IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

An injury risk-based comprehensive framework for testing and assessing ADAS functions in critical road scenarios

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

An injury risk-based comprehensive framework for testing and assessing ADAS functions in critical road scenarios

Michelangelo-Santo Gulino[1], Giulio Vichi[1], Luigi Di Lillo[2], Alessandro Gianfelici[2], Dario Vangi[1]

[1]Department of Industrial Engineering, Università degli Studi di Firenze
[2]Property & Casualty Solutions, Swiss Reinsurance Company Ltd.

E-mail: michelangelosanto.gulino@unifi.it

Abstract. Assisted driving is currently considered a key aspect for improving road safety, and automakers and OEMs are working to achieve higher levels of vehicle automation by introducing new technologies and Advanced Driver Assistance Systems (ADAS) in the circulating fleet. This trend requires test protocols for vehicle safety assessment to be frequently reviewed and updated, considering the latest advances in the state of the art regarding ADAS functions and systems. As of today, performance assessment programs (such as NCAP) mainly evaluate how an ADAS behaves in terms of crash avoidance in specific critical scenarios, which represent the most frequent crash constellations among real-world impacts. However, enhanced safety can be also obtained in case the impact is not avoided if a decrease in Injury Risk (IR) for the involved road users is achieved by ADAS intervention, compared to the case of no intervention.

The purpose of this work is to propose an overall framework to draft or update test protocols for ADAS performance assessment based on real car-to-car impact observations, representative of impact scenarios in terms of both occurrence frequency and IR. First, the in-depth accident database IGLAD is analyzed to identify the most relevant car-to-car accident scenarios based on a relevance indicator, i.e., the risk level being the multiplication of the occurrence frequency and IR for a specific scenario. For each relevant scenario, a risk level-based strategy to identify one significant closing speed between vehicles for the tests is defined; the test collision speed for the two vehicles is determined analogously, and the risk level for each combination of speeds in a scenario represents the maximum achievable score by the ADAS if the collision is averted. Considering the well-established Euro NCAP framework as a relevant starting point for the definition of test protocols, two examples are highlighted regarding the proposal of a new test protocol and an update of an already existing one. Finally, a method is proposed for ADAS performance assessment if the impact is not avoided, scaling the maximum achievable score based on the IR reduction consequent to the ADAS intervention.

1. Introduction

In the rapidly evolving landscape of automotive technology, Advanced Driver Assistance Systems (ADAS) have emerged as a pivotal force in enhancing road safety, driving convenience, and the prospect of autonomous mobility. Continuing technological advances are driven by ADAS performance evaluation methodologies capable of highlighting points of possible weakness at the functional or logical level, to increase their flexibility towards critical situations and result in a higher user acceptability. ADAS performance evaluation methods are divided into predictive (*a priori*) and retrospective (*a posteriori*) methods. If the ADAS system – or function – to be tested is implemented on a limited portion of the circulating fleet or is in the prototype phase, the method is called predictive and aims primarily at identifying conditions of highest efficiency [1, 2]. If, on the other hand, the implementation involves a large number of vehicles (as in the case of an established function such as Autonomous Emergency Braking, AEB), the method is referred to as retrospective: "what if" analyses are in this case typically performed, regarding how the outcome of a road impact would change in case of the function implementation onboard one or multiple vehicles [3].

Among the retrospective methods, protocols developed in the context of frameworks like the New Car Assessment Programme (NCAP) are an important reference for technicians and consumers. However, assessment methods are heterogeneous across continents. In the United States, NCAP is limited to assessing if a specific system is available in the vehicle and whether it performs according to a set of minimum requirements in specific situations; however, the ADAS performance scoring method is currently under definition[1]. Its European counterpart, Euro NCAP conversely introduced in 2018 a series of tests for various ADAS functions in car-to-vulnerable road users (car-to-pedestrian, car-to-bike, etc.) and car-to-car imminent collision scenarios. The latter[2] are aimed at representing the most frequent accident scenarios and those in which already established systems like AEB are able to operate at maximum efficiency in terms of crash avoidance. Nevertheless, increasing road safety does not only depend on crash avoidance but also on limiting the Injury Risk (IR) for the involved parties when an impact cannot be averted [4, 5].

An analysis of the Euro NCAP scoring criteria for an AEB system highlights that the fundamental performance evaluation parameter lies in the closing speed at collision V_r between the ego vehicle (or Vehicle Under Test, VUT) and the opponent vehicle (or Global Vehicle Target, GVT). Although V_r is an important factor influencing IR in collisions, its relationship with IR is a complex function that is often expressed by means of an S-shaped curve, derived by logistic regression on accident data [6]. As an example, a model of IR for frontal, centred impacts is reported in Figure 1, which is based on the injury metric Maximum Abbreviated Injury Scale higher than 3 (MAIS 3+) [1]. On the right in Figure 1 is reported the EuroNCAP scoring for a CCRs scenario of AEB testing with the VUT moving at 80 km/h and stationary opponent; starting from the IR value in the case of no intervention by the AEB (V_r=80 km/h, IR=53%) also known as Reference Scenario RS, the absolute reduction in IR is also reported on the right in Figure 1. This latter curve is directly derived from the IR model in the left of Figure 1. It can be seen that in the zone at $75<V_r\leq 80$ a score of 0% is applied to the ADAS because the impact occurs at almost the same speed as the RS. In the $30<V_r\leq 75$ zone, where the system has the possibility of significantly reducing IR with reduced changes to V_r, Euro NCAP provides a score of 0.25 or 0.50. Similarly, the score varies significantly between $0<V_r\leq 30$, although IR in this range is almost constant and close to 0% – IR(V_r=30 km/h)=3%. Such a gap between the IR reduction trend and Euro NCAP scores emphasises that the representativeness of real accidents in terms of IR is not currently prioritized in the definition of ADAS performance assessment protocols. It should also be considered how, in more complex impact scenarios such as intersection crashes, different activations may result in changing the impact type (e.g., from front-to-front to front-to-side) with substantial changes to IR for the occupants of the involved vehicles [7]. For these reasons, it is essential to propose a set of tools for the definition of test protocols and scenarios that can effectively represent IR in real road impacts.

This work aims to propose a framework for the definition of car-to-car testing protocols and scenarios for ADAS performance assessment that are representative of real-world impacts

[1] Docket No. NHTSA-2021-0002

[2] European New Car Assessment Programme (Euro NCAP) – Assessment Protocol – Safety Assist Collision Avoidance, Implementation 2023, v10.2, November 2022

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

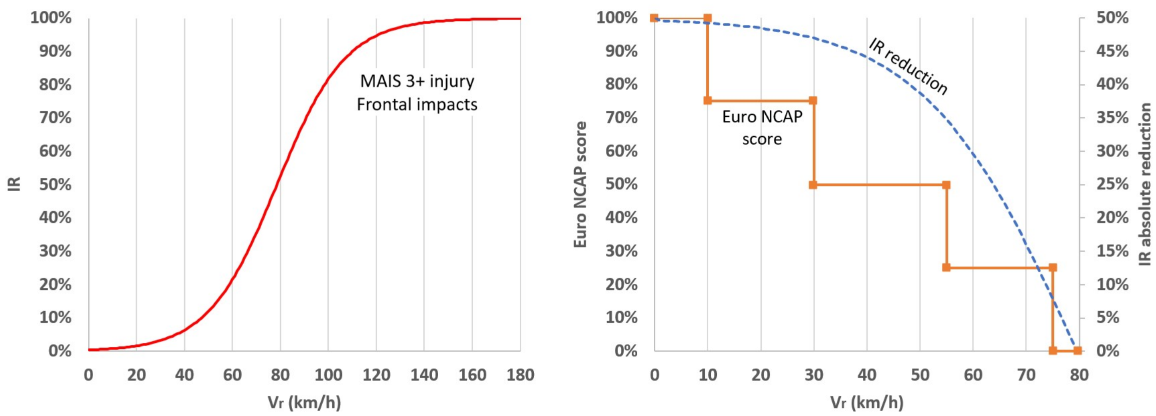


Figure 1. IR model for MAIS 3+ injuries in frontal, centred impacts (left [1]), comparison between Euro NCAP scoring method for a CCRs test at 80 km/h and achievable absolute reduction in IR as a function of V_r (right).

in terms of both frequency and IR for the vehicle occupants; this involves the provision of a methodology for evaluating performances in both cases where the onboard system is able to avoid the impact or not. The framework is applicable to both the development of new protocols and the updating of any existing protocols. From the latter perspective, the EuroNCAP protocols available to date are taken as a reference to illustrate the use of the proposed method.

The activities performed can be sequentially listed as follows:

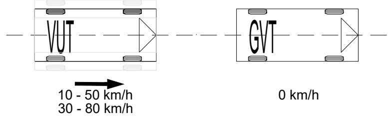
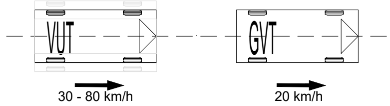
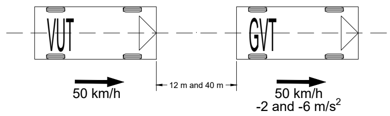
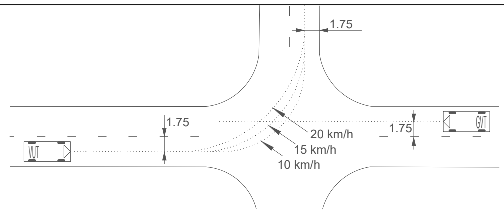
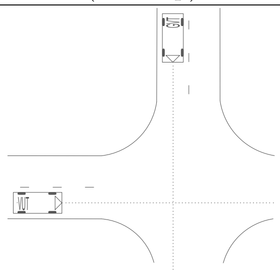
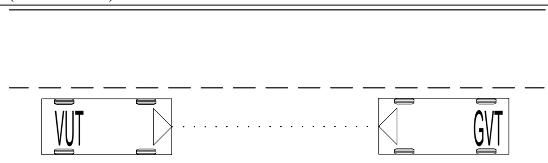
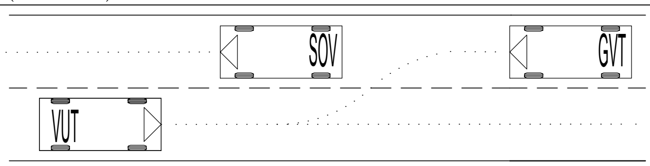
(i) An in-depth accident database is employed to extract data on real car-to-car impact scenarios in terms of frequency and IR for the involved occupants so that the most relevant scenarios for ADAS testing can be identified;
(ii) For the selected scenarios, the closing speed and collision speed to be applied to the VUT and the GVT have been chosen based on frequency and IR-related criteria;
(iii) The test protocols and the maximum score achievable by an ADAS are proposed, for test procedures still to be developed or already available inside the Euro NCAP program;
(iv) An ADAS scoring methodology is introduced to provide an assessment of ADAS performance in both cases of avoided and unavoided impacts.

2. Data extraction from an in-depth accident database and selection of relevant scenarios

2.1. IGLAD database

The IGLAD database (Initiative for the Global Harmonization of Accident Data) includes a classification of relevant scenarios for ADAS assessment, initially proposed by a team of experts from Continental AG in 2019 [8]. All IGLAD data coded after 2019 are hence classified in terms of scenario (“Scenario Type” variable). Each participant in an accident is characterized by a label among 42 possible labels. The 42 possible scenarios are divided into 6 classes: “Driving”, “Longitudinal”, “Oncoming”, “Turning”, “Crossing”, and “Other”. Some of these scenarios are already considered inside the Euro NCAP program, as synthetically reported in Table 1, evidencing all available test scenarios for AEB, car-to-car EuroNCAP protocols and the related equivalent from the IGLAD classification. Based on these highlights, the Euro NCAP tests feasible for an update with the proposed framework are represented by seven protocols.

Table 1. AEB test protocols already implemented in the EuroNCAP framework (left column) with the corresponding scenario of the IGLAD classification (right column).

	EURONCAP	**IGLAD "Scenario Type"**
1	CAR-TO-CAR REAR STATIONARY (CCRs)	Running up
		
2	CAR-TO-CAR REAR MOVING (CCRm)	Running up
		
3	CAR-TO-CAR REAR BRAKING (CCRb)	Running up
		
4	CAR-TO-CAR FRONT TURN ACROSS PATH (CCFtap)	Turning farside (object oncoming)
		
5	CAR-TO-CAR CROSSING STRAIGHT CROSSING PATH (CCCscp)	Crossing from farside
		
6	CAR-TO-CAR FRONT HEAD-ON STRAIGHT (CCFhos)	Oncoming on the same lane
		
7	CAR-TO-CAR FRONT HEAD-ON LANE CHANGE (CCFhol)	Oncoming on the same lane
		

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

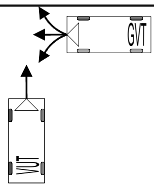
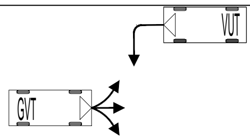
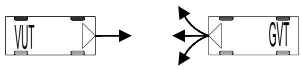
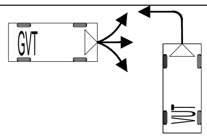
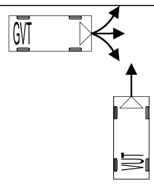
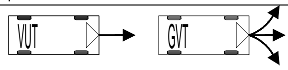
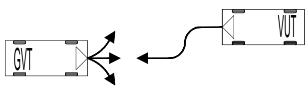
2.2. Criterion for scenario selection

Limiting the interest to car-to-car impacts with accident dates starting from 2019, the IGLAD cases available for subsequent processing are 572. Data for these cases are extracted both in terms of scenario ("Scenario Type" variable) and impact-related features, i.e., velocity change of the single vehicle during the impact (ΔV [9]) and "Impact Type" (front, back, side, near-side). In particular, ΔV is an indicator of the impact forces (based on momentum conservation) to which the vehicle and the occupants are subjected. Accident type is conversely derived based on the position of the main intrusion on the vehicle (coded as "Collision Deformation Classification", CDC); if a lateral impact involves the compartment on the same side of an occupant's seating position, the impact is classified as a "near side". Using an established IR model [7], IR can be directly derived for the occupants of a specific vehicle based on ΔV and "Impact Type". At this point, to properly select scenarios that are representative from both standpoints of frequency and IR, an overall risk level has been applied to a specific scenario by multiplying its frequency (number of occurrences) with the average IR for the ego's occupants among all impacts included in such a "Scenario type". As an example, the highest risk level is equal to 104 and is associated with the scenario "Crossing from nearside" of the IGLAD classification. The scenarios were chosen considering only those with a risk level at least equal to one-third of the maximum. Table 2 summarizes the selected IGLAD scenarios, matched with the respective EuroNCAP test (if applicable). The scenario "Other Oncoming Accident" is highlighted in this step as a relevant scenario for the tests in terms of risk level; nevertheless, this category is not treated in the remainder of the paper, being comprehensive of a broad range of critical scenarios that cannot be classified otherwise based on the IGLAD coding scheme.

3. Test speed selection

Speed selection is a fundamental element for the proposal of a new testing protocol. To this end, a method is proposed to select one significant closing speed for the tests to be performed. One closing speed is chosen here for the sake of simplicity. To obtain the sought representative closing speed, a value of V_r is associated with a value of IR for each impact [6]. Considering a specific V_r value, the frequency of such a V_r value in the population has been multiplied by the IR for each impact, resulting in a risk level according to what prescribed in Section 2.2. Subsequently, a risk curve for each scenario is built derived from such a risk level by a second-order, least-square method polynomial fit, as shown in Figure 2 for the IGLAD "Crossing from near side" scenario. The speed value that has the highest risk level is considered in the proposal of new tests. This risk level at the specific V_r value is considered as the maximum score obtainable by the VUT in a test, in case it is able to avoid the impact. The results for identification of relevant V_r in all scenarios employing such a procedure are reported in Tables 3, dividing the tests between scenarios not covered and covered by EuroNCAP protocols.

Table 2. Relevant IGLAD scenarios matched with the respective Euro NCAP test (if applicable) and related risk level.

SCENARIO	IGLAD “Scenario Type“	**RISK LEVEL**	EURONCAP TEST
Crossing from nearside		104	*Not available*
Turning farside and object oncoming		98	CCF_{tap}
Oncoming on the same lane		88	$CCFhos/CCFhol$
Turning farside and object from farside		83	*Not available*
Crossing from farside		75	$CCCscp$
Other Oncoming accident	/	70	*Not available*
Running up		48	CCR_s/CCR_m
Lane changing to offside and oncoming		42	*Not available*

In addition, the identified representative V_r values must be distributed between both vehicles participating to the specific scenario; to this end, the most frequent collision speed of the ego in each considered scenario has been identified starting from the IGLAD database information. The histogram of collision speeds related to the scenario “Crossing from nearside” is reported in Figure 3 as an example. The most frequent collision speed values of the VUT are 35 km/h and 45 km/h. Then the VUT collision speed values for the tests related to scenario ”Crossing from nearside” will be 35 km/h and 45 km/h. The results for the other scenarios are summarized in Table 4. The opponent collision speed is easily computable knowing the ego collision speed, the closing speed, and the impact configuration. Based on this, it is possible to propose new test procedures to evaluate ADAS functions, scenario by scenario.

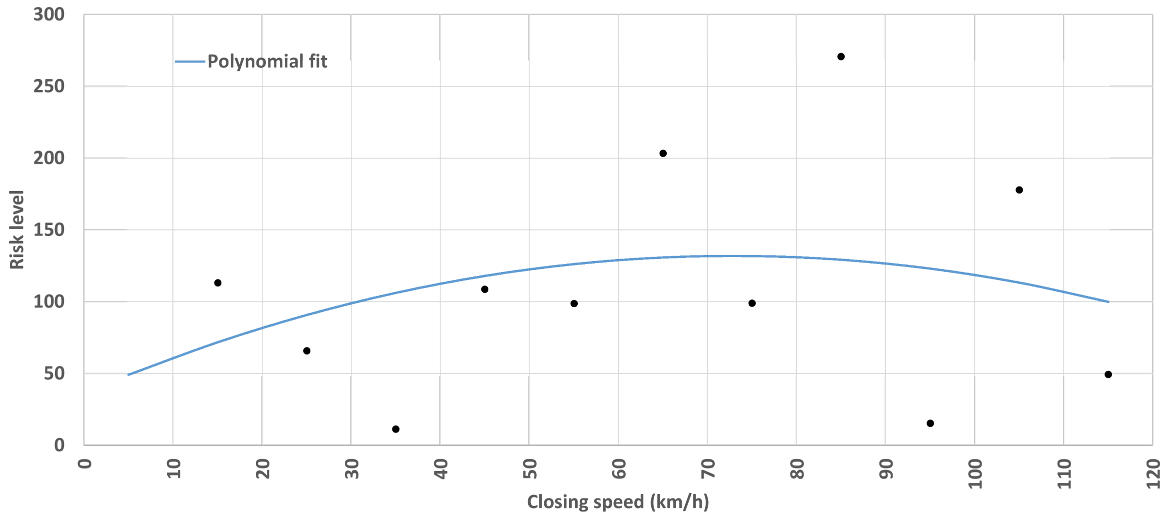


Figure 2. Risk level distribution for each V_r value in the IGLAD "Crossing from nearside" scenario.

Table 3. Closing speed and score (both for cases covered by Euro NCAP and those not).

SCENARIO	CLOSING SPEED (km/h)	RISK LEVEL
UNCOVERED CASES		
Crossing from nearside	75	140
Turning farside and object from farside	85	153
Lane changing to offside and oncoming	150	148
COVERED CASES		
Turning farside and object oncoming	90	312
Oncoming on the same lane	140	192
Crossing from farside	75	130
Running up	90	122

Table 4. Table of ego collision speed in the Euro NCAP covered and uncovered scenarios.

UNCOVERED CASES	Ego collision speed (km/h)
Crossing from nearside	35; 45
Turning farside and object from farside	15
Lane changing to offside and oncoming	0; 35; 65; 70
COVERED CASES	**Ego collision speed (km/h)**
Oncoming on the same lane	35; 40
Crossing from farside	40; 45
Turning farside and object oncoming	20
Running up	25; 35

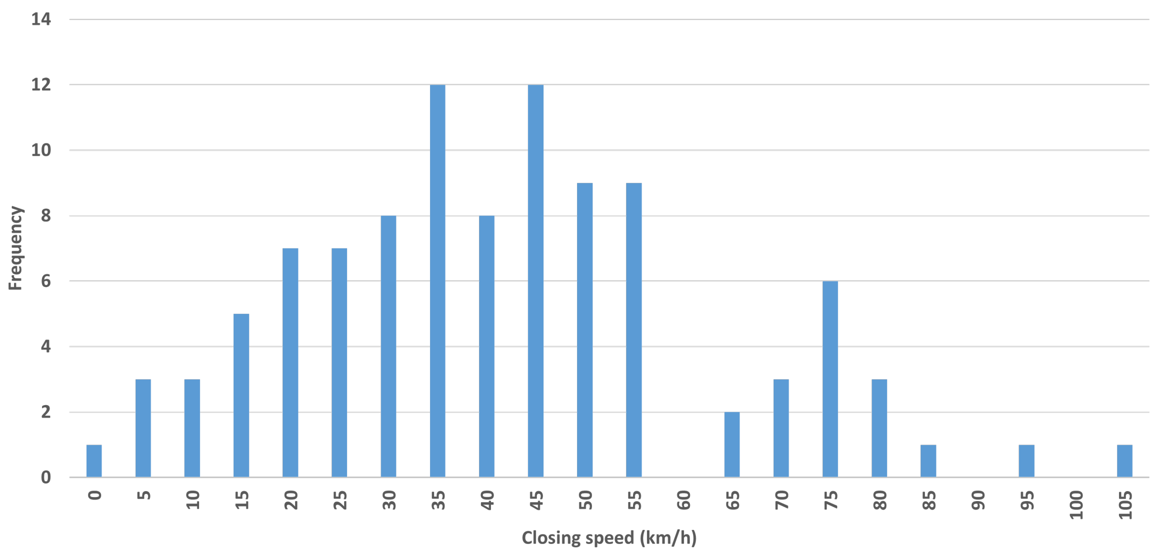


Figure 3. Histogram of collision speeds (Scenario "Crossing from nearside").

4. New proposal or update of test protocols

Once the scenarios for the tests, the VUT collision speed, and V_r have been selected, a test protocol must be proposed. As an established consumer program, Euro NCAP framework can be considered a solid reference for the proposal of new protocols or updates of already available testing procedures. For this reason, the present Section highlights two examples, one a new protocol and one regarding the update of an already available EuroNCAP protocol. In both instances and in the case of impact avoidance, the ADAS can obtain a maximum score equal to the risk level highlighted in Section 3 for the specific scenario and V_r under investigation.

4.1. New proposal: "Crossing From Nearside"

Figure 4 reports a possible configuration of the "Crossing from Nearside", identified as the most relevant scenario in terms of risk level (Table 2). Compared to the "CCCscp" test by Euro NCAP, rather then the front, the GVT impacts the side of the VUT (opposite side with respect to the driver's position). This difference in impact type enables diverse possibilities in terms of IR to be explored compared to the "CCCscp" alternative (IR in a side impact is higher than in the case of a front impact, ΔV being the same). The test must be performed two times at two different GVT and VUT collision speed combinations, in accordance with Table 5. Based on the V_r values in Table 3 and collsion speed values in Table 4, the GVT collision speed is computed as:

$$V_{GVT} = \sqrt{V_r^2 - V_{VUT}^2} \tag{1}$$

where V_{VUT} and V_{GVT} are respectively the speed of the VUT and the speed of the GVT.

Table 5. Test parameters for a newly proposed "Crossing from nearside" scenario.

TEST	Closing speed (km/h)	Ego collision speed	Opponent collision speed	MAX SCORE
1	75	35	65	140
2	75	45	60	140

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

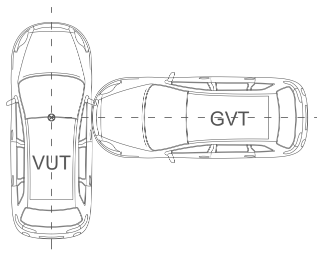


Figure 4. Impact configuration for a newly proposed "Crossing from nearside" scenario.

4.2. Update: "Turning Farside and Object Oncoming" (CCFtap)

Based on Table 1, the second most relevant scenarios in terms of risk level is the "Turning Farside and Object Oncoming" corresponding to the "CCFtap" scenario by Euro NCAP. Figure 5 reports the test path already implemented inside the Euro NCAP framework. From the data analysis in Table 3, the closing speed of interest is in this case equal to 90 km/h and the before proposed approach would suggest assigning a VUT collision speed of 20 km/h and performing only one test, with maximum score equal to 312 in case of avoided impact. Nevertheless, a solution accounting also for the already available methodology can be considered: the speed values prescribed by Euro NCAP can be employed, applying a maximum score based on the risk level corresponding to the test closing speed. For this scenario, the polynomial fit curve obtained as described in Figure 2 for the "Crossing from Nearside" scenario is used, reported in Figure 5. Referring to the EuroNCAP "CCFtap", the tests should hence be represented by 9 combinations of VUT speed values of 10, 15 and 20 km/h combined with GVT (opponent) speed values of 30, 45 and 55 km/h, as reported in Table 7.

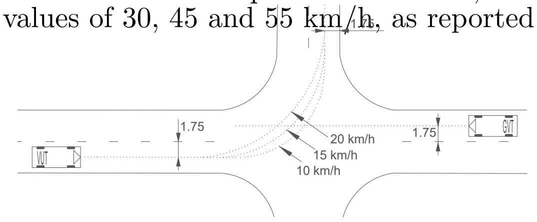


Figure 5. Test path for the already available "Turning Farside and Object Oncoming" scenario (Euro NCAP "CCFtap").

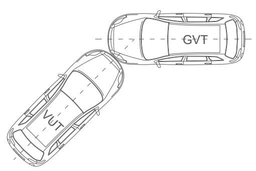


Figure 6. Impact configuration for the already available "Turning Farside and Object Oncoming" scenario (Euro NCAP "CCFtap").

The paths adopted ensure an impact configuration like the one shown in Figure 6. Based on the V_r values in Table 3 and collision speed values in Table 4, the GVT collision speed is computed according to Carnot's theorem as:

$$V_{GVT} = V_{VUT}\cos\alpha + \sqrt{V_{VUT}^2\cos^2\alpha + V_r^2 - V_{VUT}^2} = V_{VUT}\cos\alpha + \sqrt{V_r^2 - V_{VUT}^2\sin^2\alpha} \quad (2)$$

with α the angle between V_{VUT} and V_{GVT} collision speed of the closing speed vector in the velocity triangle. The value of α can be determined from the test paths shown in Figure 5. The total score for the scenario is the mean of all the scores achieved in each test.

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

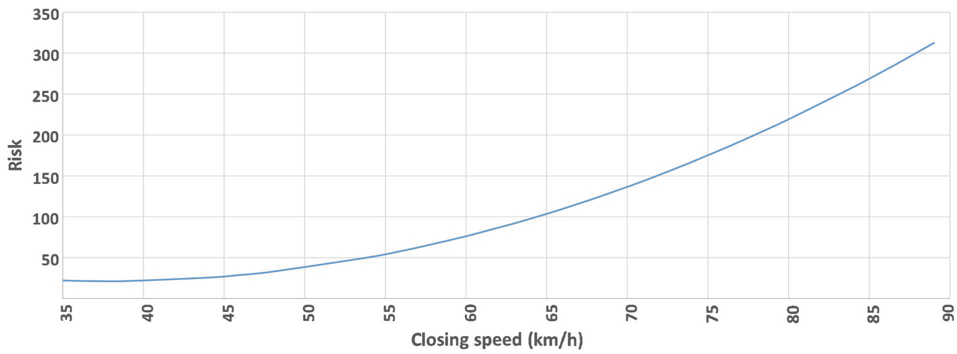


Figure 7. Risk curve for the definition of the maximum score at different V_r values in the already available "Turning Farside and Object Oncoming" scenario (Euro NCAP "CCFtap").

Table 6. Test parameters table ("Turning farside and object oncoming").

Ego speed [km/h]	Opponent speed [km/h]	Corresponding closing speed	MAX SCORE
10	30	35	22
10	45	50	38
10	60	65	100
15	30	40	22
15	45	55	54
15	60	70	130
20	30	45	27
20	45	60	76
20	60	75	170

5. SCORE SCALING CRITERIA

The previously introduced maximum score applies if the impact is avoided by the ADAS. If the ADAS intervention does not avert the impact in the test, the score is assigned by scaling the maximum score available with the IR value for the VUT as follows:

$$Score = MaxScore \cdot (IR_{reference} - IR_{modified})/IR_{reference} \quad (3)$$

where $IR_{reference}$ and $IR_{modified}$ are the IR values in the RS and in the scenario modified by the ADAS intervention, respectively. IR can be calculated, starting from the impact configuration and collision speed of the vehicles, by running a simulation with dedicated software (e.g., like that described in [10]) or by employing the so-called CMI-V_r approach (described by the authors in previous work [1, 9]): the vehicles do not actually sustain an impact because the GVT does not have inertial properties; therefore, the value ΔV for the identification of the IR cannot be directly measured. The previously reported equation accounts for the possibility that the ADAS intervention leads to an increase in IR because of a change in the impact configuration (like moving from a frontal and eccentric crash to a lateral and centred crash): in this case, the score for the ADAS in the analysed scenario becomes negative. The overall score for the ADAS is the sum of all scores achieved in each test scenario.

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012027 doi:10.1088/1757-899X/1306/1/012027

6. Conclusions

A framework has been highlighted for the proposal of testing protocols for ADAS performance assessment in car-to-car imminent impact scenarios. Compared to the previous literature, the methodological approach is based on occurrence probability (frequency) and injury consequences for the occupants (Injury Risk, IR) associated with real-world impact scenarios. These two factors are combined into a comprehensive risk level, representing an indicator of the specific scenario's relevance among all possible impact scenarios. The risk level allows also for the selection of proper closing speed at collision to be considered in the test development, as well as the definition of a maximum score obtainable by the ADAS if the impact is avoided in such relevant scenarios. A scaling criterion for such maximum score has been also highlighted in case of unavoided collision, based on IR values that can be assessed starting from the impact configuration and closing speed at collision for the vehicles.

The framework represents a valuable tool for both the proposal of new test protocols and the update of already available protocols. It also enables synthesizing the most relevant situations where ADAS function and devices can be tested, so that testing time (and cost) can be diminished. The described methodology can be further integrated by considering IR also for the occupants of the opponent vehicle, or by considering IR values associated with different injury metrics (i.e., other than MAIS 3+). In the end, a procedure able to evidence the strengths and weaknesses of active safety technology has been developed, which can efficiently contribute to the decrease in the time to market of new generation ADASs.

References

[1] Michelangelo S Gulino, Anita Fiorentino, and Dario Vangi. Prospective and retrospective performance assessment of advanced driver assistance systems in imminent collision scenarios: The cmi-vr approach. *European transport research review*, 14(1):1–14, 2022.

[2] Stefan Smit, Ernst Tomasch, Harald Kolk, Michael Alois Plank, Jürgen Gugler, and Hannes Glaser. Evaluation of a momentum based impact model in frontal car collisions for the prospective assessment of adas. *European transport research review*, 11(1):1–9, 2019.

[3] Ulrich Sander and Nils Lubbe. Market penetration of intersection aeb: Characterizing avoided and residual straight crossing path accidents. *Accident Analysis & Prevention*, 115:178–188, 2018.

[4] Anders Kullgren. Dose-response models and edr data for assessment of injury risk and effectiveness of safety systems. In *Proc of Int. IRCOBI Conf., Bern, Switzerland*, pages 3–14, 2008.

[5] Nico Kaempchen, Bruno Schiele, and Klaus Dietmayer. Situation assessment of an autonomous emergency brake for arbitrary vehicle-to-vehicle collision scenarios. *IEEE Transactions on Intelligent Transportation Systems*, 10(4):678–687, 2009.

[6] Michelangelo-Santo Gulino, Leonardo Di Gangi, Alessio Sortino, and Dario Vangi. Injury risk assessment based on pre-crash variables: The role of closing velocity and impact eccentricity. *Accident Analysis & Prevention*, 150:105864, 2021.

[7] Chris Jurewicz, Amir Sobhani, Jeremy Woolley, Jeff Dutschke, and Bruce Corben. Exploration of vehicle impact speed–injury severity relationships for application in safer road design. *Transportation research procedia*, 14:4247–4256, 2016.

[8] Antonio Lara, Jeffrey Skvarce, Harald Feifel, Michael Wagner, and Toshihisa Tengeiji. Harmonized pre-crash scenarios for reaching global vision zero. In *Proc. 26th Int. Tech. Conf. Enhanced Saf. Veh.*, pages 1–19, 2019.

[9] Dario Vangi, Michelangelo-Santo Gulino, Anita Fiorentino, and Antonio Virga. Crash momentum index and closing velocity as crash severity index. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of automobile engineering*, 233(13):3318–3326, 2019.

[10] Dario Vangi, Filippo Begani, Florian Spitzhüttl, and Michelangelo-Santo Gulino. Vehicle accident reconstruction by a reduced order impact model. *Forensic science international*, 298:426–e1, 2019.