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Effect of advanced rider assistance system on powered two wheelers crashes

Abdelkarim Ait-Moula *, Ebrahim Riahi, Thierry Serre

Univ Gustave Eiffel, TS2-LMA, F-13300, Salon de Provence, France

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ABSTRACT

Advanced Rider Assistance Systems (ARAS) are solutions developed to reduce the crashes rate of Powered Two Wheelers (PTWs). They assist riders in their driving task by transmitting information on their environment or by automatically controlling the dynamics of their vehicle. This study describes a methodology for evaluating the impact of 14 ARAS on PTWs crashes. This methodology consists first of establishing links between ARAS functionalities and riders' failures in crashes situations. Then, an analysis of real crashes cases was conducted using two reals crashes databases: the "In-depth crashes investigation at the Laboratory of Accident Mechanisms Analysis (LMA)" in Salon-de-Provence, France, and the "Initiative for the Global harmonization of Accidents Data". A total of 390 crashes were analyzed. The results showed that ARAS had an influence on 61.5% of the crashes studied. ARAS benefits at the French national level were also assessed, with a weighting of the results obtained. In the French national data, the Anti-lock Braking System had the highest overall impact among the ARASs, estimated to have influenced 39.1% of crashes. Next, emergency braking systems influenced 30.1% of crashes, and an anti-collision warning system had an impact on 29.8% of crashes. This work provided an initial assessment of the most promising technologies for PTWs road safety. It could be used to guide industry and road safety policy towards the development of the most beneficial systems, and the introduction of standards or regulations.

1. Introduction

Databases published by Our World in Data show that road traffic crashes are the twelfth leading cause of death worldwide, representing a greater mortality than HIV/AIDS and tuberculosis [1]. At present, injuries resulting from these crashes constitute the primary cause of death among individuals aged 5–29 years, as reported in Ref. [2].

The 2022 French road crashes statistics show a slight increase in deaths (+1.3%) due to road crashes compared to 2019[1] [3].

PTWs represent a very convenient but particularly risky means of transport. PTWs users are vulnerable not only to fatalities but also to a high risk of serious injuries. Fig. 1 shows the distribution by type of user and vehicle of people killed and seriously injured on French roads in 2022 [3].

The statistics clearly show that PTWs users are the second most likely group to be killed, and the most likely to be seriously injured,

* Corresponding author. 304 Chemin croix blanche, 13300, Salon de Provence, France.
E-mail addresses: aitmoulaabdelkarim@outlook.fr (A. Ait-Moula), ebrahim.riahi@univ-eiffel.fr (E. Riahi), thierry.serre@univ-eiffel.fr (T. Serre).

[1] Reference 2019: Following the different confinements applied during the years 2020 & 2021 caused by the SARS COVID-19 crisis, the French government has taken the year 2019 as a reference to compare the crashes figures for the next decade [3].

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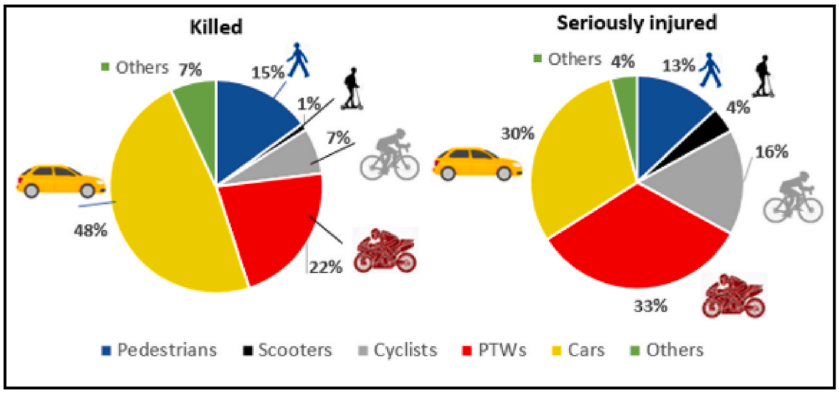


Fig. 1. Percentage of people killed and seriously injured on French roads in 2022 [3].

despite their representation accounting for less than 2% of overall road traffic. The likelihood of losing one's life on French roads, per unit distance traveled, is approximately 22 times higher for motorcyclists than for passengers in cars. Furthermore, the risk is 24 times higher for drivers of heavy motorcycles with an engine capacity of more than 125 cm^3 [3].

Accidentology is dedicated to studying and analyzing crashes and road risks [4]. The aim is to pinpoint the causes and factors contributing to each crash and suggest measures to enhance the safety of road users [5]. The central element is the crash itself, which can be treated as a story in scientific research. This story unfolds through the interaction of various elements within the driving system, such as the user, the vehicle, and the environment. The sequence of a crash unfolds through various distinct phases, starting from the initial driving scenario and progressing to the post-collision phase, and including moments of rupture, emergency, and collision situations (as illustrated in Fig. 2). The driving situation sets the context and identifies the key actors involved. The phase of rupture confronts the participants with a problem that needs to be solved, which leads to a hasty search for an emergency solution [6]. The collision phase signifies the breakdown of this emergency solution, leading to malfunctions from earlier stages, and concludes when the vehicles come to rest in their final positions. Analyzing a crash involves a retrospective examination to determine the impact and approach speeds of the vehicles. The collision phase can be analyzed using numerical and experimental methods, such as crash tests [7]. The pre-collision phase, encompassing driving, rupture, and emergency situations, poses greater challenges due to the need to evaluate multiple hypotheses in order to determine the most suitable course of action. This phase is the focus of this study.

Active[2] and passive[3] safety solutions have been developed to improve the safety of road users by reducing crashes and minimizing injuries. Advanced Driver Assistance Systems (ADAS) and Advanced Rider Assistance Systems (ARAS) are examples of active safety. ARAS for PTWs assist riders in their driving task, with interaction modes that vary from passive information systems to active vehicle control systems [8]. ARASs influence the vehicle in different ways. For example, in longitudinal control with systems like Anti-Lock Braking System (ABS) to prevent wheel lock-up, Autonomous Emergency Braking (AEB) to avoid a head-on collisions and acceleration control (e.g., Traction Control System, TCS). In lateral control, such as Motorcycle Stability Control (MSC) to assist the rider when braking on curves, and Anti-Skid system (A-S) by BOSCH® to avoid slipping. Most of these technologies are designed to be activated in emergency situation (Fig. 2). However, some systems, such as Active Cruise Control (ACC), can act in normal driving situations to maintain a safe distance through automatic braking. Passive safety systems, such as airbags, aim to prevent or reduce injuries to vehicle occupants in the event of a crash. This study focuses mainly on the active safety ARASs that are being developed or under development for PTWs.

ADASs have contributed significantly to reducing crashes involving four-wheelers [9]. However, it is important to examine active safety systems have been developed or are under development for PTWs, how effective they are, and how they would affect the dynamic behavior of PTWs in a crash situation.

Several ARASs for PTWs have been studied in previous research works:

➢ Braking systems (ABS & CBS)

The ABS and the Combined Braking System (CBS) are two technologies that assist the rider in braking. ABS prevents the wheels from locking up under heavy braking, and CBS combines the motorcycle's front and rear brakes. The first studies on ARASs started very early, after their apparition in 1986, with the BMW® K100 model: Research conducted by Kato & al [10], Ciepeka &al [11] and Vabre & al [12] compared different decelerations obtained from multiple braking systems through track tests. They found that the use of ABS and CBS enabled greater deceleration than with standard braking system. Green & al [13] and Gail & al [14] examined the braking

[2] Active safety: It refers to technologies and devices designed to help prevent crashes or reduce their impact (Driver Assistance Systems: ABS, AEB, etc.) [66].

[3] Passive safety: It refers to technologies and devices designed to minimize injury and damage in the event of a crash (airbags, seat belts, etc.) [66].

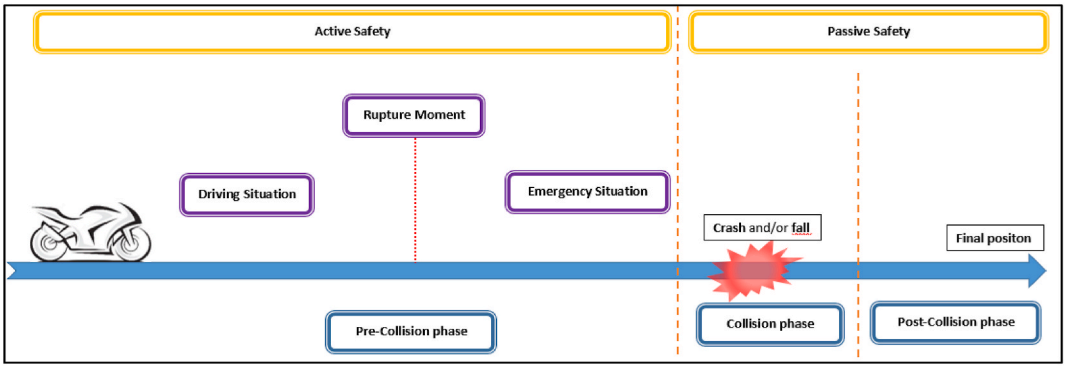


Fig. 2. General diagram of a crash.

distances of various systems: standard, ABS and the ABS + CBS combination. Their results show that ABS and CBS reduce braking distances compared with the standard system. Vavryn & al [15] and Ondrus & al [16] conducted a study evaluating the influence of ABS on the braking performance of motorcyclists, specifically comparing decelerations and braking distances. Their findings indicated that novice riders experienced increased deceleration when using an ABS-equipped system, while experienced riders did not exhibit a significant impact on their braking performance with ABS. Teoh &al [17] and Bash & al [18] used insurance data to estimate the benefits of ABS. Their results showed that motorcycles equipped with ABS had a crash involvement rate around 30% lower than non-ABS equipped motorcycles. Roll & al [19] and Lich & al [20] developed analytical methods to evaluate the benefits of ABS in real-life crashes situations. Their findings indicate that ABS is around 70% effective. Rizzi & al [21] conducted a comparison of crash risk for motorcyclists riding PTWs with and without ABS, using police reports and different crashes databases from several countries. They showed that ABS reduces the risk of fatal crashes by 34%, and the risk of injury by 24%.

➢ Cornering brake system

MSC is a new version of ABS that allows for braking maneuvers during cornering. This system is relatively new to the PTWs industry, which explains the low number of evaluation studies on it. However, Lich & al [22], Sevarin & al [23] and Aitmoula & al [24] they studied the impact of MSC on PTWs safety using analytical methods. The results of the first two studies indicate that the system could prevent around 30% of crashes in Germany and Australia. In the latest study, carried out in France, MSC could prevent up to 77% of cornering crashes.

➢ Adaptive cruise control system

ACC is a technology that helps maintain a safe distance from the vehicle in front. It is not yet used on the market and it requires further evaluation. Aitmoula & al [24] developed a numerical method to evaluate the effectiveness of ACC from a database of real crashes. The method consists in analyzing the crash data and recalculating a new impact speed taking into account the use of ACC. The results showed that when ACC was activated with a detection distance of 30 m, the estimated percentage of benefit in terms of avoidance was higher than 50% on the analyzed crash.

➢ Emergency braking system (AEB & PCB)

AEB and Pre-Crash Braking (PCB) are technologies designed for emergency braking in motorcycles. AEB is aimed at avoiding or mitigating impact, while PCB aims to brake at the last moment only to mitigate impact. Symeonidis & al [25] conducted emergency braking experiments on a PTWs simulator for volunteer drivers. They showed that different deceleration levels did not cause significant instability in the tested drivers. Savino & al [26–29] worked on the development and analyzed the effect of these technologies on a database of real-world crashes, demonstrating that they reduce the impact speed of analyzed crashes. The same authors [30] evaluated the feasibility of the “Motorcycle Autonomous Emergency Braking” (MAEB) technology, testing it on riders in a straight path. They found that all riders were able to handle the automatic decelerations of MAEB. The work of Huertas-Leyva & al [31] focused on the development of validation and acceptance test criteria for MAEB technology, based on the kinematic analysis of the motorcyclists body during unexpected braking. They showed that the unexpected braking test is a reliable estimator to design and validate the MAEB technology. Naude et al. [32] conducted an assessment on the influence of PCB on the impact speed of PTWs, utilizing actual crash data sourced from both French and Italian databases. Their devised methodology involved examining various setups of PCB parameters, including deceleration, range, angle of view, and triggering strategy, corresponding to optimistic, average, and pessimistic scenarios. The outcomes revealed that, contingent upon the specific configurations of PCB parameters, the system exhibited the potential to reduce the impact speed.

➢ General studies

Savino & al [33] carried out a literature review to establish a list of active ARASs for PTWs. These technologies include ABS, AEB, collision avoidance, intersection support, lane departure warning, man-machine interfaces, stability control, traction control and vision assistance. Huth & Gelau [34] analyzed the behavioral factors that affect the acceptance of ARASs among PTWs riders. Their model identified perceived safety during unassisted driving, interface design, and social norms as key factors that influence acceptance. Their results indicate that interface design and social norms have the greatest impact on acceptance of ARAS integration in PTWs vehicles. Terranova & al [35] carried out a comparative study to assess the effectiveness of five active safety systems—namely, ABS, MAEB, collision warning, curve warning, and curve assist—for PTWs across Australia, Italy, and the United States. The investigation utilized diverse databases containing real-world crash data. By considering crash factors, such as wheel lock for ABS, the study aimed to identify technologies with potential applicability and impact on crash outcomes. The findings revealed that ABS and collision warning emerged as the most applicable technologies based on the analysis of the respective databases.

The studies presented focus mainly on individual evaluations of certain ARASs, such as ABS, AEB, ACC and CBS … etc. However, it is crucial to note the absence of analyses concerning ARASs such as CAT (Collision Aversion Technologies), TCS … etc, which remain under-represented in the existing literature. Furthermore, while some studies focus on the individual influence of these technologies, there remains a gap in terms of assessing their collective interaction and overall impact on PTWs crashes rates. It is therefore imperative to continue research into how different technologies interact in real crashes situations, and to assess their impact on PTWs safety. To address this issue, the aim of this study was to examine and assess the effectiveness and ineffectiveness of ARAS based on crash data involving this mode of transport. To achieve this objective, the study was divided into two distinct stages. In the first stage, a methodology was developed by establishing links between ARAS and driver failures, based on their specific needs. Then, in the second stage, this methodology was implemented using different crashes databases.

2. Material and methods

This study was carried out in two stages. In the first stage, a methodology was developed to link ARASs, complementary needs (see § 2.2.2), and functional failures (see § 2.2.1) of riders. In the second step, the analysis of crashes from different databases was carried out to determine the effect of ARASs on the PTWs crashes rate. Finally, the results obtained in the second stage were weighted at the national level in France.

2.1. List of ARAS technology

The PTWs industry has experienced an important technological leap with the development of various ARASs devices to improve safety:

- *Collision warning system:* Various systems have been created to provide this warning function, employing technologies such as cameras, radars, V2V (Vehicle-to-Vehicle communication), V2X (Vehicle-to-Everything communication), and more, as discussed by Terranova & al [35]. CAT system, developed by RIDE VISION®, was chosen for this study. This passive ARAS uses cameras placed at the front and rear of the vehicle to monitor the environment at 360°. Real-time data from these cameras is analyzed and computed by a central box connected to the sensors. The system is designed to identify approaching vehicles [36]. The system's triggering criterion is based on the need to detect vehicles in the motorcycle's blind spots.
- *Dangerous Turn Warning (DTW)*: This application, created by Liberty Rider®, functions as a warning tool for riders, alerting them to hazardous turns based on their current speed [37]. Similar functionalities have been implemented in other systems, as exemplified by the work of Huth & al [38]. In the context of our study, the analysis focused on the pre-existing system offered by Liberty Rider®, already available in the market. The triggering criterion for this ARAS is based on the need to detect a dangerous bend.
- *Smart-Helmets (S–H) (in progress)*: The connected helmet incorporates multiple sensors designed to carry out diverse functions. Beyond monitoring the rider's alcohol and drug levels and issuing warnings when they surpass predefined thresholds, this system is also capable of alerting emergency contacts if the rider continues to drive despite receiving warnings, as indicated by Tapadar & al [39]. The system's triggering criterion is based on the need to detect a motorcyclist's high alcohol level.
- *Autonomous Emergency Braking (AEB) (in progress)*: This system comprises a camera and radar, designed to anticipate potential frontal collisions by issuing warnings to the rider and, subsequently, autonomously triggering the vehicle's braking system, as described by Giovannini & al [40]. The triggering criterion for this ARAS is based on the need to detect a frontal obstacle and initiate an emergency braking maneuver with the aim to avoid impact.
- *PCB (Pre-Crash Braking) (in progress)*: This system, utilizing radar and braking mechanisms, shares similarities with AEB but differs in its primary objective. While AEB is designed to prevent or mitigate collisions, PCB exclusively focuses on reducing the impact speed to lessen its severity [32]. The trigger criteria for this system are the same as for AEB, but with the aim of mitigating the impact.
- *Active Cruise Control (ACC)*: This system allows the rider to select a safe distance from the vehicle in front in advance, and then adapts the vehicle speed to maintain that distance in real-time [41]. The triggering criterion for this system is based on the need to detect that the defined safety distance has been exceeded and to initiate braking maneuvers.

- *Anti-lock Braking System (ABS)*: ABS manages braking conditions by modulating the braking pressure at certain thresholds through application and release cycles to avoid wheel locking Pickenhahn & al [42], for a maximum roll angle of 20° [22]. The criterion for triggering ABS is based on wheel speed, which must not be zero.
- *Combined Braking System (CBS)*: Also referred to as coupled braking, this system integrates the rear brake with the front brake to attain an optimal distribution of braking force across diverse conditions [43]. Its triggering criterion is based on the need to initiate braking if the rider has already done so.
- *Motorcycle Stability Control (MSC)*: Referred to as cornering ABS, this system represents an enhanced iteration of traditional ABS by dynamically adjusting braking forces on the wheels based on the cornering angle and the vehicle's speed. This feature prevents the motorcycle from straightening out during cornering, addressing a common limitation of conventional ABS braking systems [44]. The triggering criterion for this system is based on the need for braking assistance when cornering.
- *Traction Control System (TCS)*: reduces engine power within a fraction of a second to align the force exerted by the rear wheel with the tire grip on the road surface, as described by Kobayash & al [45]. The triggering criterion for this technology is based on the need to detect and avoid a loss of rear wheel grip.
- *Anti-Wheelie (A-W)*: This system reduces engine power to prevent the front wheel from losing contact with the road Steven Gray [46]. Its triggering criterion is based on the need to detect and prevent lifting of the motorcycle's front wheel.
- *Stoppie-Control (S–C)*: Unlike the A-W, a stoppie happens when the rear wheel tends to lift off and lose contact with the road. This system is designed to counteract such motion, thereby enhancing longitudinal stability, as explained by Kate Murphy & al [47]. Its triggering criterion is based on the need to detect and prevent lifting of the motorcycle's rear wheel.
- *Launch-Control (L-C)*: Launch control is an electronic assistance feature regulating the torque applied to the rear wheel during rapid acceleration from a stationary position. Its purpose is to prevent the rear wheel from spinning or the motorcycle from coasting, as discussed by Giani & al [48,49]. The triggering criterion for this ARAS is based on the need to detect and avoid front wheel lift during start-up.
- *Anti-skid (A-S)* (in progress): When wet leaves, oil puddles, or gravel are present on the road, the wheels may initiate lateral sliding if they cannot maintain adequate lateral force during cornering. Bosch has introduced a solution that involves applying an additional external lateral force to assist the rider in staying on the intended course. This force is applied in the form of pressurized gas that escapes, generating a counterforce against the skid direction [50]. The triggering criterion for this system is based on the need to detect and avoid low-side slippage.

2.2. Functional failures & complementary needs for the riders

2.2.1. Choice of the functional failure production analysis model

The literature proposes several models for analyzing the production of human error in driving crashes. One of these, called the Driver Reliability and Error Analysis Method (DREAM), is based on the Cognitive Reliability and Error Analysis model [51]. DREAM consists of two aspects: The first is classified as the "Phenotype" (critical event), which concerns the observable data and consequences of the crash process. The second is called "Genotype" and focuses on the causes that contributed to the occurrence of the critical event or phenotype. Its main objective is to explain the causes of the crash and to arrive at an overall classification of the crash. On the other hand, the "Accident Causation Analysis with Seven Steps" (ACASS) method focuses on relevant human causes, based on psychological and perceptual aspects. It begins by analyzing the crash from the initial conditions, then proceeds through the stages of perception, evaluation and finally the action that led to the occurrence of the crash. Finally, the last model, called "Human Functional Failures" (HFF), defines the human driving functions involved in each crash, as well as the various factors influencing them.

Van Esland's [52] and Atalar [53] conducted two comparative studies of these three different models. The results of these studies, which were based on questionnaires sent to experts with in-depth knowledge of crash, show that the participants considered ACASS to be the easiest method to learn and use. However, the other two methods, DREAM and HFF, were ranked as the most relevant, with a slight advantage for HFF [53]. The HFF method allows a greater number of factors to be coded, and takes into account the majority of variables that can be analyzed by an crash investigator. As a result, it enables a more in-depth analysis of failures, as well as the possibility of clearly identifying countermeasures (which we will refer to as "needs" in the remainder of this article). Another notable distinction between HFF and the other two models is that HFF divides the crash into several distinct phases (driving, rupture, emergency, collision and post-collision), a feature not present in the other methods. For all these reasons, we have opted for the HFF model for this study.

2.2.2. Functional failures

As defined by Van Eslande & al [54] in the report *"INRETS N°218"*, "functional failures occur when a function fails to fulfill its adaptive role during the sequence of treatments, leading to rupture in the driving situation". In other words, failure can be defined as what went wrong in the pre-collision phase that ultimately led to the crash.

Van Esland's functional failure model is divided into 6 categories. The first five categories refer to a logic of action succession in a sequential model of the crash, and the last one represents an alteration of the whole chain.

The methodological diagram (see § 2.2.3) presents on the left side the categories of functional failures, which are defined by:

- <u>The situation:</u> It represents the pre-collision situation (see § 1 paragraph 5).
- <u>Detection</u>: It is defined by the search for information, and represents the first action in the logical path of the driver's tasks.

- ❖ Diagnosis: It is defined by the functions of evaluation (of the speed, of the distance, etc.) and of comprehension of the various information acquired during the detection stage.
- ❖ Prognosis: It is defined by the functions of anticipation and forecasting of different expected actions.
- ❖ Decision: It is defined by the decisions taken on the maneuvers to be carried out according to the three previous stages.
- ❖ Execution: It is defined by the actions taken to implement the decisions taken.
- ❖ Global: It concerns a global analysis of the state of the driver and/or the vehicle.

2.2.3. *Additional needs of the driver*

Driver needs are defined as "the negative of failures" or "the mirror of failures" [55]. They represent compensations on the functional failures; their satisfaction makes it possible to avoid the error and consequently the crash [56,57]. They were determined by analyzing the failures of each crash in the detailed database of EDA (EDA: "Étude Détaillés d'Accident" in French, In-depth Detailed Crash Studies) [56]. Several needs were defined for each functional failure category in this study, the needs were adjusted to correspond to PTWs riders.

The list of different needs with examples has been presented in the methodological diagram. Types of needs that have been extracted in the project « *DaCoTA* » Van Eslande & al [58] and have been rehabilitated.

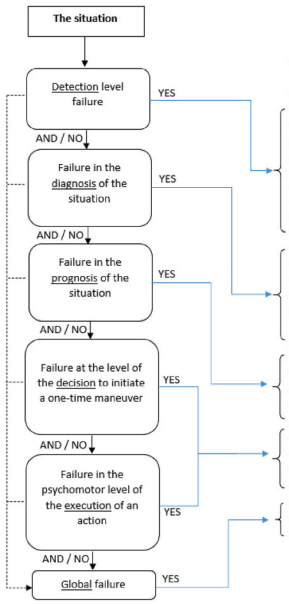
2.2.4. *Methodology to link ARAS technologies with needs & functional failures*

The methodology developed (as shown in Fig. 3) for the first step consists in starting from the pre-established list of functional failures. These were drawn up following interviews conducted by the psychologists with those involved in the crash [59]. In the EDA method, when a crash occurs, a psychologist goes to the scene of the crash to carry out an initial interview with those involved, if possible. The same psychologist then carries out a second interview with those involved after a fortnight, the aim of these interviews being to build up a summary sheet of data relating to those involved for future analysis. In addition, in the IGLAD (Initiative for the Global harmonization of Accidents Data) database, the failures have been provided with the data for each crash. Moreover, for each type of failure, the needs of PTWs riders must be identified to complete their functional failures at the time of the crash situation and thereby prevent the crash. The goal of this method is to establish links between ARAS and functional failures by identifying the complementary needs of riders.

2.3. *Application on real crashes cases*

2.3.1. *In-depth crashes investigation EDA*

The EDA was established by the Accidents Mechanisms Department of INRETS in the 1980s. The methodology employed, as illustrated in Fig. 4, is based on the collection of in-depth data gathered in real time at the scene of the crash. This approach enables the determination of crash causes, factors, and consequences, facilitating the examination of dysfunctions at play during the crash, as highlighted by Ferrandez & al [6]. In contrast to police reports, which primarily serve to assign responsibility or provide statistical data to government agencies, the EDA is designed to comprehend and elucidate the circumstances of the crash. It achieves this by identifying contributing factors, such as the psychological behavior of the driver and the dynamics of the involved vehicles. Notably, this



Complementary Needs	Example
Need for detection	
Detection of an unexpected road difficulty	Sharp bend, wet road, etc.
Detection of a fixed obstacle	Pedestrian, object, animal, vehicle
Detection of an obstacle in slow motion	(Pedestrian, object, animal, vehicle) that is in slow motion.
Detection of an approaching vehicle in the same lane	It is used for front-rear collisions and overtaking.
Detection of a user in need of visibility	Users in an intersection hidden behind constructions
Detection of a user outside the front field of vision (behind, on the side or in the blind spots)	The detection of other vehicles behind or in the blind spots.
Detection of a user in the front field of view (hidden by an object)	Vegetation, other vehicles, etc.
Detection of the deviation of the trajectory	When the driver does not detect a deviation of the trajectory of his vehicle.
Need for an external diagnosis	
Adapting speed to the road - 1: road geometry	In curve or in slippery road
Adapting speed to the road network - 2: legislation	Speed limit
Evaluation of catching up to a slower road user	Underestimation of the speed of a vehicle in front.
Estimation of a collision trajectory with another user	A bad evaluation of a trajectory with another user approaching transversally (intersection).
Evaluation of the deviation when overtaking or changing lanes	When the other user has been perceived but his maneuver has been badly evaluated.
Evaluation of gaps during insertion or crossing of vehicles	It refers to users who do not have priority, and who must insert themselves into a flow of vehicles
Forecasting needs	
Predict that another user will pull out or not stop	A vehicle that has the right of way and think that other users will let them pass.
Predict that another user will slow down, stop or not disengage	The vehicle in front suddenly engages a braking maneuver.
Predict the maneuver of another user or pedestrian	A vehicle is overtaking and changes direction at the last moment
Predict the appropriate maneuver for the site operation	misprediction of the traffic light
Need for control	
Need for longitudinal control of braking trajectory	wheel lock, application of an emergency brake
Need for longitudinal trajectory control during acceleration	wheel slippage following a major acceleration
Need for lateral trajectory control	braking in a curve or lateral slide
Need for internal diagnosis	
Diagnose the condition of the motorcyclist	Alcohol rate
Diagnose the condition of the vehicle	Braking system or tires.

Fig. 3. Methodological patterns based on the work Van Esland's [54,59] to create a link between ARAS, needs and failures.

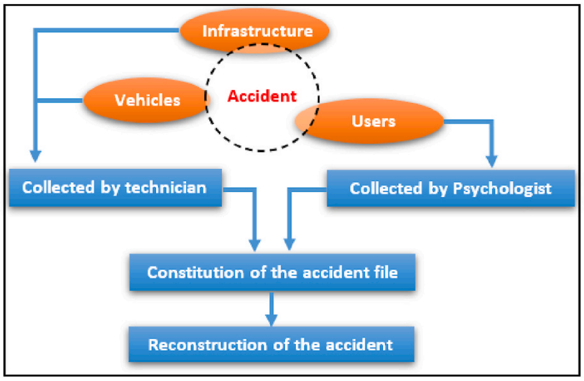


Fig. 4. Eda methodology.

database encompasses 260 PTWs crashes collected in the Salon-de-Provence region.

2.3.2. Crashes database IGLAD (Initiative for the global harmonization of Accidents Data)

The IGLAD database was created in 2011. The objective was to build a worldwide database of comprehensive crashes studies, providing for each crash detailed information about the vehicle (e.g., speed, distance), the environment (e.g., geometry and road condition), the participants and occupants (e.g., injuries). The advantage of this database lies in its standardized format of the different data related to the crash, as well as its ability to provide a real understanding of what happened in each phase of the crash [60]. As for 2021, the available database contains information on 240 motorcycles crash.

2.3.3. Methodology for evaluating the ARAS impact on crash

Once the links between ARAS, complementary needs, and functional failures have been established in the first step, the second step

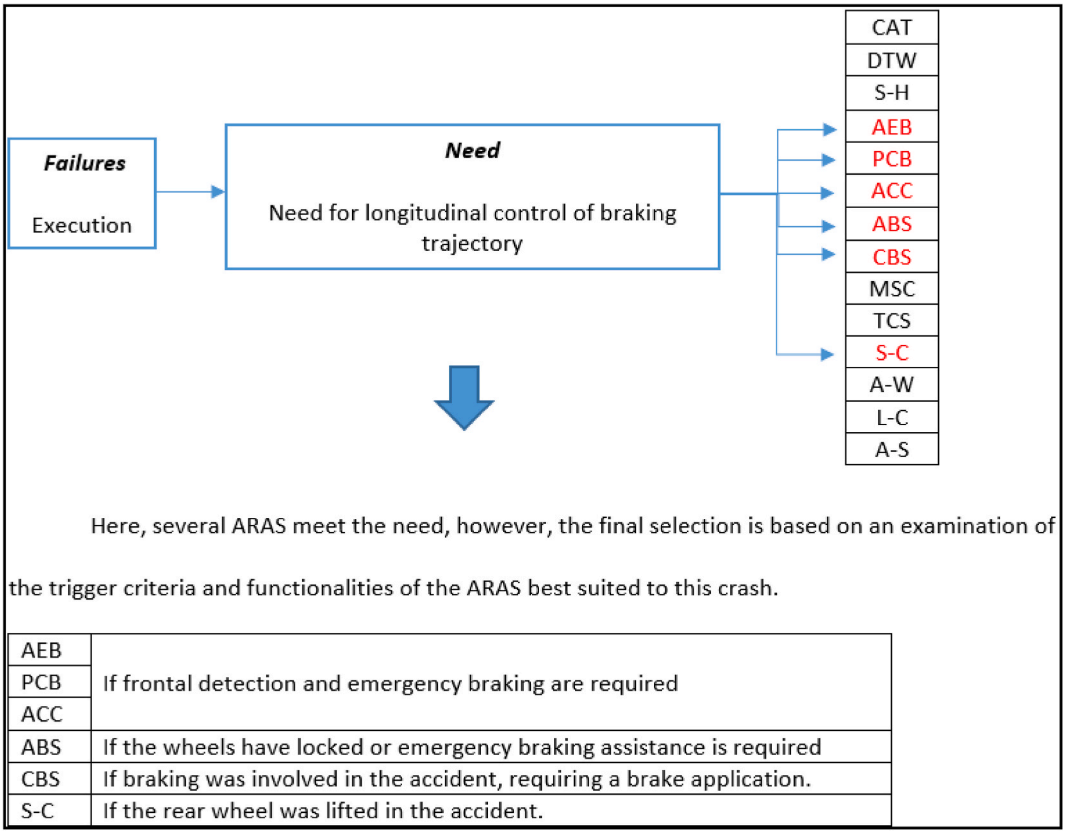


Fig. 5. Explanatory example of the methodology.

involves evaluating the impact of ARASs on crashes.

In this phase, the crash analysis was based on the added value of the ARASs. Consequently, the systems already present on each motorcycle in the databases were not taken into account when compiling the results (e.i If, at the time of an crash, a motorcycle is already equipped with an ARAS, it is considered that this system has no effect on the motorcycle in this crash, because we have set ourselves the objective of looking at the added value of ARASs on the consequences found in each crash).

Crash analysis involves examining each case individually to determine whether one or more ARAS could have influenced the course of the crash. This analysis was carried out on the basis of the failures identified in each case. These failures were then used to identify the driver's specific needs during each crash. Finally, each need was associated with one or more ARAS, according to their functionalities and triggering criteria, so the role of the need in our methodology is to converge the ARAS selection field to a more restricted list of systems than the general list.

It's important to note that the final selection of ARAS that meet the same needs is based on their functionality (Fig. 5).

2.4. Weighting of results on a national scale

In order to lend representativeness to our findings, we conducted a weighting process. This approach is solely based on the results obtained from the EDA database. Indeed, the absence of global data that for all countries would not allow us to weight the whole of our results (EDA + IGLAD).

The weighting of EDA results on a French scale was carried out through five steps:

i. In the first step, we defined the weighting variable. Weighting relies on a variable that extrapolates results from a small sample to a larger one, constituting a prerequisite for this work. This condition needs the presence of this variable in the various samples of the study. In our case, this task was not straightforward, as we needed to identify a variable present in both the EDA and a national crashes database. The only variable we managed to obtain that fulfills these conditions is "The maneuvers leading to crashes" in other words, the crashes scenarios in the pre-collision phase. This variable is found in the COMPAR project – IFSTTAR/DSR 2011 [61], which provides a breakdown of the maneuvers leading to crashes in France based on a sample of 1000 Police Reports (PR) collected between 2004 and 2009.

We divided them into 6 scenarios, as follows (these scenarios are used in the EDA database, extracted from the pictograms of the VOIESUR database [62]):

Scenario 1 (SC1): It covers all vehicle-to-vehicle crashes occurring on the same lane. This includes head-on collisions between vehicles moving in opposite directions, front-side collisions in cases where vehicles drift onto opposing lanes, and rear-end collisions during deceleration.

SC2: It covers all crashes involving overtaking maneuvers, whether on the left or right. This may include head-on collisions if a vehicle is overtaking on the same lane as another vehicle approaching from the front, rear-end collisions if a vehicle approaching from behind shares the same lane as another vehicle overtaking, and side collisions when a vehicle overtakes another and the latter decides to veer left or right.

SC3: It covers all crashes occurring at intersections. This includes crashes at various types of intersections (X-shaped, T-shaped, etc.) and all combinations of left or right turns between vehicles. Crashes can also occur in roundabouts.

SC4: It includes all crashes involving vehicles entering or leaving parking. For example, this may include crashes where a vehicle leaves its parking space while another vehicle approaches from behind or from the front. Additionally, crashes may occur when a vehicle is about to park while another vehicle approaches from behind or from the front, resulting in a collision.

SC5: It covers all crashes involving single vehicles losing control, such as losses of control during turns and losses of control caused by a vehicle's impact with embankments or sidewalks.

Other SC: It includes all other scenarios not part of the defined 5 scenarios, such as crashes involving pedestrians, etc.

ii. The next step involved classifying EDA crashes according to the defined scenarios. This was done based on the documentation of each crash (plan, crash reconstruction, etc.) to determine the most appropriate scenario for each crash.
iii. The third step involved calculating the percentage of effectiveness of each ARAS according to each scenario in the EDA.
iv. In the fourth step, the results obtained in the third step were weighted based on the national database, following the hypothesis:

"If an ARAS has an effect on X% of cases in the EDA for an SCi (i = 1 to "other"), the same ARAS could have an effect of X% on the same SCi in the 1000 PR database".

v. In the fifth step, we recalculated the percentage of effectiveness of each ARAS for the 1000 PR database:

If an ARAS has:

Xi% effectiveness in SCi EDA, it is considered that it will have Xi% effectiveness in SCi France. So, the number Yi of cases where the ARAS has effectiveness in SCi at the national level can be calculated as:

$$Yi = \frac{Xi}{SCi} \tag{1}$$

i = from 1 to "other"

Finally, the global percentage Z of effectiveness of ARAS at the national level is:

$$Z = \frac{\sum Yi}{1000} \tag{2}$$

3. Results

3.1. Results of the link between ARAS, needs & failures

The methodology of the first step allowed to establish links between functional failures, complementary needs and ARASs. Furthermore, to better differentiate the functionalities of these ARASs, a classification was made based on the degree of automation of each ARAS. The objective was to examine how the rider can influence the operation of the ARAS. For example, in the case of an autonomous system like ABS, it automatically activates when the wheels lock, and the rider can only deactivate it by releasing the brakes, which takes it out of the ABS operating range. Conversely, in the case of an assistance system like AEB, the rider can deactivate the system if he/she manages to obtain a greater deceleration than that provided by the AEB during emergency braking (inspired by the study conducted by [63]).

Fig. 6 presents the results obtained from the application of this method. It appeared that the ARAS for information and warning (such as CAT) covered the needs of the first two categories of functional failures, namely detection and diagnosis. As for the assistance ARAS (such as the AEB), their interventions covered four different categories, satisfying the needs of detection, diagnosis, decision and execution. Conversely, the majority of the so-called "Autonomous" systems (such as ABS) covered decision and execution needs, with the exception of (A-S) which can detect a deviation from the trajectory. Finally, no coverage of the ARAS for predictive needs was found.

3.2. Results for applications in real cases crash

3.2.1. Crash's selection

In order to analyze the effect of ARAS using the methodology developed in the second step, a selection of PTWs crashes was made. The EDA cases were selected on the basis of the data available for each crash. It should be noted that in order to define a functional

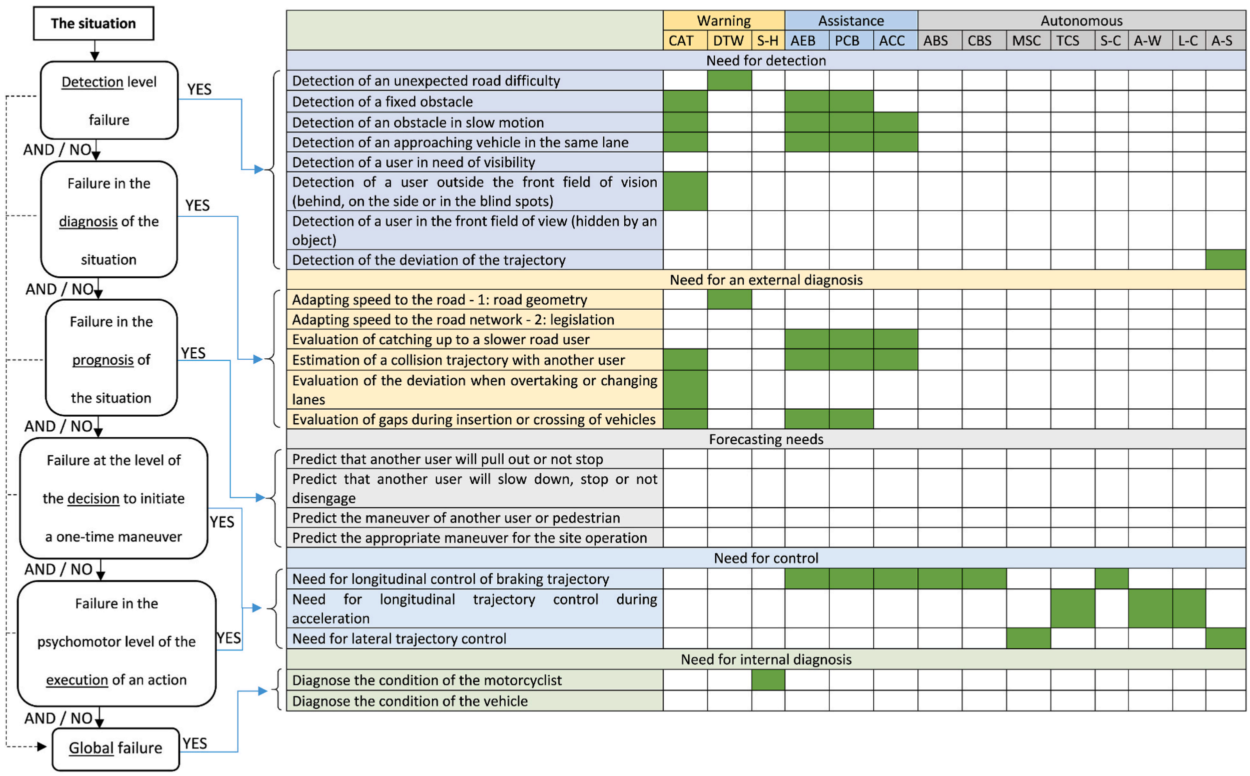


Fig. 6. Results of the link between ARAS, needs & failures.

failure in a crash, it was essential to have interviews with each participant, including the interview carried out at the crash site and the interview carried out a fortnight later. Then, analysis of these interviews in combination with other data, such as kinematic reconstructions and crash plans, enabled us to validate the choice of functional failures defined for each phase of the crash. This selection of EDA cases resulted in a list of 249 crashes cases.

On the other hand, the selection of IGLAD cases did not follow the same approach. It should be noted that IGLAD currently has around 10,000 cases, yet our laboratory only had access to crashes from the year 2021, which included 240 PTWs cases. Furthermore, it is important to point out that IGLAD does not follow the same model and coding as HFF to determine the functional failures of each crash. An analysis of the production of human error was carried out on each case, leading to the definition of numerous failures. As a result, we used these failures, together with the drawings and kinematic reconstructions available in IGLAD, to converge this failure analysis performed in IGLAD into an analysis that conforms to the HFF model and coding. As not all the necessary information was available on all 240 cases in IGLAD, a selection was made based on the availability of all this information, in order to retain only properly documented crashes. This resulted in the selection of 141 cases.

3.2.2. Overall effect des ARAS

After applying the developed method to analyze the selected crashes, the results were exploited.

The first result examined was the frequency of ARAS intervention in crashes, which is presented in Fig. 7. The analysis revealed that in more than 60% of the cases (240 crash), ARAS had an effect on the collision or fall of the PTWs. This observation highlighted the potential effectiveness of these systems in enhancing motorcycle safety.

However, in 38.5% of the crashes (150 cases), the ARAS had no impact. This finding underscored the fact that even the various ARAS developed were not able to ensure the safety of some PTWs riders. This may have been due to the inherent vulnerability of PTWs and to the riders' willingness to take risks.

3.2.3. Influence of each ARAS

The second interesting result was the frequency of intervention of each ARAS on the analyzed databases, as shown in Fig. 8. This frequency was deduced from the 61.5% of crashes in which the ARASs had an impact.

Among the ARAS analyzed, ABS was the most influential, with an intervention rate of 34.4% (nearly 134 crash). CAT comes second, with an impact on 30.8% (almost 120 cases) of the crashes analyzed. The emergency braking systems AEB and PCB were in third with an influence of 27.9% (almost 109 crash). ACC a technology similar to emergency braking was in fourth place with an influence of 17.4% (nearly 68 crash). Further down the ranking, the S–H, DTW and CBS systems had a similar impact of approximately 8% each (nearly 32 cases), MSC had an impact of 6.2% (nearly 24 crash), while TCS and A-S had an impact of approximately 2% (nearly 8 crashes). The S–C had an effect on a few crashes analyzed, accounting for 1% (almost 3 cases) of the total. Finally, the A-W and L-C systems had no influence on the analyzed crashes.

3.2.4. Prevalence of ARAS in the databases analyzed

In the databases analyzed, we noted that some motorcycles were already equipped with ARAS technology. In all, 31 motorcycles out of 349 crashes cases had at least one ARAS, representing around 9% Fig. 9. This figure is broken down as follows: 21 motorcycles in EDA, representing 5%, and 10 motorcycles in IGLAD, representing around 4%.

Going into more detail in this analysis, we found that ABS was the ARAS most present in our databases, in total we found it in 19

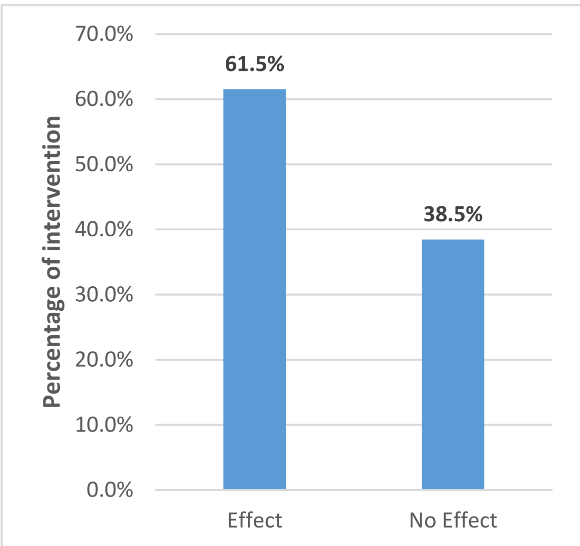


Fig. 7. ARAS effect.

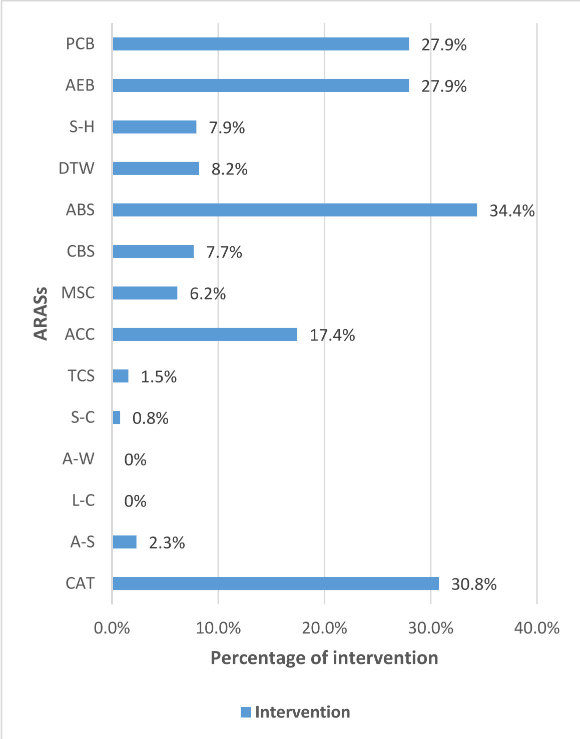


Fig. 8. Frequency of intervention of each ARAS.

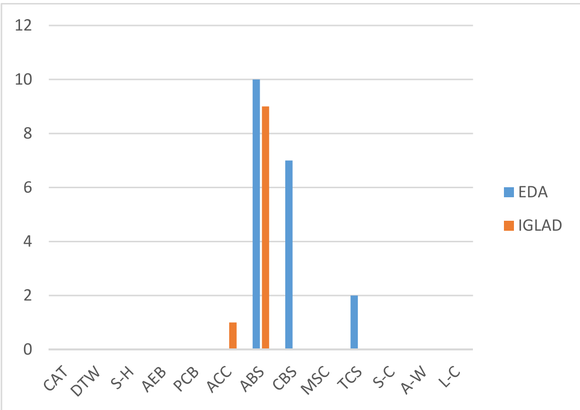


Fig. 9. Proportion of ARAS presence.

motorcycles (10 in EDA and 9 in IGLAD). Other technologies were also found, such as CBS in 7 motorcycles and TCS in 2 motorcycles, both of which were involved in crashes in the EDA database. In the IGLAD database, on the other hand, we found one motorcycle with ACC.

3.3. *Weighting results*

This work concerned the weighting of data obtained from the EDA database on a larger sample, namely a crashes database of 1000 PR. Representative of the French national data.

Table 1 shows all the results of this analysis. The first section (in green), gives the percentage of each scenario in each database. It can be observed that the proportions of scenarios in the EDA generally followed those in the 1000 PR database. The scenario SC3 that include all crashes at intersections is at the top of the list. It represents 44.2% of cases in the EDA (110 cases) while 36.7% in France (367 cases), followed by SC5 in the EDA, grouping all loss-of-control crashes (17.3% or 43 cases), and SC1 (16.9% or 42 cases)

Table 1
Weighting results, in green percentage of each scenario in EDA and French national data, in yellow percentage of effect each ARAS in each scenario and no effect of all ARAS and in blue effect of each ARAS at French national level.

Scenarios	EDA	France	Effect of each ARAS in each scenario														No effect
			CAT	DTW	S-H	AEB	PCB	ACC	ABS	CBS	MSC	TCS	S-C	A-W	L-C	A-S	
SC1	16.9	21.3	38.1	11.9	0.0	35.7	35.7	26.2	40.5	19.0	11.9	2.4	0.0	0.0	0.0	2.4	28.6
SC2	9.2	4.7	34.8	4.3	4.3	30.4	30.4	21.7	34.8	4.3	0.0	0.0	0.0	0.0	0.0	0.0	52.2
SC3	44.2	36.7	32.7	1.8	1.8	38.2	38.2	19.1	47.3	12.7	2.7	0.9	2.7	0.0	0.0	3.6	38.2
SC4	5.2	12.3	30.8	0.0	0.0	23.1	23.1	15.4	38.5	15.4	0.0	0.0	0.0	0.0	0.0	0.0	46.2
SC5	17.3	14.7	9.3	25.6	11.6	9.3	9.3	4.7	18.6	2.3	30.2	7.0	0.0	0.0	0.0	4.7	34.9
SC Other	7.2	10.3	27.8	16.7	5.6	27.8	27.8	11.1	38.9	5.6	11.1	0.0	0.0	0.0	0.0	11.1	33.3
Effect of each ARAS in French national data			29.8	8.9	3.2	30.1	30.1	17.3	39.1	11.7	9.1	1.9	1.0	0.0	0.0	3.7	36.8

grouping vehicle-to-vehicle. In France, SC1 appears as the second main scenario with 21.3% (213 cases), followed by SC5 with 14.7% (147 cases) in third place.

The second part of the table (in yellow), shows the percentages of effect of each ARAS in each scenario, and the percentages of no effect of all ARAS. It can be observed that ARASs such as (CAT, AEB, PCB, ABS, and CBS) had an effect on all the defined scenarios, while others such as (MSC, TCS) had an effect only on specific scenarios. It has been observed that the CAT had an influence of 9.3% in loss-of-control crashes, despite the fact that this technology was designed to detect other vehicles around the motorcycle. This result was attributed to a specific crash classified as SC5. These crashes involve a motorcyclist who detects a vehicle ahead at the last moment. Subsequently, in an attempt to avoid the collision, the motorcyclist initiates an evasive maneuver that concludes with a loss of control of the motorcycle. It can be also noted that the proportion of effect of each ARAS in each scenario generally followed the proportions obtained in the EDA and IGLAD, with ABS in the lead, followed by CAT and AEB PCB. The rightmost column in this section represents the percentage of crashes where ARAS have no effect in each scenario. It was observed that SC2 was the type of crash that ARAS could not influence, with more than 50% non-influence.

Finally, the last part of the table (in blue) shows the overall effect of each ARAS at a French national level. ABS had the greatest effect with 39.1% (391 cases), followed by AEB and PCB with 30.1% (301 cases) and CAT with 29.8% (298 cases). The other ARAS followed with 17.3% (173 cases) for ACC and 11.7% (117 cases) for CBS, as well as the other technologies with percentages below 10%. it was also observed that ARAS had no influence on just over 35% of crashes in the national database. This shows the risk and vulnerability of PTW users.

4. Discussion

Comparing our results with those of other studies was challenging due to the limited number of works that covered ARASs simultaneously. Most of the existing studies focused on crashes related to the specific technology studied.

The first step of our study was to create a matrix of links between ARAS, complementary needs and functional failures experienced by motorcyclists. In a first step, it was observed that the information and warning systems fulfilled the needs and failures related to detection and diagnosis thanks to their various functionalities. For instance, CAT allows can cover most detection needs because it monitors the driver's surroundings at 360° with two cameras. However, it does not cover all needs, such as "detection of users hidden by objects", which require technologies like V2V or V2X. The same technology can also analyze distances to other users, allowing it to cover some diagnostic needs. In the same category of ARAS, other technologies such as DTW and S–H cover the detection and diagnostic failures for PTWs and global failures for S–H due to their functionalities. In addition, in the "assistance" category, emergency braking technologies (AEB, PCB and ACC), cover detection, diagnosis, decision and execution needs, by using cameras/radars to detect, diagnose and to initiate an emergency braking maneuver in case of danger. Finally, the so-called "autonomous" systems meet decision and execution needs. For example, TCS detects a difference in front and rear wheel rotation, and cuts the throttle to restore vehicle stability, while ABS controls the vehicle longitudinally during braking with a maximum rolling angle of 20°, meeting execution needs.

The results obtained in the second stage of the study revealed that ARAS would have a significant influence of 61.5% on the safety of PTWs riders.

However, it was also observed that in 38.5% of the crash analyzed, ARAS had no influence. This can be explained by the absence of systems that cover specific complementary needs.

Further analysis of the effects of ARAS on crashes shows that ABS is the most influential system. This is because it prevents wheels from locking at maximum roll angle of 20°, and accompanies emergency braking. This result corroborates the studies of Teoh [17] and Rizzi & al [21] who found an influence of 37% and 34%, respectively. However, it differs from the study by Lich & al [20], where the effect of ABS was estimated at 74%. This difference may be due to the different types of crashes analyzed in the studies. In our research, all types of crashes scenarios were considered to analyze the effect of ARASs, while Lich & al [20] focused on crashes within the scope of ABS. Our study found that CAT has a high frequency of impact due to its ability to monitor the surroundings of the PTWs over a 360°

angle. This technology had proven to be very beneficial in India, where most major roads have six lanes, leading to collisions in the blind spots of PTWs. In addition, emergency braking technologies, such as AEB and PCB, have a remarkable frequency of impact. They influence the databases by 27.9%, followed closely by ACC, which has a 17.4% influence and can be considered similar to these technologies. Their reactions in detecting and implementing braking actions can be more effective and faster than those developed by PTWs riders. In addition, in some cases where the rider initiates a braking maneuver, these systems can react faster than the rider, providing a longer distance for braking, and thus crash avoidance or reduced impact speed. The CBS, DTW, and S–H technologies had a small percentage of influence in the ARAS ranking. However, each technology had an effect in 32 crashes by providing various benefits. CBS reduces braking distance necessary to stop the vehicle, DTW warns of dangerous turns, and S–H alerts the rider to cognitive impairment. Although MSC is very beneficial for PTWs, its influence was low in this analysis because of the limited number of crashes analyzed involving loss of control following braking in a turn. On the other hand, TCS and A-S are very beneficial technologies in specific situations, while A-W and L-C have no significant effect as they are mainly intended for motorcycle racing.

The second-to-last section in the results represents the proportion of presence of the ARASs in the analyzed databases. It was noted that ABS is the technology most frequently found on motorcycles. This trend can be explained in part by the functional advantages offered by this technology, notably in assisting the motorcyclist with braking maneuvers in longitudinal trajectories, and on the other hand by the European regulation which appeared in 2016 (European regulation COM 2010/542) and which requires motorcycles over 125 cc to be equipped with this system. Other safety technologies, such as CBS, ACC and TCS, and comfort technologies, including Speed limiter, Dash Bord and Cruise control, were also found.

The last result of this study presents a weighting of the results obtained from the EDA database on a French scale. This analysis emphasizes the importance of SC3 (intersection crashes), SC1 (vehicle-to-vehicle crashes), and SC5 (loss of control) in the databases, indicating the need to focus on interventions related to these scenarios to improve road safety in France. Furthermore, the differentiated effect of ARAS in each scenario suggests the relevance of specific strategies based on the type of crash. Additionally, the results highlight the notable effectiveness of ABS, AEB/PCB, and CAT on a national scale. It is also necessary to note that other ARAS such as MSC and DTW did not have a significant percentage, but they remain beneficial in specific scenarios such as SC5. These findings provide valuable information to guide road safety policies towards specific technologies. These observations can serve as a basis for practical recommendations aimed at reducing the number of crashes and improving road safety in the French road context.

This work relies on a well-documented crashes database, as it requires information on the production of human error and kinematic crash reconstructions. The methodology developed in this study enabled us to obtain an initial estimate of the effects of ARASs. It would be interesting to apply this method to other databases for a wider representativeness, provided we have sufficiently informed crash cases.

5. Limitations

One of the limitations of this study is that it remains a general analysis of the effects of ARAS on PTWs crashes. To further investigate these effects, it is necessary to develop quantitative methods based on kinematic reconstructions and numerical simulations of each ARAS. These approaches will make it possible to integrate the various numerical variables such as speed, acceleration, distance and time to collision in the calculation and estimation of the effect of ARAS.

In addition, this study does not take into account the different reactions that the rider may have when each ARAS is activated, making it difficult to distinguish between the effect of avoidance and that of mitigation. It would therefore be interesting to conduct a study on rider interaction with ARAS technologies, similar to the one conducted by Char & al [64]. In this study, researchers conducted a parametric study to examine the influence and interaction of an emergency braking system for cars on cyclists.

Finally, it should be noted that this study did not consider the potential risks associated with each ARAS for PTWs riders. Conducting an in-depth analysis of these risks could enhance the understanding of the benefits of ARAS systems in reducing the crashes rate of motorcyclists. An example of the potential benefits of analyzing the acceptability and risks of emergency braking technology for motorcyclists is demonstrated by the University of Florence Savino & al [26–29].

6. Conclusion

This study aimed to analyze the effects of ARASs on the crash rate of PTWs.

Initially, a literature review was carried out to identify the different driving assistance technologies developed or under development for PTWs, and a list of ARAS was drawn up. This list included definitions of each ARAS, specifying its advantages and benefits in terms of rider safety.

Subsequently, a methodology was developed to analyze the effects of ARAS using real crashes databases. The first step of this methodology was to start from the functional failures of each crash that led to the moment of rupture in the driving situation and, consequently, to the crash, in order to determine the complementary needs. The benefits of each ARAS were projected onto this list of needs, with the aim of identifying compatibilities and correspondences. Finally, a methodological scheme based on the principle of causality was constructed to analyze the crash.

After defining the method, analyses were carried out on 390 reals crashes extracted from the EDA and IGLAD databases. The results show the impact of ARAS on motorcycle safety, with at least one ARAS having an influence in 61.5% (240 crash) of the crashes studied. However, in 38.5% of the cases, the ARAS had no influence at all, which illustrates the vulnerability of PTWs and the potential risk-taking of some riders. In addition, the results obtained for each ARAS in the EDA database were weighted on a French scale. This weighting made it possible to give an initial estimate of the most promising ARAS on a French scale. ABS was found to be the most influential ARAS in crashes, followed by AEB/PCB, then CAT. These results are consistent with the study conducted by Terranova & al [35].

This work provides an initial assessment of the most promising technologies for PTWs road safety. It can be used to guide manufacturers towards the development of the most beneficial systems. In addition, this study can help guide road safety policies by focusing on the ARAS that seem most effective, and by considering the introduction of appropriate standards or regulations.

Finally, future studies will focus on the dynamic simulation of a PTWs using the multibody method capable of modeling the influence of the different ARAS on PTWs behavior in order to complete the model already developed by Ref. [65].

Data availability statement

The data that has been used is confidential.

CRediT authorship contribution statement

Abdelkarim Ait-Moula: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ebrahim Riahi:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thierry Serre:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization.

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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