

ROAD VEHICLES PASSIVE SAFETY RATING METHOD

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ABSTRACT

Models, procedures, validation tests of vehicle and crash tests generally aim exclusively to assess ADAS (Advanced Driver Assistance Systems) devices performances in terms of their correct behavior or reaction of the driver, but do not refer to the new scenario (residual impact). An analytical procedure aimed to analyze experimental and numerical tests for the evaluation of vehicle – driver – ADAS system performances, in terms of road safety, is proposed. If there is a collision, the procedure considers typical impact severity and configuration related to the new scenario consequent to the activation of an ADAS system and/or driver operation.

The procedure proposed does not require the use of a software for accidents reconstruction, but it is based on two parameters: the Crash Momentum Index (CMI), which expresses impact configuration and impact severity, and the relative speed combined into a single diagram CMI–Vr. The CMI–Vr diagram allows to compare different vehicles and accidents occurred at different impact configurations, considering only kinematic parameters, without considering variables related to the vehicle's occupants (gender, age, position occupied in the passenger compartment, etc.).

In a given accident, a vehicle is characterized by a CMI and a relative speed values, therefore the vehicle is indicated by a point of coordinates (CMI; Vr). The corresponding point position, on the CMI–Vr plane, identifies both the potential severity and the potential injury. To find the two points coordinates, it is necessary to identify the relative impact speed and CMI in the two impacts, potential and residual. On that plane, the iGLAD data analysis carried out (in a previous analysis) shows two different areas to which two different accident classes correspond: the former is the area regarding kinematic impact conditions of intrinsically safe accidents, for which the maximum injury level results to be MAIS 1 and the latter area is the one in which all injury levels can be found, from the lighter one up to the fatal one.

The procedure is illustrated by taking as an example an AEB system in different accident situations between two vehicles. On the CMI–Vr plane both the ADAS activation and the corrective maneuver of the driver can be verified. In particular, it is interesting to verify how and how much the point related to residual impact (post activation ADAS system) moves towards the intrinsically safe area, or towards lower injury risk. The proposed procedure can be used as a post processing of experimental tests or numerical simulations, for example aiming at: analysing the effectiveness of an ADAS system, comparing different systems, optimizing the ADAS logic or, moreover, comparing different experimental test conditions.

INTRODUCTION

European Commission announced, in the "White Paper" on European transport policy, a program of actions aimed to improve the vehicles safety, both in terms of passive and active safety, by the introduction of new technologies for driver assistance [1]. Today a large number of driver assistance systems is available for almost all vehicles. Automated driving will contribute to a new quality of mobility.

These technologies, in continuous progress, aim to ensure a better prevention of the risks faced by the occupants and are becoming established and evolving towards autonomous driving. The path to high and full automation is, however, not only one of technology, but it will also require amendments to both national and international legislation. Six levels have been defined from 0 to 5 for national and international use to classify the degree of automation of the individual systems (SAE Level [2]). This technical classification describes which tasks the system carries out, and which tasks/requirements the driver has to fulfill. At Level 0 there are no automated driving functions and there are no systems that intervene: this level can be defined as "conventional driving". If the implementation of advanced assistance technologies is carried out, the driver can be assisted, or even substituted as in Level 5 where the vehicle can completely independently perform the task of driving in full on all types of roads, in all speed ranges and in all environmental conditions. In intermediate level the responsibility of operation remain to the driver. The environment provides the stimuli (input) both to the driver and to the ADAS system, thus it's important to know the interaction between environment, driver and ADAS. These interactions can be evaluated by different approaches, as reported in [3–5]. In case of detected danger, the ADAS can alert the driver through stimuli (tactile, audible or visual), after which, if the reaction time to these exceeds established limits, the system may activate autonomously and act on the controls [6,7]. For this reason it is important to establish the requirements and test methods for the drivers alert mode [8,9], and the quality of information provided to the driver [10–14].

Generally, the correction of vehicles dynamics is related both to the driver and ADAS intervention, and as a result of these actions, the initial impact scenario changes. In case of rear–end collisions, in which only a braking action intervenes, previous researches have shown that the AEB (Autonomous Emergency Braking) carries benefits in terms of degree of injury decrease [15–20].

However, when the ADAS system makes a corrective maneuver, or the driver intervenes, a change in the impact configuration happens and the reduction of injury may not be directly proportional to the speed decrease. Usually models, procedures, validation tests of vehicle and crash tests do not refer to the new scenario of residual impact. The standards procedures, as the tests conducted by organizations such as EuroNCAP [21], or by NHTSA (National Highway Traffic Safety Administration) [22], generally aim to evaluate only the ADAS instrumental performance with standardized test procedures or virtual simulations in several impact configurations.

The purpose of this paper is to present a procedure for analyzing the performance of ADAS systems, which takes into account, in case of residual impact, also the new scenario and the new impact severity generated after the activation of that system or after a possible corrective measures put in place by the driver. Inputs for the definition of the new scenario derive from the instrumental functioning of the considered ADAS, which can be derived also from the EuroNCAP test and from hypothetical maneuver by the driver, which can be derived from an opportune driver model. The procedure proposed does not require the use of a software for accidents reconstruction, but it is based on two parameters: the Crash Momentum Index (CMI), which expresses impact configuration and impact severity, and the relative speed combined into a single diagram CMI–V_r. The procedure is illustrated by taking as an example an AEB system in different accident situations between two vehicles. On the CMI–V_r plane both the ADAS activation and the corrective maneuver of the driver can be verified.

MATERIAL AND METHOD

Crash Momentum Index (CMI) assessment - The CMI, as shown in [23], expresses the "potential" impact severity and can be formulated "*a priori*" in function of parameters that define the impact configuration and the inertial characteristics of the vehicles, as follows:

$$CMI = \frac{\gamma_1 \gamma_2 (1 + \varepsilon_1)}{(\gamma_2 + \gamma_1 R_m)} \quad (\text{Equation 1})$$

where γ_1 and γ_2 are the factors of mass reduction [23, 24], ε_1 is the coefficient of restitution, and R_m is the masses ratio of the vehicles involved in the crash. The value of the coefficient of restitution depends on the relative speed of impact in a normal direction n , V_{Rn} and can, with a good approximation, be deduced

from experimental correlations [25]. While ε_i and R_m are connected exclusively to the vehicles' typology (mass and stiffness), γ provides information about the crash configuration, being expressed as a function of the distance (h) between the vehicle's centre of mass and the straight line of pulse action. For this reason it is necessary to know the direction of the principal direction of force (PDOF). To determine the PDOF, the results reported in [26] can be referred to, assuming an impact plane t or tangential direction and a normal direction n . The impact plane is generally assumed as the plane containing the deformed profile of the vehicle [27–29], as shown in figure 1, or described in [30].

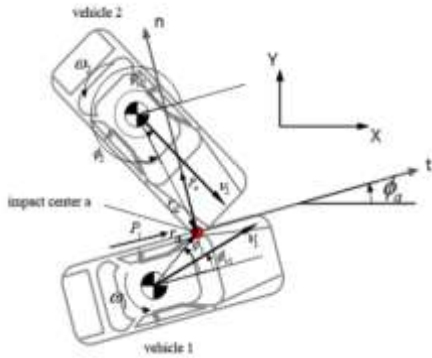


Figure 1. Diagram of the vehicles planar impact: normal, n , and tangential, t , direction [30].

Referring to these directions, the following definitions can be given:

- the speed ratio S_r , expressed as the ratio between the relative deformation speed V_{r_t} , along the tangential direction, and the relative slipping speed, along the normal direction, V_{r_n} [26]:

$$S_r = (V_{Rt}/V_{Rn}) \quad (\text{Equation 2})$$

- the coefficient of friction μ , expressed as the ratio between the component of impulse, tangential and normal, during the impact:

$$\mu = (I_t/I_n) \quad (\text{Equation 3})$$

$$\text{PDOF} = \tan^{-1}(\mu) \quad (\text{Equation 4})$$

Figure 2 shows an empirical relationship between μ and S_r [26] from which, once known the relative speed of impact between the two vehicles, and calculated the ratio between its tangential and normal components, μ can be obtained and then, using equation 4, the desired value of PDOF.

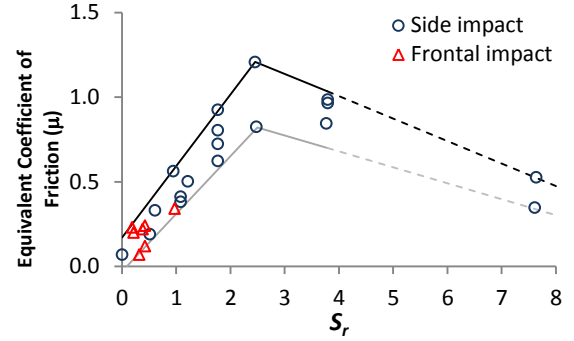


Figure 2. Equivalent coefficient of friction at impact surface [26].

Here, the expressions derived for accidents with related S_r comprised in a range between 0 and 2.50 (equation 5) and for those with S_r comprised in a range between 2.50 and 6 (equation 6) are reported.

$$\mu = 0.3287 S_r + 0.0659 \quad (\text{Equation 5})$$

$$\mu = -0.1136 S_r + 1.2991 \quad (\text{Equation 6})$$

The scatter of experimental data results showed uncertainties on the PDOF in the range of $\pm 15^\circ$. Other analysis of literature [31] confirm that the PDOF, for each vehicle, can vary by $\pm 20^\circ$ in relation to the subjective assessment of the impact plane. Using these as typical uncertainties, in [31] a degree of uncertainty in ΔV of about 15–17% for front to side impacts is found. This reduces to around 9–12% for front to front or front to rear impacts. The largest individual contribution is that due to uncertainty in PDOF.

CMI can also be expressed "*a posteriori*" [23], on the basis of the kinematic parameters obtained by reconstructing the accident (usually available in accident databases), such as the speed variation undergone by the vehicle for relative speed units:

$$\text{CMI} = \frac{\Delta V}{V_{r\text{-pdof}}} \quad (\text{Equation 7})$$

where $V_{r\text{-pdof}}$ is the component of relative impact speed along the PDOF (Principal Direction of Force) during the impact, which coincides with the direction of ΔV [27]. According to this last definition, CMI takes the meaning of "potential severity" of an impact; in fact, to higher values of this parameter correspond higher values of ΔV for relative speed units. In potential impact the relative speed between the two vehicles depends exclusively from testing or simulation conditions used.

CMI can be calculated with equation (7), if numerical simulations of the impact phase are available, for both the residual and potential impact. Numerical simulation can be carried on using FEM models (i.e. LS Dyna [32], etc.), which provide accurate results but require the specific vehicle models and a long simulation time. Alternatively for the impact simulation, impulsive models (PC Crash [33], Pro impact [34], etc.) can be used, which allow to obtain solution with a detail level lower than the FEM, but they need a very low simulation time.

CMI-Vr plane application - The ΔV is the parameter most closely related to the injury risk IR [35–37]. Figure 3 shows that each ΔV value can be associate to different value of IR [36], and the injury risk can be evaluate in different impact condition (frontal–near side/far side impact with compartment involved/not involved and rear–end).

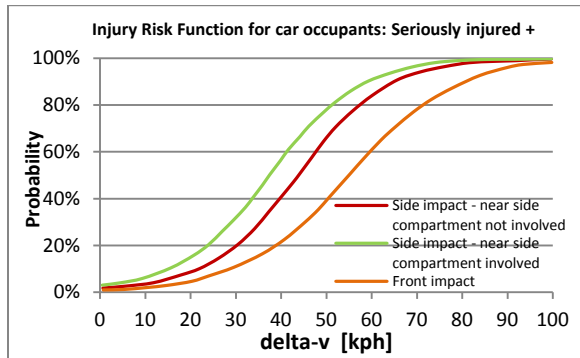


Figure 3. Injury risk function for car occupants: Seriously injured + [36].

Considering a specific value of ΔV , in the CMI–Vr plane, the iso injury risk function [36] can be represented as iso- ΔV curves by equilateral hyperbolas with centre in the origin (0;0). Thus, considering the CMI, an high level of detail in terms of impact configuration can be obtained through the factor of mass reduction γ which allows to consider the impact eccentricity. So, in the CMI–Vr plane a different classification of impact is possible in respect to principal impact configurations considered in [38], because the CMI varies in a wide range. In this plane, each vehicle is characterized by a point of coordinates (CMI; Vr) [38].

A previous analysis conducted in [38] showed that in the area below the iso- $\Delta V=20$ km/h curve only low injury degrees are present, and therefore it may be considered an intrinsically "safe area". Figure 4 shows that over this curve the injuries are characterized by the whole range of values of MAIS [39], up to MAIS 6.

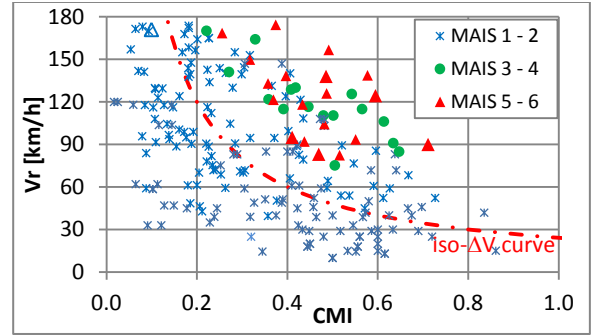


Figure 4. CMI–Vr plane: MAIS under changing iso- ΔV curves [RIF 38].

Given an impact suffered by the vehicle, the position of the corresponding point in the CMI–Vr plane therefore identifies both the potential severity and the potential injury. Considering identical vehicles ($R_m = 1$), figure 5 shows the points regarding the same impact configuration (front–side, with compartment involved), with different impact relative speed. As shown in figure 5, the IR is greater for the vehicle that undergoes the side impact than the vehicle which impacts on the front.

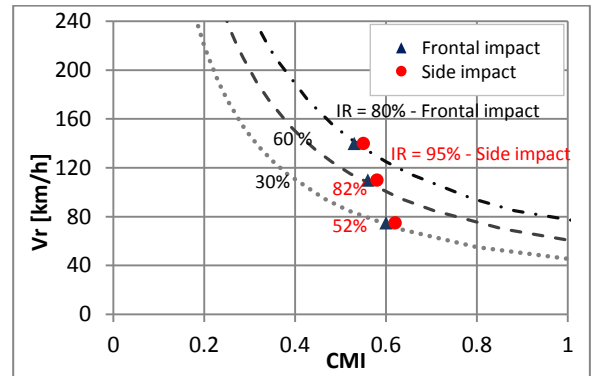


Figure 5. CMI–Vr plane: IR change in case of a frontal-side impact for the vehicles.

The position of the vehicles toward the low injury potential area, and thus the decrease of IR, can be obtained both by decreasing the relative speed Vr and by changing the impact configuration. The CMI variation, deriving from the relative speed, is due exclusively to the change of coefficient of restitution, which decreases with the increase of relative speed.

Instead, a different impact configuration due a drivers or ADAS intervention to such as to move the initial point toward areas characterized by high severity will be less effective in terms of IR reduction, if the impact configuration switch from frontal to side impact.

Procedure - The proposed procedure is based on the use of CMI–Vr plane that allow to verify, following the ADAS activation or the driver intervention, how the point corresponding to the potential impact moves, respect to the point regarding the residual impact. This procedure can be used as a post processing of experimental tests or numerical simulations, for example aiming at: analyzing the effectiveness of an ADAS system, comparing different systems, optimizing the ADAS logic or, moreover, comparing different experimental test conditions. In particular, it is interesting to verify how and in what way the point moves towards the intrinsically safe area, or towards lower IR. To find the coordinates of the two points, it is necessary to identify the relative impact speed and CMI in the two impacts, potential and residual.

RESULTS AND DISCUSSION

Real accidents analysis have shown that the scenario 'Collision with another vehicle that is turning into or crossing a road at an intersection' is the most frequent, with a percentage of 58% of the total accidents between two vehicles collected in the iGLAD database [40]. By using the software Pro-impact 6.0 [34] for this scenario and considering the all the time equal vehicles, were analyzed different impact configurations. CMI have been calculated with equation (2). The analysis carried out assuming no driver intervention.

For example, for tests on AEB City version, the EuroNCAP standards require speed between 10 and 50 km/h for the bullet vehicle while the target vehicle is standing. In case of rear-end impact the AEB system benefits are reported in [41,42]. This study is conducted referring to orthogonal impact configuration, in which the ADAS activation can to get a benefits. Previous analysis [42] showed that in case two vehicles collide in an orthogonal configuration, where the vehicle A is stopped and the vehicle B is moving with velocities in increase (20–40 km/h), the low speed of impact allow to collocate the two vehicles in low injury potential area.

Considering, instead, the vehicles A and B are initially moving at a speed of 35 km/h on orthogonal directions in conflict with each other. For this scenario were analyzed two different impact configurations, α and β , shown in table 1 (Appendix), comparable to situation resulting from the possible activation of a system AEB for the vehicle B. If the AEB system or the driver do not intervene, the vehicles will collide in the α configuration.

One second before (time to collision=1 s) the AEB system of vehicle B applies a deceleration of 8 m/s^2 and the vehicle arrives to impact in configuration β . Table 1 (Appendix) shows the results obtained assuming, for each vehicle, different impact speed and in figure 6 are shown the results of the analysis on the CMI–Vr plane. For both vehicles, the activation of the ADAS system determines a shift of the point towards lower potential severity areas. Vehicle B switches the impact configuration from eccentric frontal impact to frontal impact, with IR decreasing from 6% to 2%, whereas vehicle A switches from eccentric frontal impact to side impact (compartment involved), with an IR increase from 6% to 7.5%. Thus, in this case the ADAS activation of the vehicle B resulted in only modest benefits for vehicle B and a worsening for vehicle A.

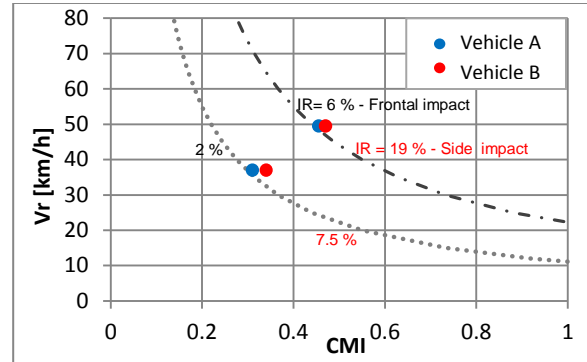


Figure 6. CMI–Vr plane: results of simulation.

In addition to this, the use of this plane allow also to lead an analysis aiming to optimize the ADAS operation, since it can be verify and identify the best maneuver strategy aiming to reduce in an effective way the injury risk, which is not guaranteed 'tout court' by applying the maximum braking action allowed be tires. In fact the injury risk reduction depends not only on the decrease of the relative speed between the vehicles, but also on the new impact configuration that is outlining. It is illustrated how braking modulation can lead to impact configuration potentially less severe, configuration to be found for an optimal performance of the ADAS.

Considering a different pair of vehicles that collide in four different impact configuration, but with the same R_m ($R_m = 1$) showed in table 2 (Appendix), is possible to observe the different situation following the activation of AEB system for the vehicle B, as a function of slowdown intensity, gradually increasing, for the vehicle B. Figure 7 shows the results on the CMI–Vr plane.

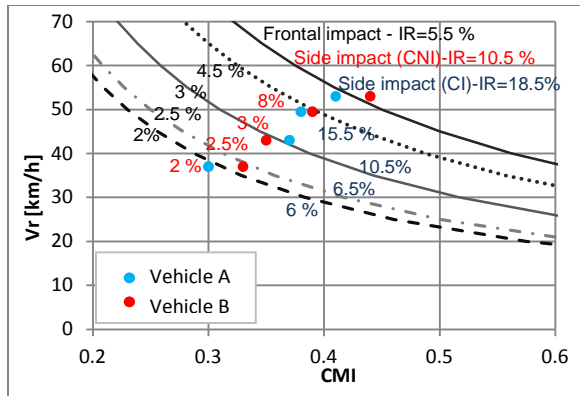


Figure 7. CMI–Vr plane: vehicle position consequently by the intervention of optimized AEB system: vehicle A (blue) and vehicle B (red).

Let us consider the case number 1, in which the two vehicles collide without any slowing of vehicle B: this impact condition, as a result of an eccentric frontal impact for both vehicles, is characterized by an IR equal to 4.8% for the vehicle A and equal to 6.8% for the vehicle B.

Following a deceleration of vehicle B, in the case number 2, the two vehicles collide with the same impact speed in configuration γ , rather than α , with a potential residual impact less severe for vehicle B. For the latter the reduction of relative speed is such that its IR decreases by 2%. Conversely, for the vehicle A, since it passes from a frontal impact to side impact without compartment involved, it is observed an increase of the IR equal to about 4.2%, so that the impact is potentially more severe.

Assuming a greater intensity of deceleration, in the case number 3, the initial configuration α modifies to β , with a potential residual impact less severe also in this case for the vehicle B, because the reduction of the relative speed is such that the IR decreases by 2.3%. For the vehicle A, instead, the impact results significantly more severe, because it suffers a side impact with compartment involved and the IR increases of 4.2%.

Let us consider a slowdown of even greater intensity in the case number 4, where the impact configuration switches from α to δ and for which the speed reduction is such that the residual impact is potentially less severe both for vehicle B, for which the IR decreases by 4.7%, and for vehicle A, for which the reduction is equal to 0.8%.

If the collision is inevitable, the analysis of the evolution of the kinematic situation in real time between the two vehicles, will allow to select the best strategy of intervention to reduce the possible injury.

CONCLUSIONS

This study presented an analysis of ADAS performance based on the CMI–Vr plane, in case of impact vehicles-to vehicles. This plane represent a useful tool that allow to evaluate the relationship between kinematic parameters, as Vr between two vehicles and the ΔV undergone by the vehicles. Each vehicle is characterized, on that plane, by a point of coordinates (CMI; Vr), where the abscissa represents the potential severity of the impact and the ordinate represents Vr. To define a point on the plane means to define the potential severity and the potential injury of the impact. Previous analysis have been found, on that plane, two different areas to which two different accident classes correspond: the former is the area regarding kinematic impact conditions of intrinsically safe accidents, for which the maximum injury level results to be MAIS 1 and the latter area is the one in which all injury levels can be found, from the lighter one up to the fatal one.

The action of an ADAS system or a corrective maneuver of the driver entails a change of impact configuration and relative speed, if the collision cannot be avoided. By comparison between the new scenario and the initial scenario is possible to evaluate the effectiveness of the performance of this device, ADAS, in term of injury risk reduction. This plane summarizes in a single tool all information necessary for an analysis of experimental tests or numerical simulations about the ADAS. In addition to this, that plane allows also to lead an analysis aiming to optimize the ADAS operation, since it can verify and identify the best maneuver strategy aiming to reduce in an effective way the injury risk, which is not guaranteed 'tout court' by applying the maximum braking action allowed by tires – pavement adherence condition. Knowing two characteristics parameters of the accidents can be verified, on the CMI - Vr plane, where the point corresponding to the two vehicles are located and how is the distance of the latter to area low injury potential. In fact, the injury risk and its reduction depends both the decrease of relative speed at the crash and the new impact configuration.

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APPENDIX

Table 1. Results of Pro impact 6.0 simulation, for front-to-side impact.

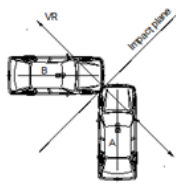
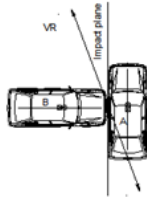
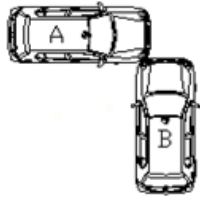
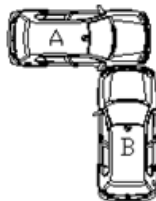
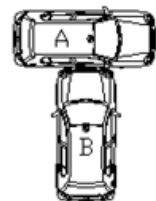
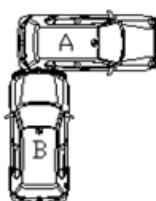
		Configuration α		Configuration β					
						Masses ratio 1:1			
Case number	Configuration	Mass [Kg]	Vehicle	V_i [km/h]	ΔV [km/h]	V_r [km/h]	PDOF ^o (Pro impact)	PDOF ^o (Procedure)	CMI
1	α	1200	A	35	22.6	49.5	46	45	0.46
	α	1200	B	35	23.1		44	45	0.47
2	β	1200	A	35	11.7	37	45	50	0.31
	β	1200	B	12	12.5		45	50	0.34

Table 2. Vehicles' positions resulting to an intervention of an optimized AEB system.

		Configuration α	Configuration γ	Configuration β	Configuration δ				
									
Case number	Configuration	Mass [Kg]	Vehicle	V_i [km/h]	ΔV [km/h]	V_r [km/h]	CMI		
1	α	1000	A	40	22	60	0.36		
		1000	B	45	24		0.40		
2	γ	1000	A	40	21.2	56	0.38		
		1000	B	40	22.1		0.39		
3	β	1000	A	35	17.1	40	0.42		
		1000	B	20	18		0.45		
4	δ	1000	A	35	10.3	37	0.28		
		1000	B	12	11.2		0.30		