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Prospective and retrospective performance assessment of Advanced Driver Assistance Systems in imminent collision scenarios: the CMI-V_r approach

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Structured abstract

Introduction: Prospective and retrospective performance assessment of Advanced Driver Assistance Systems (ADASs) is fundamental to pilot future enhancements for active safety devices. In critical road scenarios between two vehicles where ADAS activation enables collision mitigation only, currently available assessment methodologies rely on the reconstruction of the impact phase consequent to the specific intervention on braking and steering: the velocity change sustained by the vehicle in the collision (ΔV) is retrieved, so that IR decrease for the vehicle occupants can be obtained by appropriate Injury Risk (IR) models. However, information regarding the ADAS performance is available only after the impact phase reconstruction and not just as when the criticality occurs in the pre-impact phase: the best braking and steering alternative cannot be immediately envisaged, since a direct correlation lacks between the braking/steering intervention and IR.

Method: This work highlights an ADAS performance assessment method based on the disaggregation of ΔV in the two pre-impact parameters closing velocity at collision (V_r) and impact eccentricity, represented by the Crash Momentum Index (CMI). Such a disaggregation leads to the determination of IR based solely on impact configuration between the vehicles, without directly considering the impact phase. The performance of diverse ADASs in terms of intervention logic are directly comparable based on the resulting impact configuration, associated with a single coordinate in the CMI-V_r plane and a sole IR value as a consequence.

Results: The CMI-V_r approach is employable for both purposes of prospective and retrospective performance assessment of ADAS devices. To illustrate the advantages of the methodology, a solution for prospective assessment based on the CMI-V_r plane is initially proposed and applied to case studies: this provides direct suggestions regarding the most appropriate interventions on braking and steering for IR minimization, fundamental in the tuning or development phase of an ADAS. A method for retrospective assessment is ultimately contextualized in the EuroNCAP "Car-to-Car Rear moving" test for an Inter-Urban Autonomous Emergency Braking system, a device implemented on a significant portion of the circulating fleet.

Conclusions: Based on the evidenced highlights, it is demonstrated that the approach provides complementary information compared to well-established performance assessment methodologies in all stages of an ADAS life cycle,

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by suggesting a direct physical connection in the pre-impact phase between the possible ADAS interventions and the foreseeable injury outcomes.

Keywords: Velocity change (ΔV), Closing velocity, Impact eccentricity, Consumer program, Injury risk, Adaptive logic

1 Introduction

Historically, the enhancement in road safety at the vehicle level has been initially sought through the increase in its resistance to impacts (crashworthiness), subsequently by unfolding passive protection systems, and finally through the development of active safety devices. This trend is part of the consolidated scheme [1] according to which the reduction of injuries on the road can be favored through the pursuit of three diverse objectives: the reduction of the number of accidents, the reduction of Injury Risk (IR) at a given impact severity and the reduction of impact severity. While for the second objective crashworthiness and passive protection systems are crucial [2], for the first and third objective a substantial role is played by the use of Advanced Driver Assistance Systems (ADASs). ADASs can in fact be decisive for minimizing the probability of a collision and mitigating the consequences associated with an inevitable impact.

Encouraging results emerge from studies as that of Sander and Lubbe [3], inferring that a total penetration into the market of the Autonomous Emergency Braking (AEB) entails a drastic decrement in the severity of impacts thanks to a simultaneous reduction in the relative collision speed between vehicles (decrease in severe injuries of almost 90%). A system like the AEB, intervening directly on the vehicle speed (longitudinal deceleration), frequently leads to impact avoidance [4]; the principle of emergency braking is also exploited by certain ADASs such as pedestrian/bike assist to promote the safety of numerous categories of vulnerable road users [5]; similarly, devices as the Lane Keeping Assist intervene on the degree of steering of the vehicle (transverse acceleration) to prevent the risk of involuntary insertion into adjacent lanes [6].

The importance of ADASs, both for road safety and for use within the context of autonomous driving [7–9], has produced the need to identify and define their field of operation, in terms of pre-accident scenarios on which they act as well as technical parameters related to instrumental performance. Furthermore, and perhaps more importantly, there is a need to evaluate the global performance of ADASs in terms of effectiveness in preventing accidents and reducing their severity. The methods used to evaluate the performance of ADASs in one or more reference scenarios can be divided into a priori and a posteriori methods [10, 11]. The classification is based on the instant considered for the assessment in terms of the ADAS life cycle: if the system is already present on a considerable number of vehicles within the circulating fleet, the methods are defined a posteriori or retrospective; if the assessments are performed before the placing on the market of the system (development) or its large-scale diffusion, the evaluation is considered a priori or prospective.

Among the retrospective methods, one of the most widely employed is the paired comparison [12]: on the basis of the distribution of real impacts between two vehicles, each representing a specific category of the circulating fleet, the injury outcomes are assessed affecting the occupants of both vehicles; the overall risk associated with collisions between these vehicle categories is obtained from the observation of how many cases result in injuries to the occupants of the first vehicle category only, the second one, or both at the same time. It is hence possible to compare collisions among extremely different vehicles (appropriately weighing the risks for any differences in mass, year of type-approval, etc. [13]) especially in terms of active safety systems implemented on board: this allows for retrospective evaluation of the effectiveness of various ADAS families in diverse contexts. It is impossible, however, to produce assessments regarding the cases of avoided impact, as the analysis is completely based on the observation of collisions that have actually taken place.

The a priori methodologies include simulation techniques that, in suitably selected reference situations [9], enable verification of the results associated with specific interventions and actuation time/scan time of the scenario by the ADAS systems; the simulation aims at the identification of the vehicle's pre-impact kinematics determined by the degree of steering and braking activated by the ADAS, as well as the consequent eventual collision phase with other vehicles. The assessments are based on a direct comparison between the results in case of presence and absence of the system on board the vehicle; these assessments may concern both the system's ability to avoid collisions and the reduction in the impact severity achievable through ADAS intervention. For the evaluation of impact severity, typically indicated by means of the velocity change sustained by the vehicle in the impact (ΔV), finite element models/multibody systems [14, 15], special-purpose reduced-order dynamic models [16, 17], or approximated analytical methods [18] can be used. This is a fundamental step, since ΔV

is acknowledged as one of the most important contributors to IR in vehicle-to-vehicle impacts [19]. For what specifically regards IR estimates in vehicle-to-pedestrian or vehicle-to-bicycle accidents, the collision speed of the vehicle substitutes the ΔV of the subjects [20]; however, the importance of ΔV is not lessened even in those cases: the post-impact speed and the ΔV of the pedestrian/bicycle typically coincide with the collision speed of the vehicle, since the mass of the pedestrian/bicycle is negligible compared to the vehicle mass (momentum conservation [21]).

Numerical simulation is implemented in the design process of new ADAS systems [22] in Software-in-the-Loop (SiL) mode and can represent an onerous phase: a refinement of the ADAS intervention logic is generally envisaged based on the results obtained in specific test configurations, depending on the activation time of sensors, of the braking/steering system, as well as the warning time for the driver [23]. If these factors' combination involves crash conditions, the tuning phase extends by the time required for impact reconstruction to calculate post-impact parameters like the occupants' accelerations [24, 25] or, equivalently, the ΔV. For thorough assessments, conditions where the impact cannot be avoided—Inevitable Collision States (ICS)—must hence also be evaluated [14], relying on the reconstruction of the collisions associated with each ADAS intervention on steering and braking [26]. Although there are only sporadic cases on the market of systems capable of intervening by steering in the event of an emergency,[1] the regulatory adaptation to level 3 SAE systems [27] planned for the next few years will definitely bring evolutions in the vehicle landscape; the interest of the market in this area is for example demonstrated by the EuroNCAP 2025 Roadmap, in which the integration of *ad hoc* test protocols of Autonomous Emergency Steering technologies is planned for 2022.[2]

In cases where the ADAS intervention on braking and steering does not avoid a collision with other vehicles, prospective and retrospective methodologies foresee evaluating the effectiveness of the systems only at the end of the impact phase reconstruction, on the basis of the resulting ΔV value. There are currently no methodologies that provide performance assessment on the ADAS intervention just as when the criticality occurs, i.e., in the pre-impact phase when a targeted intervention on the degrees of braking and steering can still limit the severity of the vehicle-to-vehicle impact. An ADAS performance evaluation approach of this type can therefore contribute to the selection of the most suitable logic to manage a specific critical road scenario, indicating to the ADAS how to appropriately set the motion parameters it can directly control. A significant contribution to the topic is represented by a recent work [28], which favors the analysis of ADAS performance even when the intervention involves a collision. In this case, the ΔV variable is disaggregated into two pre-impact contributions representing the closing velocity between vehicles at the collision instant (V_r) and impact eccentricity, the latter identified by means of the Crash Momentum Index (CMI, refer to Fig. 1). Since a different intervention on steering and braking in the pre-crash phase corresponds to a direct modification to the values of CMI and V_r, the disaggregation of ΔV makes it possible to retrieve the outcome associated with an ADAS activation once the intervention parameters have been established, without reconstructing the collision. The focus is therefore no longer on the outcome of the intervention itself (ΔV), but on the identification of the braking and steering combination that leads to such an outcome. The ADAS behaviour can also be monitored and piloted by referring to the CMI-V_r plane, where a coordinate (CMI; V_r) corresponds to each intervention on braking and steering.

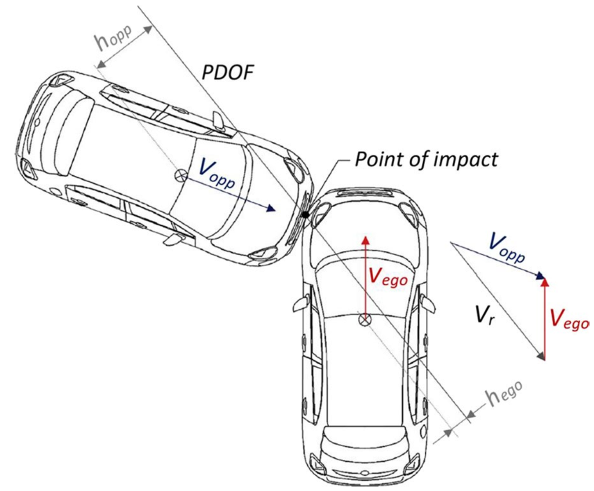


Fig. 1 Elements of a crash configuration that lead to the CMI determination (modified from Gulino et al. [30])

Since the values of CMI and V_r for an intervention result in a sole value of ΔV, it is possible to determine which interventions reduce impact severity already in the pre-impact phase: given a specific test scenario, pre-impact assessments can be performed regarding the outcomes associated with the various ADAS interventions, while providing an overview of the intervention margins and indications on how to optimize activation to minimize impact severity. Starting from ΔV, ADAS performance assessments can also be performed in terms of

[1] https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/autonomous_emergency_steering_system.html.

[2] https://cdn.euroncap.com/media/30700/euroncap-roadmap-2025-v4.pdf.

IR using appropriate correlations; for example, referring to IR models for injury index represented by the Maximum Abbreviated Injury Scale equal to or greater than 3 (MAIS 3+), a review of the literature by Jurewicz et al. [29] demonstrates how the use of parameters different from ΔV like the vehicle area involved in the intrusion ("impact type") is rooted in the definition of impact severity. By splitting ΔV into the two contributions CMI and V_r, Gulino et al. [30] evidence how IR for MAIS 3+ depends primarily on impact-related variables (V_r, and CMI), and secondarily on the age of the occupant; the vehicle category, on the other hand, is not an influencing variable on IR, unlike the registration year. In the vast scientific literature on the subject, studies can be found that deal with additional variables as the gender of the occupant [31, 32] or the occupied row [33, 34], but with ambiguous results in terms of ability of the individual variables in influencing IR. Regardless of the employed model, it is essential to introduce performance evaluation methods like the one based on CMI and V_r that allow for a direct identification of ΔV and IR values starting from the ADAS actuation degrees: for example, the EuroNCAP consumer program foresees the performance assessment of an Inter-Urban AEB based on V_r [35]; however, V_r represents only a contribution to impact severity, while the significant influence of eccentricity (CMI) on ΔV and IR is neglected.

This work aims at illustrating the application of the CMI and V_r-based method to various case studies, to demonstrate its effectiveness in evaluating the performance of ADASs in critical road scenarios of impending collision between vehicles. The methodology can be used both for a priori evaluations (on ADAS under development or whose operation needs to be optimized in certain road scenarios before being placed on the market) and a posteriori (as a method for evaluating the performance of an ADAS subjected to consumer/manufacturer tests). The general objective is therefore to provide the necessary tools for the evaluation of an ADAS in all phases of its life cycle, starting from SiL and moving towards Hardware-in-the-Loop (also considering the necessary physical sensor-fusion [36]), up to the tests conducted after implementation on board the vehicle. To this end, the theoretical basis of the methodology is first illustrated to subsequently present application examples of prospective and retrospective assessment of ADAS performance, useful for highlighting the approach potential.

2 Materials and methods

The described methodology basis is the evidence that relation among ΔV, V_r, and CMI exists [37, 38], so that $\Delta V = \text{CMI} \cdot V_r$ (a posteriori formulation). Such relation entails that ΔV can be obtained by the combination of two parameters that represent the impact initial conditions, i.e., V_r and CMI (indicator of impact eccentricity); specifically, impact eccentricity increases as CMI decreases. The use of these two parameters rather than ΔV leads to the following advantages:

- CMI and V_r can be retrieved based solely on the manoeuvres the vehicles perform before the impact, i.e., on the pre-impact kinematics and not through the impact phase reconstruction;
- CMI and V_r can be directly affected by the ADAS through modifications to the vehicle speed and steering degree (trajectory), so that a direct correlation between the ADAS intervention and the occupants' IR can be identified before the collision occurrence.

In its a priori formulation, CMI for the ego-vehicle (analogous relations apply to the opponent) can be obtained as in Eq. 1 [38]:

$$CMI_{ego} = \frac{\gamma_{ego} \cdot \gamma_{opp} \cdot (1+\epsilon)}{\gamma_{ego} + \gamma_{opp} \cdot R_m} \tag{1}$$

In Eq. 1, $R_m = m_{ego}/m_{opp}$ where m_{ego} and m_{opp} are respectively the mass of the ego-vehicle and the opponent vehicle, $\gamma_{ego} = \frac{k_{ego}^2}{k_{ego}^2 + h_{ego}^2}$ where k_{ego} and h_{ego} are respectively the radius of gyration and the arm of the force for the ego-vehicle, $\gamma_{opp} = \frac{k_{opp}^2}{k_{opp}^2 + h_{opp}^2}$ where k_{opp} and h_{opp} are respectively the radius of gyration and the arm of the force for the opponent, and ϵ is the restitution coefficient in correspondence of the point of impact: ϵ is a function of V_r as highlighted by Eq. 2, V_r being expressed in m/s [39]:

$$\epsilon = 0.5992 \cdot \exp\left(-0.2508 \cdot V_r + 0.01934 \cdot V_r^2 - 0.001279 \cdot V_r^3\right) \tag{2}$$

The formula in Eq. 2 was obtained by Antonetti [39] based on data from five diverse literature studies regarding vehicle-to-vehicle impacts (correlation coefficient of the model equal to 90.4%). The a posteriori formulation of CMI ($\text{CMI} = \Delta V / V_r$) directly derives from Eq. 1 and hence expresses analogous concepts [38]. The a posteriori formulation however leads to the CMI calculation based on parameters that are more easily retrieved retrospectively, being thus appropriate for a posteriori analyses; conversely, Eq. 1 fits a priori studies because it refers to variables that can be estimated prospectively, based solely on the impact configuration.

Representation of the required elements for CMI calculation is exemplified by Fig. 1: based on Eq. 1, CMI is an indicator of impact eccentricity and can be obtained based solely on the impact configuration, i.e., on the point of impact and the arm of the forces; Eq. 1 can be applied when no sliding occurs between the impacting surfaces of the vehicles and V_r direction can be assumed coincident with the Principal Direction Of Force (PDOF) [40]. Still, compared to full impacts and closing velocity being the same, sliding impacts typically feature lower values of ΔV and IR as a consequence.

The CMI was first introduced by Huang for application to centred impacts (null arms of the force) [37] and later on extended by Vangi to whichever type of impact [38]: in impacts that are centred for both vehicles, the CMI is maximum because of null arms of the force; in eccentric impacts, the CMI decreases as the arms of the force increase. Additionally, an impact can be eccentric for a vehicle but not for the other, a condition where the CMI is lower than in the case of centred impact for both vehicles. It is derived that the CMI is not an eccentricity metric alone, but rather a comprehensive indicator of the exchanged impact forces which depend on the impact configuration of both vehicles. Such an impact configuration results from the eventual manoeuvres the drivers and the ADAS devices perform in the pre-impact phase: if both vehicles perform manoeuvres, deriving from actions by their respective driver or ADAS, an impact finally occurs featuring specific values of CMI and V_r. The CMI-V_r approach hence represents a mean for the prospective and retrospective evaluation of impact severity and IR even in the case of interaction among interventions by drivers and ADAS devices. For more information regarding the CMI, refer to additional works [28, 30].

Equation 1 highlights the possibility to jointly employ CMI and V_r as impact severity indicators instead of ΔV alone. In fact, let us assume a critical road scenario identified by specific positions and velocities for the ego-vehicle and the opponent: an intervention on braking and steering by an ADAS involves an impact configuration totally defined by a value of V_r and a value of CMI. The CMI-V_r plane, depicted in Fig. 2, hence synthetically collects all possible alternatives of intervention on braking and steering for an ADAS device. Since $V_r = \Delta V/\text{CMI}$, points in such plane which possess the same value of ΔV (iso-ΔV points) belong to an equilateral hyperbola. If no intervention is considered, represented in the CMI-V_r plane by point A, the best intervention by the ADAS should be aimed at maximizing occupants' safety. This can be achieved by following the maximum gradient of impact severity that, in this case, is represented by ΔV alone; activating the braking and the steering degrees so as to pass from point A to point B, the ADAS leads to a scenario where the V_r and CMI values are compatible with the lowest possible ΔV [41]. The CMI-V_r plane can hence be employed also to compare, in terms of resulting ΔV, a specific intervention logic on braking and steering with a lack of intervention or with a different activation logic.

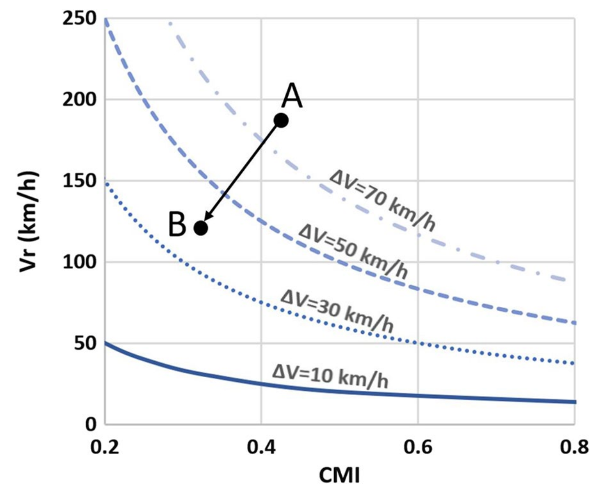


Fig. 2 Example of visualization on the CMI-V_r plane, in which iso-ΔV curves are highlighted (equilateral hyperbolas); two types of activation logic are generically visualized, namely no intervention (point A) and an activation on braking and steering (point B)

In general, iso-ΔV curves do not directly correspond to iso-IR curves. For instance, impact severity can be additionally described by the "impact type" variable, since intrusion in correspondence of different vehicle areas can provide substantial differences in terms of injury outcome. "Near side" impacts, where the compartment is involved on the same side of the occupant seating position, are those mostly associated with fatal and serious injuries [2]. An ADAS intervention on steering and braking can hence result in changes to IR because of modifications to the impact side, even for equal ΔV values. The CMI-V_r approach applies also to these cases independently on the complexity level of the IR model. In addition, disaggregation of ΔV provides in itself important insights on the injury outcome for a specific intervention, because both CMI and V_r have been demonstrated to significantly affect IR [30]. The best possible intervention on braking and steering for the specific scenario is the one featuring V_r and CMI values that correspond to the lowest possible IR; that is, interventions following the maximum IR gradient should be sought. In Fig. 3, a model for frontal impacts where IR continuously varies as a function of CMI

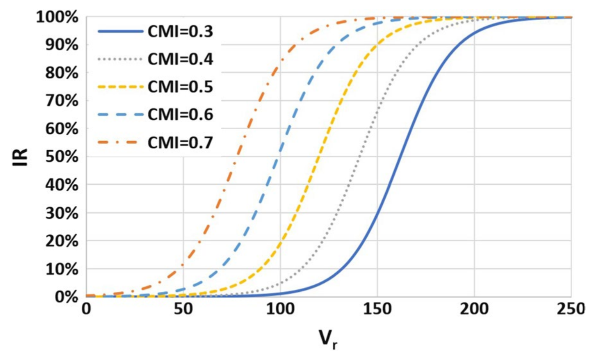


Fig. 3 Example model for frontal impacts where IR continuously varies as a function of CMI and V_r, based on the results by Gulino et al. [30]

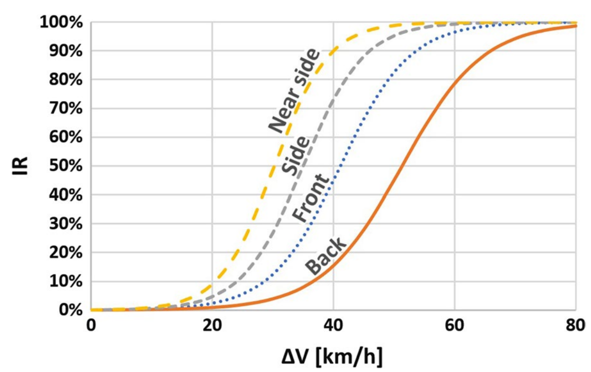


Fig. 4 Example model where IR is a function of ΔV, impact zone and position of the occupant [42]

and V_r is exemplarily depicted, based on the results by Gulino et al. [30] obtained through a mixed-effects logistic regression on a sample of more than 1400 vehicle-to-vehicle collisions. V_r being the same, IR increases as CMI raises, i.e., when impact eccentricity decreases.

3 Application

The present section illustrates some possible applications of the CMI and V_r-based approach for the prospective and retrospective assessment of ADAS performance. To this end and without losing generality, the IR model in Fig. 4 is employed [29] where IR is a function of ΔV, the region of the vehicle affected by the intrusion, and the occupant position; the model relates to the injury index MAIS 3+ (serious injuries). The types of impact are divided into "near side", "side" (for impacts involving all lateral regions to which "near side" does not apply), "front" (intrusion in the frontal region), "back" (intrusion in the posterior region); the order in which the types of impact are reported reflects gradually decreasing IR values for the same ΔV. The model for the single impact type consists of a logistic regression (logit).

For the sake of simplicity, the following concepts are introduced [10]:

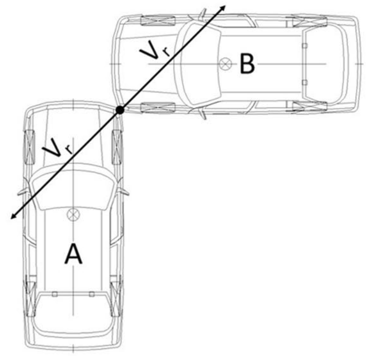
- Reference Scenario (RS), i.e., the eventual crash scenario in case activation by the referred ADAS is disabled (or the vehicle is not equipped with the ADAS);
- Modified Scenario (MS), i.e., the eventual crash scenario in case of intervention by the referred ADAS.

3.1 Prospective analyses—comparison between different types of ADAS activation logic

As preliminarily highlighted by Fig. 2, each possible impact configuration corresponds to a different point along the CMI-V_r plane. Hence, based on the ADAS activation logic, it is possible to verify how and how much the MS point moves along the CMI-V_r plane with respect to the RS point, enabling evaluation of IR differences between the MS and the RS [41]. This solution is particularly suitable to compare different types of activation logic in terms of MS modifications and a priori determine the best intervention, providing interesting highlights during the development phase of a newly conceived ADAS. In the RS, V_r between the two vehicles is initially imposed and depends exclusively on test or simulation conditions (it is foreseen that the two vehicles will collide with a specific closing speed if the ADAS does not intervene). In the MS, V_r must be obtained experimentally or via simulations and it can also consider the possible intervention of the drivers.

To evidence the benefits deriving from the CMI-V_r prospective approach, an analysis regarding a hypothetical, so-called "Collision with another vehicle that is turning into or crossing a road at an intersection" scenario is exemplarily reported (Fig. 5): the RS corresponds to a condition where vehicle A travels straight at 60 km/h, while vehicle B approaches from the right with the same longitudinal speed of vehicle A; the vehicles have equal mass ($R_m = 1$), length (4.2 m) and width (1.8 m). Figure 5 summarizes input data and results in terms of CMI and V_r deriving from activation (MS) or non-activation (RS) of an AEB implemented on board vehicle A. With the AEB, it is assumed that a maximum deceleration equal to 8 m/s^2 can be achieved by the ADAS device [42]. Vehicle A decelerates for approximately 0.4 s, reaching a longitudinal collision speed V_i of 50 km/h and impacting Vehicle B in correspondence of the compartment. CMI is calculated based on the arms of the forces and radius of gyration for the two vehicles, based on Eq. 1 and Fig. 1.

In the CMI-V_r plane visualization of Fig. 6, the ADAS activation determines a change in the coordinates



Scenario	Mass [kg]	Vehicle	V_i [km/h]	CMI	V_r [km/h]	Derived ΔV [km/h]
Reference Scenario	1200	A	60	0.42	84	35.3
	1200	B	60	0.42		35.3
Modified Scenario	1200	A	50	0.35	78	27.3
	1200	B	60	0.35		27.3

Fig. 5 Visualization and data for the "Collision with another vehicle that is turning into or crossing a road at an intersection"-type scenario

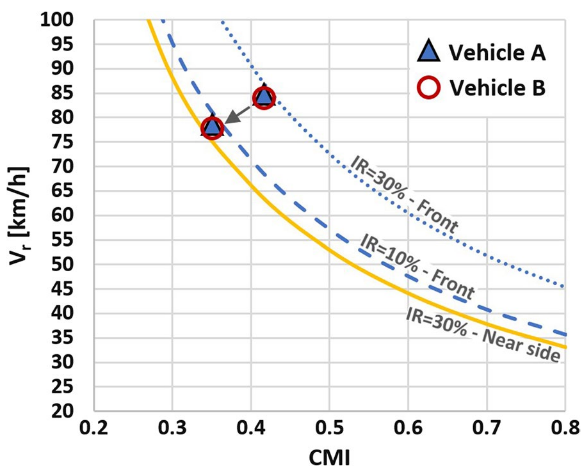
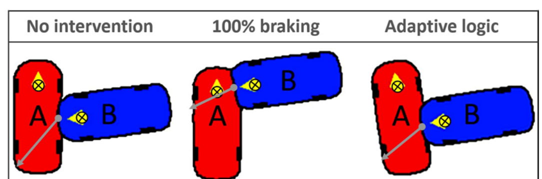


Fig. 6 Changes of position on the CMI-V_r plane for the two vehicles, moving from the RS to the MS because of activation of the AEB on board vehicle A



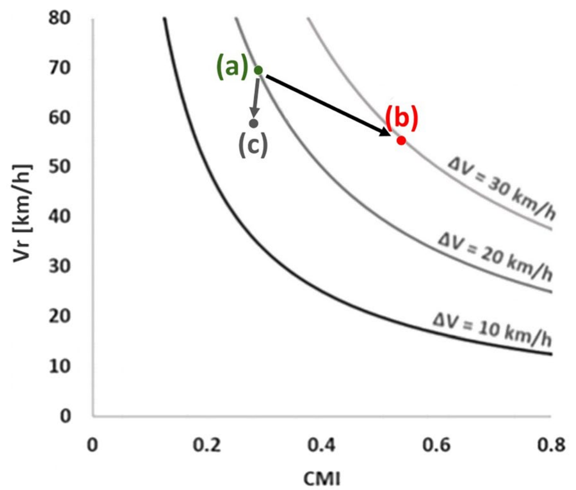
	No intervention	100% braking	Adaptive logic
V_{iA}	50 km/h	16 km/h	30 km/h
V_r	70 km/h	55 km/h	58 km/h
CMI	0.29	0.55	0.28
ΔV	20 km/h	30 km/h	16 km/h
IR	9%	34%	4%

Fig. 7 Impact configurations, Δ*V* and IR values for a case study extracted from Vangi et al. [42], in case of "no intervention", "100% braking" (AEB) and "adaptive logic" for an ADAS implemented on board vehicle A (arrows represent the closing velocity vectors, starting from the point of impact)

toward areas characterized by low IR for vehicle A that sustains a frontal impact in both scenarios (from 27% to 7% according to Fig. 4); however, in the MS vehicle B undergoes a near side impact, so that IR associated with the MS is almost equal to that of the RS (27%). Based on the impact configuration solely, the benefits related to an AEB deployment is hence highlighted for vehicle A only; both impacts are associated with high eccentricity, so differences in IR between the RS and the MS are mainly attributable to modification to the impact type and closing speed. It is emphasized that such evaluations have been obtained only based on the impact configurations in the RS and MS, regardless of the detailed reconstruction of the impact phase between the two vehicles.

Based on such results, additional highlights can be obtained regarding the best intervention logic which globally applies to a specific critical road scenario. Figure 7 evidences that the AEB intervention results in no substantial benefit for vehicle B in terms of IR , as reported in a case study by Vangi et al. [42] where the ego-vehicle (A) and the opponent (B) travel an intersection at 50 km/h; the scenario is similar to that of Fig. 6, the difference lying in the vehicles' position at the beginning of the criticality. In addition, Vehicle B steers to the left while approaching the intersection: this is instrumental for highlighting the capability of the presented approach to study the ADAS behaviour also in the case of interaction with the opponent vehicle manoeuvres. The impact configurations in Fig. 7 highlight that the 100% braking, namely corresponding to the AEB intervention (centre), leads to a lowly eccentric impact as testified by a high CMI: the distance between the centre of mass of the two vehicles and the closing velocity vector (represented by an arrow, starting from the point of impact) is the minimum between the three cases; this consequently entails a high ΔV, even if compared to the "No activation" logic (left) which features higher values of V_r and collision velocity V_{iA} for Vehicle A (Vehicle B collides at a longitudinal speed of 50 km/h in all three cases). The third type of activation (right) corresponds to an "adaptive" logic that aims at minimizing the IR for the ego-vehicle also based on the behaviour of the opponent's driver: the ego-vehicle performs IR evaluations regarding each possible intervention on braking and steering in an ICS, selecting the activation on braking and steering that minimizes IR at each time step (depending on the time required to the sensors for scanning the environment). Evolution in the environment is triggered by several factors, e.g., the opponent driver intervening on the braking and steering degree; the adaptive logic adapts to such changes and counters by a suitable braking/steering response.

Figure 8 highlights the CMI-V_r plane visualization of the different impact configurations of Fig. 7, where the points represent conditions for both vehicles: the two vehicles have equal mass and also equal ΔV as a consequence (momentum conservation); since V_r applies to both vehicles, the CMI is also identical for the two subjects. Impact type, ΔV, and IR for the ego-vehicle are additionally highlighted in the table. The three types of impact possess almost equal V_r; still, the adaptive logic generates an impact configuration that is more eccentric (lower CMI), resulting in an overall reduction of ΔV and IR compared to the lack of intervention (4% vs 9%). Conversely, the "100% braking" intervention is associated with a higher CMI because of the limited impact eccentricity; this leads to a high value of IR (34%), even if a "side" impact occurs instead of a "near side". Overall, the adaptive logic is determined as the most suitable to decrease IR for the ego-vehicle, since it moves towards the maximum IR gradient direction along the CMI-V_r plane. The decrease in the IR value provides a direct feedback regarding which intervention involves the highest benefits in terms of injury outcome for the vehicle occupants.



Case	Intervention	Impact type	ΔV (km/h)	IR
a)	No intervention	Near side	20	9%
b)	100% braking	Side	30	34%
c)	Adaptive intervention	Near side	16	4%

Fig. 8 Visualization of the three impact configurations of Fig. 7 along the CMI-V_r plane with the associated values of impact type, ΔV, and IR for vehicle A (ego-vehicle)

3.2 Retrospective analyses—performance assessment in consumer program tests

The CMI-V_r plane approach can be employed for the assessment of ADAS performances for devices already implemented on the circulating fleet, mainly based on results from tests in a controlled environment. In case of consumer tests regarding two-vehicle conflict scenarios, ΔV and its direction (coinciding with the PDOF) is typically unknown. In fact, the Vehicle Under Test (VUT) does not hit a real vehicle, but a balloon representing the opponent vehicle structure which is referred to as Global Vehicle Target (GVT); forces are not the real ones and kinematic parameters of the MS crash are unknown. Because ΔV is not available, these tests do not directly provide information regarding the IR for the vehicle occupants.

To explore the possibilities guaranteed by the CMI-V_r plane, the approach is applied to the results of an EuroNCAP hypothetical test. The test corresponds to a Car-to-Car Rear moving (CCRm) Inter-Urban AEB assessment program,[3] whose characteristics are summarized in

[3] https://cdn.euroncap.com/media/62794/euro-ncap-aeb-c2c-test-protocol-v303.pdf.

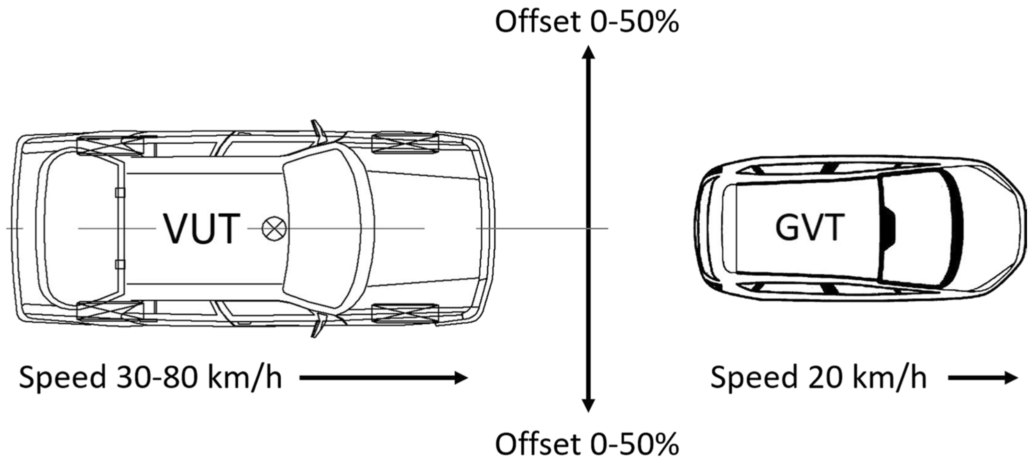


Fig. 9 Scheme of a EuroNCAP CCRm test for an Inter-Urban AEB

Table 1 Results of a hypotetical Car-to-Car Rear moving test with 0% offset

AEB function test results in CCRm scenario						
Ego initial speed (km/h)	**GVT speed (km/h)**	**Initial closing speed (V_r RS) (km/h)**	**Available points**	**Ego impact speed (km/h)**	**V_r MS (km/h)**	**Test score**
30	20	10	1.00	0	0	1.00
35	20	15	1.00	0	0	1.00
40	20	20	1.00	0	0	1.00
45	20	25	1.00	0	0	1.00
50	20	30	1.00	30	10	0.75
55	20	35	1.00	45	25	0.50
60	20	40	1.00	55	35	0.25
65	20	45	2.00	65	45	0.00
70	20	50	2.00	70	50	0.00
75	20	55	2.00	75	55	0.00
80	20	60	2.00	80	60	0.00
Total			15.00			5.5
Normalized score						36.7%

Fig. 9. In the first test, the ego-vehicle travels straight with a speed of 30 km/h and, in case of no intervention, would collide with the GVT that moves straight at a fixed speed of 20 km/h. The test is repeated increasing the ego-vehicle's speed of 5 km/h or 10 km/h, until an ego-vehicle test speed of 80 km/h is reached. Once these tests are completed, the position of the ego-vehicle with respect to the longitudinal direction of the GVT is modified and the previous tests repeated, until all results are available for − 50%, − 25%, 0%, 25%, 50% offset between the two vehicles.

Results of the hypothetical CCRm test are reported in Table 1, following the actual scoring method of the EuroNCAP; to ease comprehension, the most intuitive case of 0% offset between the ego-vehicle and the GVT is first illustrated. The available points for each test, set by EuroNCAP in the current procedure, equal 2 if the ego-vehicle initial speed is higher than 60 km/h, 1 otherwise; the concept behind this choice is to reward ADAS devices that perform better in the most dangerous scenarios, i.e., at a higher travelling speed and outside the typical speed range of urban environments. For an initial speed for the ego-vehicle lower than 50 km/h, the hypothetical AEB stops the vehicle and no crash occurs; in these cases, the score is full. For higher velocities, the crash is not avoided, and the score decreases. For an initial speed higher than 60 km/h, the system under test exits from its working range of speed and does not intervene. In case of impact, EuroNCAP scores correspond to a percentage of the available points based on V_r reduction: 100% for $V_r < 5$ km/h, 75% for $5 \leq V_r < 15$ km/h, 50% for $15 \leq V_r < 30$ km/h, 25% for $30 \leq V_r < 40$ km/h, 0% otherwise. In Table 1, the ego-vehicle initial speed, the GVT speed, and the ego-vehicle impact speed are measured values; while the available points are set by EuroNCAP, V_r in the RS, V_r in the MS, and the test score are derived values.

For each hypothetical crash (both in the RS and MS), the corresponding point can be drawn on the CMI-V_r plane. In fact, a lowly eccentric frontal impact occurs in both the RS and MS, so $\gamma = 1$ for both vehicles and Eq. 1 results in:

$$CMI = \frac{1+\varepsilon}{1+R_m} \tag{3}$$

That is, CMI depends only on the values of ε and R_m. The proposed procedure requires to assume a value of R_m, because only the ego-vehicle can be considered (the GVT has unrealistic inertial properties). Table 2 considers $R_m = 1$, while ε is calculated by Eq. 2; the value of ΔV obtained from V_r and CMI is also reported, so that IR is directly obtained based on the models in Fig. 4. As already stated, actual values of ΔV cannot be retrieved, because the hit GVT does not possess inertial properties; the "derived ΔV" in Table 2 hence represents a virtual value, assessed by directly multiplying CMI and V_r: the real advantage of the methodology lies in the possibility to retrieve direct information regarding the decrease in IR which is observed moving from the RS to the MS. Based on Table 2, different initial speeds are associated with diverse IR values, with IR for 60 km/h which is 15 times the one for 30 km/h. The EuroNCAP test protocol correctly accounts for this instance by applying a score of 2 for interventions with speed higher than 60 km/h (Table 1); nevertheless, the CMI-V_r approach provides a more granular view regarding the different outcomes associated with the possible interventions in terms of IR. In the example, the major benefits associated with the considered Inter-Urban AEB are achieved in the 50 km/h test (Table 2). Summing IR decreases in all tests, overall IR reduction of 5.5% is obtained by activation of the ADAS under test. Dividing such overall reduction by the sum of IR values in case of no activation by the ADAS (41.0%), the obtained normalized score (13.4%) provides a direct efficiency measure of the ADAS under test; results from the EuroNCAP and the CMI-V_r approach are significantly different, considering that the normalized score obtained by the latter is approximately one third of that by EuroNCAP. The main reason for such difference is that EuroNCAP applies a score equal to 1 to conditions in which closing speed at impact would be limited in the RS; this entails that IR would be extremely low even if the ADAS does not activate. The employment of the CMI-V_r approach hence makes it possible to identify the real risk associated with a specific testing condition, as well as to adjust the scores accordingly.

To exemplify the meaning of the scoring method, Fig. 10 reports the 60 km/h test results on the CMI-V_r plane. The starting and the ending point of the test are shown, the IR for the RS being 3.1% and 2.1% in the MS. As can be seen, the activation does not follow a maximum IR gradient (i.e., simultaneous decrease in both CMI and V_r) because the steering degree of the vehicle cannot be modified directly by the ADAS, as conversely occurs in the case of prospective evaluation of Fig. 6: the ADAS has no actual option to change the impact configuration by steering, rather it can only reduce the closing velocity at the collision instant by braking; impact eccentricity cannot be modified and CMI only depends on the restitution coefficient and mass ratio.

Data reported in Table 2 correspond to the case $R_m = 1$. If R_m is used as a variable, it is also possible to draw IR reduction curves as a function of the ego-vehicle initial speed for the test, as outlined in Fig. 11. As can be derived, difference in mass between the vehicles significantly modifies the IR reduction trend; the maximum values of IR decrease are also highlighted by point indicators along the three curves, so that it can be assessed that the major benefits are obtained for different values of the ego-vehicle initial speed depending on the involved vehicles' mass ratio. This peculiarity hence makes it possible to extend, based only on the highlights from a consumer testing campaign, the obtained results also to potential critical scenarios involving vehicles with diverse mass: the single GVT can represent a wide variety of vehicles ranging among different body categories (SUVs, sedans, etc.), dimensions of these vehicles being the same. Impacts can be additionally studied involving the ego-vehicle and two variants of the same vehicle model, differing only in their mass: that is the case of the internal combustion engine (ICE) variant versus the electric alternative, the latter being several hundreds of kilos heavier of the ICE one because of the presence of a battery pack.

If the tests of Fig. 9 are repeated setting an offset value between the VUT and the GVT that differs from 0%, the form of Eq. 3 must be modified to account for the non-negligible arms of the forces. Specifically, considering an offset of 50% for the VUT and starting from Eq. 1, the following form of the CMI for the ego-vehicle can be obtained:

$$CMI_{50\%} = CMI_{0\%} \frac{1}{1+\frac{W_{VUT}^2}{16k_{VUT}^2}} \tag{4}$$

In Eq. 4, $CMI_{50\%}$ represents the value of CMI for the VUT in the test with 50% offset, $CMI_{0\%}$ the value of CMI for the VUT in the test with 0% offset, k_{VUT} the radius of

Table 2 Comparison between the proposed procedure and results of a hypotetical Car-to-Car Rear moving test

$R_m = 1$	Reference scenario				Modified scenario					
Ego initial speed (km/h)	**Ego-GVT closing speed (V_r) (km/h)**	**CMI**	**Derived ΔV (km/h)**	**IR (frontal impact) (%)**	**Ego collision speed (km/h)**	**Ego-GVT closing speed (V_r) (km/h)**	**CMI**	**Derived ΔV (km/h)**	**IR (frontal impact) (%)**	**IR decrease (%)**
30	10	0.67	6.7	0.2	0	0	0.00	0	0.0	0.2
35	15	0.63	9.5	0.4	0	0	0.00	0	0.0	0.4
40	20	0.61	12.2	0.6	0	0	0.00	0	0.0	0.6
45	25	0.59	14.7	1.0	0	0	0.00	0	0.0	1.0
50	30	0.57	17.0	1.4	30	10	0.67	6.7	0.2	1.2
55	35	0.55	19.3	2.1	45	25	0.59	14.7	1.0	1.1
60	40	0.53	21.4	3.1	55	35	0.55	19.3	2.1	1.0
65	45	0.52	23.5	4.4	65	45	0.52	23.5	4.4	0.0
70	50	0.51	25.6	6.2	70	50	0.51	25.6	6.2	0.0
75	55	0.51	27.8	8.8	75	55	0.51	27.8	8.8	0.0
80	60	0.50	30.2	12.8	80	60	0.50	30.2	12.8	0.0
Total				41.0						5.5
Normalized score										13.4%

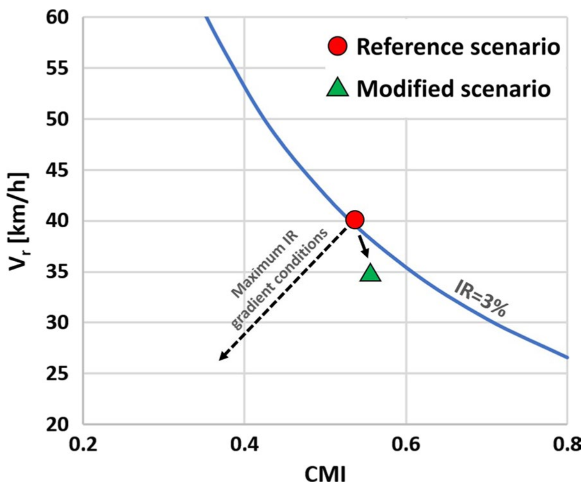


Fig. 10 Change of coordinates on the CMI-V_r plane for the two vehicles in the 60 km/h test from Table 2, moving from the crash in the Reference Scenario to that in the Modified Scenario

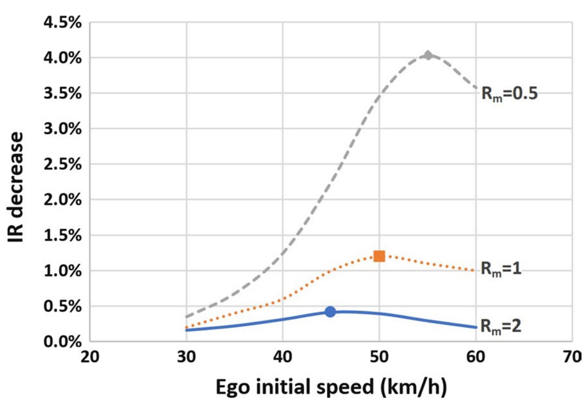


Fig. 11 IR decrease for the CCRm test with 0% offset in case of application of the CMI-V_r prospective approach, as a function of the ego-vehicle initial velocity and mass ratio

gyration of the VUT, and W_{VUT} its width; to obtain such relation, it has been considered that $\gamma_{opp} = 1$ independently of the offset value, while $h_{ego} = \frac{W_{VUT}}{2}$ in case of 50% offset. Being the term $\frac{1}{1+\frac{W_{VUT}^2}{16k_{VUT}^2}} < 1$ whichever the value of the (always positive) included variables, $CMI_{50\%} < CMI_{0\%}$; this conclusion is physically intuitive, considering that the CMI decreases as impact eccentricity increases. In particular, if the generic values $W = 1.8$ m and $k_{VUT} = 1.4$ m are introduced in Eq. 2 while also hypothesizing $R_m = 1$, it is derived that $CMI_{50\%} = 0.88\, CMI_{0\%}$; referring to the fundamental relation $\Delta V = CMI \cdot V_r$, this also entails that ΔV values for the 50% offset tests will be 12% lower than those associated with the 0% offset tests, V_r being the same. Diverse results will be hence highlighted by the 0% and the 50% offset tests in terms of IR, magnified by the non-linear relation between IR and ΔV. The obtained analytical formulation does not however bypass the requirement to conduct such physical tests with changes in the offset: the values of V_r can significantly vary also considering that, for relevant values of the offset, activation is prevented for a wide variety of ADASs to minimize the risk of false positive identification of criticalities [43].

4 Future applications

What was discussed in Sect. 3 is a direct consequence of the employment of the IR models depicted in Fig. 4; more sophisticated IR models that consider the characteristics of the occupants, the vehicle, and the impact (like Collision Deformation Classification) can also be applied to obtain IR values as reliable as possible in output of the evaluations: the complexity of the iso-IR curves increases because of the ampler number of independent variables used for modeling (e.g., age and gender of the occupant); similarly, the curves depend on the employed modeling technique: while iso-ΔV curves will always be equilateral hyperbolas in the CMI-V_r plane, iso-IR curves will alter their shape according to the relationship (logit, probit, etc.) which links them to ΔV and other independent variables. These changes to the starting models do not compromise the validity of the approach; to be specific, it is worth considering the possibility of using IR models developed starting from different injury outcomes, both based on different levels of Maximum AIS (e.g., MAIS 2+), on the Injury Severity Score (e.g., ISS 15+) or on injuries for different body segments (e.g., chest or head AIS).

The CMI-V_r approach is specifically designed for the study of eccentric impact configurations and is functional for the evaluation of system performances also with a view towards collaboration between ADAS and driver. For example, it is possible to analyze the case where the driver steers when alarmed by the Forward Collision Warning. Using an appropriate driver model [44, 45], it is possible to evaluate impact eccentricity at the instant of collision, based on the driver's reaction time and according to the time-to-collision at which the audible warning is activated. The visualization on the CMI-V_r plane hence directly identifies, both a priori and a posteriori, the variation in the efficiency of a specific ADAS as the driver's behaviour changes (while maintaining the driver-in-the-loop [46]). This possibility is extremely promising for the near future, where it is expected that ADAS systems capable of also intervening on the steering degree will be subjected to EuroNCAP tests starting from 2022; given the coexistence of two diverse systems (man and machine) capable of intervening simultaneously on the degree of steering, the approach based on CMI and V_r could provide new perspectives for exploring the dynamics of cooperation within the vehicle environment.

5 Conclusions

Since the velocity change (ΔV) experienced by the vehicle in a collision is universally recognized as an indicator of impact severity, ADAS performance assessments in scenarios of impending collision between two vehicles typically foresee its recovery through simulation of the impact phase. The illustrated ADAS performance evaluation approach conversely provides for the disaggregation of ΔV into the two pre-impact parameters closing speed at the collision instant (V_r) and impact eccentricity (Crash Momentum Index, CMI), enabling evaluation of ADAS performance already in a phase preceding the crash: the intervention of the system on steering and braking modifies both these parameters, so that the ADAS performance can be assessed before the impact occurs in terms of ΔV and Injury Risk (IR) for the occupants of the involved vehicles. In the ADAS performance assessment method based on CMI and V_r, the interest is therefore no longer focused on the injury outcome itself, but on the interventions that can be implemented by the ADAS in terms of braking and steering to achieve such an outcome.

The prospective (or a priori) approach based on the CMI-V_r plane relies on the evaluation of the vehicle kinematics following the activation by the system on the degrees of braking and steering: via simulation or by tests performed by ADAS manufacturers, the IR associated with any possible intervention on steering and braking is traceable. Diverse types of activation logic can be hence mutually compared to determine the most appropriate action in terms of IR. The CMI-V_r approach can equally be adopted for retrospective (or a posteriori) evaluations, e.g., for ADAS already implemented on board a significant part of the circulating fleet. Referring to an EuroNCAP test, it has been shown that IR assessments through the CMI-V_r plane supports more consolidated scoring methodologies. The approach based on CMI and V_r thus proves to be a flexible ADAS performance assessment tool, usable for the analysis of the outcomes obtainable in a broad range of road scenarios and applicable throughout the entire life cycle of the active safety system.

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Authors' contributions
Conceptualization: MSG, AF, DV; Data curation: MSG, DV; Formal Analysis: AF, DV; Investigation: MSG; Methodology: DV; Project administration: DV; Resources: AF, DV; Software: MSG; Supervision: DV; Visualization: MSG; Writing — original draft: MSG; Writing — review & editing: AF, DV. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Kullgren, A. (2008). Dose-response models and EDR data for assessment of injury risk and effectiveness of safety systems. In *IRCOBI Conference*, Bern, Switzerland, pp. 3–14.
2. Bareiss, M., & Gabler, H. C. (2020). Estimating near side crash injury risk in best performing passenger vehicles in the United States. *Accident Analysis & Prevention, 138*, 105434. https://doi.org/10.1016/j.aap.2020.105434.
3. Sander, U., & Lubbe, N. (2018). Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents. *Accident Analysis & Prevention, 115*, 178–188.
4. Kusano, K., & Gabler, H. C. (2014). Comparison and validation of injury risk classifiers for advanced automated crash notification systems. *Traffic Injury Prevention, 15*(sup1), 126–133.
5. Kovaceva, J., Bálint, A., Schindler, R., & Schneider, A. (2020). Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results. *Accident Analysis & Prevention, 136*, 105352. https://doi.org/10.1016/j.aap.2019.105352.
6. Merah, A., Hartani, K., & Draou, A. (2016). A new shared control for lane keeping and road departure prevention. *Vehicle System Dynamics, 54*(1), 86–101. https://doi.org/10.1080/00423114.2015.1115882.
7. Sohrabi, S., Khodadadi, A., Mousavi, S. M., Dadashova, B., & Lord, D. (2021). Quantifying the automated vehicle safety performance: A scoping review of the literature, evaluation of methods, and directions for future research. *Accident Analysis & Prevention, 152*, 106003. https://doi.org/10.1016/j.aap.2021.106003.
8. Song, Y., Chitturi, M. V., & Noyce, D. A. (2021). Automated vehicle crash sequences: Patterns and potential uses in safety testing. *Accident Analysis & Prevention, 153*, 106017. https://doi.org/10.1016/j.aap.2021.106017.
9. Liu, Q., Wang, X., Wu, X., Glaser, Y., & He, L. (2021). Crash comparison of autonomous and conventional vehicles using pre-crash scenario typology. *Accident Analysis & Prevention, 159*, 106281. https://doi.org/10.1016/j.aap.2021.106281.
10. Alvarez, S., Page, Y., Sander, U., Fahrenkrog, F., Helmer, T., Jung, O., Hermitte, T., Düering, M., Döering, S., & Op den Camp, O. (2017). Prospective effectiveness assessment of ADAS and active safety systems via virtual simulation: A review of the current practices. In *25th international technical conference on the Enhanced Safety of Vehicles (ESV) National Highway Traffic Safety Administration* (2017).
11. Smit, S., Tomasch, E., Kolk, H., Plank, M. A., Gugler, J., & Glaser, H. (2019). Evaluation of a momentum based impact model in frontal car collisions for the prospective assessment of ADAS. *European Transport Research Review, 11*(1), 2. https://doi.org/10.1186/s12544-018-0343-3.
12. Evans, L. (1986). Double pair comparison—A new method to determine how occupant characteristics affect fatality risk in traffic crashes. *Accident*

Analysis & Prevention, 18(3), 217–227. https://doi.org/10.1016/0001-4575(86)90006-0.
13. Lie, A., Kullgren, A., & Tingvall, C. (2001). *Comparison of Euro NCAP test results with Folksam car model safety ratings*. Technical report, SAE Technical Paper.
14. Wang, Q., Gan, S., Chen, W., Li, Q., & Nie, B. (2021). A data-driven, kinematic feature-based, near real-time algorithm for injury severity prediction of vehicle occupants. *Accident Analysis & Prevention, 156,* 106149.
15. Gursel, K. T., & Nane, S. N. (2010). Non-linear finite element analyses of automobiles and their elements in crashes. *International Journal of Crashworthiness, 15*(6), 667–692. https://doi.org/10.1080/13588261003737286.
16. Vangi, D., Begani, F., Spitzhüttl, F., & Gulino, M.-S. (2019). Vehicle accident reconstruction by a reduced order impact model. *Forensic Science International, 298,* 426-e1.
17. Vangi, D., Begani, F., Gulino, M.-S., & Spitzhüttl, F. (2018). A vehicle model for crash stage simulation. *IFAC-PapersOnLine, 51*(2), 837–842. https://doi.org/10.1016/j.ifacol.2018.04.018.
18. Vangi, D., & Begani, F. (2012). Performance of triangle method for evaluating energy loss in vehicle collisions. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 226*(3), 338–347. https://doi.org/10.1177/0954407011419007.
19. Doecke, S. D., Baldock, M. R. J., Kloeden, C. N., & Dutschke, J. K. (2020). Impact speed and the risk of serious injury in vehicle crashes. *Accident Analysis & Prevention, 144,* 105629. https://doi.org/10.1016/j.aap.2020.105629.
20. Otte, D. (2015). *Wrap around distance wad of pedestrian and bicyclists and relevance as influence parameter for head injuries*. Technical report. SAE Technical Paper.
21. Vangi, D. (2020). *Vehicle collision dynamics: Analysis and reconstruction*. Butterworth-Heinemann.
22. Hakuli, S., & Krug, M. (2016). Virtual integration in the development process of ADAS. In H. Winner, S. Hakuli, F. Lotz, & C. Singer (Eds.), *Handbook of driver assistance systems* (pp. 159–176). Springer.
23. Panou, M. C. (2018). Intelligent personalized ADAS warnings. *European Transport Research Review, 10*(2), 1–10.
24. Baranowski, P., Damaziak, K., Mazurkiewicz, L., Malachowski, J., Muszynski, A., & Vangi, D. (2018). Analysis of mechanics of side impact test defined in UN/ECE Regulation 129. *Traffic Injury Prevention, 19*(3), 256–263. https://doi.org/10.1080/15389588.2017.1378813.
25. Mazurkiewicz, L., Baranowski, P., Karimi, H. R., Damaziak, K., Malachowski, J., Muszynski, A., et al. (2018). Improved child-resistant system for better side impact protection. *The International Journal of Advanced Manufacturing Technology, 97*(9), 3925–3935.
26. Kaempchen, N., Schiele, B., & Dietmayer, K. (2009). Situation assessment of an autonomous emergency brake for arbitrary vehicle-to-vehicle collision scenarios. *IEEE Transactions on Intelligent Transportation Systems, 10*(4), 678–687. https://doi.org/10.1109/TITS.2009.2026452.
27. *On-Road Automated Driving (ORAD) committee: Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. Technical report, SAE International.
28. Vangi, D., Gulino, M.-S., Fiorentino, A., & Virga, A. (2019). 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. https://doi.org/10.1177/0954407018823658.
29. Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., & Corben, B. (2016). Exploration of vehicle impact speed–injury severity relationships for application in safer road design. *Transportation Research Procedia, 14,* 4247–4256.
30. Gulino, M.-S., Gangi, L. D., Sortino, A., & Vangi, D. (2021). Injury risk assessment based on pre-crash variables: The role of closing velocity and impact eccentricity. *Accident Analysis & Prevention, 150,* 105864. https://doi.org/10.1016/j.aap.2020.105864.
31. Vadeby, A. (2004). Modeling of relative collision safety including driver characteristics. *Accident Analysis & Prevention, 36*(5), 909–917.
32. Newgard, C. D. (2008). Defining the "older" crash victim: The relationship between age and serious injury in motor vehicle crashes. *Accident Analysis & Prevention, 40*(4), 1498–1505.
33. Mitchell, R., Bambach, M., & Toson, B. (2015). Injury risk for matched front and rear seat car passengers by injury severity and crash type: An exploratory study. *Accident Analysis & Prevention, 82,* 171–179.
34. Atkinson, T., Gawarecki, L., & Tavakoli, M. (2016). Paired vehicle occupant analysis indicates age and crash severity moderate likelihood of higher severity injury in second row seated adults in frontal crashes. *Accident Analysis & Prevention, 89,* 88–94.
35. Török, Á. (2020). A novel methodological framework for testing automated vehicle functions. *European Transport Research Review, 12*(1), 1–9.
36. Darms, M. (2016). Data fusion of environment-perception sensors for ADAS. In H. Winner, S. Hakuli, F. Lotz, & C. Singer (Eds.), *Handbook of driver assistance systems* (pp. 549–566). Springer.
37. Huang, M. (2002). *Vehicle crash mechanics*. CRC Press.
38. Vangi, D. (2014). Impact severity assessment in vehicle accidents. *International Journal of Crashworthiness, 19*(6), 576–587.
39. Antonetti, V. W. (1998). *Estimating the coefficient of restitution of vehicle-to-vehicle bumper impacts*. Technical report, SAE Technical Paper.
40. Ishikawa, H. (1985). Computer simulation of automobile collision—Reconstruction of accidents. In *29th Stapp Car Crash Conference*, p. 851729. https://doi.org/10.4271/851729
41. Ranfagni, S., Vangi, D., & Florentino, A. (2017). Road vehicles passive safety rating method. In *25th international technical conference on the Enhanced Safety of Vehicles (ESV) National Highway Traffic Safety Administration*.
42. Vangi, D., Virga, A., & Gulino, M.-S. (2020). Adaptive intervention logic for automated driving systems based on injury risk minimization. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 234*(13), 2975–2987. https://doi.org/10.1177/0954407020931228.
43. Domus, E. (2019.) Q TECH—July 2019. In *Quattroruote Dossier*, Vol. 76.
44. Khakzar, M., Bond, A., Rakotonirainy, A., Trespalacios, O. O., & Dehkordi, S. G. (2021). Driver influence on vehicle trajectory prediction. *Accident Analysis & Prevention, 157,* 106165. https://doi.org/10.1016/j.aap.2021.106165.
45. Scanlon, J. M., Kusano, K. D., & Gabler, H. C. (2015). Analysis of driver evasive maneuvering prior to intersection crashes using event data recorders. *Traffic Injury Prevention, 16*(sup2), 182–189. https://doi.org/10.1080/15389588.2015.1066500.
46. Banks, V., Shaw, E., & Large, D. R. (2019). Keeping the driver in the loop: The 'Other' ethics of automation. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, T., & Y. Fujita (Eds.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (Vol. 823, pp. 70–79). Springer.

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