Are emergency steering assistance systems the new frontier for further enhancing motorcyclists' safety? An exploratory analysis based on crash simulations and field testing

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Research question / Starting point for investigation

While braking assistance systems are gradually being introduced on standard motorcycles, different studies indicate that a large percentage of crashes cannot be avoided or mitigated only by automated braking systems. Recent studies suggested that one of the most promising functionalities among active safety solutions is the Autonomous Emergency Steering System (MAES). MAES could prevent motorcycle crashes in which autonomous braking-based technologies are ineffective, by allowing autonomous emergency avoidance manoeuvres.
This study aims to provide an exploratory estimation of the potential benefits and real-world application of the Autonomous Emergency Steering System (MAES) functionality, in order to foster its development.

Methods

Thirty crash cases sourced from the Italian in-depth databases INSAFE were reconstructed using customised 2D simulation software. For each case, potential swerving options were assessed based on the positions of the host motorcycle and the opponent car, as well as the specific road geometry. Also, different levels of MAES intervention parameters (target roll, roll rate and timing of intervention) were employed to simulate MAES activations aiming to perform lateral evasive manoeuvres. The MAES working parameters employed in the simulations were validated with detailed motorcycle dynamics simulations and compared with those obtained from an exploratory field test campaign which involved an instrumented test vehicle and a surrogate for MAES intervention.

Results

The analysis of the 30 simulated crash cases indicated that MAES could intervene in up to 73.3% of crash cases and potentially prevent the crash with the opponent vehicle in up to 56.7% of cases. The effectiveness of MAES in avoiding crashes depends mainly on the timing of MAES intervention before the crash and secondary on the levels of roll and roll rates used for the evasive manoeuvre (ranging between 25-35° and 50-90°/s in this study). MAES interventions considered to be managed by riders without loss of control presented in previous exploratory studies could provide substantial benefit in preventing crashes if employed with early triggering.

Impacts / Effects / Consequences

Our results indicate that Motorcycle Autonomous Emergency Steering systems can potentially avoid real world. While the development of MAES for integration on standard vehicles remains in its early stages and presents numerous challenges, the promising findings of this exploratory study motivate further research in this area.

1. Introduction

The safety of Powered Two-Wheelers (PTWs) has become a major concern for researchers and industry experts due to the heightened vulnerability of riders in traffic [1-2]. Although there have been significant advancements in road safety, leading to a general reduction of fatalities over the last decades, PTW fatalities increased in both Europe [3] and United States (U.S.) [4]. Even accounting for the Vehicles Mile Travelled (VMT) national estimations from Australia (rates per kilometre) and U.S. (rates per miles) showed that the PTW fatality rates per distance travelled are respectively 29 and 24 times higher than for passenger cars [5-6].

To address this issue, active safety systems have emerged as a promising solution. Among the proposed technologies, several systems focused on the development of braking assistance systems, such as the Anti-lock Braking System (ABS) [7-8] or the Motorcycle Autonomous Emergency Braking (MAEB) [9]. However, despite their promising applicability [10], injury reduction potential [11] and manageable interventions for the riders [12] there is a non-negligible proportion of crashes in which they cannot be employed, or their effectiveness is modest [10]. These are crash configurations in which an avoidance manoeuvre or a trajectory adjustment is more effective than a braking action in avoiding the crash, such high-speed crashes with other vehicles, or single-vehicle loss of controls [13].

Along the lines of the evasive steering systems for passenger vehicles [14-17], emerging research highlights the potential of Motorcycle Autonomous Emergency Steering (MAES) as a complementary safety feature that could address limitations inherent in braking-based technologies [18]. MAES offers an opportunity to enhance rider safety by enabling controlled evasive steering manoeuvres when emergency braking is either insufficient or not applicable.

An initial evaluation of the Motorcycle Autonomous Emergency Steering (MAES) system was conducted in [19], using both simulations and experimental testing. Nine crashes, in which the system was deemed applicable, were reconstructed from real-world incidents that occurred in Italy. These crashes were then simulated to assess the intervention of an ideal MAES system. A straightforward kinematic model was applied in the simulations, with MAES activation simulated at three different lateral acceleration levels: 0.3g, 0.5g, and 0.7g. These accelerations altered the vehicle's trajectory, producing changes in yaw angle and lateral displacement over time.

This paper aims to investigate the potential benefits and feasibility of MAES systems for motorcycles extending the number of simulated crashes and parameters employed. Using crash simulations based on in-depth crash data from the "In-Safe" database, we assess the ability of MAES to perform autonomous evasive manoeuvres and its effectiveness in preventing crashes. By providing insights into the functionality of the MAES, this work contributes to ongoing discussions about the future of motorcycle safety and the potential integration of emergency steering systems into standard motorcycles.

2. Background and Exploratory Testing

A previous study by the authors [19] analysed with systematic approach three new motorcycle emergency steering safety functions. The functionalities were: i) Motorcycle Curve Assist (MCA), which uses digital maps, Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU) to assess the motorcycle's state and provide control actions applying steering torque and deceleration when necessary [2]. This function is intended to support riders in maintaining control, especially during curve navigation, by preventing loss of control or veering off the road; ii) Motorcycle Stabilisation (MS), which monitors the motorcycle's dynamics and uses steering torque to help maintain or regain stability after disturbances, to assist riders during sudden oscillations caused by environmental factors like wind or road unevenness; and iii) Motorcycle Autonomous Emergency Steering (MAES), which uses sensors to detect obstacles and adjusts the motorcycle's trajectory through autonomous steering, based on lateral and longitudinal grip, road conditions, and vehicle positions, aiming to prevent imminent collisions by adjusting the motorcycle's path.

Each function was analysed based on its functionality, purpose, and application using consolidated approaches employed for other safety functions for PTWs. Results indicated that MAES is the most applicable, being relevant in 28.8% of crash cases and with the highest number of crashes (9.8%) in which was classified as fully applicable. MAES was also considered the most effective system across the different crash investigation methods, while the others safety functions are applicable to a smaller proportion of crashes and therefore have lower impact to prevent injuries. The combination of three systems (MCA + MS + MAES) turn out to be applicable in 22.8% of crashes, showing that the systems complement each other without overlap in applicability. MAES provided also the best outcomes in terms of crash mitigation. It had a greater number of crashes where it was considered to have a substantial or excellent effect in avoiding or mitigating crashes compared to MCA and MS, which had lower relevance.

The study also presented an exploratory field test of Motorcycle Autonomous Emergency Steering (MAES) – see Figure 1. The test was designed to evaluate MAES feasibility, particularly focusing on how the rider responds to external steering inputs. This was performed using an instrumented motorcycle, with an inertial measurement unit (IMU) to measure the motorcycle's motion. Steering torque was measured via strain gauges attached to the handlebars. To simulate the steering assistance, the external steering torque was applied manually by a passenger using a rod connected to the handlebars. The test involved lane-change scenarios where the rider had to avoid an obstacle, and the torque application was designed to simulate how a steering assistance system would act in such a case. The experiment measured vehicle behaviour and rider reaction to maintain and regain control after the external steering torque.

The analysis of the data collected during test revealed that the external steering torque applied during the experiment was significant, reaching values of up to 20 Nm, with a duration of over one second. This produced a pronounced motorcycle response, with a roll angle exceeding 20°. Despite the high intensity of the external action, no instability or loss of control was detected. The motorcycle maintained stability, even when the rider applied minimal steering input after the external torque was removed. This suggests that MAES can be integrated into real-world applications without significant risk of destabilizing the motorcycle. The rider provided feedback after each trial, confirming that although the external action was intense, it was manageable. The rider rated the intensity of the external steering action as 6-7 out of 10, indicating moderate-high intensity. They also suggested that an inexperienced rider could probably maintain control, although it would be demanding.

In cases where external steering torque was applied both at the start and midway through the manoeuvre (double actuation), the rider found it easier to regain control compared to when torque was applied only at the start (single actuation). The motorcycle's lateral displacement during the test was significant, averaging 3.7 meters in the double actuation trial. The external steering action produced a lateral acceleration of 0.425 g on average, showing the effectiveness of the external torque in modifying the motorcycle's trajectory.

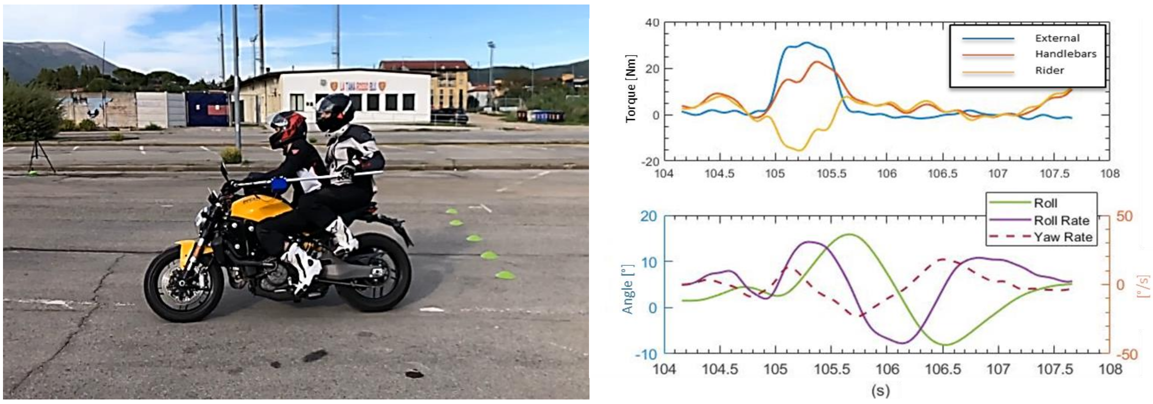

Figure 1 - MAES experimental testing using a rod connected to the handlebar (left) and resulting manoeuvre in terms of steering torque and vehicle dynamics (right) [19].

The overall conclusion was that the external steering assistance system showed promise in improving motorcycle safety in emergency scenarios. The results demonstrated the feasibility of using external steering torque for motorcycle crash avoidance and highlighted the necessity to further investigate the MAES functionality in terms of parameters of intervention and related benefits before performing extensive field testing.

3. Methods

Computer simulations were used in this study to reconstruct real-world crashes sourced from the Italian crash database "In-Safe" and evaluate the potential applicability and benefits of MAES with different intervention parameters using a counterfactual approach. The simulations considered a range of MAES parameters as defined in the following paragraph.

3.1. Crash data and reconstruction model

Crash cases for simulations were sourced from the "In-Safe" database, which compiles crash data from the metropolitan area of Florence, Italy [20]. A total of thirty cases (convenience sample) were selected and reconstructed as employed in previous studies [21] based on detailed crash descriptions provided in the database. These descriptions included factors such as road layout, marks recorded at the crash scene, vehicle damage, rider injuries, and police reports. The crashes analysed primarily involved L3 PTWs (77%) and a smaller proportion of L1 PTWs (23%). The distribution of crash types was as follows: head-to-side (T-bone) (56.7%), head-on (16.7%), sideswipe (16.7%), and head-to-rear (10.0%) - for a detailed definition of crash configurations, refer to [22].

The crash reconstructions were carried out using a 2D simulation tool developed by UNIFI, which had been utilized in previous studies on Motorcycle Autonomous Emergency Braking (MAEB) [9]. Each case was initially reconstructed within the virtual environment and validated by cross-referencing with data from the database, including impact speeds and the relative positions of the vehicles, in alignment with detailed information from crash investigators. Following the reconstruction, the intervention of MAES, under various parameter settings, was simulated (see the next section). The impact of MAES was assessed in terms of crash avoidance success, MAES activation, and trajectory modification.

3.2. Simulation

The intervention of MAES was tested using the same 2D software employed for crash reconstruction, with various operational parameters under consideration. Starting from crash simulations, the autonomous steering intervention was modelled by adjusting the vehicle's roll according to a specified ramp profile of roll rate. The trajectory modelling approach for swerve manoeuvres operated by MAES is inspired by the theory and experimental results presented previous work on emergency evasive manoeuvres [13]. The working parameters of MAES intervention were selected based on prior studies and testing [19]. For each crash scenario, simulations were conducted under different triggering strategies and by varying a set of parameters, as discussed in the following section. After MAES activation, a linear ramp of roll rate was applied to the host PTW, continuing until the roll target value was reached. The roll rate remained constant during the ramp, with its duration dependent on the vehicle's pre-crash conditions. Once the maximum roll was achieved, it was maintained for about 1 seconds from the initiation of the manoeuvre. This duration was chosen to ensure a total manoeuvre time of approximately 1.5 seconds, which aligns with previous studies that tested similar swerve manoeuvres [19]. The MAES intervention was evaluated in terms of trajectory change compared to the crash (see Figure 2) and crash avoidance. In the simulations, both the host PTW and the opponent vehicle were represented as simplified two-dimensional (2D) rectangular boxes. A crash event was defined as the moment when the edges of the two boxes came into contact.

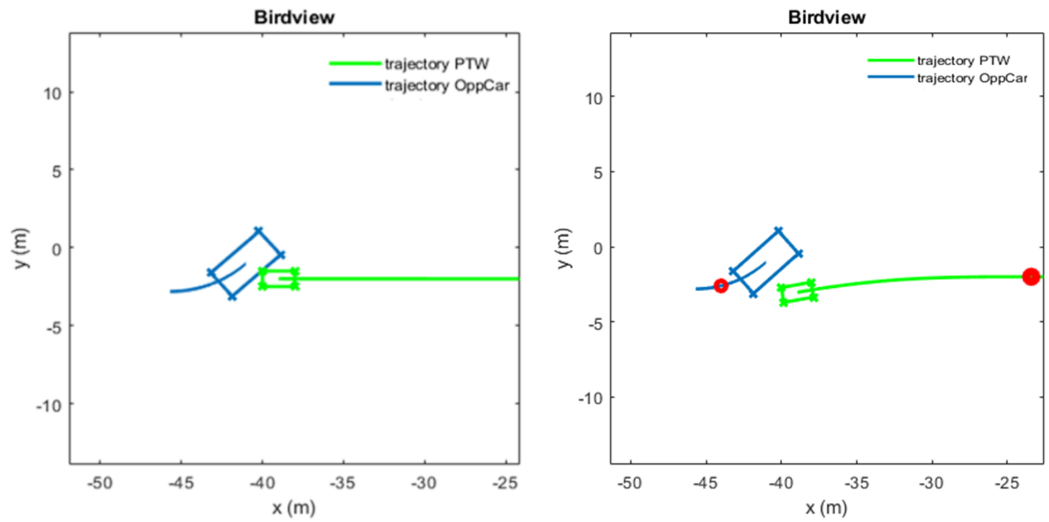

Figure 2 - Trajectory of the two vehicles (case ID-46: motorcycle, in green and opponent car, in blue) in crash reconstruction without intervention of MAES (left) and with intervention of MAES (right – red point is vehicles position at MAES trigger).

3.3. Emergency Steering intervention parameters

Crash simulations were conducted to evaluate the impact of four parameters associated with the automatic steering system (Triggering Strategy, Roll target, Roll rate target, and Swerve direction) on the effectiveness of MAES. An overview of the parameters' ranges utilized in the simulations is provided in Table 1.

The **Triggering Strategy** determines the timing for deploying MAES by identifying the point at which a collision between the PTW and the opposing vehicle or object becomes inevitable. Different triggering strategies are defined based on various deceleration thresholds in both the longitudinal and lateral directions achievable by the PTW, corresponding to distinct time-to-collision points at which the MAES is activated. Detailed definitions of these triggering strategies are provided in [23]. For this study, the three triggering strategies named "Conservative", "Standard," and "Progressive" were employed, assuming an extra 0.5 s of time-to-collision compared to the baseline used in a previous study [21] in autonomous emergency braking.

Three values of ***Roll target*** were employed in crash simulations: this parameter represents the target roll the MAES is intended to achieve during its intervention to provide the swerve manoeuvre. Values up to 35° were employed in the simulation as considered achievable and by most motorcycles and controllable even on wet surfaces. These values were selected starting from the 25° of roll angle in previous studies in field testing

Three levels of ***Roll rate target*** were tested in the simulations, respectively 50°/s, 70°/s, 90°/s. These parameters represent the sharpness of the swerve manoeuvre once the MAES is triggered up to achieving the roll target.

The ***Swerve direction*** represents the direction in which the motorcycle is intended to swerve; such direction influences the sign of roll target and roll rate employed for simulations. In this study, both directions of swerving were analysed, considering that the MAES intervention in each case could be triggered in both directions based on the specific environmental conditions (e.g. carriageway width and position, other vehicles, etc.). In the results presented in the following sections, for each crash case the left-hand-side swerve was first considered as the preferred option for the MAES manoeuvre. In cases in which the left-hand-side swerve was not effective, right-hand-side swerve was considered. The optimal group reported in the result section considers cases in which the crash was mitigated or avoided with MAES swerve on left- or right-hand side.

For other MAES parameters which were not the core of the analysis presented in this paper, a single value was used in simulations. Regarding the obstacle recognition system which identifies the opponent vehicle up to MAES triggering, a theoretical ***Field of View*** of 100° and a ***Range*** of 60 m were employed. The combination of Range and Field of view represents the width in degrees and the maximum distance of the obstacle recognition cone in which an opponent vehicle or object can be recognised by the obstacle recognition system. Even though state-of-the-art radar technology is capable to wider range and field of view, previous studies on motorcycle automated safety functions indicated that these values are adequate to cover the vast majority of crash cases [21].

Table 1 - Set of MAES intervention parameter tested in simulations

Parameter	Range
Triggering strategy	[conservative, standard, progressive]
Roll target	[25°, 30°, 35°]
Roll rate target	[50°/s, 70°/s, 90°/s]
Swerve direction	[left, right]

3.4. PTW trajectory validation using BikeSim

To validate the Motorcycle Autonomous Emergency Steering (MAES) intervention used in the simplified model presented in the previous paragraph, a set of swerve manoeuvres were simulated using the detailed motorcycle simulation software BikeSim. The simulation setup involved a

motorcycle and a scooter subjected to simulated emergency steering actions at three different speeds (see Table 2). These speeds were chosen as approximately the 25th and 75th percentile of driving speed of PTWs involved in the 30 crash cases considered in this study.
A swerve manoeuvre was designed to emulate a sudden obstacle avoidance scenario. The manoeuvre involved a lateral displacement of the vehicle with a steering input using a roll rate of 70°/s up to a target roll of 30°.
The simulations were performed for all combinations of vehicle types and speeds, resulting in six test cases (see Table 2). For each scenario, the same external conditions were applied, including road surface friction and weather, to ensure comparability across simulations.
The swerve trajectory and steering torque result of BikeSim simulations were used as a baseline for validating the MAES system intervention result of the simplified model.

Table 2 – Simulated swerve manoeuvres

Type of PTW	Speed [km/h]	Target Roll [°]	Roll rate [°/s]
Motorcycle	40	30	70
	60	30	70
	80	30	70
Scooter	40	30	70
	60	30	70
	80	30	70

4. Results

The effects of the MAES safety system and its parameters were analysed by reconstructing and simulating thirty real-world crash cases occurred in Italy. Notably, over 50% of these crashes were PTW front-end collisions with the side of another vehicle.
Three configurations of the trigger strategy, three for the roll rate target, and three for roll angle target were utilized to investigate the impact of these parameters on the MAES effectiveness. Considering all the possible combinations of these parameters, a total of 810 simulations were conducted for both the left- and right-hand swerving directions. Additionally, to obtain a best-case scenario, for cases where swerving towards the left did not lead to crash avoidance, the right-hand-side simulation was examined and employed if it successfully prevented the crash. As expected, this optimal scenario -which assumes the MAES can accurately determine the best swerving direction and that swerving in that direction is feasible- yielded the highest number of simulations that resulted in crash avoidance (Table 3).

Table 3 - Simulation outcome by swerving directions and for the optimal scenario

Simulation outcome	Left swerving	Right swerving	Optimal scenario
MAES inactive, crash not avoided	359 (44.3 %)	396 (48.9 %)	336 (41.5 %)
MAES active, crash not avoided	312 (38.5 %)	263 (32.5 %)	248 (30.61 %)
MAES active, crash avoided	139 (17.2 %)	151 (18.6 %)	226 (27.9 %)

4.1. Crash avoidance

The effectiveness of MAES in avoiding crashes is positively correlated with the intensity of the emergency swerving manoeuvre (Figure 3). For instance, as the roll angle and roll rate of the manoeuvre increase, the number of simulations resulting in crash avoidance rises by approximately 20% to 30% - see Figure 3.

Table 4 - Proportions of crash avoided by nominal parameter variations

Triggering strategy	MAES active, crash avoided	Roll angle target (°)	MAES active, crash avoided	Roll rate target (°/sec)	MAES active, crash avoided
Conservative	25/270 (9%)	|25|	61/270 (23%)	|50|	62/270 (23%)
Standard	66/270 (24%)	|30|	76/270 (28%)	|70|	77/270 (29%)
Progressive	135/270 (50%)	|35|	89/270 (33%)	|90|	87/270 (32%)

At the same time, the choice of triggering strategy had a more significant impact on crash outcomes compared to roll angle and roll rate (see Figure 3). Early intervention by MAES ("Standard" and "Progressive" triggering strategies) led to a more than double increase in the proportion of crashes avoided independently from the roll angle and the roll rate adopted. In contrast, the two parameters roll angle and roll rate exhibited a slighter increase in the proportions of crashes avoided as their values increased, indicating that while they contribute to improved performance, the triggering strategy is the more decisive factor for crash avoidance.

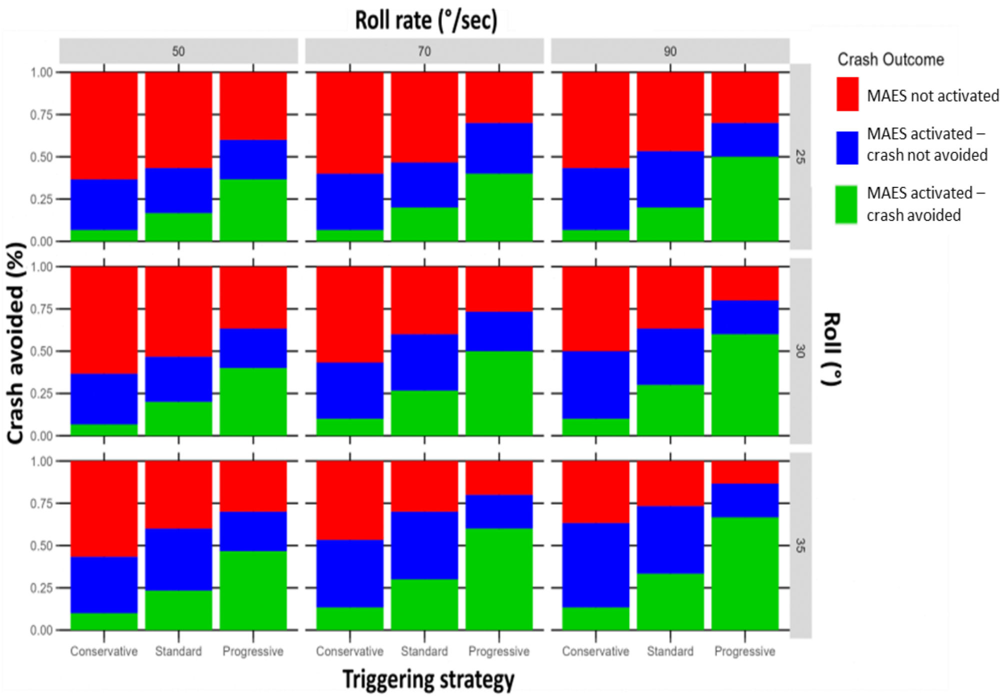

Figure 3 - Crash outcome distribution among the different nominal parameter investigated

4.2. MAES Activation

In all simulations, MAES was able to complete over 50% of the avoidance manoeuvre, intended as the achievement of the target roll angle, showing a consistent performance regardless of the target roll angle employed (see Figure 4). However, conservative triggering and higher roll target entailed lower proportion of cases in which the roll target was achieved.

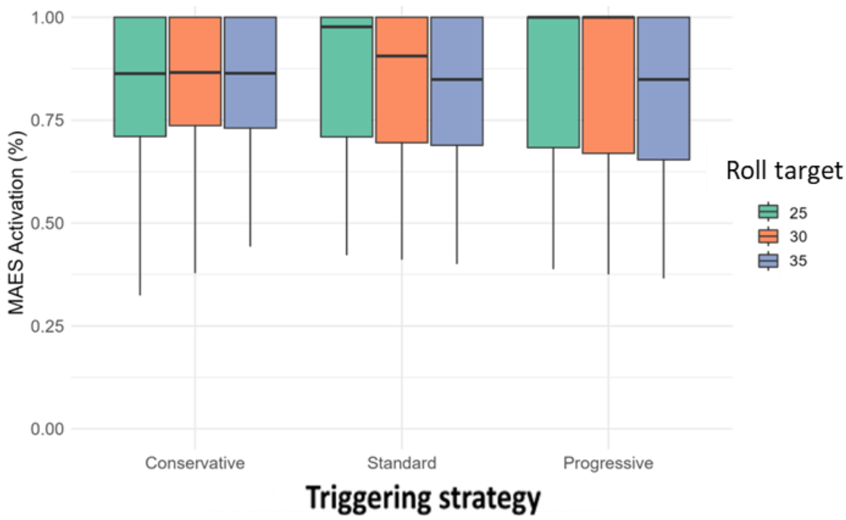

Figure 4 - MAES activation: roll target achievement distribution with different triggering strategies

In opposing, changes in the target roll rate considerably affected the completion of the manoeuvre. As expected, a lower roll rate of 50°/s resulted in an increased time required for MAES to complete the avoidance manoeuvre, ultimately preventing it from achieving full completion before the crash (see Figure 5).

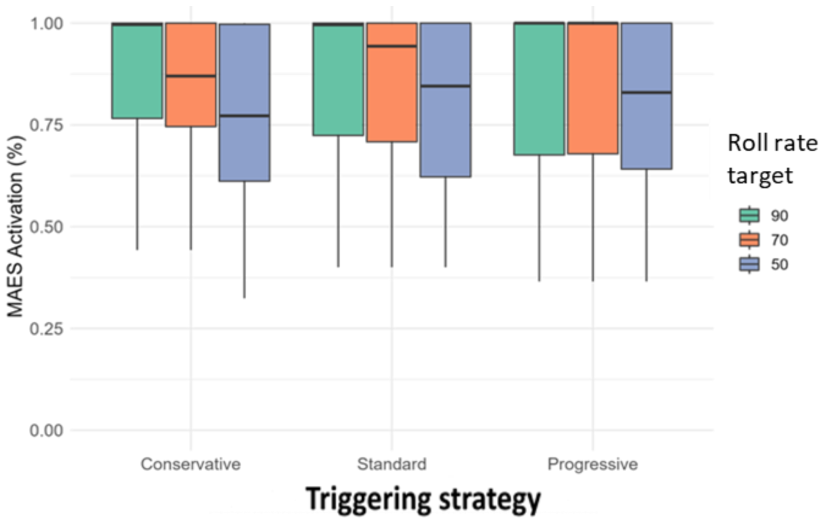

Figure 5 - MAES activation: roll target achievement distribution with different triggering strategies and target roll rates

4.3. Lateral Displacement

Most of the simulations among the different crash configurations reached at most 1 m of lateral displacement, while only few reached higher values (Figure 6). Notably, small variations were observed considering the specific crash configuration.

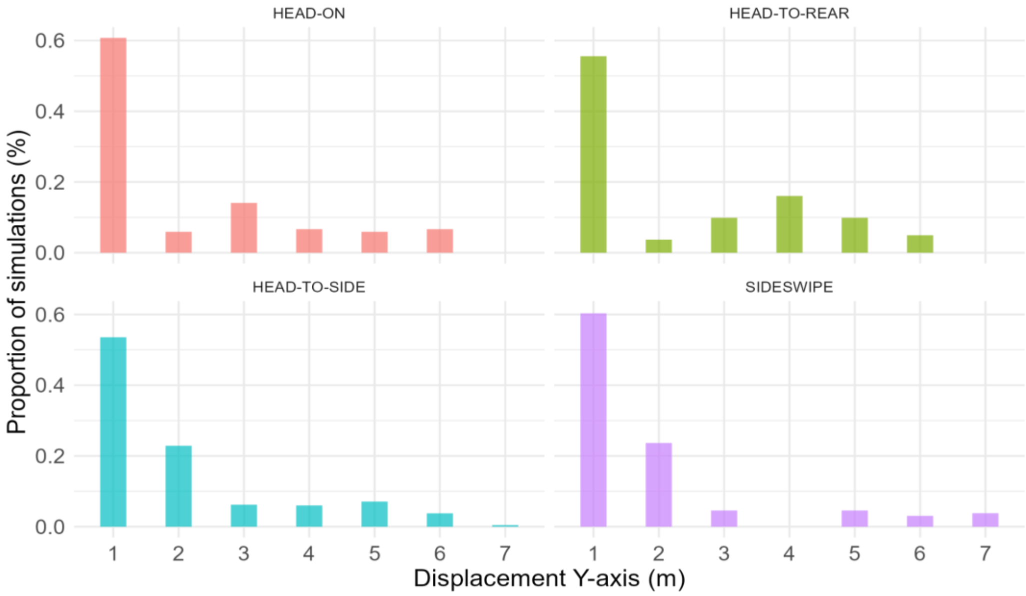

Figure 6 - Lateral displacement of PTW after MAES intervention clustered for crash configuration

However, considering only simulations that resulted in crash avoidance, sideswipe-type crashes required higher displacement values to avoid collisions compared to other configurations (*Figure 7*).

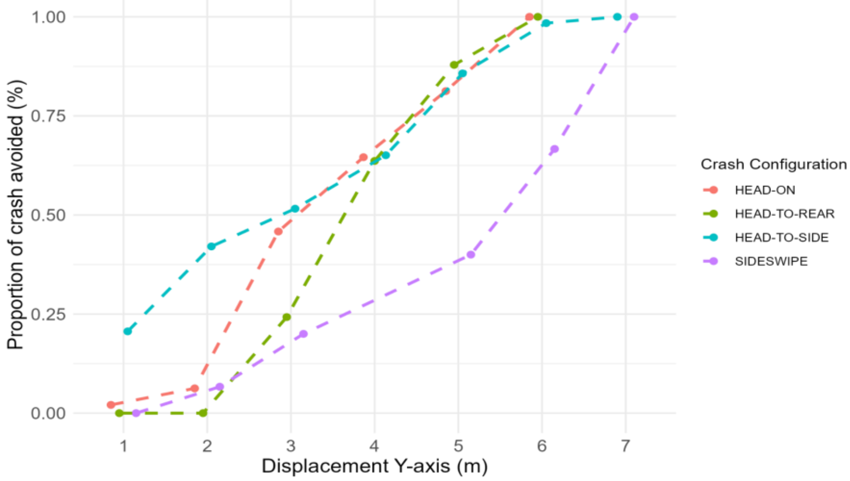

Figure 7 - Simulated lateral displacement of PTW after 1.5 s of MAES intervention in the different crash configurations

4.4. Comparison of trajectories

The BikeSim simulation results show that the steering torque required for both motorcycles and scooters increased with speed, ranging from 20 Nm at 40 km/h to 37 Nm at 80 km/h for the motorcycle, and from 23 Nm to 34 Nm for the scooter. The swerve manoeuvre at higher speeds resulted in a longer swerve trajectory, as shown in Figure 8. The PTW trajectories after MAES intervention indicated that as activation speed increased, the lateral displacement and overall manoeuvre duration extended.

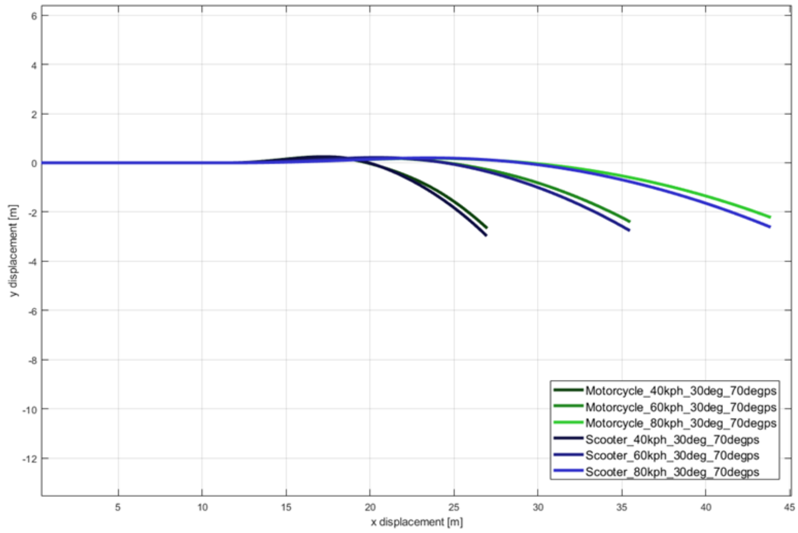

Figure 8 - Simulated PTW trajectories after MAES intervention at 40, 60, and 80 km/h

Figure 9 presents a comparison of the PTW trajectories from the simplified model and the detailed BikeSim simulations. The differences between the two models are minimal, with trajectory deviations limited within a small margin across two test cases, supporting the validity of the simplified approach for predicting swerve manoeuvres. These differences are primarily due to BikeSim's more detailed and physically accurate representation of motorcycle dynamics, which accounts for factors such as suspension and tire behaviour.

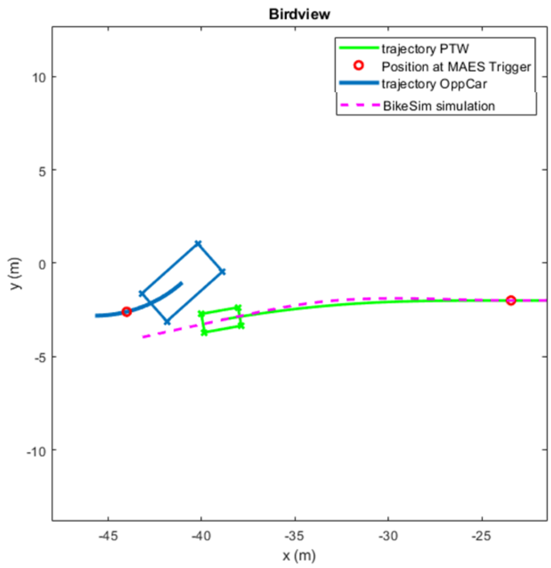

Figure 9 - Trajectory of the two vehicles (case ID-46: motorcycle, in green and opponent car, in blue) in simplified crash reconstruction and BikeSim detailed trajectory simulation (dotted purple)

5. Discussion

The main goal of this study was to evaluate the influence of different parameters of Motorcycle Autonomous Emergency Steering (MAES) system in preventing crashes through emergency swerve manoeuvres. Using a simplified simulation model, 30 real-world crash cases from the "In-Safe" database were reconstructed, and the impact of relevant MAES parameters (namely, triggering strategy, target roll angle, and target roll rate) was analysed. The results showed that early activation of MAES, particularly with "Standard" and "Progressive" triggering strategies, significantly improved crash avoidance rates. Roll target and Roll rate has also an influence on MAES capability to avoid first impact in crash cases, but lower compared to the triggering strategy. The analysis was validated with detailed motorcycle dynamics simulation software, indicating a good accordance with the simplified model in terms of trajectory and parameters.

While the results of this study offer valuable insights into the potential effectiveness of automated emergency steering actions for crash avoidance, some limitations must be acknowledged. First, the simulations were based on a limited number of crash cases, and a broader analysis with a larger dataset is needed to ensure the generalizability of the findings. Additionally, the crash reconstructions used a simplified model, which, although validated in one case using BikeSim, requires further validation using a wider range of scenarios to strengthen the robustness of the analysis.

A key point of the study lies in the significant influence of the triggering strategy on the capability of MAES to avoid crashes: the results showed that early MAES intervention using the "Standard" and "Progressive" strategies had a greater impact on avoiding collisions compared to variations in roll angle or roll rate. This suggests that optimizing the timing of activation may be more critical than adjusting the manoeuvre dynamics. However, from previous studies on automated braking for PTWs, we know that early intervention can have an influence on MAES acceptability among users. Active safety system such as MAES have always to ensure on standard vehicles a very limited number of false positives, and these cases must always ensure safety and controllability of the vehicle for users. This issue remains the greater challenge to be addressed for automated safety systems as MAES.

While the MAES in most cases completed the avoidance manoeuvre reaching the target roll angle, further investigation is needed to evaluate the influence on its intervention on trajectories. The analysis was performed without considering the effect of lateral displacement and its feasibility in the real world. This remains a further key point to be investigated, in order to identify the real applicability in the different crash conditions. The validation proposed in this study indicated a limited discrepancy in trajectory outcomes between the simplified and detailed simulation method, suggesting that the simplified model can reliably replicate the dynamic behaviour observed in more complex simulations.

The findings of this study build on the conclusions of previous research, which highlighted the potential of external steering assistance systems in enhancing motorcycle safety during emergency situations. While the earlier study suggested a preliminary feasibility of using external steering torque for crash avoidance, it emphasized the need for further investigation into MAES intervention parameters and their benefits. This study expands that by exploring a wide range of MAES parameters and highlighting that early activation plays a critical role in improving crash outcomes, while MAES parameters tested in previous studies showed in our simulations a potential to prevent crashes when used with early intervention strategies.

6. Conclusions

The analysis of the different MAES intervention parameters indicated that emergency steering can provide collision avoidance in different crash scenarios involving a host PTW and an opponent vehicle. The results highlight how the choice of triggering strategy, roll angle, and roll rate influences the success of the avoidance manoeuvre. The selection of an appropriate set of parameters is key for the effective implementation of MAES. Future analysis should now aim to assess the feasibility of such parameters from both a technical and rider perspective.

Additional focus should be placed to evaluate if MAES trajectories are compatible with real-world crash cases, with a focus on vehicle's realignment phase (completion of lane change manoeuvre up to regain initial PTW roll), which requires smooth interaction with the rider, ensuring a gradual recovery of control.

Disclosure statement: *All authors have read and agreed to the submitted version of the manuscript. The authors declare no conflict of interest.*

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