Highlights

Motorcycle emergency steering assistance: A systematic approach from system definition to benefit estimation and exploratory field testing

Mirco Bartolozzi, Adelmo Niccolai, Cosimo Lucci, Giovanni Savino

- Steering assistance systems for motorcycles can prevent or mitigate crashes
- Three systems were defined, having complementary applicability and effectiveness
- Motorcycle Autonomous Emergency Steering (MAES) is particularly promising
- Moderate actions avoided simulated real-world crashes or reduced fatality risk
- Applying a superimposed action to avoid an obstacle was manageable by a real rider

Motorcycle emergency steering assistance: A systematic approach from system definition to benefit estimation and exploratory field testing

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Abstract

Braking assistance systems are already contributing to improving motorcyclists' safety, however, research on emergency systems acting on the steering is lacking. These systems, already available for passenger cars, could prevent or mitigate motorcycle crashes in which safety functions based only on braking are ineffective. The first research question was to quantify the safety impact of diverse emergency assistance systems acting on the steering of a motorcycle. For the most promising system, the second research question was to assess the feasibility of its intervention using a real motorcycle.

Three emergency steering assistance systems were defined in terms of Functionality, Purpose, and Applicability: Motorcycle Curve Assist (MCA), Motorcycle Stabilisation (MS), and Motorcycle Autonomous Emergency Steering (MAES). Experts evaluated each system's applicability and effectiveness based on the specific crash configuration (using Definitions for Classifying Accidents - DCA), the Knowledge-Based system of Motorcycle Safety (KBMS), and the In-Depth Crash Reconstruction (IDCR). An experimental campaign was conducted with an instrumented motorcycle to assess the rider's reaction to external steering input. A surrogate method for an active steering assistance system imparted

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external steering torques in correspondence with a lane change to analyse the effect of the steering inputs on motorcycle dynamics and rider controllability.

MAES globally got the best score for each assessment method. MS received better evaluations than MCA in two out of three methods. The union of the three systems covered a sizeable fraction of the crashes considered (maximum score in 22.8% of the cases). An estimation of the injury potential mitigation, based on injury risk functions for motorcyclists, was made for the most promising system (MAES). The field test data and video footage showed no instability or loss of control, despite the high intensity ($> 20\,\mathrm{N\,m}$) of the external steering input. The rider interviews confirmed that the external action was intense but manageable.

For the first time, this study presents an exploratory assessment of the applicability, benefits, and feasibility of motorcycle safety functions acting on the steering. MAES, in particular, was found applicable to a relevant share of crashes involving motorcycles. Remarkably, applying an external action to produce a lateral avoidance manoeuvre proved feasible in a real-world test setting.

Keywords: Road safety, Motorcycle steering assistance, Injury mitigation, Emergency avoidance, Crash prevention, Experimental testing

1. Introduction

1.1. Background

The safety performance of road vehicles has seen significant improvement in the past two decades due to recent technological advancements and the introduction of advanced driver assistance systems. This development has also extended to Powered Two-Wheelers (PTWs - which include motorcycles, scooters, and mopeds), for which several systems like the Anti-lock Braking System (ABS), Traction Control (TC), and Motorcycle Stability Control (MSC) have already gained recognition in preventing crashes [1, 2, 3].

Despite significant improvements, PTWs still represent a high-risk option compared to other modes of transportation due to the increased likelihood of severe injuries and fatalities in the event of a crash [4]. In order to further enhance the safety performance of PTWs, various assistance systems are currently under design or in early-stage testing, and they could become available in the future. Such systems include collision avoidance, intersection support, and curve warning [5]. According to a recent systematic review, among the active onboard systems under development, those capable of autonomously modifying vehicle dynamics are considered the most promising [5].

An example is Motorcycle Autonomous Emergency Braking (MAEB), a system designed to deploy a braking action autonomously without requiring input from the rider when an imminent collision is detected to mitigate rider injuries by reducing impact speed. Its applicability has been investigated in different traffic environments [6], with promising outcomes in reducing injuries [7], and its intervention resulted manageable by ordinary riders in real-world conditions [8]. Although MAEB was shown to be applicable also during lane change manoeuvres [7], its application is essentially designed for straight-line riding conditions with limited roll angles.

There is a non-negligible proportion of crashes in which MAEB cannot be employed, or its effectiveness is modest [6]. These are the crash configurations in which an avoidance manoeuvre or a trajectory adjustment is more effective than a braking action in avoiding the crash [9], such as crashes without the direct involvement of other vehicles or crashes caused by vehicle loss of control. At present, no active assistance system for PTWs that control the steering of the vehicle to modify the trajectory autonomously is currently available, as identified by the aforementioned systematic review [5].

1.2. Objective and outline

This paper aims to provide an exploratory assessment of the potential of innovative safety systems for PTWs based on emergency steer control actions aiming to modify or stabilise the trajectory of a PTW to prevent or mitigate crashes. The assessment will be based on their applicability to different crash scenarios and configurations and on the estimate of their effectiveness in avoiding or mitigating crashes. The most promising system shall also be evaluated concerning its benefits in reducing the risk of injuries for the rider and the feasibility of its action in the real world through preliminary field trials.

The article is structured as follows. Section 2 describes the three safety systems considered in the article, the three investigation methods used to assess the applicability and effectiveness of each function, the approach used to estimate the injury reduction in a selected case of real crashes, and the test protocol used to experimentally test the feasibility of changing the PTW's lateral position through external steering actions. Section 3 presents the results regarding applicability and effectiveness. Additional results regarding injury mitigation potential and experimentally tested feasibility are provided for the most promising system. Section 4 presents a detailed discussion regarding these results and their significance. Finally, Section 5 summarises these findings, their potential consequences, and potential future uses.

2. Materials and Methods

2.1. Safety Functions Considered

This work employs the concept of *Safety Function* (SF). Following the definition of Gil et al., an SF "unequivocally describes the desired outcome for a safety solution, emphasising its goals regardless of the constitutive mechanisms or sub-systems" [10, p. 2]. The three SFs proposed and evaluated in this work are Motorcycle Curve Assist (MCA), Motorcycle Stabilisation (MS), and Motorcycle Autonomous Emergency Steering (MAES), defined as follows:

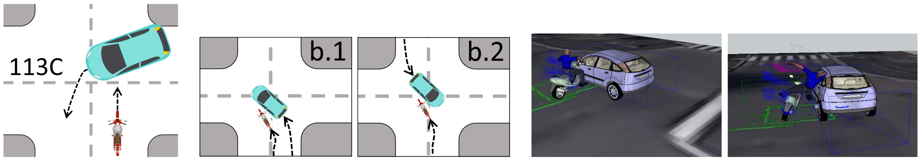
- MCA: Helps the rider to approach or negotiate a curve when the current speed or trajectory is inappropriate [11].
- MS: Helps the rider to assure the vehicle stability or dampen the oscillations after some perturbation which might cause the loss of control (road unevenness, wind, momentary loss of friction).

- MAES: Acts autonomously or assists the rider in modifying the motorcycle trajectory to avoid an imminent collision or a crash.

Each SF is defined in terms of Functionality (What it does, and how), Purpose (Its aim), and Application (The conditions under which it applies to the scenario), described in detail in Table 1. In the article, the SFs will be evaluated through the concepts of *Applicability* ("Does the SF apply to the crash scenario? Is the SF relevant in the crash scene?") and *Effectiveness* ("If the safety function applies to the scenario, how helpful is it?"). Functionality, Purpose and Application are characteristics inherent to the SF; instead, Applicability and Effectiveness are relative to the interaction of the SF with a specific scenario.

Table 1: The Functionality, Purpose, and Application of each Safety Function (SF) considered in the study.

SF	Functionality	Purpose	Application
MCA	Utilises a motorcycle model, digital map, GNSS, and an IMU to estimate the motorcycle's state and compute control actions to keep the rider safe on the road. Intervenes through steering torque and deceleration adjustments if the actual manoeuvre deviates from that computed over a threshold.	Helps the rider to stay on the road and in their lane, while approaching and navigating curves by applying countermeasures, namely reducing speed or adjusting lane position, to prevent loss of control or veering off the road.	Applicable when the rider may be approaching or navigating a curve with excessive speed, incorrect trajectory, or improper inputs.
MS	Monitors the motorcycle dynamics and adjusts steering torque to prevent or reduce potential loss of control or oscillation.	Assists rider in controlling the vehicle during disturbances (e.g. lateral wind, loss of friction, wobble) to minimise oscillation or maintain control.	Applies when the rider struggles to maintain motorcycle stability due to external disturbances or inherent oscillation modes
MAES	Scans surroundings using sensors, predicts collisions, and applies steering torque to adjust trajectory based on constraints (lateral, longitudinal grip) and boundary conditions (road width, vehicles positions) when the time to collision falls below a threshold.	Prevents imminent crashes or assists the rider in avoiding them by adjusting the vehicle's trajectory	Applicable when it detects an obstacle and is feasible to trigger a new trajectory by obtaining the required lateral acceleration. It can be applied when there are other vehicles or obstacles present in the surroundings.



(a) DCA Configuration 113C.

(b) KBMS Scenario b (Configurations b.1, b.2).

(c) IDCR Crash ID116.

Figure 1: Examples of crash scenarios for the DCA, KBMS, and IDCR approaches.

2.2. *Crash Data Investigation*

This work involved six evaluators, academic mechanical engineers with experience in road safety research and motorcycle dynamics. The group consisted of the four authors and two external evaluators. Four of them owned a motorcycle licence. Their experience ranged from two to 15 years, with a 4 year median and 6.8 year mean.

2.2.1. *DCA*

The VicRoads Definitions for Classifying Accidents (DCA) is a coded chart used to report crashes in Australia and to describe the crash configurations [12]. Savino et al. [13] expanded the number of configurations from 81 to 152 to unequivocally describe the trajectory of the motorcycles concerning the opposing vehicle. Each configuration was represented through a specific pictogram: an example, re-drawn, is shown in Figure 1a (crash configuration 113C - 'Adjacent direction, PTW into car' [6]).

A four-class code system was developed to describe the *Applicability*. The possible classes, or scores, were '1' ("The system would *not* have applied to crashes belonging to this specific scenario"), '2' ("Would possibly have applied", controversial), '3' ("Would probably have applied", technical challenges still need to be solved), and 4 ("Would have applied", typical application of the system).

In the current article, detailed and specific rules were defined for each SF considered and each rating class; this reduced the possibility of an incorrect interpretation by the examiners during the evaluation process. The examiners were aided by one flowchart for each SF (provided in Appendix A). Scores were given only on whether a system would be relevant to the crash scenario; the possible, consequent crash avoidance or mitigation was not considered. A subset of the evaluators was used: two authors independently assigned a score to each SF for the DCA scenario. When the two evaluators disagreed, a third examiner provided an additional score, and the score given twice was chosen. If all three evaluators disagreed, as it happened in two scenarios, the median of the three scores was taken. The categorisation agreement was analysed through Cohen's quadratically weighted kappa coefficient and used as a measure of inter-rater reliability statistics [14, 15]. Weights of 0, 0.55, 0.88, and 1 were used for instances of complete agreement, a difference of one class, a difference of two classes, and a difference of three classes, respectively. Consequently, higher degrees of disagreement were weighted more than lower ones to reflect the unequal distinction between categories.

In this work, the Prato-X database was used for the DCA assessment. The database includes the crash reports collected by the police in 2018 on the roads of the municipality of Prato (Italy). In particular, only the crashes involving at least one Powered Two-Wheeler (PTW) were used: these were extracted from the database by Terranova et al. [6]. A total of 285 crashes were classified following the DCA, using additional variables in some scenarios, like the presence of loss of control, to specify the circumstances of each crash better. To summarise, the evaluators assessed the applicability of each safety function for each of the 152 DCA scenarios; each of the 285 crashes of the Prato-X database then received the score of its corresponding DCA scenario.

2.2.2. KBMS

The Knowledge-Based system of Motorcycle Safety (KBMS) was used in a previous work by Gil et al. [10] to evaluate the *Effectiveness* of SFs for PTWs. A summary of the methods is given here: refer to Gil's work for a more detailed description. The process is divided into two phases:

Table 2: Scoring scale used to evaluate the *Effectiveness* of each Safety Function with respect to the three intervention mechanisms: 'Prevention' (the SF prevents the occurrence of a dangerous situation), 'Avoidance' (the SF intervenes in a dangerous situation and avoids the crash), and 'Mitigation' (the SF intervenes in a dangerous situation and mitigates the crash consequences).

Score	Meaning
0	The SF *never* activates / produces *no effect*
1	Assuming activation, the outcomes are *poor*
2	Assuming activation, the outcomes are *minor*
3	Assuming activation, the outcomes are *good*
4	Assuming activation, the outcomes are *excellent*

1. *Collecting Phase.* Crashes are extracted from crash databases and divided into subsets by crash configuration (26 crash scenarios, grouped into 9 general scenarios) based on a set of queries. Figure 1b shows, as an example, a re-drawn version of the pictogram corresponding to the general scenario 'b', divided into the two crash scenarios 'b.1' and 'b.2' [6]. A panel of experts is defined; each evaluator assesses the *effectiveness* of each SF for each motorcycle road crash scenario. A scoring scale was defined to guarantee consistency in the scores assigned by evaluators, and it is provided in Table 2. The scores ranged from '0' ("The SF *never* activates or produces *no effect*") to '4' ("Assuming activation, the outcomes are *excellent*") and were given concerning each of the following intervention mechanisms: *Prevention*, *Avoidance*, and *Mitigation*.
2. *Processing Phase.* A crash database is chosen. All information collected about crashes, like the statistical relevance of each type of crash and the potential of each SF given by the expert, are implemented through the equations described by Gil et al. to obtain a list of prioritised SFs.

In this article, the KBMS method was employed considering three years of the ISTAT database (2010-2012, comprising 205,272 PTW crashes that occurred in Italy). The KBMS was populated through the assessment by the complete pool of experts, who estimated the potential of each of the three SF proposed in this article.

2.2.3. IDCR

The In-Depth Crash Reconstruction (IDCR) method evaluates the effectiveness of the SFs on real crash scenarios, contrary to the DCA and KBMS methods, where the crashes were schematised and simplified in appropriate crash configurations. Therefore, the IDCR method requires more time to investigate a single crash. This method allows checking whether the results obtained by the SFs when using a large number of less detailed crashes are coherent with those obtained considering a smaller number of crashes described in-depth.

In this work, the method was applied to crashes in the In-SAFE database, which occurred in the area of Florence (Italy), where at least one PTW was involved, in the 2009-2013 period [16]. The pre and post-crash dynamics of each case collected were reconstructed in detail: the travelling speed, the trajectory of the vehicles, and other parameters, such as the weather and lighting conditions, are known. Figure 1c provides an example, showing the reconstructed crash 'ID116'. A subset of the pool of experts was used in the assessment, consisting of three evaluators (only one also took part in the DCA assessment). They evaluated 19 cases; the final score for the safety function in the specific crash is obtained from the discussion and agreement between the three researchers. The scoring scale is the same one used in the KBMS method (Table 2).

2.2.4. Injury Mitigation

Lucci et al. [11] estimated the predicted injury risk reduction due to a system that slowed down the motorcycle when approaching a corner at excessive speed. This safety function, called Motorcycle Curve Assist, had a similar aim to the version proposed in the current article (which also acts on the steering). For MS, this method for estimating injury mitigation was not appropriate, as it was based on reducing relative crash speed; in fact, MS focused on crash avoidance instead of mitigation. Therefore, the approach was applied only to MAES.

A subset of the crashes employed in the IDCR method was used to evaluate the injury reduction benefits of MAES intervention, even when there were insufficient times to avoid the opposing vehicle since the system was activated. In particular, nine crashes (more than the number of crashes that received scores '3' or '4' in IDCR, equal to eight) were considered among those where another vehicle was involved. After reconstructing the crash scenario, the same crash was simulated with the hypothesis of a MAES intervention which changed the vehicle's trajectory. Three MAES activation simulations were done for each crash, using three lateral acceleration values (0.3g, 0.5g, 0.7g). Given the potential complexity of MAES control logic, and the exploratory scope of this work, a simple kinematic approach was used. The activation of the system modified the vehicle's trajectory: it produced a lateral acceleration, inducing a yaw angle variation and a lateral displacement over time. The vehicle speed did not change compared to the same crash simulated without MAES activation. The variation of the vehicle lateral acceleration was instantaneous as soon as MAES activated, going from zero to a constant value with no transient. The idea behind this hypothesis was to evaluate the impact of the system regardless of the rider's action, the vehicle dynamics, or the constructive constraint, like whether the torque needed to steer the motorcycle would be compatible with a specific electromechanical system. Giovannini used this simplified approach to model an evasive manoeuvre; as in that work, the initial small outwards yaw rate typical of PTWs was neglected [9].

Under the previous hypothesis, the equations that govern the vehicle motion through time are the following:

$$\psi(t) = \psi_0 + \int_0^t \frac{a_y}{v(\tau)}\, d\tau, \tag{1}$$

$$v_x(t) = v(t)\cos(\psi(t)), \tag{2}$$

$$v_y(t) = v(t)\sin(\psi(t)), \tag{3}$$

where ψ is the yaw angle, a_y is the lateral acceleration (0.3g, 0.5g, 0.7g), v is the vehicle's speed, and $v_{x,y}$ are the x, y components of the vehicle velocity in the ground frame of reference. The x and y vehicle coordinates were then obtained by integrating Equations (2) and (3) with respect to time. Avoidance of the crash was obtained in some cases. The time when the system was active was different for each crash and depended on the dynamics of the crash. The relative crash speed was computed as the magnitude of the relative velocity between the PTW and the obstacle at the time of the crash:

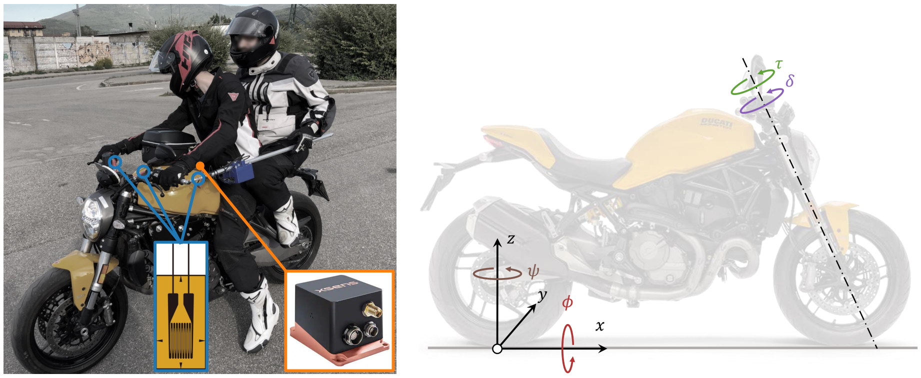
$$v^{\mathrm{rel}} = \|\boldsymbol{v}^{\mathrm{rel}}\| = \|\boldsymbol{v} - \boldsymbol{v}^{\mathrm{obstacle}}\| = \sqrt{\left(v_x - v_x^{\mathrm{obstacle}}\right)^2 + \left(v_y - v_y^{\mathrm{obstacle}}\right)^2}. \quad (4)$$

The change of PTW yaw angle caused a variation of the ‘Relative Heading Angle’ between the vehicles, which was responsible for the variation of the relative speed v^{rel} when the system activated. The relative speed was then employed to calculate the injury risk reduction provided by system intervention, using the Risk Functions proposed by [17]. These are multivariate injury risk models for PTW users to estimate the risk of sustaining different levels of injuries based on the relative speed and crash characteristics. Absolute and relative injury risk reductions were calculated, as detailed in a previous study [7], based on the variation of the relative impact speed of the PTW thanks to MAES intervention. Three levels of injury severity were considered: ‘MAIS2+F’, ‘MAIS3+F’, and ‘Fatal’ injuries, where MAIS is the maximum injury score reported by the rider using the Abbreviated Injury Scale [18].

2.3. Experimental Test

The most promising system, concerning applicability and effectiveness, was tested in terms of feasibility using a real motorcycle. MAES was the SF with the highest applicability and effectiveness, as shown in Section 3; consequently, the rider’s reaction to its external steering input was tested in a lane change scenario, corresponding to avoiding an obstacle.

An experimental test was conducted using an instrumented motorcycle, shown in Figure 2a. An inertial measurement unit (XSens MTi-680G) acquired the vehicle’s motion, measuring its orientation, position, and corresponding derivatives. The steering torque was computed through the measurement made



(a) Instrumented Motorcycle and Rod.

(b) Reference Frame.

Figure 2: The instrumented motorcycle and rod used in the experiment and the coordinate frame used in the study showing the positive signs for roll ϕ and yaw ψ motions and steering torque τ and angle δ. The strain gauges on the handlebars and on the rod were located in the positions marked in blue. The IMU was placed on the tank in the location marked in orange.

by two pairs of strain gauges; each pair was applied to each half-handlebar. The strain gauge reading (a voltage value linked to its deformation) was converted into a steering torque around the steering axis through a calibration procedure. The steering torque τ was computed as the difference between the right and left measurements [19]. In the current work, the ISO 8855 [20] signs convention was used (Figure 2b): the roll angle ϕ around the forward, longitudinal axis was positive when the motorcycle was leaning towards the right; the yaw angle ψ around the upward, vertical axis was positive when the motorcycle was headed towards the left; lastly, the steering torque and the steering angle were defined around the steering axis, and were positive when anti-clockwise when seen from above. The tests involved one of the authors as the rider, having 15 years of motorcycle licence with daily vehicle use and around 7000 km ridden per year. The rider was used to riding in special experimental tests.

A surrogate method for an active steering assistance system was employed: the external steering torque was applied by the pillion passenger through an instrumented rod, shown in Figure 2a. The pillion passenger, who was external to the team of investigators, held one side of the rod in his left hand while the other was connected to the handlebar through a spherical joint. By pushing the rod, the passenger could apply a clockwise steering torque; pulling the rod, instead, generated anti-clockwise steering torque. This method was straightforward and, therefore, more appropriate for an initial feasibility evaluation than a mechatronic system acting on the front assembly through a power steering or steer-by-wire action. The system was simple and unaffected by electrical failures or bugs, making the test safer and not influenced by the specific control properties of the system: this exploratory test aimed to evaluate the rider's response to an external, concurrent steering action and not the control logic of the system itself. Due to the behavioural aim of the test, the effect of the added inertia due to the passenger was not considered a limiting factor. A strain gauge was applied to a rod section and measured its axial deformation. The sensor was calibrated by manually applying sinusoidal steering inputs to the handlebar through the rod itself, while no other actions were present on the handlebar. A linear regression between the steering torque computed from the left semi-handlebar strain gauges readings and the strain gauge applied on the rod provided the sensitivity coefficient needed to compute the external steering torque τ_{ext} applied by the rod. The rider and the passenger contributed to the total steering torque, measured by the strain gauges on the handlebar. The steering torque contribution τ_{rider} applied by the rider was then derived as:

$$\tau_{\text{rider}} = \tau - \tau_{\text{ext}}. \tag{5}$$

The test comprised two trials performed on a cone course in a parking lot closed to traffic. Each trial consisted of four lane change manoeuvres in each direction. Figure 3 shows the manoeuvre geometry: the motorcycle performed a lane change with 1.8 m lateral offset and a 7 m transition distance at the end of a narrow gate, at approximately $10\,\mathrm{m\,s^{-1}}$. In the first trial, called *Single Actuation*, an external steering torque was imparted at the beginning of the manoeuvre. The passenger used the rod to initiate the cornering phase; the external torque returned to zero, leaving the rider alone in performing the second part of the manoeuvre. The second trial, named *Double Actuation*, was identical

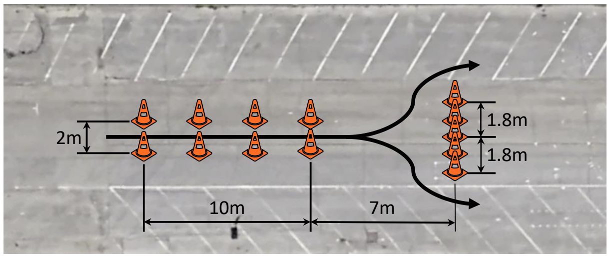


Figure 3: The experimental test protocol. The rider performed a 1.8 m×7 m lane change, in a predefined direction. The rod always exerted an additional steering torque in the initial phase. In the case of the Double Actuation trial, it also acted in the straightening phase.

to the previous one in the corner entry phase; in addition to the initial steering input, the passenger applied an external steering torque to straighten the bike midway through the manoeuvre. For example, in the case of a leftward lane change, the passenger first pushed the rod to apply a clockwise[1] steering torque to make the bike lean leftward; after the roll angle became maximum, he would apply anti-clockwise steering torque to make the motorcycle straighten and lean to the right to set the conditions for the last part of the manoeuvre. The rider could act in any manoeuvre section, independent of the external torque. In particular, evaluating the rider's reaction to the external steering action during this relatively demanding transient manoeuvre was of interest.

At the end of each trial, the rider filled out a questionnaire to provide subjective feedback. The questions, relative globally to the four runs of the trial, concerned the intensity of the external steering action, the controllability of such an action by an inexperienced rider during everyday riding, taking back control of the motorcycle after the activation, and whether he seconded or opposed the external action. The answer to each question consisted of a value between 0 and 10.

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[1] For most riding conditions, the steering torque to be applied has a sign opposite to the yaw rate. This phenomenon is called *counter-steering* [21].

3. Results

3.1. Crash Data Investigation

3.1.1. DCA

Table 3 shows the evaluation results of each Safety Function or combination of SFs, regarding the number of crashes in the Prato-X database whose DCA-classification received a given *applicability* score.

MCA received score '4' ("would have applied") in 13 cases out of 285 (4.6%). Concerning the other crashes, it never received score '3' ("would probably have applied") and received score '2' ("would possibly have applied") in just 2 cases (0.7%). The first score class ("would definitely *not* have applied") covered the vast majority of cases (270, or 94.7%). MS was at least category 3 relevant in 69 cases (24.2%). MAES was at least category 3 relevant in 82 cases (28.8%). MAES was the SF with the highest number of crashes classified in category 4 (28, or 9.8%), followed by MS (24, or 8.4%) and finally MCA (13, or 4.5%). MAES would have definitely not applied in only 89 cases, or 31.2%.

Table 3 also shows the system-relevant number of crashes that could be covered by combining two or three systems. By definition, the sum of the crashes classified as categories 3 and 4 for the combinations of multiple systems increased compared to each SFs. In particular, the combination of the three systems (MCA + MS + MAES) was category 4 relevant for 65 (22.8%) crashes, which coincided with the sum of the number of crashes where each system was category 4 relevant. Therefore, there was no overlap between the SFs concerning this category: the SFs were complementary, and when one would have definitely applied, the other two would not have. Therefore, their typical applications were mutually exclusive. Including category 3, the SFs combination captured 154 crashes (54%), just ten less than the arithmetic sum of the results of the three SFs. The highest weighted kappa value, describing inter-rater agreement, was obtained by MCA (0.979), followed by MS (0.785) and MAES (0.559).

Table 3: The DCA results. Each row corresponds to a Safety Function (SF) or combination of SFs. Each column corresponds to an applicability score. Each cell contains the percentage of crashes in the Prato-X database in which a given SF or combination of SFs received a given applicability score. In the case of positive scores (‘3’ and ‘4’), a darker colour corresponds to a higher percentage of cases.

	Score (%)			
	1	**2**	**3**	**4**
MCA	94.7	0.7	0.0	4.6
MS	73.3	2.5	15.8	8.4
MAES	31.2	40.0	18.9	9.8
MCA + MS	71.9	1.8	12.3	13.0
MCA + MAES	26.3	40.4	18.9	14.4
MS + MAES	7.7	39.3	34.7	18.2
MCA + MS + MAES	7.7	38.2	31.2	22.8

Table 4: The KBMS results. Each row corresponds to a Safety Function, and each column to a crash scenario. Each cell contains the product of the average score received in that scenario and the scenario’s weight, so the SFs must be compared by columns. The three safety functions’ total scores, from 0 to 4, are in the rightmost column, corresponding to the sum of the cells on the same row. The SFs are prioritised based on their KBMS metric (larger numbers indicate greater importance; higher values are indicated by a darker green colour).

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**System Total**
MAES	0.52	0.22	0.25	0.00	0.21	0.32	0.23	0.25	0.09	**2.08**
MS	0.42	0.18	0.15	0.24	0.08	0.17	0.11	0.15	0.09	**1.58**
MCA	0.22	0.11	0.01	0.29	0.01	0.09	0.05	0.02	0.08	**0.89**

3.1.2. KBMS

Applying the KBMS method to the 2010-2012 ISTAT database, a prioritised list of SFs is obtained. The higher the priority, the higher the potential to avoid and mitigate the greatest possible number of motorcycle crashes in the database (Italy).

Table 4 shows the results: each row corresponds to a Safety Function (SF), and each column to one of the nine macro-scenarios grouping the 26 crash scenarios. The final result obtained by each SF, from 0 to 4, is in the rightmost column. MAES achieved the highest score (2.08), followed by MS with a 1.58 score and MCA with a score of 0.89.

Table 5: The IDCR results. Each row corresponds to a Safety Function (SF) or combination of SFs. Each column corresponds to an effectiveness score. Each cell contains the number of crashes out of the 19 crashes from the In-SAFE database in which a given SF or combination of SFs received a given score. The corresponding frequency, in percentage, is shown in brackets

SF	**Score**				
	0	1	2	3	4
MCA	13 (68%)	0 (0%)	2 (11%)	0 (0%)	4 (21%)
MS	13 (68%)	3 (16%)	2 (11%)	1 (5%)	0 (0%)
MAES	2 (11%)	9 (47%)	2 (11%)	4 (21%)	2 (11%)
MCA + MS	10 (53%)	2 (11%)	2 (11%)	1 (5%)	4 (21%)
MCA + MAES	2 (11%)	6 (32%)	3 (16%)	2 (11%)	6 (32%)
MS + MAES	2 (11%)	8 (42%)	2 (11%)	5 (26%)	2 (11%)
MCA + MS + MAES	2 (11%)	6 (32%)	2 (11%)	3 (16%)	6 (32%)

3.1.3. IDCR

Applying the In-Depth Crash Reconstruction method to the 19 cases from the In-SAFE database provided the results of effectiveness evaluation shown by Table 5. Each row corresponds to a Safety Function (SF) or combination of SFs. Each column corresponds to a scoring class, from 0 to 4.

MCA had the most crashes classified in category 4 ("excellent outcomes, assuming activation") (4, 21%) than the sum of the other two SFs (2, 11%). Concerning the other crashes, it was placed 13 times (68%) in category 0 ("no effect"), never in categories 1 ("poor outcomes, assuming activation"), twice (11%) in category 2 ("minor outcomes, assuming activation"), and never in category 3 ("good outcomes, assuming activation"). MS obtained the worst result, with zero crashes classified as category 4 and just one (1, 5.6%) as category 3. Like MCA, MS was not relevant (category 0) for more than half of the crashes. MAES provided at least *good* outcomes (category 3 or 4) in more cases (6, 31.7%) than the other SFs combined. Furthermore, fewer cases were categorised as 0 (2 10.5%); the sum of categories 1 and 2 covered more than half of the crashes (11, 57,8%).

Combining more SFs led to significantly improved results. MCA and MS combination still had over half the crashes classified as category 0 (10 52.6%). Lastly, the combination of the three systems (MCA + MS + MAES) was at least category 3 relevant for nine crashes (47,3%). As with the DCA method result, there was no overlap between the SFs for category 4: each system's effectiveness was complementary to that of the other systems when one system would have had excellent outcomes. There was also no overlap between SFs concerning scores equal to or greater than 3 for every combination of two SFs. In particular, the combination of MCA and MAES provided results analogous to the combination of all the SFs.

3.1.4. Injury Mitigation

From the 19 cases included in the IDCR analysis from the In-SAFE database, ten were excluded because they were unsuitable for MAES application; nine were reconstructed (an example is shown in Figure 4) for the analysis concerning MAES potential for injury mitigation. The nine crashes included in the analyses were characterised by different crash configurations (including rear-end, vehicles from adjacent directions, and manoeuvring), with a mean speed of 52.3 km/h (SD 14.23 km/h). The time for MAES intervention used in the simulation ranged from 0.3 s to 1.2 s, according to the crash configuration (mean value 0.6 s, SD 0.32 s).

In one case, MAES prevented the crash thanks to an avoidance manoeuvre with 0.3g of lateral acceleration, in one case with an acceleration of 0.5g, and in a third one with 0.7g. In the remaining six crashes, MAES did not prevent the crash even with 0.7g lateral deceleration but resulted in reduced relative crash speed, resulting in reduced injury risk. The calculated relative injury risk reduction for each case, calculated for MAIS2+F, MAIS3+F, and Fatal injuries, is displayed in Figure 5. The relative injury risk reduction has a wide variability among cases, but more severe injuries achieve higher values of injury

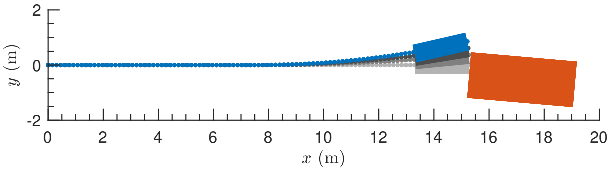


Figure 4: Comparison between PTW trajectory without MAES intervention (light grey) and simulated PTW trajectories employing three levels of MAES lateral acceleration (0.3g in medium grey, 0.5g in dark grey and 0.7g in blue), relative to the 'ID115' crash. The 0.7g lateral acceleration value led to avoiding the obstacle (a parked car, in orange). The corresponding animation is available in the online version of the article.

risk reduction, up to 15-20%.

3.2. Experimental Test

Figure 6 presents the signals describing two runs of the Single Actuation trial. The upper subplot shows the steering torque inputs: the rider action is represented in blue; the external action is shown in orange; their sum is the resulting steering torque plotted in green. The middle subplot shows the resulting motorcycle lateral response in terms of roll angle (red), steering angle (purple) and yaw rate (brown). Lastly, the lower subplot shows the motorcycle trajectory during the manoeuvre, superimposed over a hypothetical roadway as a reference (lane width equal to 2.5 m, a typical value for European urban roads). The part of the run where the rod applies a steering torque is highlighted in yellow. Notice that the upper and middle subplots use "time since actuation" as the independent variable; in contrast, the lower subplot uses longitudinal distance. As the speed is not perfectly constant during the trial, the abscissae shift slightly through each run, as can be appreciated by comparing the highlighted sections in the subplots.

Figure 6a, in particular, shows the very first run of the first trial (lane change towards the right). Although the external action was still declared and performed in a controlled environment, as for all the runs, this action should result in the most genuine rider reaction due to the lack of previous experience concerning this condition. The motorcycle initially travelled straight: the roll

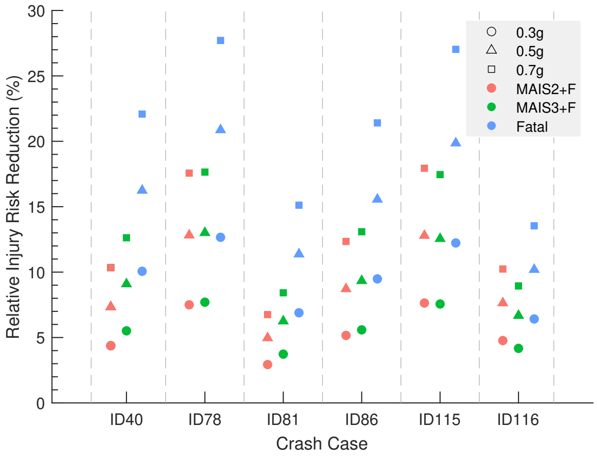
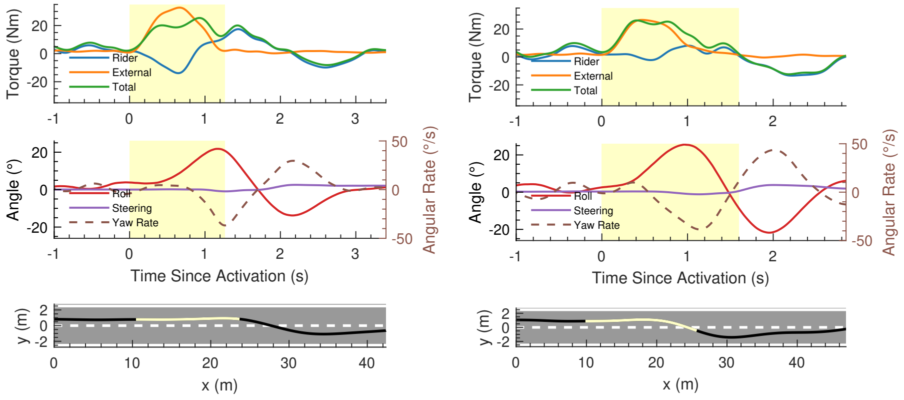


Figure 5: Calculated relative injury risk reduction due to MAES intervention for MAIS2+F, MAIS3+F and Fatal injuries for six cases (ID 40, 78, 81, 95, 115, 116) reconstructed from the In-SAFE database. For each case, the relative injury risk reduction is presented for MAES intervention characterised by 0.3g, 0.5g, and 0.7 g lateral acceleration.



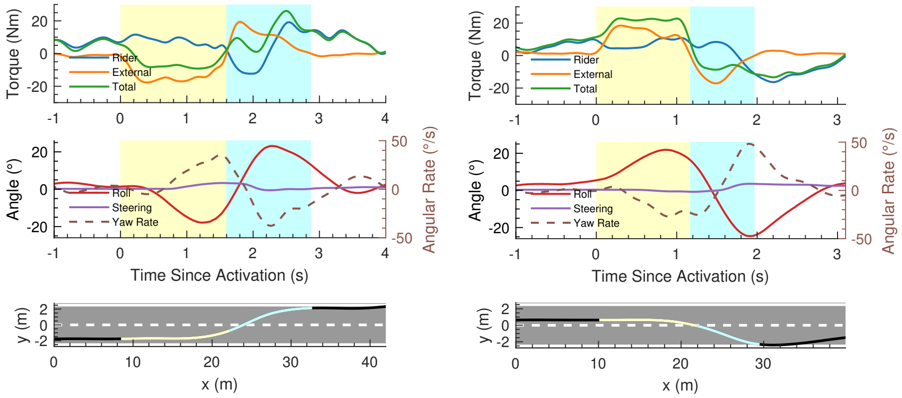
(a) First Run (Rightward).

(b) Subsequent Run (Second, Rightward).

Figure 6: Steering torque inputs (top), motorcycle response signals (middle) and trajectory (bottom) during two lane changes with *single* steering actuation (on corner entry).

angle, steering angle and yaw rate were minimal, and the rider applied minimal steering torque to correct the small oscillations. As the external steering torque was null, the total steering torque was produced by the rider action alone. The pillion passenger then applied a positive (anti-clockwise) steering torque: the rider reacted by exerting a smaller and negative (clockwise) steering torque action; the total steering torque had the same sign as that applied through the rod and initially grew with similar dynamics. Then, the rider action became more intense, while the external steering action reached its maximum: the total steering torque became perceptibly lower than that applied through the rod. The net, positive (anti-clockwise) steering torque applied made the motorcycle lean towards the right (positive roll) and turn to the right (negative yaw rate) with a clockwise (positive) steering angle. The external steering torque then decreased, reaching zero when the entity of the motorcycle response was maximum. Meanwhile, the rider changed the sign of the steering torque he applied: the total steering torque was positive as in the previous part but was now due to the rider's action and not exerted through the rod. The total steering torque progressively reduced, and the motorcycle tended to straighten due to its stability properties [22]. The rider performed the second part of the lane change with no external action: he applied a negative (clockwise) steering torque to make the motorcycle lean, steer, head towards the left, and complete the manoeuvre. The motorcycle trajectory shows that the external steering torque made the motorcycle head towards the right. Its effect grew with its duration, so the heading change became remarkable only after some time, although the torque applied was significant (exceeding 20 N m for several tenths of a second). At the end of its action, the yaw rate was maximum, so the heading of the motorcycle was changing quickly towards the right. The rider decreased the yaw rate to reduce the rate at which the maximum yaw angle was reached to then restore the null yaw angle with a shifted lateral position onto the roadway.

Figure 6b shows the following run. This time, the rider applied just a tiny steering torque while the passenger applied the external action: the total steering torque almost coincided with the latter contribution. The second part of



(a) First Run (Leftward).

(b) Subsequent Run (Sixth, Rightward).

Figure 7: Steering torque inputs (top), motorcycle response signals (middle) and trajectory (bottom) during two lane changes with *double* steering actuation (on corner entry and midway through).

the manoeuvre was similar to the previous run: the external steering action declined, making the motorcycle straighten itself; after some tenths of a second, the rider applied a negative steering torque to perform the last part of the manoeuvre and to restore the initial heading direction. In this second run, the motorcycle had more intense dynamics, with higher amplitude of the roll angle, steering angle and yaw rate produced. The maximum lateral displacement was slightly larger than in the previous run.

Figure 7 shows the previous quantities for two runs of the Double Actuation trial. The part relative to the second external steering action is highlighted in blue. Figure 7a shows the first run of the first trial (left): the external action did not change the rider's action, and the total steering torque became negative. The motorcycle leaned and turned towards the left; the passenger applied a second external steering action, with a sign opposite to the previous one: this happened when the yaw rate and roll angle were close to their maximum values. The sudden change of the external steering torque (from $\approx -20\,\mathrm{N\,m}$ to $\approx 20\,\mathrm{N\,m}$) produced a sign change of the rider's steering torque; the total steering torque became positive. The effect of this second external steering action was to change the signs of the signals describing the motorcycle response. The external steering torque was then removed, and the rider performed the last part of the manoeuvre restoring the initial heading direction. The total lateral displacement during the manoeuvre was significant, around 4 m.

Figure 7b shows a subsequent run (the sixth, towards the right) of the same trial. In this run, in the corner entry phase, the rider applied a steering torque with the same sign as the external steering torque: consequently, the total steering torque was higher than both contributions. The passenger then changed the sign of the steering torque he applied, making the total torque change sign even though the rider's steering action did not change for a few tenths of a second. As the external steering torque became less negative, the rider applied a growing negative contribution keeping the total torque approximately constant in the last part of the manoeuvre.

A summary of the experimental results is provided by Table 6 for the *single actuation* trial and Table 7 for the *double actuation* trial. Each table reports the maximum values of the lateral acceleration, external steering torque, roll angle and lateral displacement during the entry phase of each run of the corresponding trial, along with the mean and standard deviation of each. The external steering torque reached high values on average (24.7 N m in the single actuation trial and 20.0 N m in case of double actuation), producing moderate lateral acceleration values (0.425 g and 0.425 g, respectively). Test repeatability was high: the lateral acceleration produced had a modest standard deviation (0.031 g and 0.038 g, respectively). The lateral displacement produced was, on average, 3.2 m in the case of single actuation and 3.7 m when the actuation was double.

Concerning the survey, the question 'how intense do you think the action on the handlebars was? (0: very low intensity, 10: very high intensity)' was answered '6-7' in both trials, indicating a moderate-high intensity. 'If such a trigger occurred during a real lane change manoeuvre, would an inexperienced driver be able to maintain control? (0: they would not, 10: they easily would)' was answered '6' after both trials, meaning that the rider would probably do it albeit with effort. To the question 'At the end of the activation, were you able

Table 6: Maximum values of the lateral acceleration, external steering torque, roll angle and lateral displacement during the entry phase of each run of the *Single Actuation* trial. The mean and standard deviation are in bold.

Run	**Maximum**			
	a_y (g)	τ_{ext} (N m)	ϕ (°)	Δy (m)
1	0.396	32.7	21.8	2.33
2	0.424	26.5	25.5	2.67
3	0.403	25.7	24.6	3.04
4	0.383	31.8	23.2	2.88
5	0.476	17.2	21.2	3.36
6	0.428	21.4	20.0	2.97
7	0.435	18.7	19.5	3.25
8	0.457	23.3	19.6	5.08
Mean	**0.425**	**24.7**	**21.9**	**3.20**
SD	**0.031**	**5.7**	**2.3**	**0.83**

Table 7: Maximum values of the lateral acceleration, external steering torque, roll angle and lateral displacement during the entry phase of each run of the *Double Actuation* trial. The mean and standard deviation are in bold.

Run	**Maximum**			
	a_y (g)	τ_{ext} (N m)	ϕ (°)	Δy (m)
1	0.415	17.7	17.9	4.54
2	0.400	18.1	19.6	4.26
3	0.432	21.2	20.1	3.55
4	0.396	20.3	19.7	4.78
5	0.316	23.1	18.2	2.42
6	0.371	18.4	21.9	4.06
7	0.351	20.3	20.2	2.21
8	0.411	20.8	22.2	3.75
Mean	**0.387**	**20.0**	**20.0**	**3.70**
SD	**0.038**	**1.8**	**1.5**	**0.94**

to regain control of the motorbike? (0: I was not, 10: I did it easily)', the rider answered '7' in case of single activation and '8-9' in case of double activation. Lastly, he answered '8' in both trials to the question 'During the activation, did you second the external action or oppose it? (0: I completely opposed it, 10: I completely seconded it)', meaning that he definitely seconded it. The rider added that the presence of the 'obstacle' (the cones) made it more intuitive to accommodate the external action.

4. Discussion

4.1. Crash Data Investigation

The investigation, conducted through the three investigation methods (DCA, KBMS, IDCR), aimed to evaluate the potential benefits, concerning crash avoidance or mitigation, of steering assistance for motorcycles when applied to real crash scenarios. The hypothetical impact of these systems on road safety was evaluated concerning *applicability* and *effectiveness*.

The DCA method showed that MAES might be the most applicable system, with the most crashes covered by categories 3 and 4, followed by MS and MCA. The latter was not applicable for a consistent number of crashes (270, or 94.7%). This result, however, was coherent with the characteristics of the database used in the study: crashes in bends were underrepresented due to the urban context considered (Prato municipality). For the same reason, MAES was the most applicable SF because changing the trajectory to avoid an obstacle was more compatible with crashes involving other vehicles, which are the majority of the crash scenarios in urban areas. However, PTWs are more often subject to these crashes, particularly the "looked-but-failed-to-see" case, because they are smaller and less visible than cars. The result obtained by the combination of the three systems is noteworthy: it was deemed inapplicable only in a few cases (22, or 7.7%), while the majority of the cases were covered by category 2 ("Would possibly have applied", controversial), and category 3 ("Would probably have applied", technical challenges still need to be solved). The SFs considered were complementary, and when one ‘would have applied’, the other two would not have had the same degree of applicability. This result is remarkable because the three systems would be based on the same hardware, leading to sharing the cost of implementation while adding up the benefits. Advancements in technology concerning obstacle detection and the control logic and simulation or experimental campaigns could reduce the uncertainty concerning this system. According to Landis and Koch [23], the kappa value obtained by MCA (0.979) can be interpreted as ‘almost perfect inter-rater agreement’; that for MS (0.785) as ‘substantial agreement’, and the one of MAES (0.557) as ‘moderate agreement’. The strength of agreement for each system reflects the different applicability characteristics of each system: MCA typical application is more focused (it only covers bends); instead, MAES has broader applications (it can cover many types of collision); MS is in between the two, as it can also apply outside of bends but it is not as general as MAES. The more focused the scope of a system, the easier it was for the examiners to give an applicability rating.

The concept of applicability describes the number of crashes the system covers; however, it gives no information about the effects in terms of mitigation or avoidance. These aspects are covered by the other key concept of this investigation, effectiveness, evaluated through the KBMS method. The advantage of the KBMS is that it provides a quantitative metric which allows one to interpret the results and rank the systems directly. MAES was, again, the SF with the best score (2.08), followed by MS (1.58) and MCA (0.89). Thus, MAES was rated more important than MS and over twice as influential as MCA. The database used is the same as in Gil et al. [10], as is the way the KBMS was applied as well[2]. Therefore, the KBMS metrics for the three SFs considered in the current article can be compared to the 10 SFs evaluated by Gil et al. for a total of 13 SFs. MAES ranked 6th, MS 7th and MCA 11th. MAES SF was about as effective as the SF that restricts the speed of the PTW to the legal limit (2.16, 5th) and more than the SF that dissipates the rider’s kinetic energy during a

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[2] The panel of experts is different, potentially influencing the results

crash (1.51, 8th). These systems were less effective on average than the SFs acting on braking evaluated by Gil et al. [10]. Although the different pool of experts could impact the outcome, this result was coherent with the assumption that a braking action implies a vehicle speed reduction and so injury reduction, as predicted by the injury risk functions. In fact, the two systems that aimed at reducing the speed significantly got the two best scores, close to the theoretical maximum. The SFs proposed by the authors of this article do not change the vehicle speed, with the possible exception of MCA. Therefore, these systems are more suitable for avoidance or prevention than mitigation, as mitigation would primarily be caused by a different impact angle and relative speed. The rank got by the systems like MAES was coherent with the other SFs acting mainly on prevention, like restricting the vehicle's maximum speed, alerting the rider of an oncoming vehicle, and sending a signal to slow/stop the other vehicle.

The IDCR method allowed testing of whether the systems would impact real-world crashes. MCA obtained better coverage in the highest class but was inapplicable for most scenarios, as shown through the DCA assessment. Indeed, it is a system conceived to perform a particular task. MAES received the fewest instances of the lowest effectiveness score: this result was coherent with the fact that this system might intervene to modify the trajectory; however, the forecast and application are challenging. MS obtained the worst result than the other systems, while in the other investigations, it consistently scored above MCA. This evidence could be explained by the fact that the pictograms used in the KBMS were not sufficiently detailed to represent the cause of the possible loss of control: in the DCA scenarios, the loss of control was often specified as the 'scenario' variable; this was not the case for the KBMS. In both DCA and IDCR datasets, the crashes collected occurred in the urban context. This bias influences both the type of collisions (sideswipe, Crossing, cut PTW off) and the type of PTW involved in the crash, more moped, which often lacks ABS. Locking up the rear wheel in response to an imminent collision was the leading cause of instability, not oscillatory mode or external perturbation. Thus, an intervention on the lateral dynamics could not be correctly performed by MS.

The results obtained are influenced by the crash databases considered. For example, the DCA classification was applied to the Prato-X database relative to a specific Italian municipality. A previous study by Terranova et al. assessed the variability in the distribution of crash characteristics and in the applicability of several active safety systems between the Prato-X database and Australian (MICIMS, relative to the state of Victoria) and American (CRSS) databases [6]. Future work should consider extending the evaluation to other, wider geographic regions. The IDCR method considered crashes in the 2009-2013 period: due to the lower diffusion of the ABS at the time, cases of loss of control under braking could be over-represented compared to the current situation. When interpreting the results, one must take the hypothetical nature of the assessment process into account, as it quantifies the usefulness of assistance systems, defined conceptually and not yet developed, in crash scenarios which are a categorisation of real crashes. Nevertheless, the diversity of the assessment methods and the multiple evaluators should make the process more robust: in fact, the agreement among the evaluators (expressed, for example, by the relatively high Cohen's kappa values) and between the results of each system when evaluated through different approaches suggests this.

In conclusion, MAES obtained the best results (1st, 1st, 2nd) on two out of three investigations (DCA, KBMS, IDCR); MS was evaluated second at best (2nd, 2nd, 3rd) and MCA has the best result in one method (3rd, 3rd, 1st). Thus, MCA could perform a specific task very well, but it was not suitable for the majority of cases; MS could apply in more scenarios but with poor or even negligible effects (as was the case in the IDCR investigation); finally, MAES was the most applicable and had good or relevant effects on the crash scenario.

4.2. Injury Mitigation

The analysis aiming to investigate the effectiveness of MAES intervention in reducing injury risks in different crash configurations finally included nine crashes reconstructed in a simplified 2D simulation environment, using time for MAES intervention ranging from 0.3 s to 1.2 s, depending on the crash configuration. The results indicate that MAES intervention successfully prevented three crashes by implementing an avoidance manoeuvre with lateral accelerations of 0.3g, 0.5g, and 0.7g, respectively. In the remaining six crashes, MAES did not prevent the crash despite 0.7g lateral acceleration, but it did reduce the relative crash speed, thereby reducing injury risk. The 0.7g lateral acceleration value is taken as an upper limit, as it is indeed high for an assistance system. However, Savino et al. showed that ordinary riders can reach analogous values on a scooter in a last-second swerving manoeuvre [9]; still, the lower lateral acceleration values considered are sufficient to avoid at least one crash and to mitigate the estimated injury risk. The relative injury risk reduction varied widely among cases but reached high values of injury risk reduction (up to 20% for severe and fatal injuries).

Although the crashes simulated in this study are genuine and realistic, they constitute only a small sample size. Thus, the outcomes obtained lack statistical significance and cannot be used as a robust estimate of MAES's capability to mitigate injuries. Nonetheless, a non-random sample demonstrates that there are real-world crashes where MAES can avert severe or fatal crashes, even when using conservative time for intervention (similar to that considered for the autonomous braking system [8]) and moderate lateral accelerations.

These findings suggest that MAES intervention may effectively reduce injuries in different crash configurations; however, its success may depend on factors such as the type of crash, time for intervention, and lateral acceleration implemented. The findings also highlight the importance of implementing such interventions in time to prevent crashes or mitigate their severity. Further research is needed to investigate the potential of MAES intervention in reducing injuries using detailed crash reconstructions (which can also account for variations of the point of impact) and a comprehensive sample of cases to achieve statistical significance.

4.3. Experimental Test

The experiment evaluated the feasibility of changing the motorcycle's state of motion through external steering actions. The external steering torque applied was significant, often reaching 20 N m, and was applied for longer than a second. Consequently, the motorcycle response was pronounced, with the roll angle exceeding 20°. The high external steering torque was also applied when the roll angle and yaw rate were close to their maximum values, as in the terminal part of the yellow segment in Figures 6,7. No instability phenomena were detected in the acquired data, nor were they underlined by the rider at the end of the experiment.

The value and duration of the total steering torque determined the motorcycle response, independent of the value of the single contributions (due to the rider and the rod). However, when interpreting the results, one cannot neglect how the two combine, for example, whether the rider strongly opposes the external steering action significantly, if they are indifferent to it, or if they even second it. An active assistance device acts together with the human controller, and it must be compatible with the rider's action to be effective and not dangerous. Academic research (Lovato et al. [24]) and industrial development (Honda's patented 'Motorcycle Lane Keep Assist' system) showed the feasibility of designing compact systems to exert torque around the motorcycle steering axis. In the case of this study, the rider's and external torques were exerted in parallel as in a power steering system. During the tests, the rider either moderately opposed (as in Figures 6a, 7a) or was indifferent to the external action (as shown by Figure 6a). In one instance shown (Figure 7b, entry section), he applied a steering torque concordant with the external one, producing a very high total steering torque. Compared to the previous instants, one can also notice that the external steering torque shifts the rider's steering torque that opposes the external action.

In particular, the rider acts both as a dynamical system, with its specific inertia, damping and stiffness properties, and as a controller with physiological limits on the forces they can apply, the movement speeds they can reach, and the time required to sense a change in the state [25]. Combining the two aspects should explain what is seen at the beginning of the first run (Figure 6a). When the positive external steering torque is applied, the rider's action becomes negative, growing with a slope that is a fraction of the one of the external torque. Therefore, the resulting steering torque grows similarly to the external steering torque, albeit with a smaller derivative. This fact is probably the effect of the stiffness of the rider's arms: the positive (anti-clockwise) external steering torque pushes the left handle against his hand and pulls the right handle from his other hand. This action produces a reactive, negative rider steering torque proportional to the external action. Around 0.2 s after the beginning, this relationship breaks up: the total steering torque has a dynamics different to the external steering action, as the rider's steering torque is now growing faster than the external steering torque. In this phase, the rider probably sensed the change in motorcycle motion and reacted by applying an additional conscious effort to impose the total steering torque. One can compare it to the next run (Figure 6b), where the rider's action in the entry phase is much tinier: in the very first run, the rider was probably more concerned about the consequences of the external action, so he held the handlebar more tightly, producing a higher reactive torque. After the first run, his action following the external steering torque was much more modest, as shown in all the other runs.

A steering action requires time to generate tangible results: the steering torque produces a yaw rate, which must be maintained through time to generate a change in the yaw angle and, at last, a lateral displacement over the roadway. Therefore, a steering assistance device should apply a steering action soon enough to change the motorcycle's state and guide the rider towards the correct evasive action. The motorcycle considered, which had its inertial properties influenced by the presence of the pillion passenger, was self-stable at the speed of the tests: removing or even reducing the steering torque led to a straightening of the vehicle. This behaviour benefits the system's safety: even if the rider does not apply a steering action after the external steering torque ceased, he would not fall. This phenomenon is generally true for most motorcycles in wide speed ranges [22]. In particular, motorcycles tend to be unstable at low enough speeds; however, as swerving becomes more effective than braking at high enough speeds [9], such a system would apply in place of an autonomous braking system only starting from medium speeds. A successful lane change requires restoring the initial heading while bringing all the dynamical states back to zero: this is achieved by applying a total steering torque having the opposite sign to the one used to start the manoeuvre, which can be left to the rider (Single Actuation trial) or assisted by an external action (Double Actuation trial). The motorcycle does not have a clearly distinct behaviour in the second part of the manoeuvre in the case of the Double Actuation runs compared to those of the Single Actuation trial, apart from slightly less smooth dynamics of the yaw rate. The test runs were consistent, with modest variation in the external steering torque inputs and the consequent motorcycle response. In each of the 16 runs conducted, the external action produced a lateral acceleration higher than the lowest value (0.3 g) considered in the study on injury mitigation. This value was sufficient to avoid one of the nine crashes considered. As the inter-run variability was modest, the four lane changes shown are descriptive of the whole experimental test.

The survey showed that, although the rider confirmed the moderately high intensity of the external action, he seconded it. In a real scenario, he thought an inexperienced rider would probably be able to maintain control, even though they would find it demanding. Only one question received a different answer depending on the trial: he found it easy to regain control in the case of single activation and very easy in the case of double activation. The rider preferred the external action to continue throughout the manoeuvre instead of terminating in the middle of it.

The experiment showed the feasibility of changing the lateral motorcycle dynamics through external steering actions, albeit in a controlled environment. The rider was experienced and aware of the system: as it was a preliminary test, it was necessary to conduct this potentially dangerous experiment in the safest conditions without expecting results that could be extended to the entire population. Although straightforward, the test constitutes a first step towards experimentally testing the compatibility of steering assistance systems with a real rider; the resulting pieces of evidence look promising and suggest performing a more extensive experimental campaign involving riders with diverse experience levels.

5. Conclusions

Active steering assistance systems for powered two-wheelers have yet to be studied extensively; however, they have the potential to be highly effective in preventing and mitigating motorcycle crashes while complementing the well-researched brake assist systems. For the first time, this study presented an exploratory assessment of such systems. This preliminary analysis indicates that the three systems we proposed - MCA, MS, and MAES - are applicable in different emergency scenarios and are complementary, responding well to different situations.

Among the three systems, MAES appears to have the highest potential benefits, with good estimated applicability across a wide range of emergency scenarios and promising estimated effects in reducing injuries and preventing crashes. This evidence motivated us to conduct exploratory field trials: remarkably, applying a superimposed steering action to produce a lateral avoidance manoeuvre was easily manageable by a real rider. These findings highlight the potential of active steering assistance systems to enhance motorcycle safety, potentially fostering further research in this area.

CRediT authorship contribution statement

Mirco Bartolozzi: Conceptualisation, Methodology, Software, Validation, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualisation, Project administration. **Adelmo Niccolai:** Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualisation. **Cosimo Lucci:** Software, Resources, Writing - Original Draft, Writing - Review & Editing. **Giovanni Savino:** Conceptualisation, Writing - Review & Editing, Supervision, Formal analysis, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this study are available from the corresponding author, Bartolozzi M, upon reasonable request.

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Appendix A. Flow Chart for Applicability Evaluation

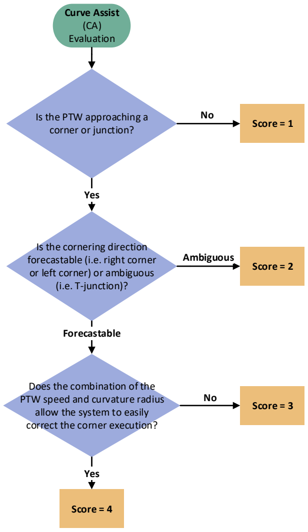

Figure A.1: Flow chart used to evaluate the applicability of the *Curve Assist* Safety Function.

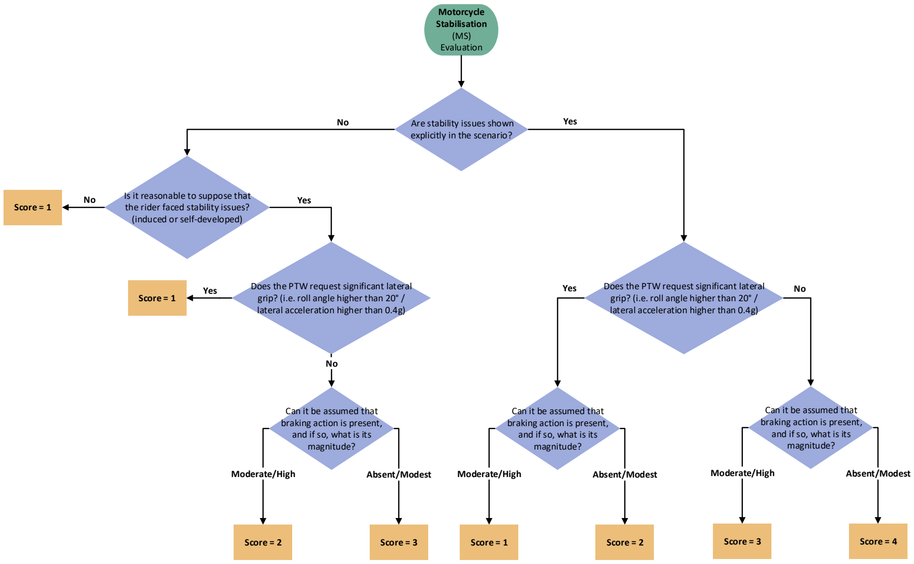

Figure A.2: Flow chart used to evaluate the applicability of the *Motorcycle Stabilisation* Safety Function.

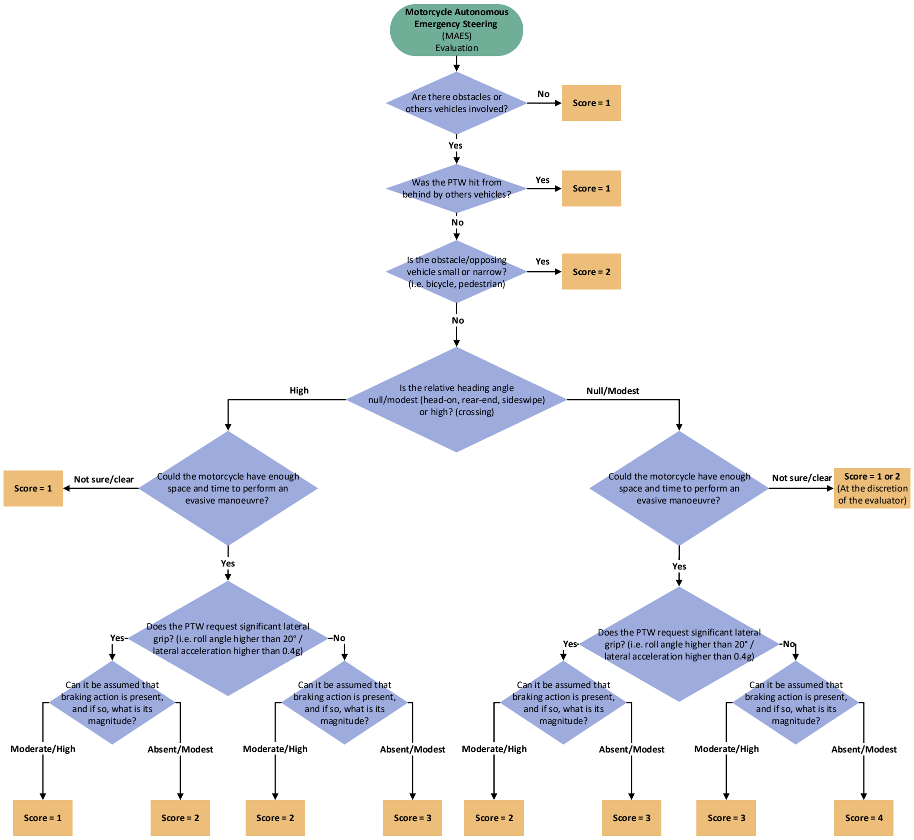

Figure A.3: Flow chart used to evaluate the applicability of the *Motorcycle Autonomous Emergency Steering* Safety Function.