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Impact Speed Reduction Induced By Pre-Crash Braking For Motorcycles – Parametric Evaluation Based on Real Accidents

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Abstract

Motorcycle safety is a major issue, and motorcyclists have not benefited as much as motorists from advances in active safety technology. Pre-crash braking, intended to mitigate rather than avoid impact, was evaluated by simulating 60 real-world crashes from two detailed databases. A parametric study was conducted to estimate the influence of the field of view, range, triggering strategy, applied deceleration, and the presence of a visibility mask. Three representative configurations among 450 possibilities have been defined as pessimistic, average and optimistic. The median reductions in motorcyclist impact speed are respectively 0 km/h, 7.4 km/h and 11.6 km/h. The results are useful to evaluate injury and cost reduction benefits and to improve the design of detection systems as well as triggering and braking algorithms. This method, based on real accidents and pre-crash braking modeling and simulation, is reliable and relevant and can be used to evaluate other active safety systems.

Keywords

Pre-Crash Braking, Active Safety, Powered Two-Wheeler, Motorcycle Autonomous Emergency Braking

Introduction

The risk of being seriously injured or killed is higher for Powered Two-Wheelers (PTW) riders than for other motorized road users. In 2019, motorcyclists accounted for 18% of all road fatalities in Europe (1) whereas they represent less than 2% of the traffic. PTW is the most dangerous form of motorized transport, particularly because of the lack of protection provided by the vehicle structure, the lack of internal protection by restraint systems, and the high speeds involved. It therefore appears very interesting from a safety and economic point of view to develop safety measures for them. Yet progress in driver assistance systems is unequally distributed across modes, with lower development for two-wheelers, even though the most common types of PTW accidents could be effectively mitigated by a broader implementation of safety systems. PTW crashes often occur at intersections with a limited time to undertake an evasive maneuver. There is often inadequate braking of the PTW and problems with detection of the PTW by the other road users due to low conspicuity and high speed. Over the past five decades, passenger cars have benefited from many new safety technologies, some of which were later transferred to motorcycles - sometimes with proven success, such as the anti-lock braking system (2, 3), which has been mandatory in Europe since 2016 for new types of motorcycles 125 cc or larger, and Motorcycle Stability Control (MSC), a system which supports the rider while braking at higher lean-angle (4).

Active safety systems that would benefit PTWs include enhanced and assisted braking systems, collision warning systems, side vision assist systems, enhanced stability systems, and intersection assist systems.

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Currently, one of the most advanced safety systems is Autonomous Emergency Braking (AEB). AEB is a system that uses radar and sometimes laser sensors and cameras to detect an imminent crash and activate emergency braking to decelerate the vehicle and avoid or mitigate the accident. Pre-crash braking (PCB) has similarities with AEB, but AEB is intended to avoid or mitigate impact by a target braking, while PCB is only intended to mitigate an impact by reducing the impact speed and, therefore, reduce the risk of injury during impact.

The presented study was carried out within the framework of the European project PIONEERS (5), whose main objective was to improve the safety of PTWs by suggesting an integrated approach to rider protection through personal protective equipment and onboard systems. The active safety component aimed at evaluating the benefits of a PCB in terms of crash severity reduction. PCB is not a commercialized system but it has already been prototyped on some types of motorbikes and experimentally tested on track with different motorcyclists. The objective of these experiments was to verify the acceptability of the maneuvers generated by the system in case of emergency. Previous works evaluating active safety systems such as AEB have shown the significant potential benefits of such a system for cars, trucks, PTWs and pedestrians. They were mostly based on in-depth crashes reconstruction and evaluated the safety system ability to reduce impact speed (6, 7). For PTW, simulations of AEB for motorcycles (MAEB) triggered by the system were performed, taking into account the kinematics of the accident and the dynamic capabilities of the vehicle by checking the possibilities in terms of accident avoidance or impact speed reduction (8-11). Prototype MAEBs have been studied first for straight-line scenarios (12) and more recently in a swerve maneuver with experts (13) and common riders (14). Savino et al. (15) showed that MAEB associated with an advanced ABS (anti-lock braking system) could also be applied to cases where the PTW is inclined. To ensure a gradual introduction of MAEB and a higher acceptability among end-users, its first application may be as PCB, which would be better accepted by users since it would not be triggered untimely or too soon, when the situation is still manageable by the motorcyclist, i.e. when they can still avoid the accident by braking or swerving.

This paper presents the results of the evaluation of PCB using 60 actual crashes from two highly detailed crash databases. A parametric study is presented as well as the impact speed reductions of PTWs in three realistic configurations of PCB among 450 possibilities, a "pessimistic" configuration, an "average" configuration and an "optimistic" configuration.

Material and methods

Data

The PCB evaluation was performed using computer simulations of a set of 60 real-world crashes from two highly detailed databases: the Italian InSafe database (16) and the French EDA database (17). 30 InSafe cases were simulated by the University of Florence (UniFI) and 30 EDA cases were simulated by the University Gustave Eiffel (Univ. Eiffel).

Each accident case report includes a detailed description of the scenario and circumstances of the accident, the description of the route of the vehicles involved, the road configuration, the marks (skidding, scratching, painting...), the damage of the vehicles and interviews of witnesses and subjects involved. These reports are very complete and allow a great precision in the reconstruction of the accident. The configurations retained are collisions between a motorcycle or a scooter and a car. Loss of control of a PTW alone and accident cases where the other vehicle is coming from the side or the rear of the PTW were not considered. Both datasets show a prevalence of L3 PTW (motorcycle with an engine capacity $\geq 125 \text{ cm}^3$, without sidecar) accounting for an overall 77%. In both InSafe and EDA datasets, two-thirds of the selected crashes occurred at intersections and the majority at junctions (four road segments). The main differences between

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the two datasets can be found for crashes that occurred on a straight road (33% in InSafe vs. 10% in EDA) and curves (no cases in InSafe vs. 7% in EDA).

PCB simulation

The simulations were performed by UniFI and Univ. Eiffel with a common methodological base already experimented by UniFI (18) and two specific internal software tools. A set of 20 cases was simulated and analyzed by both UniFI and Univ. Eiffel to highlight their similarities and differences. The effects of PCB were assessed in terms of reduction of the absolute and relative impact speed of the PTW.

First, the cases were reconstructed as accurately as possible to the real situation. The trajectories of the two vehicles involved (PTW and opponent car) and their kinematics were identified from a few seconds before the collision until a few seconds after the expected point of impact, with synchronization at impact. Then the PCB system was simulated for each case, according to the following principles (Illustrated in Figure1).

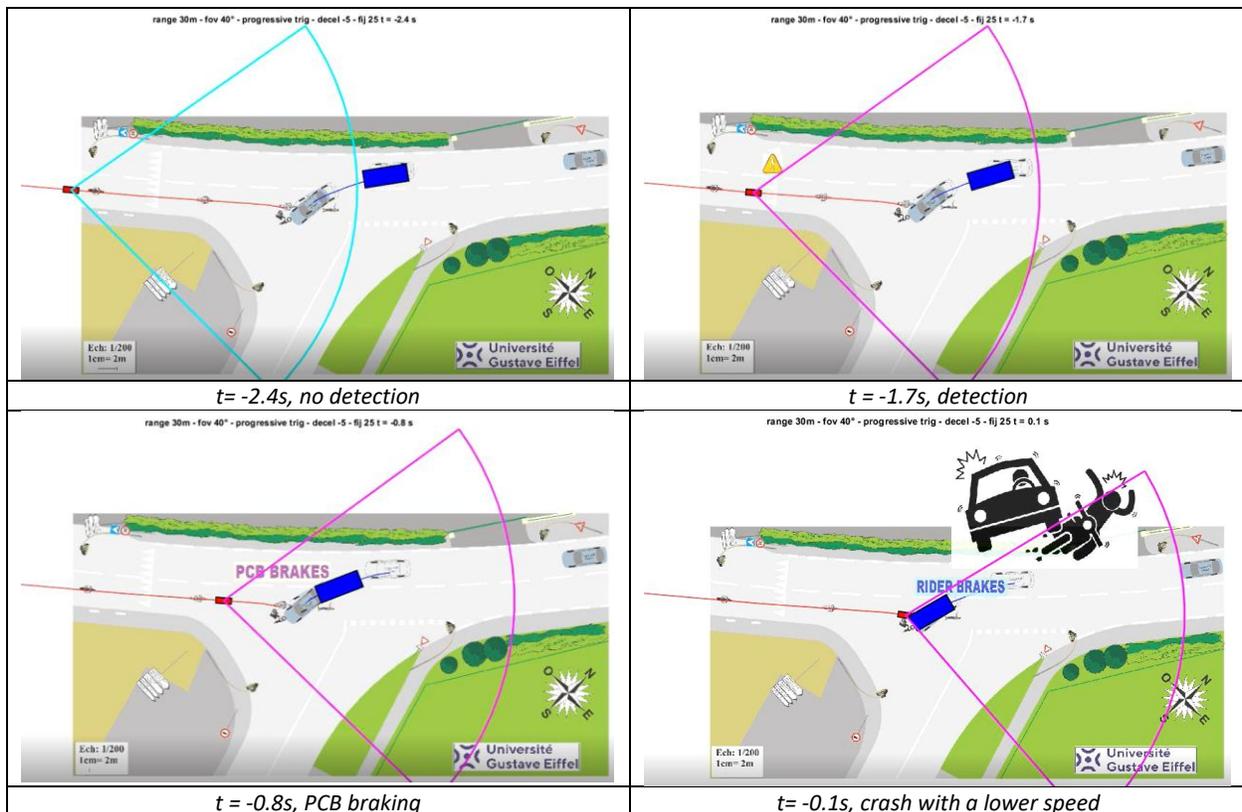


Figure 1. Example of a PCB simulation for an EDA accident - key moments

1/ Detection: The sensor is represented by a cone, which is added to the motorcycle to help determine when the other vehicle is detected. This cone is characterized by the field of view (FOV) on either side of its longitudinal axis and by the range, i.e. the maximum distance at which the opponent vehicle can be detected by the system. The definition of the cone (sensor) is based on a state-of-the-art radar technology.

2/ Triggering: The PCB system is triggered when any action of at least one of the vehicles (PTW or opponent) can no longer avoid the collision within the physical limits, with assumptions on the actual

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maneuverability of the vehicles involved. This "Inevitable Collision State" (ICS) algorithm was developed by UniFI in a previous study (19).

Three PCB triggering algorithms are analyzed. On the one hand, the "standard" triggering approach deploys the PCB system as soon as the impact becomes physically unavoidable with any combination of maneuvers with constant decelerations up to 5 m/s². A so-called "progressive" approach deploys the PCB system when the collision becomes unavoidable with any combination of maneuvers with constant deceleration up to 3 m/s², thus earlier. A third approach called "conservative" deploys the PCB system with maneuvers up to 7 m/s², thus closer to collision.

3/ Activation: Once triggered, the braking maneuver is initiated at a constant level among 3 m/s², 5 m/s² and 7 m/s², after a progressive fade-in-jerk period with a jerk between 15 m/s³ and 25 m/s³. The decelerations of 3 m/s² and 5 m/s² are the nominal values studied in field tests (20). The deceleration of 7 m/s² was not experimentally tested and is included in the analysis to simulate the effects of PCB with new parameters that need to be studied and validated later. Furthermore, braking is only activated if in the actual accident the motorcyclist was not already braking at that moment with a higher intensity.

In some cases, PCB intervention can prevent an accident altogether. This was not the primary objective of the system and it was treated as a side effect positively influencing the assessment of the benefits of PCB.

Differences between the UniFI and Univ. Eiffel simulations

According to the UniFI approach, the collision is estimated to be unavoidable when the maneuvers of the motorcyclist and the opponent motorist are no longer able to avoid the collision, with longitudinal and lateral accelerations below predefined thresholds based on the estimated maximum available grip of the studied crash case (friction ellipsoid theory). When computing the possible maneuvers, the modulus of the vectorial combination of the longitudinal and lateral accelerations does not exceed the maximum adherence available. Fixed threshold values for triggering were identified in advance using an iterative trial-and-error process, such that the median TTC at PCB triggering corresponds to the nominal values of 0.6 s, 0.8 s, and 1.0 s for the conservative, standard, and progressive activation criteria, respectively.

Univ. Eiffel also used the standard, progressive and conservative triggering strategies, but with a collision avoidance algorithm using motorcyclist braking alone, with deceleration values of 5 m/s², 3 m/s² and 7 m/s². In order to obtain a more realistic behavior for detection and to take into account the results of previous UniFI studies, a constraint on the time to collision was added with realistic values of 0.6 s (conservative), 0.8 s (standard) and 1 s (progressive).

Parametric approach

A parametric study was undertaken in which the values of the PCB characteristics (field of view, range, triggering strategy, applied deceleration, speed of application...) were varying according to Table 1.

Parameter	Levels
Range	30 m, 45 m, 60 m, 75 m, 90 m
Field of View (FOV)	+/- 10°, 25°, 40°, 55°, 70°
Triggering	Conservative, Standard, Progressive
Deceleration	-3 m/s ² , -5 m/s ² , -7 m/s ²
Fade-in-jerk	15 m/s ³ , 25 m/s ³

Table 1. PCB parameters variation

The influence of the range could be studied in 40 cases, among which are 30 EDA and 10 InSafe cases. A specific study was also conducted on 30 EDA cases to estimate the influence of a visibility mask when present in the accident, such as buildings in an intersection configuration, a stopped vehicle or a wooded

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shoulder in a curve. In some cases, especially at intersections or in curves, with certain combinations of PCB parameters, this visibility mask prevents or delays the detection of the opponent vehicle.

Results

Parametric study

The influence of the FOV for an average set of parameters has been evaluated and results are presented in (Figure 2, left). With a FOV of 10°, detection of the opponent vehicle is zero in at least half the cases. At 25° FOV, the median impact speed reduction is 4 km/h; at 40° it is 7.5 km/h. Beyond this value, the speed reduction gain is small. All other parameters being equal, the triggering strategy induces a median reduction in impact speed of 5 km/h (conservative), 7.5 km/h (standard) and 12 km/h (progressive) (Figure 2, right).

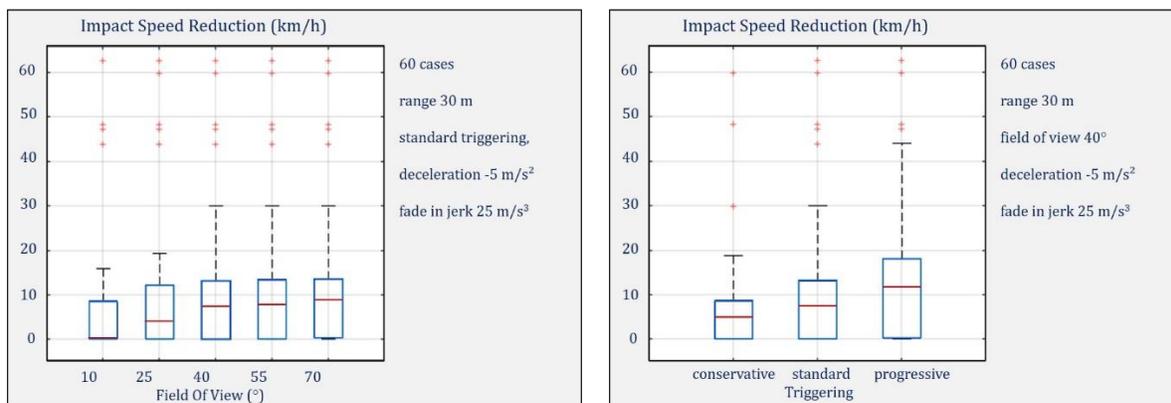


Figure 2. Influence of the Field Of View (Left) and the triggering strategy (Right) in PCB simulation for a set of average parameters

If we now consider the PCB deceleration variation between 3, 5 and 7 m/s², in average condition for the other parameters, the median speed reduction induced is 2.5 km/h, 7.5 km/h and 9 km/h (Figure 3, left). The influence of the fade-in-jerk is quite small, with median speed reductions of 6 km/h for a fade-in-jerk of 15 m/s³ and 7 km/h for a fade-in-jerk of 25 m/s³ (Figure 3, right).

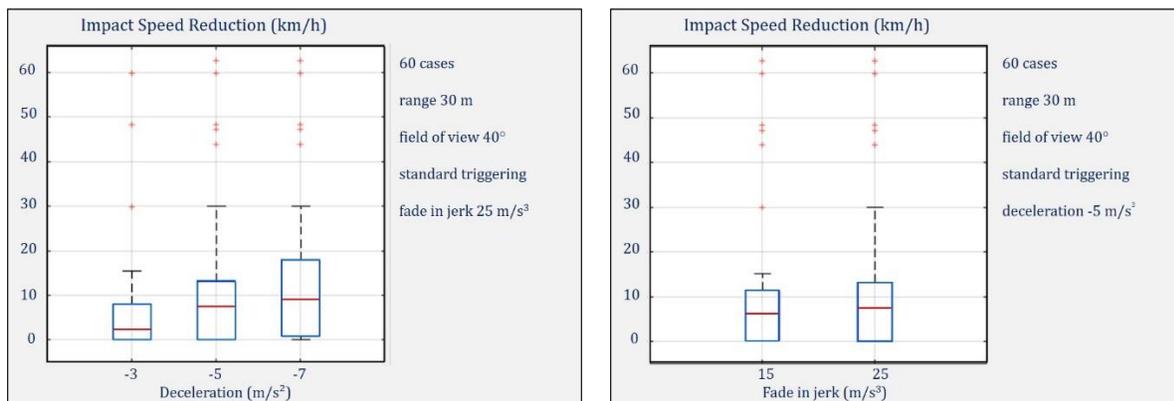


Figure 3. Influence of the deceleration (Left) and the fade-in-jerk (Right) in PCB simulation for a set of average parameters

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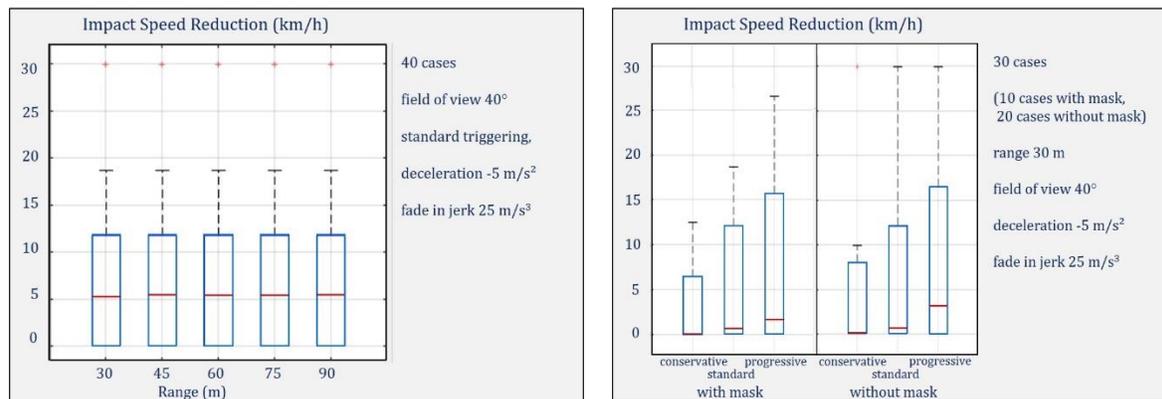
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For the 40 cases simulated by Univ. Eiffel, the influence of the range could be estimated (Figure 4, left). There is only a small difference of 0.2 km/h in median value between a 30 m and a 45 m range, and this difference is due to only one case. There is no difference beyond a 45 m range. The presence of a visibility mask that hinders the detection of the opponent vehicle by the PCB system was modeled for the 10 crash cases out of the 30 cases where it was present. PCB-related speed reductions with standard parameters were evaluated for the three triggering strategies, considering the 30 cases. Only the progressive strategy, with an earlier triggering, shows an influence of the presence of the obstacle to visibility, with a median speed reduction of 1.6 km/h instead of 3.1 km/h without mask (Figure 4, right).



Global influence of PCB

The five parameters taken into account for PCB and their modalities lead to 450 different configurations that allow to explore widely the different possible combinations of system settings. Nevertheless, it is difficult to get a clear picture of the expected benefits of the system. Three parameter combinations were identified to characterize typical system effects assuming a pessimistic (low efficiency), an average and an optimistic (high efficiency) configuration (Table 2).

A typical radar sensor has a range of about 60 m and a field of view of +/-45°. However, the triggering of PCB is calibrated to be quite late, in order to avoid "false positive" triggers and to not intervene when the situation is catchable by the motorcyclist and/or the motorist. The parametric study showed that the field of view and the range have a limited influence on the effectiveness of the system for various crash configurations. The range was set at 30 m for the three configurations and the field of view at 25° for the pessimistic configuration and at 40° for the other two configurations. The most conservative deceleration (3 m/s²) was chosen for the pessimistic evaluation. Given the overall encouraging results of the field tests (21), a deceleration of 5 m/s² was chosen for the medium and optimistic parameter configurations.

Configuration	Range (m)	FOV (°)	Triggering	Deceleration (m/s ²)	Fade-in-jerk (m/s ³)
PESSIMISTIC	30	25	conservative	-3	15
AVERAGE	30	40	standard	-5	25
OPTIMISTIC	30	40	progressive	-5	25

Table 2. Pessimistic, average and optimistic configurations of PCB

For the 60 simulated cases, the median reductions in PTW impact speeds in the three pessimistic, average, and optimistic configurations are 0 km/h, 7.4 km/h, and 11.6 km/h (Figure 5, left). There are, however, 15 crash cases for which PCB does not activate in any of the three configurations, 4 because of the crash configuration and 11 because the rider was already braking with higher deceleration. Excluding these cases, the median speed reduction values are 2.8 km/h, 10.7 km/h and 15.1 km/h (Figure 5, right).

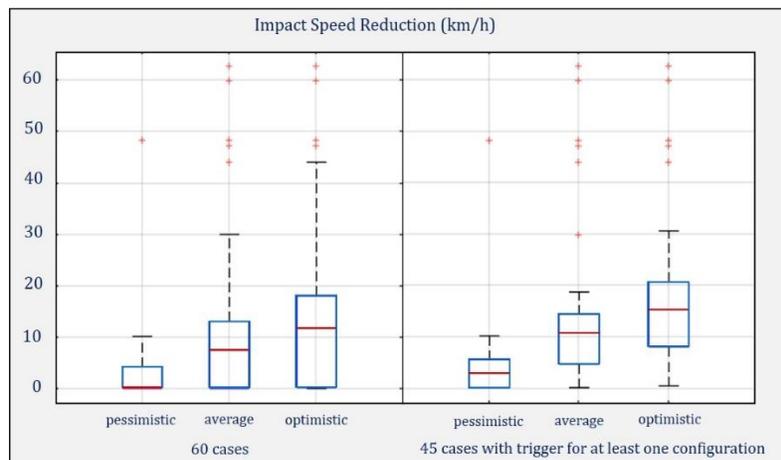


Figure 5. Impact speed reduction for pessimistic, average and optimistic configurations

Discussion

The PCB evaluation was performed through numerical simulations of a set of 60 real-world crashes selected from the InSafe database provided by UniFI and the EDA database provided by Univ. Eiffel, and cinematically reconstructed. The main interest of the study is related to the overall method, which consisted in simulating real accident cases. This approach was especially enriching since the data were crossed between two different databases with accidents having occurred in two different regions. This allowed for a greater variety of situations to be analyzed, in terms of road configuration, accident scenario and speeds of the motorcyclists and motorists involved. However, there are some differences between the samples which made the comparison of the methods more difficult.

The effects were evaluated in terms of PTW impact speed reduction and a parametric approach was conducted. The large number of parameters considered in the analysis (field of view, range, deceleration, fade saccade, triggering, i.e. $5 \times 5 \times 3 \times 2 \times 3 = 450$ configurations) allowed for a wide exploration of the different combinations of system settings. Choices had to be made to exploit the results. In particular, the influence of each PCB parameter was studied by setting average values for the other parameters. Other crossings would be interesting as well.

To achieve useful and realistic levels of speed reduction, it was decided to focus on three parameter combinations, representative of typical system effects with pessimistic (low efficiency), medium, and optimistic (high efficiency) approaches. In 8 out of 60 cases, at least one of the three configurations avoids the accident, which was not foreseen. This positively influences the benefits of PCB. In one third of the cases, the motorcyclist had braked suddenly during the accident, too late to avoid the impact. In these crashes, PCB intervention occurred only in an early activation configuration, before the motorcyclist braked. These cases reduce the overall effectiveness of PCB. The influence of the 15 accident cases where the PCB system did not activate in any of the three configurations is negative on the median reduction of impact speeds. Their inclusion reduces the values obtained from 2.8 to 3.5 km/h. This dispersion of speed

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reduction values led us to focus the results on the median values, which are more robust to extreme values than mean values.

The results obtained for 60 cases allow general trends to be identified. To verify the representativeness and significance of the speed reduction values obtained, a much larger number of cases would have to be found, studied, reconstructed and simulated, which would be a considerable task.

It should be noted that the PCB simulation method involves a rather late triggering, which reduces the influence of the consideration of visibility masks. In reality, these obstacles have a greater influence upstream and delay the detection by the motorcyclist of the opponent vehicle.

Conclusion

This study evaluated the influence of different PCB parameters on the induced PTW impact speed reduction. A FOV value of at least 25° seems required and allows a reduction in impact velocity of about 4 km/h. Going up to 40° the reduction can reach 7.5 km/h and this performance is not significantly improved for a higher FOV. The range has a limited influence on the efficiency of the system since the speed reduction gain is only 0.2 km/h between 30 m and 45 m. The three triggering strategies induce a median reduction in impact speed of 5 km/h, 7.5 km/h and 12 km/h. Taking into account the obstacles to visibility induces an increase in the impact speed of the PTW of 1.5 km/h, only in the case of an early triggering (progressive strategy). Three configurations considered realistic of a pessimistic, an average and an optimistic version of the PCB system were studied. The reductions of PTW impact speeds are 0 km/h, 7.4 km/h and 11.6 km/h.

The results of the parametric study could be useful for the manufacturers of active safety systems for PTWs, for the design of the detection systems, the triggering algorithms and the automatic braking i.e., setting the deceleration level itself. The final objective is to increase the performance of safety systems such as PCB with high field robustness and rider acceptability.

In the framework of the PIONEERS project, these results in terms of impact speed reduction in the pessimistic, average and optimistic configurations were directly used to evaluate injury reductions. Injury risk reductions were then converted into economic gains using the SafetyCube calculator developed in a previous project (22) to evaluate cost benefits.

This study proved the feasibility, relevance and efficiency of a method based on real accident case study combined with PCB modeling and simulation. It can be used to evaluate other active safety systems already on the market or to be prototyped.

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