A 2 in the Appendices for further details).

Step 1 – Proportion of cases where MAEB might be applicable

As shown in Table 3, triggering of MAEB was considered likely in 37%-53% of cases. MAEB would definitely not have triggered in 15%-24% of cases. Table A 3 in the Appendices details reasons for Score 1 ratings.

Step 2 – Simulations

91 cases were simulated including 67 intersection crashes, 11 rear-end crashes, 6 U-turns, 5 side swipes and 2 head on crashes.

MAEB logic detected an ICS before actual collision in 81 cases (89%) with an average TTC of 0.38 s. The TTC values with respect to the actual impact speed of the host motorcycle are depicted in Figure A 3.

In 10 cases, MAEB logic did not identify an ICS prior to collision. These were 2 side swipe and 8 intersection cases in which the relative heading was below 45 degrees or the opponent was the striking vehicle.

MAEB activated in 68 (75%) of simulated cases. This represented 33%, 38% and 28% of cases identified in the three datasets and 32% of the 212 cases in the combined dataset.

Considering the 13 cases where the system identified an ICS but MAEB did not activate, MAEB was inhibited in 11 due to a swerve action by the rider before ICS detection. In the remaining two cases, MAEB was inhibited by an estimated lean angle >10 degrees as the motorcycle travelled a curved path. Enhanced braking was also disengaged in a further three cases after MAEB deployment due to swerving actions of the rider.

Average impact speed reductions by braking condition and MAEB activation by crash type are presented in Table 4. Absolute impact speed reductions due to MAEB are presented in Figure 2 (see also Figure A 4 for relative values).

The results shown in Table 3 and Figure 2 include 10 cases where a fall event occurred prior to collision. Excluding these cases, the average impact speed reduction produced by MAEB was 3.5 km/h. The lowest impact speed reduction was produced when MAEB operated as EB only (average 2.7 km/h), whereas the highest reduction was produced when MAEB operated in AB+EB mode (average 4.0 km/h)

In the 10 cases where a fall event occurred prior to the collision in the real word crash, simulations were attempted assuming the ABS embedded in the MAEB system would prevent the fall. Prevention of the fall, even without MAEB activation, resulted in an average speed reduction of 9.6 km/h. With activation of MAEB the reduction increased to an average of 11.7 km/h.

DISCUSSION

This analysis indicated that MAEB with the enhanced triggering algorithm would potentially address a third of crashes collected in a multi-national dataset of serious injury and fatal motorcycle crashes, and this proportion was consistent across individual datasets from the three participating countries. Importantly, this work also demonstrated that the MAEB system may achieve impact speed reductions above 10 km/h depending on the crash type and the pre-impact braking behaviour of the rider. The greatest impact reductions appear likely in cases where a fall event prior to impact is prevented. Excluding cases where pre-impact falls have occurred, the upper range of potential impact speed reduction is approximately 6 km/h.

It should be noted that the present paper was the first attempt to evaluate the benefits of MAEB on a large crash dataset. Three sources were used, including different crash and injury severities, as well different distributions of crash types. While caution may be needed in order to draw general conclusions, it could be argued that the impact speed reductions were generally consistent across the databases, thus suggesting that the study design was robust. The benefits in terms of injury mitigation, however, would probably differ a lot across the datasets, i.e. depending on the crash severity. For instance, for passenger car occupants it is established that small reductions in impact speed are associated with a reduction in likely injury severity, especially in low and medium impact speed range (Kullgren 2008). Although there is currently no impact speed/risk curve for motorcycle riders, we would expect lower impact speeds to be associated with lower transfers of energy and therefore we believe reductions in impact speed estimated here are likely to be associated with substantial reductions in injury risk, at least at lower impact speeds.

It is also important to point out that the absolute speed reductions estimated in this analysis is limited due to general constraints of MAEB in itself such as short time between activation and actual collision, limited deceleration applied by the system in AB mode, and limited increase in deceleration than MAEB typically obtains in EB mode, when the rider has already started braking.

The results also demonstrated TTC values when detecting ICS in the range between 0.2 s and 0.6 s across the whole range of impact speeds of the modelled crashes. The speed of the host motorcycle had little influence on estimated TTC indicating MAEB may typically be more effective for lower impact speeds (see Figure A 4).

While we have previously shown the potential effectiveness of MAEB in reducing impact speeds in motorcycle to rear end crashes and stationary object crashes (Savino *et al.*), this work shows the potential of MAEB to other crash types including intersection cases. Intersection crashes accounted for 34% of crashes in the combined dataset and the majority of crashes identified as being potentially amenable to MAEB (74% of simulated cases and 70% where MAEB deployed). Furthermore, impact speed reductions for intersection crashes were comparable with that seen in rear end crashes. Interestingly, in intersection crashes, the average impact speed reduction was slightly greater when there was no pre-impact braking (MAEB in AB mode), whereas greater impact speed reductions were obtained when the rider applied the brakes prior to collision (MAEB in AB+EB and EB modes) in rear end crashes. This supports the importance of AB for intersection cases and EB for rear end cases, as the authors had hypothesised with a simpler approach in a previous study (Savino *et al.* 2013b).

It should be noted that part of the calculated benefits of MAEB could be due to ABS, especially in cases involving fall prior to collision, as preventing wheel-locking would naturally increase stability during braking (Vavryn and Winkelbauer 2004, Gail *et al.* 2009). However, it could be argued that ABS would not have influenced the cases in which MAEB deployed in pure AB mode. In those cases, impact speed reductions of similar magnitude were obtained, thus suggesting that the benefits of MAEB go beyond those of ABS alone. From a holistic point of view, these two technologies seem to boost each other, although future research should further investigate this aspect.

Limitations

The rider and driver's actions, vehicles' trajectories and impact points have a significant influence on the estimated benefits of MAEB and defining these from crash investigation is challenging. In this study they were estimated during the simulation process based on the in-depth crash investigation reports. A number of assumptions were made in making these estimations. In the Swedish and Italian cases a general reaction time of approximately one second was assumed when pre-impact braking occurred and no other data were available. Furthermore, for the cases in which the impact speed was lower than the actual speed limit, a deceleration equal to 50% of the value achievable with optimal braking was assumed.

For InSAFE and STA datasets, confidence in the input parameters was increased by using computer based crash reconstructions conducted with PC-CRASH software (Datentechnik Group, Linz, Austria). Similar reconstructions have not yet been completed on the NeuRA cases.

There are also limitations related to modelling the benefits of the MAEB system with enhanced triggering algorithms before the system has been field tested. In this analysis the MAEB could detect ICS in a large number of intersection crashes due to a wide perception angle and it has not been confirmed that laser scanner can be reliable in achieving this level of detection in real world conditions. For real time implementation, the accuracy of sensors measuring the states of the host and opponent vehicles is critical to ICS detection. When accurate sensors are available, the cost of the system will be crucial for practical implementation. Similarly, the system liability and reliability are major issues to be investigated before market implementation of MAEB.

Motorcycle dynamics were not included in the simulations as the primary purpose of the simulations were to estimate relative positions and speeds of vehicles in the crash, however simulations with MAEB using detailed motorcycle models have been performed previously (Savino *et al.* 2013a). Furthermore, analysis of vehicle stability while MAEB operates is beyond the scope of the present paper. The assumption used here was that motorcycle stability and rider control would be preserved when the roll angle is below 10 degrees, (Savino *et al.* 2013a, Savino *et al.* 2013b).

Finally, the enhanced algorithm used here was created for motorcycle impact speeds up to 90 km/h. Results obtained for cases with higher impact speeds may underestimate TTC at ICS detection and impact speed reductions.

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REFERENCES

ACEM - Motorcycle Industry in Europe, 2013. 2013 statistical overview (provisional figures) version 24.01.14.

Althoff, M., Mergel, A., 2011. Comparison of markov chain abstraction and monte carlo simulation for the safety assessment of autonomous cars. Intelligent Transportation Systems, IEEE Transactions on 12 (4), 1237-1247.

Australia Bureau Statistics, 2010. Motor vehicle census, australia, 31 mar 2010. Abs catalogue 9308.0. Canberra, australian bureau of statistics.

Barbani, D., Baldanzini, N., Pierini, M., 2014. Development and validation of an fe model for motorcycle–car crash test simulations. International Journal of Crashworthiness (ahead-of-print), 1-21.

Corno, M., Savaresi, S.M., Tanelli, M., Fabbri, L., 2008. On optimal motorcycle braking. Control Engineering Practice 16 (6), 644-657.

European Transport Safety Council, 2007. Reducing motorcyclist deaths in europe. Etsc pin flash n.7.

European Transport Safety Council, 2013. Position paper on the proposal for a regulation on the approval and market surveillance of two- or three- wheel vehicles and quadricycles.

Fraichard, T., Asama, H., 2004. Inevitable collision states — a step towards safer robots? Advanced Robotics 18 (10), 1001-1024.

Gail, J., Funke, J., Seiniger, P., Westerkamp, U., Year. Anti lock braking and vehicle stabilty control for motorcycles-who or why not. In: Proceedings of the 21st International Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany.

Giovannini, F., Savino, G., Pierini, M., Baldanzini, N., 2013. Analysis of the minimum swerving distance for the development of a motorcycle autonomous braking system. Accident Analysis and Prevention 59, 170-184.

Henley, G., Harrison, J.E., 2009. Serious injury due to land transport accidents, australia, 2006-07 Australian Institute of Health and Welfare Canberra.

Johnson, P., Brooks, C., Savage, H., 2008. Fatal and serious road crashes involving motorcyclists.

Joint Oecd/Itf Transport Research Committee, 2008. Workshop of motorcycling safety held in lillehammer (norway) on 10-11 june 2008: Final report. Itf/oecd/jtrc/ts6(2008)1. Organisation for economic and co-operation and development.

Kiefer, R.J., Leblanc, D.J., Flannagan, C.A., 2005. Developing an inverse time-to-collision crash alert timing approach based on drivers' last-second braking and steering judgments. Accid Anal Prev 37 (2), 295-303.

Kullgren, A., Year. Dose-response models and edr data for assessment of injury risk and effectiveness of safety systems. In: Proceedings of the PROCEEDINGS OF IRCOBI 2008 (INTERNATIONAL RESEARCH COUNCIL ON THE BIOMECHANICS OF INJURY) CONFERENCE.

Kusano, K.D., Gabler, H.C., 2012. Safety benefits of forward collisionwarning, brake assist, and autonomous braking systems in rear-end collisions. IEEE Transactions on Intelligent Transportation Systems.

Martinez-Gomez, L., Fraichard, T., Year. An efficient and generic 2d inevitable collision state-checker. In: Proceedings of the Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on, pp. 234-241.

Piantini, S., Grassi, D., Mangini, M., Pierini, M., Zagli, G., Spina, R., Peris, A., 2013. Advanced accident research system based on a medical and engineering data in the metropolitan area of florence. Bmc emergency medicine 13 (1), 3.

Rizzi, M., Strandroth, J., Tingvall, C., 2009. The effectiveness of antilock brake systems on motorcycles in reducing real-life crashes and injuries. Traffic Inj Prev 10 (5), 479-87.

Roessler, B., Kauvo, K., 2009. Laserscanner based adas for motorcycle safety. Advanced microsystems for automotive applications 2009. Springer, pp. 245-253.

Roll, G., Hoffmann, O., Konig, J., Year. Effectiveness evaluation of antilock brake systems (abs) for motorcycles in real-world accident scenarios. In: Proceedings of the ESV Conference.

Savino, G., Giovannini, F., Baldanzini, N., Pierini, M., Rizzi, M., 2013a. Assessing the potential benefits of the motorcycle autonomous emergency braking using detailed crash reconstructions. Traffic Injury Prevention 14 (S1), S40-S49.

Savino, G., Giovannini, F., Fitzharris, M., Pierini, M., Forthcoming. Inevitable collision states for arbitrary motorcycle-to-car collision scenarios.

Savino, G., Pierini, M., Baldanzini, N., 2012. Decision logic of an active braking system for powered two wheelers. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 226 (8), 1026-1036.

Savino, G., Pierini, M., Grant, R., Frampton, R., Talbot, R., Peldschus, S., Schuller, E., Oudenhuijzen, A., Pauwelussen, J., Scheepers, B., Teerhuis, A., Year. Pisa – powered two-wheeler integrated safety. Development, implementation and testing of ptw integrated safety systems. In: Proceedings of the IFZ International Motorcycle Conference, Cologne, Germany.

Savino, G., Pierini, M., Rizzi, M., Frampton, R., 2013b. Evaluation of an autonomous braking system in real-world ptw crashes. Traffic Inj Prev 14 (5), 532-43.

Sferco, R., Year. Potential effectiveness of electronic stability programs (esp) - what european field studies tell us. In: Proceedings of the ESV Conference.

Sporner, A., Kramlich, T., Year. Motorcycle braking and its influence on severity of injury. In: Proceedings of the Enhanced Safety Vehicles.

Swedish Transport Administration, 2010. Improved safety for motorcycle and moped riders - joint strategy for the period 2010-2020, publication number 2010:043.

Symeonidis, I., Kavadarli, G., Erich, S., Graw, M., Peldschus, S., 2012. Analysis of the stability of ptw riders in autonomous braking scenarios. Accid Anal Prev 49, 212-22.

Vavryn, K., Winkelbauer, M., 2004. Braking performance of experienced and novice motorcycle riders - results of a field study. International Conference on Transport and Traffic Psychology.

Yannis, G., Antoniou, C., Evgenikos, P., Papantoniou, P., Kirk, A., 2012. Characteristics and causes of power two wheeler accidents in europe. Procedia - Social and Behavioral Sciences 48 (0), 1535-1544.

FIGURES

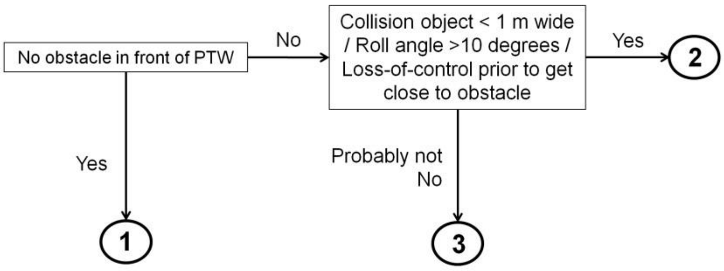

Figure 1. Decision tree for the analysis of MAEB applicability

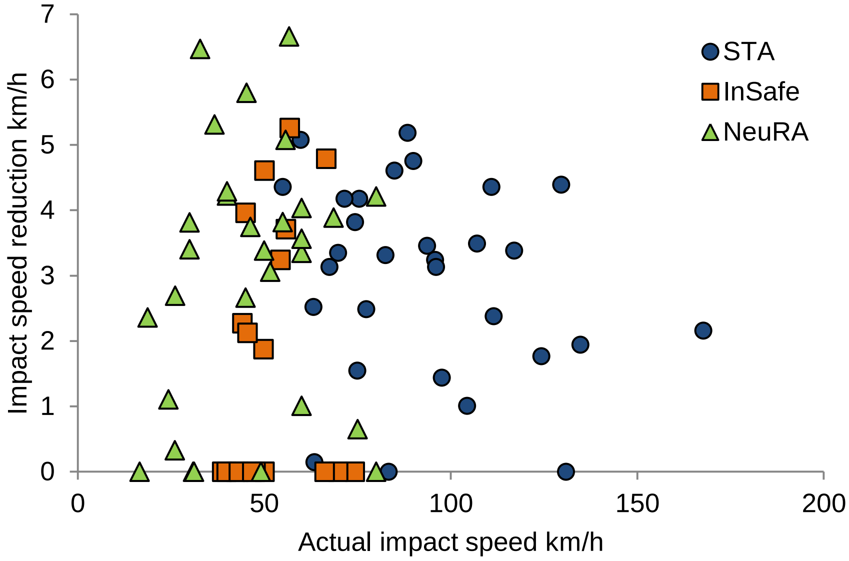

Figure 2. Absolute impact speed reduction due to MAEB plotted against the actual impact speed for each simulated case (excluding cases involving a fall event prior to collision)

TABLES

Table 1. Overview of the material included in the study

	AUS - NeuRA	ITA - InSAFE	SWE – STA
period	2012-2013	2009-2013	2008-2009
n crashes for analysis	80	40	92
% urban roads	57.5%	92.5%	32%
% scooters	4%	41%	4%
% sports motorcycles	56%	6%	50%
Rider age, % <18	5%	13%	-
% 18-24	17.5%	28%	13%
% 25-34	34%	13%	30%
% >34	43.5%	48%	57%

Table 2. Distribution of crash types in each database

	AUS - NeuRA		ITA – InSAFE		SWE - STA	
	N.	n PTW braking	N.	n PTW braking	N.	n PTW braking
head-on	7	1	4	2	14	7
crashes at intersections	19	7	21	13	32	30
rear-end	13	8	2	0	6	2
single vehicle	22	8	4	0	35	17
others	19	8	9	6	5	5
SUM	80	32	40	21	92	61

Table 3. Applicability of MAEB in the analysed crashes

	AUS - NeuRA		ITA - InSAFE		SWE - STA	
Score 1	19	24%	6	15%	15	16%
Score 2	25	31%	13	33%	43	47%
Score 3	36	45%	21	53%	34	37%
Total	80	100%	40	100%	92	100%

Table 4 Average impact speed reduction (ISR) due to MAEB in the simulated crash cases for the three datasets and for different crash scenarios

	AB		AB+EB		EB		Any activation		No activation	
	ISR* km/h	N.	ISR* km/h	N.	ISR* km/h	N.	ISR* km/h	N.	N.	Total N.
ITA - InSafe	4.38	4	3.33	2	2.54	3 (7)	3.54	9 (13)	10	19 (23)
Intersection	4.38	4	3.33	2	2.20	2 (5)	3.57	8 (11)	9	17 (20)
Sideswipe									1	1
U-turn					3.24	1 (2)	3.24	1 (2)		1
AUS - NeuRA	3.61	15	5.84	3	2.45	7 (11)	3.56	25 (29)	5	30 (34)
Intersection	4.11	10	5.08	1	2.19	5 (6)	3.57	16 (17)	3	19 (20)
Rear end	2.00	2	6.23	2	3.12	2 (5)	3.78	6 (9)		6 (9)
Sideswipe	1.01	1					1.01	1	2	3
U-turn	4.02	2					4.02	2		2
SWE - STA	3.95	6	3.54	9	2.91	10 (11)	3.39	25 (26)	7 (8)	32 (34)
Head on	3.35	1					3.35	1	(1)	1 (2)
Intersection	4.07	5	3.58	8	2.93	8	3.45	21	6	27
Rear end					2.48	1 (2)	2.48	1 (2)		1 (2)
Sideswipe					3.13	1	3.13	1		1
U-turn			3.24	1			3.24	1	1	2
Full dataset	3.82	25	4.01	14	2.69	20 (29)	3.48	59	22 (23)	81 (91)

*Average value computed over the cases in which MAEB deployed, excluding fall events.
In brackets the numbers including fall events.

APPENDICES

Figures

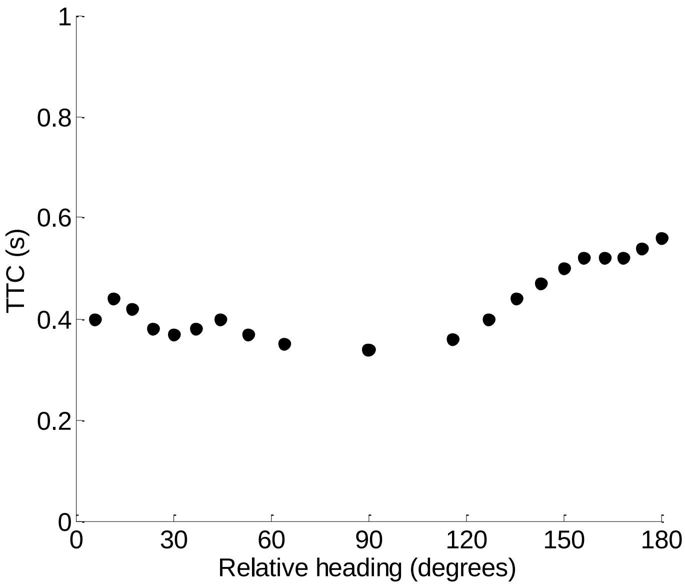

Figure A 1. Time to collision (TTC) at inevitable collision state detection (ICS) computed with MAEB algorithm for a host motorcycle travelling at 54 km/h and opponent vehicle travelling at 36 km/h with relative heading in the range from 0 degrees to 180 degrees

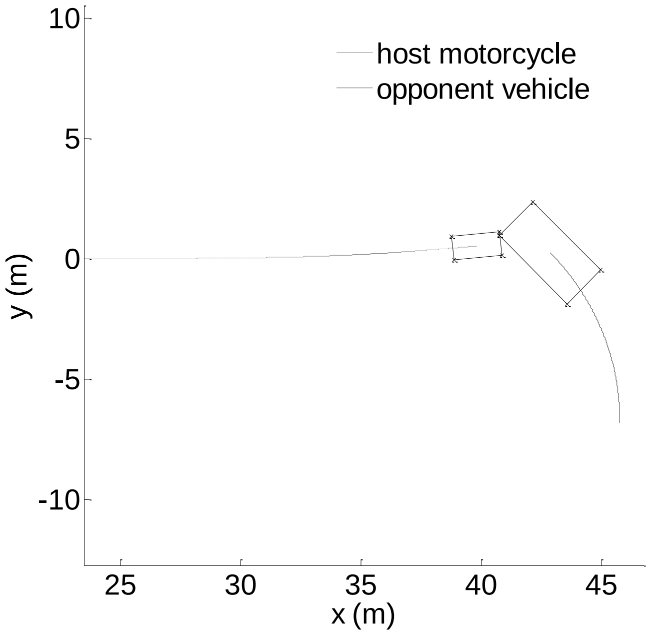

Figure A 2. Trajectories of the host motorcycle and opponent vehicles in a typical intersection crash

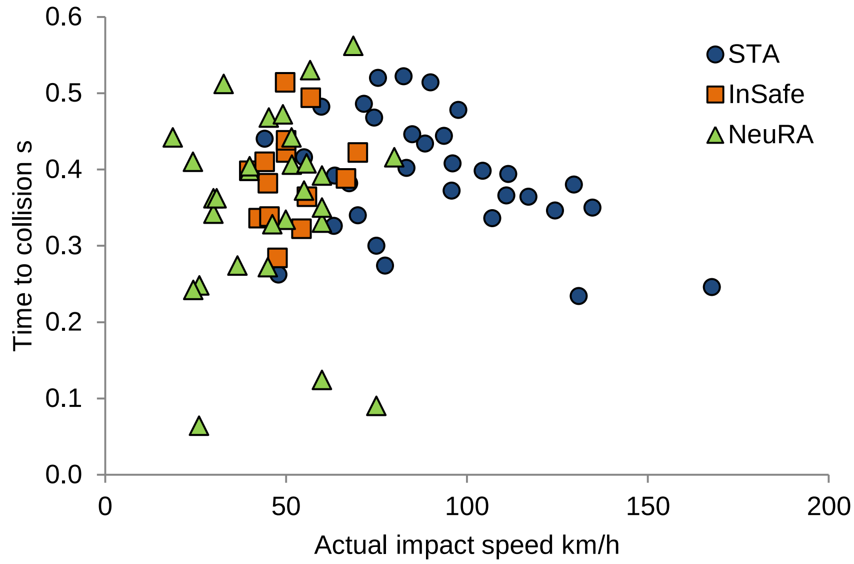

Figure A 3. Time to collision values at ICS detection

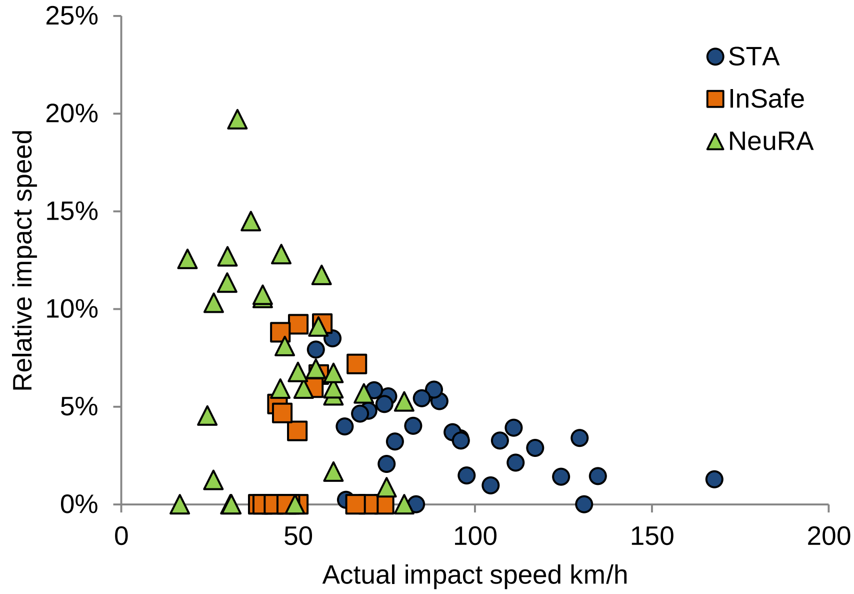

Figure A 4. Relative impact speed reduction due to MAEB plotted against the actual impact speed for each simulated case (excluding cases involving a fall event prior to collision)

Tables

Table A 1. Parameters characterising the kinematic and dynamic model for host motorcycle and opponent vehicle

	Host motorcycle	Opponent vehicle
Dimensions (length, width)	2 m, 1 m	4 m, 2 m
Yaw rate during swerving	30 deg/s	30 deg/s
Braking jerk	30 m/s2 (MAEB: 50 m/s2)	30 m/s2

Table A 2. Crash and injury severity across the databases

	AUS - NeuRA	ITA - InSAFE	SWE - STA
mean impact speed (km/h)	45	48	85
% PTW braking prior to collision	40%	52%	66%
% riders with helmet	100%	100%	92%
% fatally injured	0%	5%	100%
% ISS > 15, non-fatal	22%	68%	-

Table A 3. Reasons for Scores 1 or 2 in the analysed crashes.

Scores 1-2	AUS - NeuRA	ITA - InSAFE	SWE - STA
Collision object < 1 m wide	16%	63%	12%
No obstacle in front of PTW	58%	21%	26%
Roll angle was > 10 deg	26%	16%	62%
Total Scores 1-2	100%	100%	100%