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Correlation of Road Safety Criteria with Occupant Safety Criteria in Impacts on Crash Cushions

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Abstract: Road restraint systems are used to protect vehicle occupants if the vehicle runs off the road and potentially collides with a dangerous obstacle. These road restraint systems must successfully pass the tests defined in EN 1317, or the Manual for Assessing Safety Hardware (MASH) before they are allowed to be installed. The safety assessment is carried out according to the criteria of ASI (Acceleration Severity Index), THIV (Theoretical Head Impact Velocity), OIV (Occupant Impact Velocity), ORA (Occupant Ridedown Acceleration), and PHD (Post-Impact Head Deceleration). Usually very old vehicles are used for these tests, and there is no assessment of occupant criteria such as HIC (Head Injury Criteria), chest deflection, etc. The objective of the study was to compare the occupant safety of vehicles that are commonly used in EN 1317 with vehicles that have improved safety equipment. Test results from two different vehicles (a commonly used vehicle in EN 1317 and a vehicle with improved safety equipment) and two different impact conditions (full overlap and an overlap of 50%) were compared. Measurement data from a Hybrid HIII 50th percentile anthropomorphic test device (ATD) (Denton ATD, INC.) was recorded during the tests to assess occupant safety. The tests have shown that vehicles with improved safety equipment perform better than vehicles that are commonly used in EN 1317-3 tests. The values for the occupant safety criteria assessed were well below the Euro NCAP (New Car Assessment Programme) or Federal Motor Vehicle Safety Standard (FMVSS) limits. However, the limits of the road safety criteria were in some cases considerably exceeded regardless of the vehicle. This has been observed in particular for the offset impact condition. THIV and OIV were supposed to be able to assess the risk of head injuries. However, these two criteria correlated negatively with the head criteria, HIC or a3ms. However, a positive correlation was found for the ASI with the HIC and the a3ms head acceleration. Even if some of the criteria for road safety correlate with the criteria for occupant safety, it is doubtful whether the criteria for road safety are suitable for assessing the risk of injury to vehicle occupants.

Keywords: road restraint system; EN 1317; ASI; THIV; PHD; OIV; ORA; HIC; Nij; a3ms; femur force

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1. Introduction

Single-vehicle accidents represent almost one-third of all road fatalities in Europe [1]. Passenger car occupants account for approximately 61%, i.e., 3840 passengers are killed every year. 66% of single-vehicle accidents occur on motorways or rural roads. In a single-vehicle accident, the vehicle runs off the carriageway and collides with an object at the roadside. In order to mitigate or prevent these accidents, road restraint systems, such as concrete barriers or guardrails, are used to shield road sections with dangerously distributed objects, i.e., potential hazards extending over a greater length of the roadside (e.g., embankments, ditches, rock face cuttings, forest and closely spaced trees, etc.). Crash cushions, on the other hand, are set up at selective hazard points (e.g., tunnel lay-bys, tunnel portals, gore points). Concrete safety barriers, guardrails, and crash cushions must meet the requirements defined in the EN 1317 standard in order to be allowed to be installed in Europe [2–4]. The main criteria for the protection level of passenger car occupants are

the ASI (Acceleration Severity Index) and THIV (Theoretical Head Impact Velocity). The PHD (Post-Impact Head Deceleration) is no longer considered in EN 1317 since edition 2011. In the Manual for Assessing Safety Hardware (MASH), ASI, THIV, and PHD are not required [5]. Nevertheless, testing agencies are encouraged to calculate these criteria. Assessment criteria in MASH are determined based on the flail space model of Michie [6], namely OIV (Occupant Impact Velocity) and ORA (Occupant Ridedown Acceleration). These metrics have in common that they are based on the vehicle body acceleration near the vehicle's centre of gravity and the yaw rate. Even though they are indicators of occupant loads, no assessment based on anthropometric test devices (ATD) is currently considered.

In contrast, for the development of vehicles, ATD is used for the assessment of occupant loads and injury risk [7–9]. Thereby, different metrics all over the body regions are captured and put in relation to biomechanical injury risk curves.

Some studies summarised in Table 1 compared occupant criteria (from ATC) with road safety criteria (e.g., ASI, THIV, etc.) [10–18]. Except for Gabauer and Thomson [16,17], all other studies used vehicles with the same weight according to EN 1317 or MASH test conditions to compare road safety criteria with occupant criteria. Gabauer and Thomson, however, analysed occupant responses from crash tests from the NHTSA (National Highway Traffic Safety Administration) with different vehicles and vehicle weights. Compared with the other studies, the collision speed was significantly lower, and the collision angle also differed significantly. Ziegler et al. [17] used vehicles with 1100 kg and 2100 kg, which do not correspond to test vehicles in EN 1317. Some studies used finite element simulations or Madymo simulations for their analysis [12,14,18,19]. In these studies, the collision speed and the collision angle were varied.

Table 1. Overview of studies on the correlation of road safety criteria and occupant criteria in the order of appearance.

Study	Method	Specimen	No. tests	Vehicle Class	Collision Speed	Collision Angle	Criteria
Shojaati [10]	Physical test	Guardrail	9	900 kg	100 km/h	20°	ASI, HIC
Anghileri et al. [13]	Physical test	Guardrail, concrete barrier	23	900 kg	100 km/h	20°	ASI, THIV, HIC
Gabauer and Thomson [16]	Physical test	Concrete wall	24	Varied types	40–64 km/h	90°	ASI, OIV, ORA, HIC, a3ms chest acceleration and chest deflection and femur force
Klootwijk and Hoogvelt [14]	Numerical simulation	Guardrail	22	900 kg	36–100 km/h	0 to 45°	ASI, THIV, PHD, HIC, Viscous Criterion, chest deflection
Sturt and Fell [12]	Physical test	Concrete barrier	3	900 kg	109–113 km/h	15 to 20°	ASI, THI, HIC, neck injuries and chest compression
Sturt and Fell [12]	Numerical simulation	Concrete barrier	47	900 kg	90–150 km/h	10 to 25°	ASI, THIV, HIC, neck injuries and chest compression
Li et al. [18]	Numerical simulation	Guardrail, concrete barrier	28	2500 kg	50–120 km/h	15° to 30°	ASI, THIV, OIV, ORA, PHD, HIC, chest deflection
Meng and Untaroiu [20]	Numerical simulation	Terminal	20	1100 kg	65–120 km/h	0° and 15°	ASI, THIV, OIV, ORA, HIC, chest acceleration and chest deflection and femur force
Chell et al. [15]	Physical test	Guardrail, concrete barrier	28	900 kg	100 km/h	20°	ASI, THIV, HIC, a3ms head acceleration, neck injuries

Table 1. *Cont.*

Study	Method	Specimen	No. tests	Vehicle Class	Collision Speed	Collision Angle	Criteria
Tomasch and Gstrein [21]	Physical test	Guardrail, concrete barrier	73	900 kg	100 km/h	20°	ASI, THIV, HIC
Ziegler et al. [17]	Physical test	Guardrail	3	1100 kg, 2100 kg	110 km/h	20°	ASI, THIV, HIC15, a3ms head acceleration, a3ms chest acceleration, a3ms pelvis acceleration
Ziegler et al. [17]	Numerical simulation	Guardrail	16	1100 kg, 2100 kg	50–130 km/h	8° and 20°	ASI, THIV, HIC15, a3ms head acceleration, a3ms chest acceleration, a3ms pelvis acceleration

Of the studies mentioned, only Gabauer and Thomson [16] considered the effect of the occupant restraint systems (seat belt, airbag). However, this was based on crash test data, which were used to evaluate the safety performance of vehicles, and occupant restraint systems are of decisive importance for occupant protection. A direct comparison of occupant criteria and road safety criteria under EN 1317 impact conditions was not carried out, even though airbags, belt pretensioners, or seat belt load limiters have a huge impact on the risk of injury [22–25]. The safety performance of occupant restraint systems is not considered in EN 1317 since no ATD, equipped with respective sensors, is used, and an ATD is not even placed in all test vehicles. Furthermore, for the evaluation of road safety according to EN 1317, vehicles used are typically very old, in particular for the passenger car test condition (TB11), which has a mass of 900 kg, including an 80 kg ATD. An analysis of test data at the testing laboratory of the Vehicle Safety Institute at Graz University of Technology showed that the average age of light and medium-weight passenger cars is more than 20 years [26]. Even though the vehicles must meet some basic requirements, it is not necessary for them to be state-of-the-art. If the passenger cars are equipped with airbags, they are switched off for the safety of the test personnel.

2. Objective

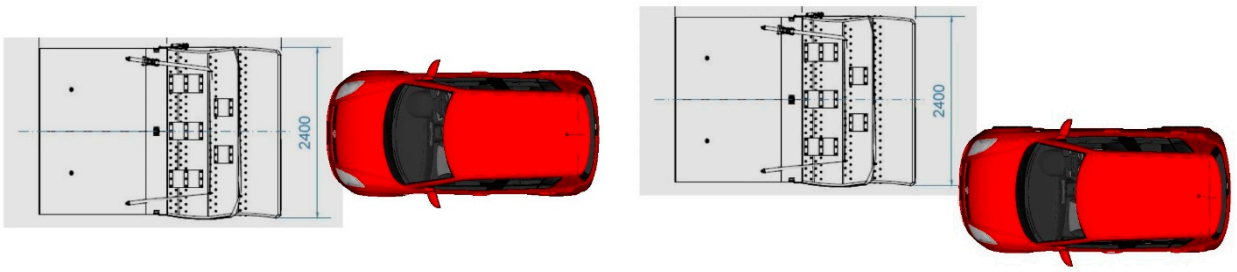
The objective of this study is to compare occupant criteria for different body regions (head, neck, chest, upper legs, shoulder) with road safety criteria (ASI, THIV/OIV, PHD/ORA) utilising crash tests against crash cushions with passenger cars commonly used in EN 1317 and passenger cars with improved occupant safety equipment (airbag, seat belt pretensioner, and load limiter).

3. Method

3.1. Experimental Set-Up

The detailed experimental set-up is described in Tomasch and Gstrein [26]. A non-redirective crash cushion F1-80 from the ALPINA manufacturer was used as a test specimen. The crash cushion is not mounted on the road surface. The test speed was defined beyond the speed of the approval tests, i.e., the approval test speed of this crash cushion is 80 km/h. The test speed was set to 100 km/h to cover real collision speed conditions in road crashes. Two tests with a full overlap and two tests with an offset impact were performed (Figure 1).

At the time of testing, the vehicles were 13 (both VW Golf), 22 and 23 (Opel Corsa) years old (Table 2). The Opel Corsa corresponds to a regular test vehicle used in EN 1317. The VW Golf corresponds to a vehicle with improved standard safety equipment. All of the vehicles were equipped with airbags and pretensioners. All airbags were activated in the tests. In addition, the VW Golfs were equipped with load limiters.



(**a**) (**b**)

Figure 1. Test set-up: vehicle position and overlap (cf. Tomasch and Gstrein [26]); (**a**) full overlap; (**b**): offset impact.

Table 2. Test matrix of the performed tests (Tomasch and Gstrein [26]).

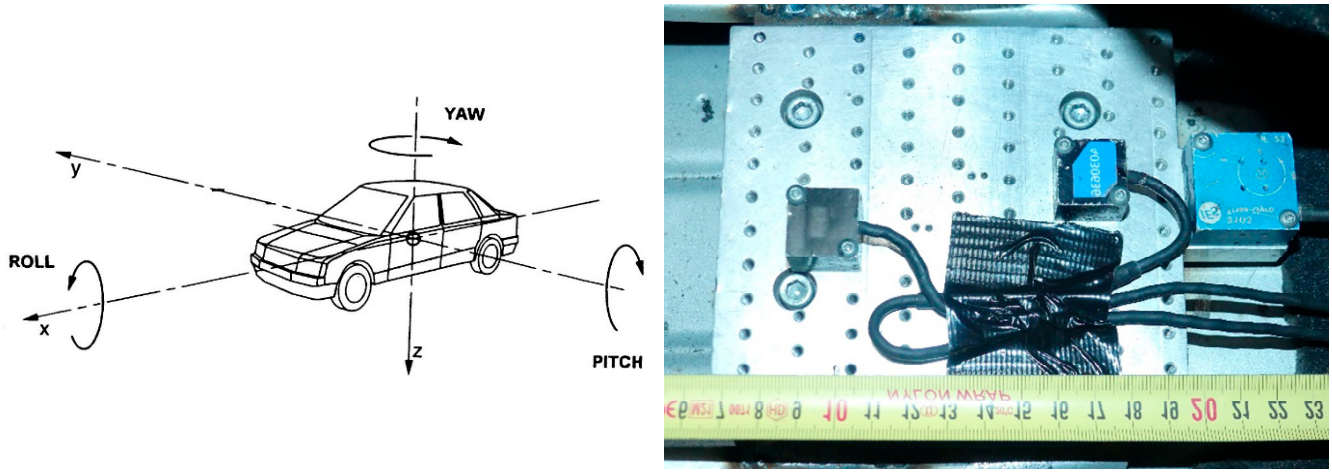
	Unit	#1	#2	#3	#4
Specimen	-	ALPINA F1-80	ALPINA F1-80	ALPINA F1-80	ALPINA F1-80
Vehicle	-	VW Golf 6	Opel Corsa	VW Golf 6	Opel Corsa
Age of vehicle	-	13	23	13	22
Weight incl. ATD	[kg]	1245	935	1245	937
Airbag	-	activated	activated	activated	activated
Pretensioner	-	yes	yes	yes	yes
Load limiter	-	yes	no	yes	no
Overlap	[%]	100	100	50	50

3.2. Data Acquisition

The measurement data acquisition for the vehicle and video data recording were carried out according to the description in Tomasch and Gstrein [26]. A male Hybrid HIII 50th percentile anthropomorphic test device (ATD) weighing approximately 78 kg was used to capture measurement data for a vehicle occupant. Following the Euro NCAP (New Car Assessment Programme) frontal impact tests [27], the ATD was instrumented with the sensors given in Table 3. The sensor locations are shown in Figures 2 and 3. The knee, lower leg, and lumbar spine are only recorded for monitoring purposes in Euro NCAP and are not included in an assessment. They were, therefore, not taken into account in the test.

Table 3. Sensor positions in the vehicle and the ATD.

Location	Parameter	Channel	Manufacturer	Model	Number
Vehicle centre of gravity	Acceleration 1	A_x, A_y, A_z	Meas-Spec	1203	3
	Acceleration 2	A_x, A_y, A_z	Meas-Spec	1203	3
	Angular velocity	A_z	IES	2103-2400	1
Head	Acceleration	A_x, A_y, A_z	Endevco	7264-2000TZ	3
Neck	Force	F_x, F_y, F_z	Denton	J1716A	3
	Moment	M_x, M_y, M_z	Denton	J1716A	3
Chest	Acceleration	A_x	Humanetics	H64B-2000	1
	Acceleration	A_y	Endevco	7264-2000	1
	Acceleration	A_z	Humanetics	H64B-2000	1
	Displacement	D_{chest}	FTSS	14CB1-3615	1
Pelvis	Acceleration	A_x	Humanetics	H64B-2000	1
	Acceleration	A_y	Meas-spec.	H64B-2000-360	1
	Acceleration	A_z	Endevco	7264-2000	1
Femur (L & R)	Force	F_z	Denton	2121A	2
Shoulder belt	Force	F	MSC	5111L/SB-16-TI	1
Pelvis belt	Force	F	MSC	5111L/SB-16-TI	1



(**a**) (**b**)

Figure 2. Vehicle coordinate system (**a**) and position of the acceleration sensors mounted at the centre of gravity (**b**) (cf. Tomasch et al., Tomasch and Gstrein [26,28]).

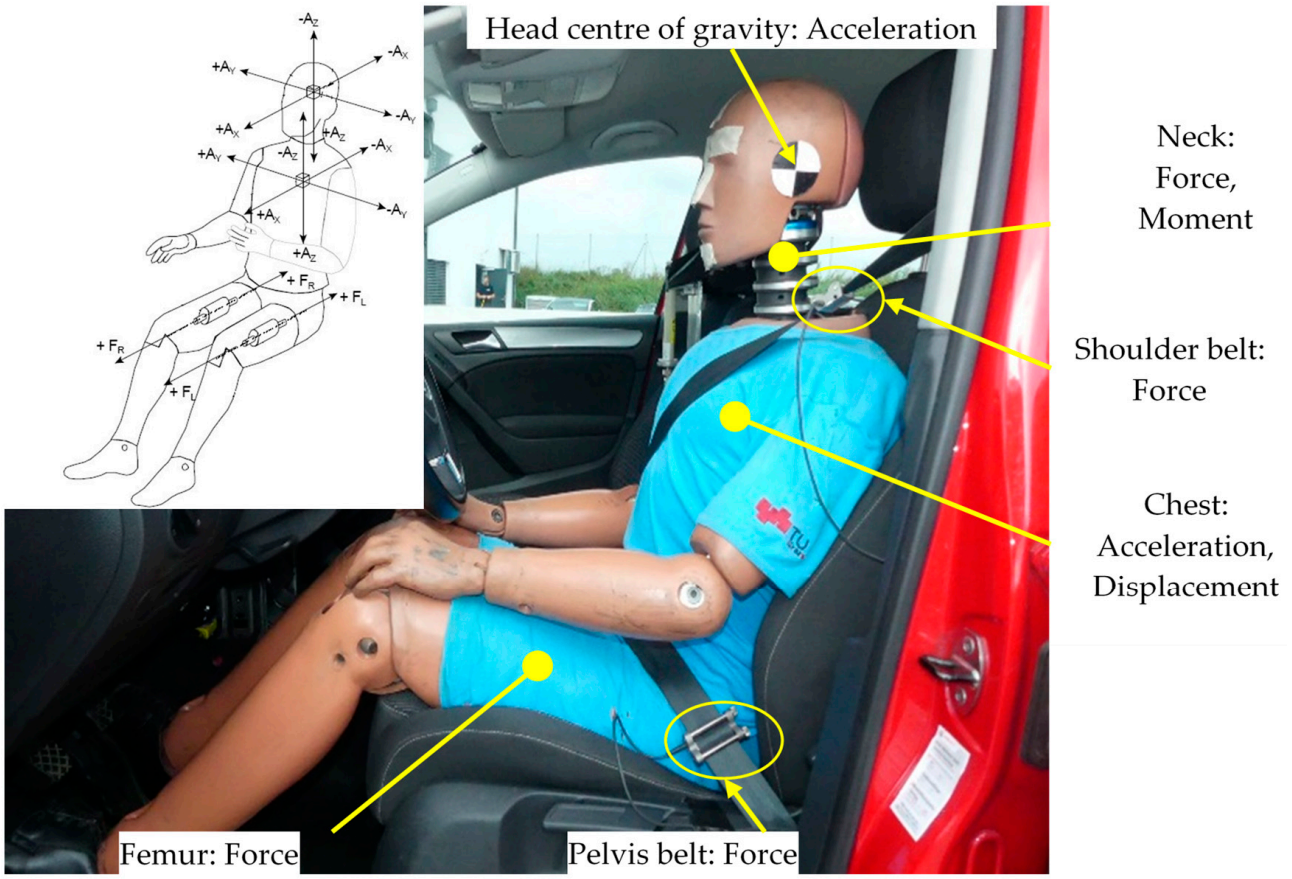


Figure 3. Sensor location and direction in the ATD.

The calculation methods for the individual criteria are described in the following two chapters. An overview of all criteria and corresponding calculation methods is provided in Appendix A.

3.3. Assessment of Road Safety Criteria

3.3.1. Acceleration Severity Index (ASI)

The ASI is calculated according to the norm EN 1317-1 [2] with the following formula. A_x, A_y, and A_z are the three components of the acceleration measured at the centre of gravity. A specific reference is not given in EN 1317 for the specific thresholds in the longitudinal, lateral, and vertical directions. However, the "Severity Index" developed by Weaver and Marquis [29,30] looks similar to that of the ASI, including the tolerance limits for the components of the acceleration.

$$\mathrm{ASI}(k) = \left[\left(\frac{\overline{A}_x}{12}\right)^2 + \left(\frac{\overline{A}_y}{9}\right)^2 + \left(\frac{\overline{A}_z}{10}\right)^2\right]^{0.5} \quad (1)$$

The vehicle impact severity values are separated into impact severity levels A and B. Impact severity A provides a higher level of safety for occupants compared with impact severity B and should be preferred. For impact severity level A, the ASI must be less than or equal to 1.0, and for impact severity level B, the ASI must be less than or equal to 1.4.

3.3.2. Theoretical Head Impact Velocity (THIV)

The THIV is calculated according to the norm EN1317-1 [2] with the following formula: V_x and V_y are the head velocities in the longitudinal and lateral directions of the car coordinate system.

$$\mathrm{THIV} = \left[V_x^2(T) + V_y^2(T)\right]^{0.5} \quad (2)$$

As with the ASI, a distinction is made between impact levels A and B in the THIV. The THIV is the same for both impact severity levels, but a distinction is made according to the direction of impact. The limit for the THIV must be less than or equal to 44 km/h for frontal impacts and equal to or less than 33 km/h for lateral impacts.

3.3.3. Occupant Impact Velocity (OIV)

Even though the concept of the OIV is similar to the THIV, for the calculation of the OIV, vehicle yaw, pitch, and roll motions are not considered, i.e., lateral and longitudinal kinematics are assumed to be independent. OIV is calculated according to the following formula [5]. $V_{I_{x,y}}$ is the occupant-to-car interior impact velocity in the longitudinal and lateral direction and $a_{x,y}$ are the corresponding accelerations. t* is the time in which the occupant travelled 0.6 m longitudinally or 0.3 m laterally, whichever time is shorter.

$$V_{I_{x,y}} = \int_0^{t^*} a_{x,y}\, dt \quad (3)$$

The threshold for the OIV is distinguished into a preferred and a maximum level for the longitudinal and lateral directions. The limit for the preferred level is 9.1 m/s (30 ft/s), and the maximum level is 12.2 m/s (40 ft/s).

3.3.4. Post-Head Deceleration (PHD)

Although the PHD is no longer considered in the current edition of the norm EN 1317-1 [2], it is used for correlation with occupant criteria. For the calculation of the PHD, it is assumed that the head of the ATD impacts against the interior of the vehicle and subsequently experiences the same deceleration as the vehicle itself. The PHD is the maximum acceleration during contact, calculated from the longitudinal and lateral acceleration components. The THIV is calculated according to the norm EN 1317-1 [31].

$$\mathrm{PHD} = \max\left[(a_x(t))^2 + (a_y(t))^2\right]^{0.5} \quad (4)$$

The impact severity level for the PHD is 20 g for both severity levels A and B [31].

3.3.5. Occupant Ridedown Acceleration (ORA)

What applies to the OIV also applies to the ORA. The vehicle rotations (yaw, pitch, roll) are not taken into consideration. Lateral and longitudinal acceleration components are assessed independently [5]. The acceleration is calculated by taking a moving 10 ms average acceleration in the longitudinal and lateral directions. The ORA is the maximum 10 ms acceleration value. The ORA limit for the preferred level is 15 G, and for the maximum level is 20.49 G.

3.4. Assessment of Occupant Criteria

3.4.1. Head Injury Criterion (HIC)

The HIC is based on the Wayne State Tolerance Curve (WSTC). The WSTC was first introduced by Lissner [32] and extended by Gurdjian et al. [33]. Gadd [34] developed the Gadd Severity Index (GSI), and finally, the HIC was first introduced by Versace [35], replacing the GSI. The NHTSA (National Highway Traffic Safety Administration) modified the HIC slightly and incorporated it into the FMVSS 208 (Federal Motor Vehicle Safety Standard) test standard [36]. The HIC is calculated as the maximum value of the resulting head acceleration related to a time window of 36 ms or 15 ms.

$$\mathrm{HIC} = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}(t_2 - t_1) \quad (5)$$

The limits for the HIC are given in Table 4. Euro NCAP distinguishes between three levels of safety. In FMVSS 208, only one limit is defined and corresponds to the "capping limit".

Table 4. HIC limits according to the Euro NCAP frontal test [7] and FMVSS 208 [8].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	HIC15	[-]	500.00	700.00	700.00
FMVSS 208	HIC15	[-]	Not applicable	Not applicable	700.00
	HIC36	[-]	Not applicable	Not applicable	1000.00

3.4.2. a3ms Head Acceleration

The a3ms head acceleration as a criterion is also based on the WTSC. To avoid brain injury, accelerations must not exceed a value of 80 g (Table 5) and a time span of more than 3 ms [37] and Seiffert and Wech [38] cited in [15]. The a3ms is not evaluated in FMVSS 208.

Table 5. Head acceleration limits according to the Euro NCAP frontal test [7].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	a3ms exceedance	[g]	72.00	80.00	80.00

3.4.3. Neck Force and Moment

Neck shear force, tensile force, and neck moment are considered for neck injury in Euro NCAP [7]. Limit values for tensile and shear forces are based on Nyquist et al. ([39] cited in Kleinberger et al. [40]), with limit values for tensile forces of 3.3 kN and shear forces of 3.0 kN. Limits on allowable neck moments were determined by Mertz ([41] cited in Kleinberger et al. [40]) from experiments with volunteers and extended by PMHS (Post Mortem Human Surrogates) for severe injuries. The limit value for neck moment in extension was set at 57 Nm. No injuries were detected during the flexion motion. In FMVSS 208 [8], the axial neck forces are assessed for compression and tension. Table 6 shows the limits for Euro NCAP frontal tests and FMVSS 208.

Table 6. Neck force and moment limits according to Euro NCAP frontal tests [7] and FMVSS 208 [8].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	Shear force	[kN]	1.20	1.95	2.70 (driver)
	Tension force	[kN]	1.70	2.62	2.90 (driver)
	Extension moment	[Nm]	36.00	49.00	57.00 (driver)
FMVSS 208	Peak tension force	[kN]	not applicable	not applicable	4.17
	Peak compression force	[kN]	not applicable	not applicable	4.0

3.4.4. Neck Criterion Nij

The concept of the neck injury criterion Nij was developed by Prasad and Daniel [42] and is considered in FMVSS 208 [8]. The Nij is a combination of the axial forces and moments for flexion and extension, which are normalised by limit values [40]. The Nij is calculated for four different load cases: TE: Tension/Extension, TF: Tension/Flexion, CE: Compression/Extension, and CF: Compression/Flexion. The limits are given in Table 7. The Nij is not evaluated in the Euro NCAP.

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (6)$$

Table 7. Limits for the Nij according to FMVSS 208 [8].

Regulation	Criterion	Unit	Limit
FMVSS 208	N_{ij}	[-]	1.0
	Tension	[kN]	6.806
	Compression	[kN]	6.160
	Flexion moment	[Nm]	310
	Extension moment	[Nm]	135

F_z Tension force
F_{int} Critical limit of tension force
M_y Flexion/Extension neck moment
M_{int} Critical limit of the neck moment

3.4.5. a3ms Chest Acceleration

The first studies on chest accelerations go back to Stapp ([43] cited in Kleinberger et al. [40]), and Mertz and Gadd ([44] cited in Kleinberger et al. [40]) suggested an acceleration limit of 60 g (Table 8). a3ms chest acceleration is considered in FMVSS 208 [8]. In the Euro NCAP [7] frontal test protocol, chest accelerations are not considered as a separate criterion.

Table 8. a3ms chest acceleration limit according to FMVSS 208 [8].

Regulation	Criterion	Unit	Limit
FMVSS 208	a3ms	[g]	60

3.4.6. Chest Compression

According to Neathery et al. [45], the maximum chest compression should not exceed 76 mm. Based on the data of Neathery et al. ([45] cited in Kleinberger et al. [40]), Lau and Viano [46] suggested a maximum chest compression of 65 mm. In the FMVSS 208, a maximum deflection of 63 mm is defined (Table 9). Euro NCAP distinguishes between different levels. However, the capping limit is 42 mm, with the limit being reduced to 34 mm as of 2023.

Table 9. Chest compression limits according to Euro NCAP frontal tests [7] and FMVSS 208 [8].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	Compression	[mm]	18.00	42.00 *	42.00 *
FMVSS 208	Deflection	[mm]	Not applicable	Not applicable	63.00

* From 2023, the lower and capping limit is 34.00 mm.

3.4.7. Viscous Criterion (VC)

The viscous criterion developed by Lau and Viano [47] is taken into consideration in the Euro NCAP frontal impact [7] and the UN ECE-R 94 [48]. The criterion is a combination of loading velocity and chest compression. The following table (Table 10) shows the limits. In FMVSS 208, the VC is not evaluated.

$$(V \cdot C)_{(t)} = V_{(t)} \cdot C_{(t)} = \frac{d[D_{(t)}]}{dt} \cdot \frac{D_{(t)}}{Defkonst} \quad (7)$$

Table 10. Viscous criterion limits according to the Euro NCAP frontal tests [7].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	Viscous Criterion	[m/s]	0.50	1.00	1.00

$V_{(t)}$ Velocity of deformation
$C_{(t)}$ Instantaneous compression
$D_{(t)}$ Instantaneous deformation along the direction of the applied impact to the torso
Defkonst Initial torso thickness

3.4.8. Femur Force

According to Mertz (1989), cited in Kleinberger et al. [40], the limiting load for the femur is 10 kN for a male occupant and 6.8 kN for a female occupant. The limits of the femur compression force in the Euro NCAP frontal impact [7] are given in Table 11. In FMVSS 208, the limit for a 5th percentile female must not exceed 6.805 kN. For the 50th percentile male dummy, the limit is 10 kN [8].

Table 11. Femur compression force limits according to the Euro NCAP frontal tests [7] and FMVSS 208 [8].

Regulation	Criterion	Unit	Higher Limit	Lower Limit	Capping Limit
Euro NCAP	Femur compression	[kN]	2.60	6.20	Not applicable
FMVSS 208	Femur compression	[kN]	Not applicable	Not applicable	6.80510.000

3.4.9. Shoulder Belt Force

Based on frontal impact with full overlap, according to Euro NCAP, the limit for shoulder belt forces is 6 kN [7].

4. Results

The road safety criteria and occupant safety criteria are summarised in Table 12. A detailed description of the resulting values for the road safety criteria as well as the damage pattern of the vehicles is given in Tomasch and Gstrein [26]. Corresponding curves of the time relationships for the criteria are in Appendix B.

Table 12. Road safety criteria [26] and occupant safety criteria.

Position	Criterion	Unit	#1	#2	#3	#4
			VW Golf 6	Opel Corsa	VW Golf 6	Opel Corsa
	Overlap	[%]	100	100	50	50
	ASI (Sensor 1)	[-]	1.60	1.66	2.11	2.63
	ASI (Sensor 2)	[-]	1.58	1.64	2.09	2.60
	THIV (Sensor 1)	[km/h]	48.53	49.09	51.56	43.37
	THIV (Sensor 2)	[km/h]	48.35	48.95	50.70	43.29
Vehicle centre of gravity	PHD (Sensor 1)	[g]	20.94	20.76	30.83	42.41
	PHD (Sensor 2)	[g]	20.81	20.67	30.80	42.22
	OIV (Sensor 1)	[m/s]	48.52	49.09	48.13	43.90
	OIV (Sensor 2)	[m/s]	48.37	49.03	47.53	43.74
	ORA (Sensor 1)	[g]	20.94	21.78	31.90	42.41
	ORA (Sensor 2)	[g]	20.81	21.67	31.78	42.22
	CoG amax (Sensor 1)	[g]	28.47	22.73	37.85	48.17
	HIC15	[-]	52	157	209	272
Head	HIC36	[-]	113	331	363	312
	a3ms	[g]	26.01	40.63	47.44	67.97
	Shear force	[kN]	0.26	0.9	0.88	0.69
	Tension force	[kN]	0.88	1.59	1.22	1.14
Neck	Extension moment	[kN]	11.16	23.45	9.68	22.48
	Flexion moment	[Nm]	18.65	54.46	68.56	120.91
	Nij max	[-]	0.083	0.403	0.221	0.390
	a3ms	[g]	23.47	28.3	34.36	45.76
Chest	Compression	[mm]	31.52	35	27.67	37.91
	Viscous criterion	[m/s]	0.1367	0.1137	0.1709	0.1608
	Shoulder belt force	[kN]	4.15	5.76	4.53	7.61
	Femur force left (+)	[kN]	0.82	1.11	0.82	1.2
Lower extremities	Femur force right (+)	[kN]	0.79	0.81	0.65	0.87
	Femur force left (−)	[kN]	−0.8	−0.88	−1.999	−0.299
	Femur force right (−)	[kN]	−1.13	−2.72	−0.82	−0.392

4.1. Head

In the impact with full overlap, the VW Golf (with belt pretensioner, belt load limiter, and airbag) was found to have a HIC15 of 52. The Opel Corsa was equipped with a belt pretensioner but no belt force limiter and the airbag was deactivated for the test. The HIC15 for this vehicle was calculated as 157. In the offset impact, the HIC15 for the VW Golf was 209 and for the Opel Corsa 272. For both cars, the peak loads did rise, mainly due to the direct impact of the car against the concrete backup at the rear of the crash cushion.

The analysis showed that the HIC was still partly significantly below the limits according to the Euro NCAP frontal impact [7] or FMVSS 208 [8]. The highest HIC15 was found to be 272 for the Opel Corsa and an offset impact, but still far below the higher limit of the Euro NCAP frontal impact [7] set at 500. In any case, the HIC15 was far below the capping limit of Euro NCAP, with an HIC15 of 700 or the limit value according to FMVSS 208 [8], with an HIC15 of 700.

According to NHTSA and Prasad and Mertz [49], the risk of sustaining an AIS 3 injury would be 0.1% for the VW Golf and the full overlap related to HIC15. For the Opel Corsa, the risk is 1.7%. Within the offset impact, the risk of an AIS 3 injury would be 2.7% for the VW Golf and 4.3% for the Opel Corsa.

The risk of an AIS 3 injury is 0.9% related to the HIC36 for the VW Golf in the full overlap test. For the highest HIC (Opel Corsa with offset impact), the risk of an AIS3 injury would be 7.0%. Much higher are the risks for AIS 1 and AIS 2 injuries. However, these are also significantly less severe.

A similar picture emerges from the analysis of the a3ms head acceleration. Here, too, the lowest acceleration of approx. 26 g was found for the VW Golf with full overlap. The head acceleration of the ATD in the Opel Corsa was considerably higher at approx. 41 g. A

good occupant restraint system can influence and significantly reduce head loads. In the offsetting impact, an impact against the backup was observed [26]. This led to an a3ms head acceleration of approx. 47 g for the VW Golf and approx. 68 g for the Opel Corsa, which was significantly higher compared with the full overlap. In all four tests, however, the values remain below the higher limit of the Euro NCAP frontal impact NCAP [7], with a limit of 72 g. In the case of the offset impact, the front airbag becomes visible 128 ms after impact [26]. The dummy head was just in front of the steering wheel and was hit by the deploying airbag. Immediately at this point, a clear acceleration peak can be detected in the acceleration signal of the head. This peak is up to approx. 67 g. However, this is not relevant for the calculation of the a3ms acceleration since the time span is too short for this. Nevertheless, the interaction of the airbag with the occupant during deployment is associated with a considerable risk of injury [50].

4.2. Neck

The higher limits for shear and tension force as well as neck extension according to Euro NCAP frontal impact [7] were not exceeded in any of the four tests. Here, too, the VW Golf performed best in the impact with full overlap. However, in the Opel Corsa, the neck shear force was lower in the offset impact than in the VW Golf in the same impact configuration. In the VW Golf, the airbag deployed shortly before the dummy head hit the steering wheel. This may explain the higher shear force in the VW Golf compared with the Opel Corsa. Furthermore, the Opel Corsa had a higher yaw movement due to the impact, which can also influence the shear force. Since the shear force in the test with the Opel Corsa was also lower compared with the full overlap, the lower shear force in the offset impact can be explained.

A similar characteristic was found for the tension forces. The higher limit according to the Euro NCAP front impact [7] was not reached in any of the tests. In the full overlap, the tension force in the Opel Corsa, 1.59 kN, was relatively close to the higher limit of 1.7 kN. The capping limit of 1.95 kN, on the other hand, was also clearly undercut in this test. The VW Golf showed the lowest value (0.88 kN) at the full overlap.

In the case of the extension moment, the maximum extension moment was about the same for both the full overlap and the offset impact, which was observed in both vehicles. The higher limit of the Euro NCAP front impact [7] is not nearly reached in any of the four tests. Even though the flexion moment is not evaluated in the Euro NCAP front impact, the limit of 190 Nm according to Mertz ([41] cited in Kleinberger et al. [40]) was not reached in any of the four tests.

The lowest Nij of 0.08 was found in the VW Golf with full overlap. According to Mertz [51] and Prasad [42] cited in [40], the risk of an AIS 3+ neck injury would be 2.3% and for an AIS 5+ injury, 1.5%. Offset impacts would result in a maximum Nij of 0.22 for the VW Golf. This would correspond to a risk of an AIS 3+ neck injury of 3.2% and a risk of an AIS 5+ injury of 1.8%. For the Opel Corsa with full overlap, the maximum Nij was 0.4, and with the offset impact, it was 0.39. The risk of an AIS 3+ neck injury would be approximately 4.6%, and the risk of an AIS 5+ neck injury would be approximately 2.3%.

4.3. Chest

The a3ms chest acceleration was in all four tests well below the limit according to FMVSS 208 [8] with 60 g. In Euro NCAP, there is no separate evaluation of chest acceleration, but chest compression and the viscous criterion are evaluated.

In the case of chest compression, at least the currently valid limit of 42 mm was undercut in all tests. The highest compression of 38 mm was observed in the Opel Corsa, with an offset impact. The lowest, 28 mm, was found for the VW Golf for the offset impact. The capping limit of 34 mm, which has been applied since 2023, was exceeded in both of the Opel Corsa test configurations. The higher limit of 18 mm was clearly exceeded in all of the tests. The limit of 63 mm in FMVSS 208 [8] was not reached.

The VC remained below the limit value of 1.0 m/s in all tests, according to the Euro NCAP Frontal Impact [7]. Even the higher limit of 0.5 m/s was clearly undercut in all four tests. For this criterion, however, the Opel Corsa had a lower value than the VW Golf. The seat belt does influence occupant loads. In the Opel Corsa, the loads (compression and acceleration) were higher than in the Golf in both impact configurations, which can be attributed to the lack of a belt force limiter.

The VW Golf was equipped with a seat belt pretensioner and a seat belt force limiter. The maximum shoulder belt force was limited to approx. 4 kN, regardless of the impact configuration, and was thus well below the 6 kN limit of the Euro NCAP frontal impact [7]. In the Opel Corsa, the shoulder belt force (5.8 kN) was significantly higher in the case of an impact with full overlap. For the offset impact, the shoulder belt force in the Opel Corsa clearly exceeded the limit and reached a maximum value of 7.6 kN.

4.4. Femur

In all four tests, there was knee contact with the dashboard. In the tests with the VW Golf, the femur forces were lower compared with the Opel Corsa. In particular, this could be determined for the right femur. The maximum femur force of 2.72 kN was found for the Opel Corsa, and there was a full overlap. The higher limit of the Euro NCAP frontal impact [7] of 2.7 kN was exceeded. In the other three tests, the higher limit was not reached.

4.5. Correlation of Occupant Safety and Road Safety Criterion

Table 13 summarises the linear regression coefficient r (Pearson's r) according to the corresponding road safety and occupant safety criteria. Significance was tested using the *t*-test.

Table 13. Linear regression coefficient and level of significance. Correlation coefficients with a magnitude above 0.7 and below −0.7 are highlighted.

Criterion	ASI	THIV	PHD	OIV	ORA
HIC36	0.49 (p = 0.514)	0.10 (p = 0.902)	0.43 (p = 0.567)	−0.19 (p = 0.811)	0.48 (p = 0.519)
HIC15	0.90 (p = 0.099)	−0.43 (p = 0.572)	0.87 (p = 0.127)	−0.73 (p = 0.271)	0.90 (p = 0.104)
Head a3ms	0.95 (p = 0.047)	−0.63 (p = 0.373)	0.94 (p = 0.064)	−0.86 (p = 0.136)	0.95 (p = 0.054)
Shear	0.29 (p = 0.711)	0.22 (p = 0.780)	0.23 (p = 0.770)	0.00 (p = 0.998)	0.28 (p = 0.718)
Tension	−0.10 (p = 0.904)	0.2 (p = 0.802)	−0.15 (p = 0.846)	0.25 (p = 0.749)	−0.11 (p = 0.888)
Extension	−0.27 (p = 0.733)	0.63 (p = 0.370)	−0.24 (p = 0.760)	0.39 (p = 0.611)	−0.24 (p = 0.759)
Nij max	0.46 (p = 0.542)	−0.44 (p = 0.563)	−0.87 (p = 0.129)	0.94 (p = 0.058)	0.84 (p = 0.157)
Chest a3ms	0.99 (p = 0.014)	−0.65 (p = 0.351)	0.98 (p = 0.023)	−0.91 (p = 0.090)	0.98 (p = 0.018)
Chest compression	0.38 (p = 0.618)	−0.88 (p = 0.117)	0.38 (p = 0.621)	−0.61 (p = 0.385)	0.36 (p = 0.642)
Viscous criterion	0.73 (p = 0.271)	−0.07 (p = 0.925)	0.74 (p = 0.258)	−0.54 (p = 0.459)	0.75 (p = 0.252)
Femur	0.63 (p = 0.374)	−0.76 (p = 0.235)	0.67 (p = 0.329)	−0.82 (p = 0.185)	0.63 (p = 0.371)
Shoulder belt	0.75 (p = 0.250)	−0.85 (p = 0.150)	0.74 (p = 0.264)	−0.83 (p = 0.174)	0.73 (p = 0.269)

5. Discussion

For the conducted tests, the analysed road safety criteria are mostly quite significantly above the limits according to the certification test conditions of EN 1317 or MASH. This is mainly caused by the higher impact speed compared with the certification tests according to EN 1317-3 [3] for the investigated crash cushion. In particular, the road safety criteria for offset impacts are significantly worse for both vehicles compared with the full overlap configuration.

However, the occupant safety criteria evaluated in this work do not exceed the limits. Corresponding limits for the occupant criteria according to specifications for frontal impact in Euro NCAP [7] or FMVSS 208 [8] are largely undercut. A vehicle with improved safety equipment (airbag, load limiter, etc.) has clear advantages compared with a vehicle

conventionally used for EN 1317 tests. This is true for the full overlap as well as for the offset impact.

Even though only a small number of experiments were conducted, correlations between individual variables were calculated. While the ASI of the two vehicles in the full overlap is comparable, the HIC15 in the Opel Corsa is approximately three times higher than in the VW Golf. In the case of the offset impact, the ASI and the HIC are much higher compared with the full overlap but do not differ that much between vehicles. The much higher ASI for this impact configuration is a result of the hard impact against the concrete backup of the crash cushion after penetrating the cushion bag. The relatively high HIC in the VW Golf can be explained by the lack of protection provided by the airbag in the offset impact test. The airbag deploys just before the head hits the steering wheel. Therefore, the HIC15 for the VW Golf and the Opel Corsa is not that different. The HIC15 shows a positive correlation with the ASI (r = 0.9, p = 0.099). However, the HIC15 does not come close to the limits of the regulations under consideration [7,8], while the ASI is in some cases significantly above the respective limits [3]. Similar results for the ASI could also be found for the correlation of the HIC15 with PHD and ORA. As for HIC15, correlations were also found between ASI and a3ms head acceleration, a3ms chest acceleration, viscous criterion, as well as femur forces. The strongest correlation, however, was observed for the a3ms chest acceleration of the examined occupant injury criteria (e.g., ASI: r = 0.99, p = 0.014).

There are only a few studies in the literature on the correlation of ASI with occupant criteria such as HIC on experimental tests. From the data of Shojaati and Schüler [10,11], one could assume an exponential relationship between ASI and HIC (r = 0.82). Due to the lack of experimental results in the study, the data for calculating the correlation coefficient were retrieved manually from the image material. Furthermore, the authors did not describe whether HIC15 or HIC36 were calculated, but it is assumed that they calculated HIC36. The correlation between Sturt and Fell [12] and Ziegler et al. [17] yields an exponential r of greater than 0.9 and is comparable with Shojaati and Schüler [10,11]. However, only three real experiments from each study were available. In the present study, an exponential correlation between ASI and HIC36 would result in an r of 0.51 and be of a much lower magnitude. In other studies [13,15,21], which established a correlation between ASI and HIC, the correlations are comparable with the present results. Even from Gabauer and Thomson [16], who analysed only frontal collisions, only a very low exponential correlation with an r of 0.36 can be observed (values retrieved manually from the images). Numerical calculations by Klootwijk et al. [14] yield an exponential correlation between ASI and HIC15 with an r of 0.88 or a linear correlation with an r of 0.9 (values retrieved manually from the images). In Sturt and Fell [12], an exponential correlation coefficient of 0.93 was obtained. Li et al. [18] yield an exponential correlation between ASI and HIC15 of 0.91 (values retrieved manually from the images). The exponential correlation between ASI and HIC15 in Meng et al. [20] is of a lower magnitude (r = 0.47).

If all available studies on ASI and HIC are analysed, a minor exponential correlation can be observed (Figure 4). The test data are divided into frontal impacts (r = 0.54) and oblique impacts (r = 0.47), with a further distinction made between numerical simulation and physical tests.

Even though there is a significant spread of head loads (HIC15, a3ms) in the four Entsprechende Kurven zu den Kriterien sind im Anhang.tests, THIV and OIV show only minor variance between the results. The correlation of HIC15 with THIV and OIV, however, is negative (r = −0.43, p = 0.572, and r = −0.73, p = 0.271). This is curious because the THIV and OIV are used to assess the head injury risk. In Sturt and Fell [12], an exponential correlation between THIV and HIC could be assumed (r = 0.95), but information on some of the individual values is missing, and the data were manually extracted from the image material. Gabauer and Thomson [16] found a negative linear correlation between the OIV and the HIC. Within the analysed tests, at the same collision speed, OIV correlated negatively with HIC (25 mph: r = −0.07; 30 mph: −0.61; 35 mph: −0.29). These correlations are comparable

to the findings in the current study. In Meng et al. [20], there is no correlation between THIV and HIC15 (r = 0.07). In contrast, the numerical simulation in Li et al. [18] yields an exponential correlation of r = 0.95 between THIV and HIC15. However, both the speed and the impact angle were varied in this study, which can have a major influence on the values. It was observed that HIC increased much more than THIV. Ziegler et al. [17] conclude that the THIV is actually inappropriate for assessing the head injury risk. Chell et al. [15] also conclude that the THIV does not adequately represent real head impact velocity.

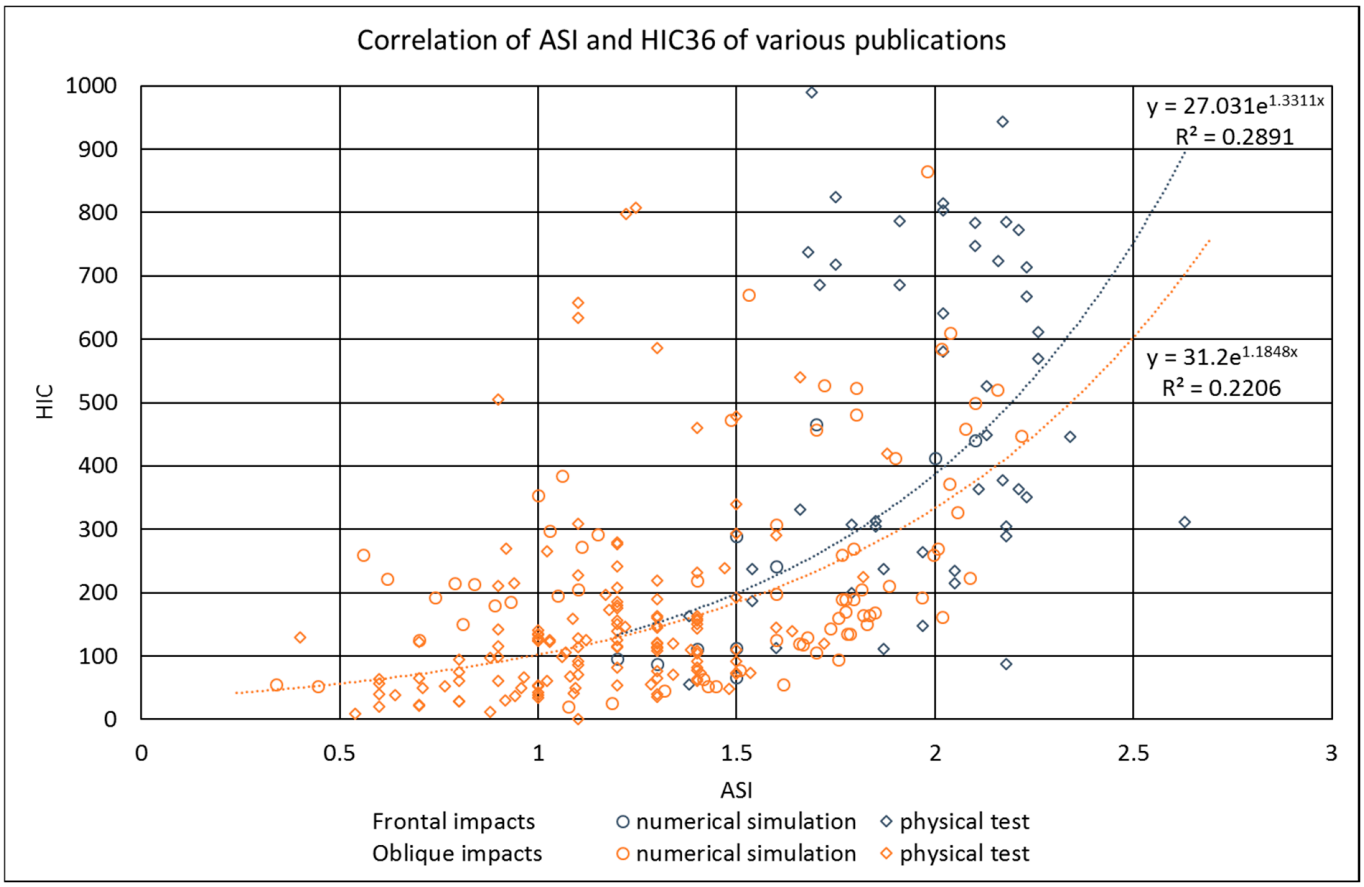


Figure 4. Correlation of ASI and HIC36 of various publications.

From the literature, only the study by Gabauer and Thomson [16] is comparable with the present results. Gabauer and Thomson were the only authors who analysed frontal collisions. They found a negative linear correlation between THIV and HIC if impact velocities were clustered. In the other studies (Li et al. [18], Meng et al. [20], Ziegler et al. [17]), different impact angles were considered, and the collision velocity was also varied and therefore not directly comparable.

The reason for the negative correlation between the HIC and the THIV is possibly due to the calculation method. The HIC is calculated directly from the measured accelerations in the head of the ATD [35], and the THIV is based on the flail space model of Michie [6]. In this model, it is assumed that the occupant collides with a part of the vehicle after moving in free flight ("flail"). The THIV corresponds to the speed after this free-flight motion.

Figure 5 summarises all available studies on the correlation of THIV and HIC36. A minor exponential correlation is found for frontal test configurations (r = 0.50) and oblique impacts (r = 0.48).

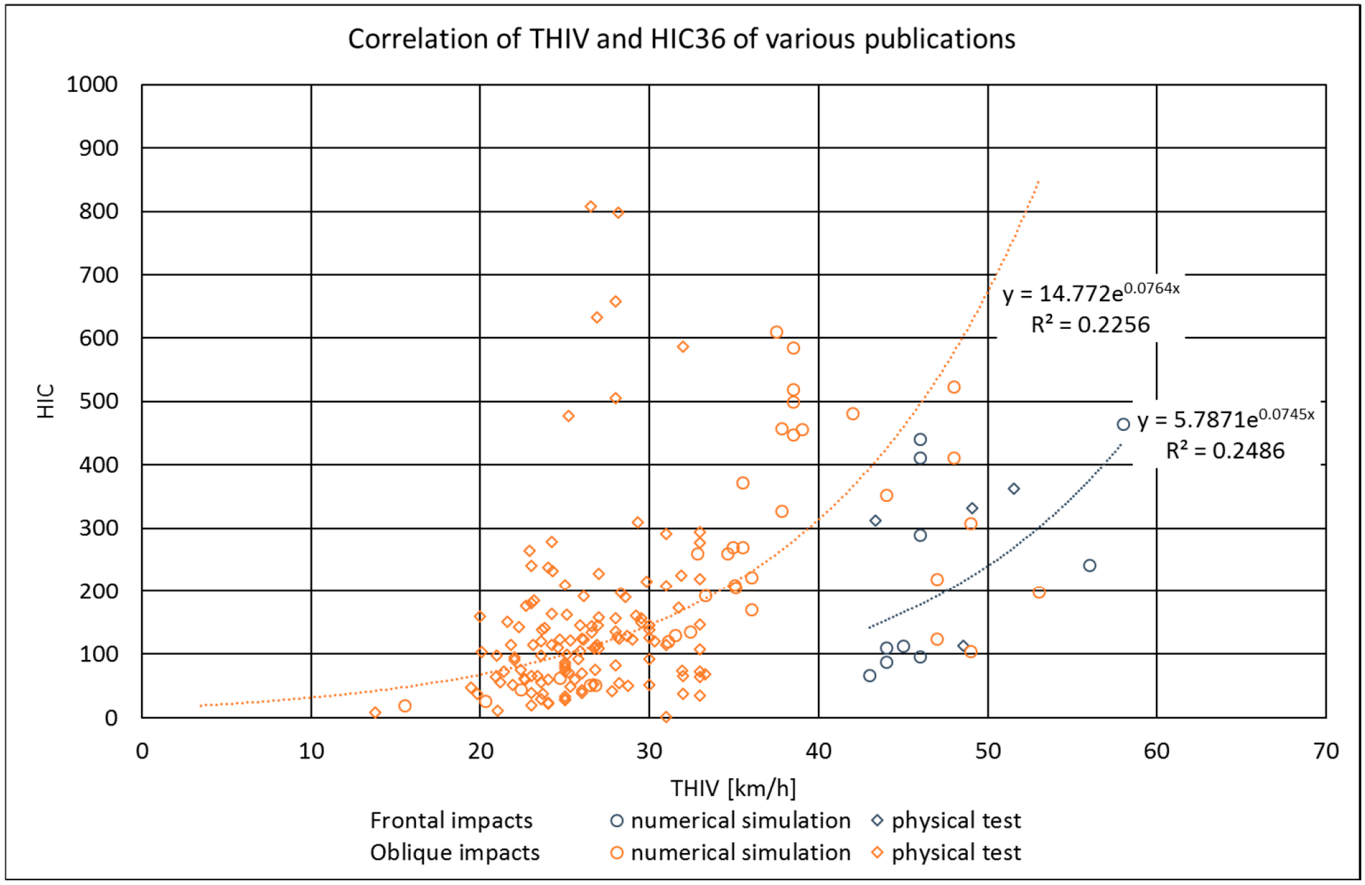


Figure 5. Correlation of THIV and HIC36 of various publications.

The other injury criteria also correlate negatively with THIV or OIV. An exception is the OIV with Nij and the THIV with neck extension. In Ziegler et al. [17], a strong correlation between THIV and a3ms chest acceleration is identified. This correlation is highly related to the impacts of concrete barriers.

According to the accident analysis, in the case of a car collision with a vehicle restraint system, the main body regions affected are the head and face, the chest, the spine, specifically the cervical spine, and the extremities [17,52]. With increasing injury severity, the head and thorax are by far the most frequently affected, with the extremities increasingly losing significance in terms of injury [52]. Consequently, for tests according to EN 1317, it makes sense to supplement ASI and THIV by evaluating corresponding body regions. The most promising body region might be the head. Head acceleration can be used to calculate the HIC and the a3ms head acceleration. Chell et al. [15] have already proposed instrumentation of the dummy head with accelerometers. Injury criteria such as HIC, chest criteria, etc. are very strongly dependent on the occupant restraint system [16] and can significantly contribute to minimising the risk of injury [22–25]. Consequently, for a comparable assessment of occupant loads at impacts against different crash cushions or guardrails, evenly equipped test vehicles have to be used. Otherwise, the worse performance of the restraint system could be overcompensated by a well-performing occupant protection system.

Furthermore, according to Chell et al. [15], neck injury criteria such as the Nij should also be considered when evaluating vehicle restraint systems. Approximately 25% of injuries involve the cervical spine [17]. Although whiplash-associated disorders have low injury severity, they are a major economic burden on European society and account for four billion euros annually [53].

Although the chest is also clearly relevant regarding injuries, vehicles with improved safety equipment (e.g., seat belt force limiters) have significantly lower chest compressions and significantly lower shoulder belt forces. It is to be expected that the same applies to other vehicles with belt-force limiters. The more stringent requirements for frontal collisions in Euro NCAP [7] from 2023 onwards will lead to an additional reduction in the risk of injury to the chest. Therefore, there might be no need for data recording of chest characteristics.

Injury criteria such as HIC, chest criteria, etc. are very strongly dependent on the occupant restraint system and the interaction with the ATD. In the offsetting impact of the vehicle with improved safety equipment, the airbag was deployed directly before the head hit the steering wheel, i.e., the airbag was deployed very late. The acceleration time history of the offset impacts shows a very low acceleration level of approximately 10–12 g in the first 100 ms [26]. Because of the hard impact against the backup of the crash cushion, the acceleration starts to increase, and the airbag is thus triggered. Late airbag deployment was also noted by Johansson and Otte, in particular under poor impact conditions (e.g., small overlap) [54], comparable with the offset impact test condition in the present study. An increasing tendency for HIC and maximum head acceleration with increasing airbag trigger time was observed by Asadinia [55]. Even though a late airbag trigger time is not necessarily related to increased injury severity, a link is likely [54].

In addition to the improved safety equipment, a higher vehicle mass is considered beneficial for occupants, although this cannot be concluded beyond doubt from the tests since the vehicle with the higher mass is also the vehicle with the improved safety equipment. In a study by Burbridge et al. [56], however, a correlation was established between vehicle mass and the criteria ASI, OIV, and ORA. For all three values, lower values were found with increasing vehicle mass, i.e., according to the results in Burbridge et al. [56], vehicles with higher mass would perform significantly better.

In Germany, a trend towards higher vehicle weights in newly registered passenger cars has been observed [57], which should therefore also have a positive effect on occupant injuries in the event of a collision with a vehicle restraint system. The average vehicle weight of newly registered passenger cars increased from 1426 kg to 1515 kg between 2005 and 2018. Hernandez et al. [58] studied the vehicle weight of newly registered vehicles in Spain. The total vehicle fleet between 2007 and 2016 showed a massive decrease in the proportion of vehicles weighing less than 1000 kg, dropping by 32% during the period. Newly registered vehicles with less than 1000 kg only have a share of 10%. The minimum weight of different manufacturers in Europe has been consistently above 1000 kg since 2001 and was just under 1200 kg in 2017 [59]. In real accidents, the vehicle weight of passenger cars below 1000 kg accounts for only 7.3% [17]. The vehicle used in EN 1317, with a total mass of 900 kg, is thus clearly below the vehicle weights according to the aforementioned studies. It would therefore make sense to adapt the mass of the passenger cars in the EN 1317 tests to the current situation; at least the vehicle mass of the smallest vehicle should be evaluated in any case.

6. Limitations

The analysis of the data comprises only four tests. The calculated correlation is therefore based on a small sample size. This may lead to results that cannot be fully explained, as in the case of THIV and OIV, for example. No positive correlation was observed between THIV or OIV and HIC or a3ms head acceleration, but this was expected as these two criteria are used to assess the risk of head injury. This may also be due to the small sample size, although the ASI correlates positively with the HIC and a3ms head acceleration.

Only one test was carried out in each test configuration. Thus, the influence of different impact angles on the correlation of the investigated criteria cannot be assessed.

The tests only included a single crash cushion with one specific performance level. The extent to which other crash cushions or restraint systems influence the criteria or the correlation between the criteria cannot be explained.

Likewise, the influence of different vehicle masses or stiffness cannot be derived from the test data. Although lower values would be expected with higher vehicle masses [56].

7. Conclusions

The study was able to show that the assessment of road restraint systems using the existing ASI and THIV criteria does not necessarily reflect the risk of injury to occupants when compared with corresponding occupant criteria such as HIC. The study showed that there is a huge difference when the criteria are associated with injury risks. According to the study of Gabauer and Gabler [60], the worst THIV identified within the tests would result in an injury risk of approximately 66% for an occupant sustaining MAIS 2+ injuries. Based on the HIC, however, the risk of sustaining MAIS2+ injuries to the head would be approximately 10%, according to Hertz ([61] cited in [40]). This is quite a large difference, as both criteria should actually be used to assess the risk of injury. However, the tests also showed that vehicles with improved safety equipment perform significantly better. The tests have clearly demonstrated that for occupants in vehicles with improved safety equipment, almost all of the occupant criteria values are significantly lower than the frontal impact limits in Euro NCAP or FMVSS 208. However, this was not the case for the road safety criteria. In some cases, these were considerably above the limits. Although THIV and OIV are used to assess the risk of head injuries, there is not much difference in scores in the four tests, and no correlation was observed with the head criteria HIC or a3ms. Although correlations between the road safety criteria and occupant safety criteria have been found in some cases, it is uncertain whether the road criteria are appropriate for assessing the risk of injury to vehicle occupants. Li et al. [18] also concluded that ASI, THIV, OIV, ORA, and PHD may not necessarily be good metrics to assess occupant injury risk. Therefore, it would make sense to include corresponding criteria for the assessment of occupant safety, at least in addition to ASI and THIV. The evaluation of vehicle restraint systems, which is based exclusively on the ASI and THIV, is also questioned critically by Sturt and Fell [12] and Ziegler et al. [17].

Many vehicles are already equipped with airbags, belt force limiters, etc., which reduce the forces acting on the body regions and are therefore definitely beneficial for the vehicle occupant. These technologies are not considered at all in the road safety criteria.

8. Future Developments

Due to the limited number of tests, the test matrix would have to be extended eventually with more participating partners (manufacturers of crash cushions). This would allow an assessment of the influence of different impact configurations, containment levels, etc. on the occupant criteria, as well as the correlation between the criteria.

Although THIV or OIV and HIC or a3ms should show a positive correlation, as all these criteria assess the risk of injury to the head, a negative correlation in this context could be observed. In order to evaluate the plausibility of the data, the number of tests should be increased.

Criteria such as HIC, a3ms, etc. have already been proposed in other studies to evaluate occupant safety. Despite this, appropriate ATDs would have to be used in the tests to evaluate these criteria. This would lead to higher costs, which manufacturers of restraint systems would not necessarily accept. The development of new criteria (used in conjunction with existing ones) based on current measurement data at the centre of gravity would thus be a reasonable step towards improving passenger safety.

Even if there are studies on the assessment criteria of road restraint systems, a comprehensive literature study would be recommended in order to process the findings to date and highlight all aspects that are either included or missing.

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Appendix A

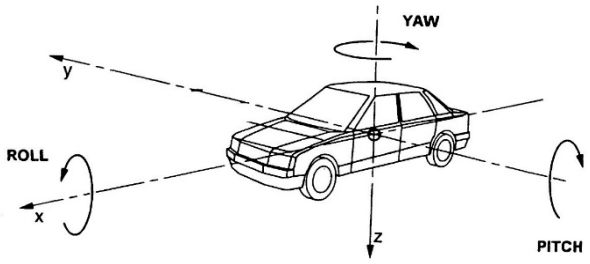

Figure A1. Vehicle coordinate system in the centre of gravity.

Table A1. Measurement parameters and calculation methods for road safety criteria.

Criterion	Parameters				Calculation Method
	ax	ay	az	$\dot{\varphi}_z$	
ASI	x	x	x		$\mathrm{ASI(k)} = \left[\left(\frac{\overline{A}_x}{12}\right)^2 + \left(\frac{\overline{A}_y}{9}\right)^2 + \left(\frac{\overline{A}_z}{10}\right)^2\right]^{0.5}$
THIV	x	x		x	$\mathrm{THIV} = \left[V_x^2(T) + V_y^2(T)\right]^{0.5}$
OIV	x	x			$V_{I_{x,y}} = \int_0^{t^*} a_{x,y}\, dt$
PHD	x	x			$\mathrm{PHD} = \max\left[(a_x(t))^2 + (a_y(t))^2\right]^{0.5}$
ORA	x	x			Maximum acceleration within a time span of 10 ms

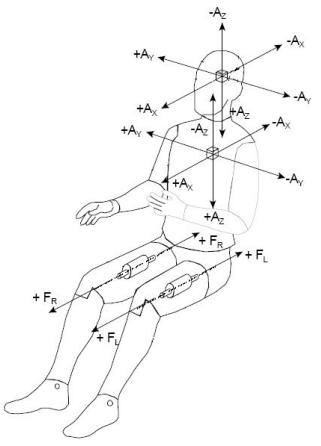

Figure A2. ATD coordinate system.

Table A2. Measurement parameters and calculation methods for occupant safety criteria.

Criterion	Parameters											Calculation Method
	ax	**ay**	**az**	**Fx**	**Fy**	**Fz**	**F**	**Mx**	**My**	**Mz**	**D**	
HIC	x	x	x									$HIC = \max\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}(t_2-t_1)$
a3ms head acceleration	x	x	x									Maximum acceleration within the time span of 3 ms
Neck force and moment				x		x			x			Maximum force and moment and duration
Neck criterion nij						x			x			$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}}$
a3ms chest acceleration	x	x	x									Maximum acceleration within the time span of 3 ms
Chest compression											x	Maximum chest compression
Viscous criterion		x									x	$(V{\cdot}C)_{(t)} = V_{(t)}{\cdot}C_{(t)} = \frac{d[D_{(t)}]}{dt}\cdot\frac{D_{(t)}}{Defkonst}$
Femur force							x					Maximum force
Shoulder belt force							x					Maximum force

Appendix B

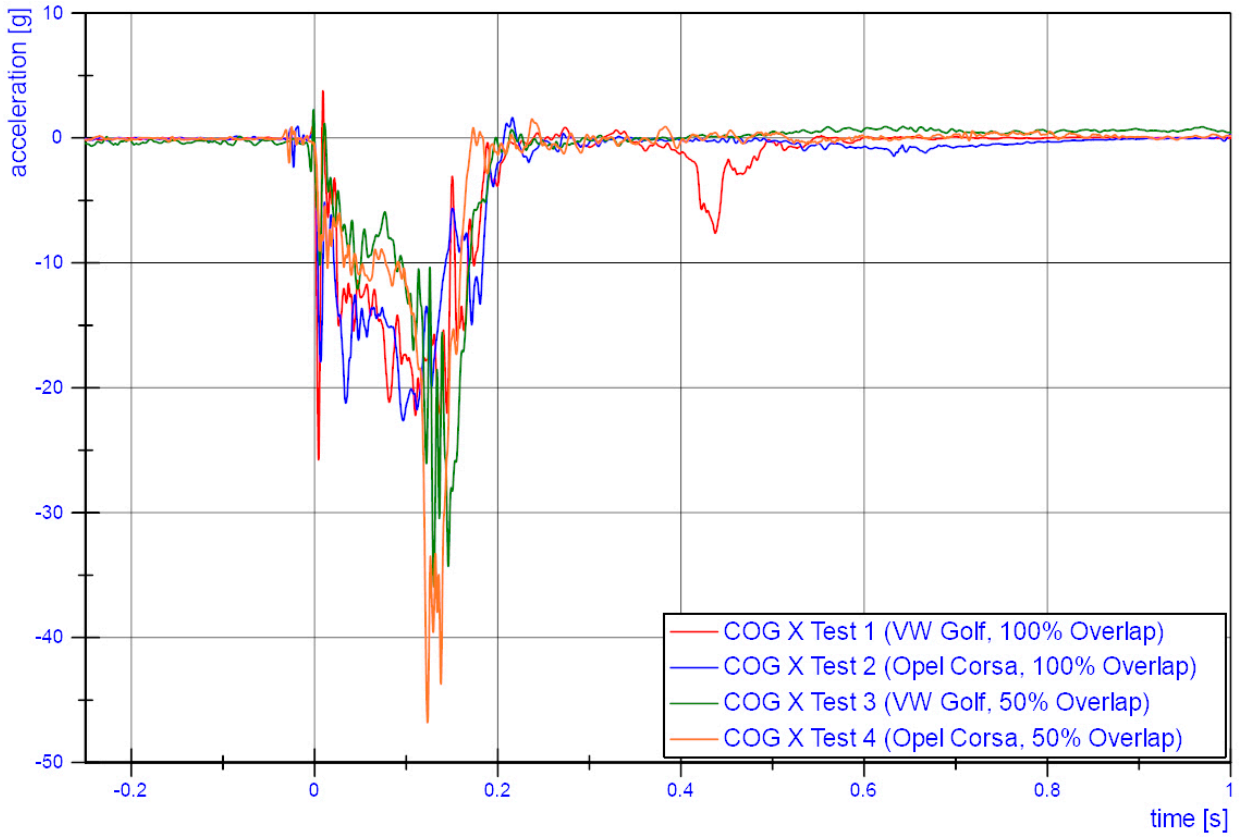

Figure A3. Vehicle acceleration time history of the centre of gravity in x-direction.

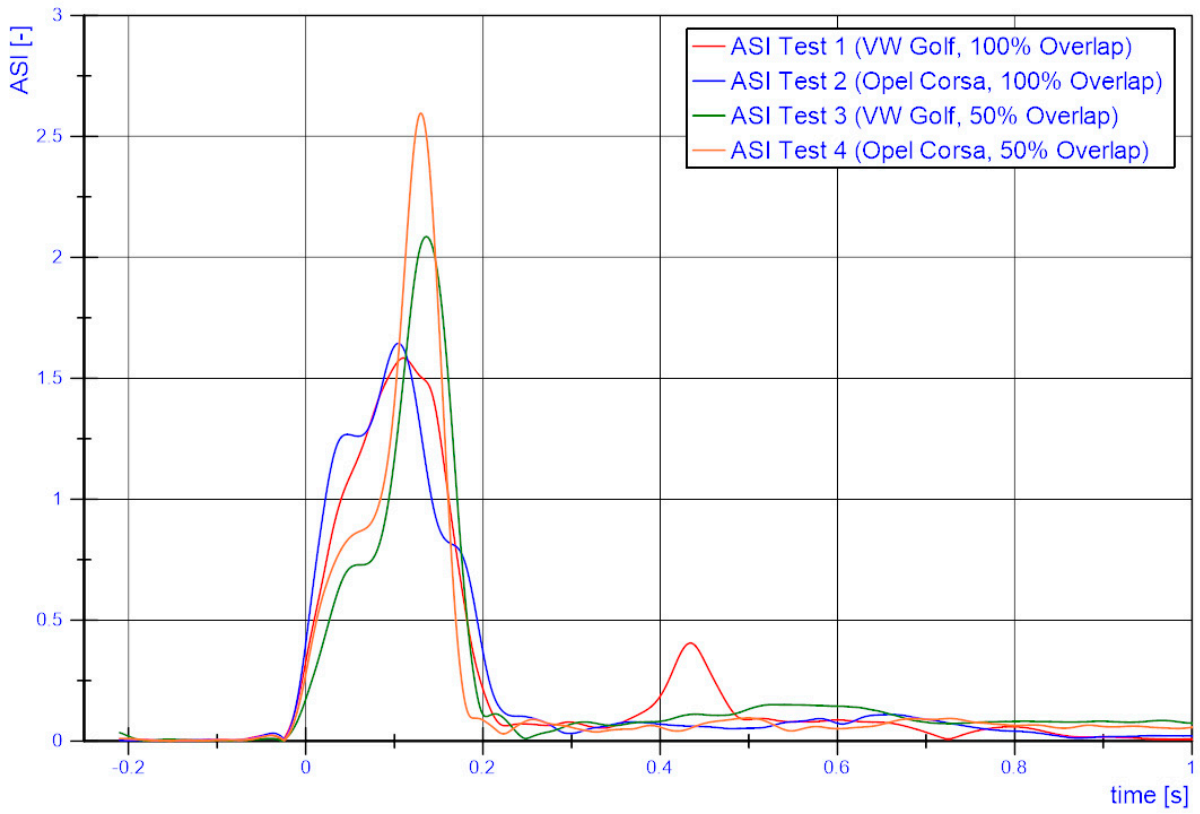

Figure A4. ASI time history.

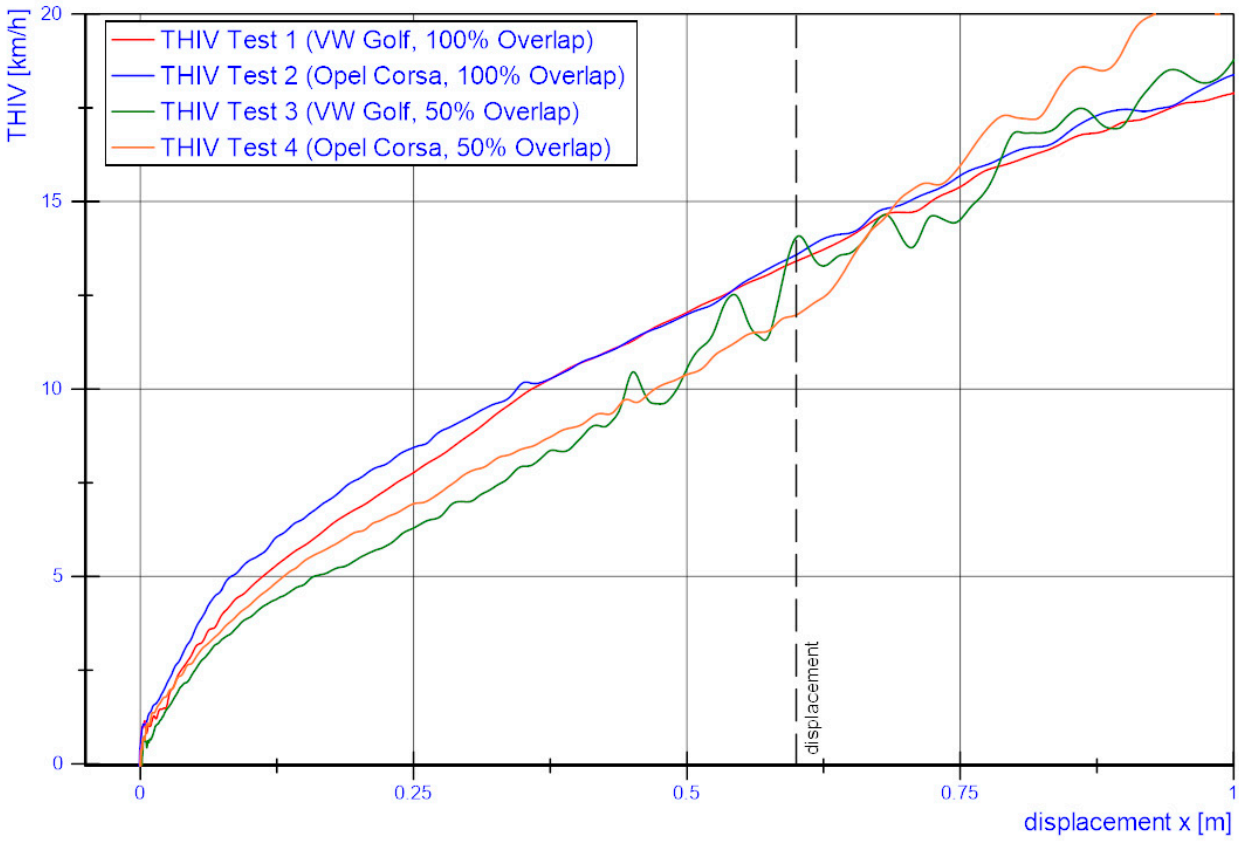

Figure A5. THIV displacement.

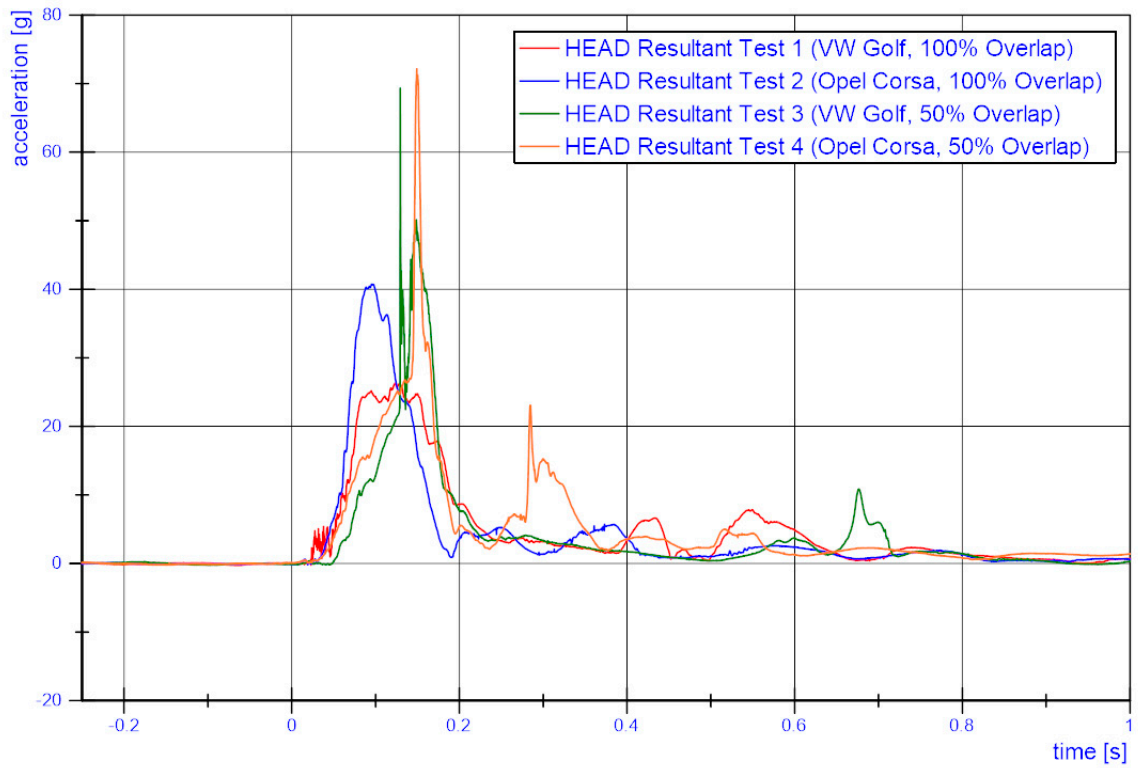

Figure A6. Resultant head acceleration time history.

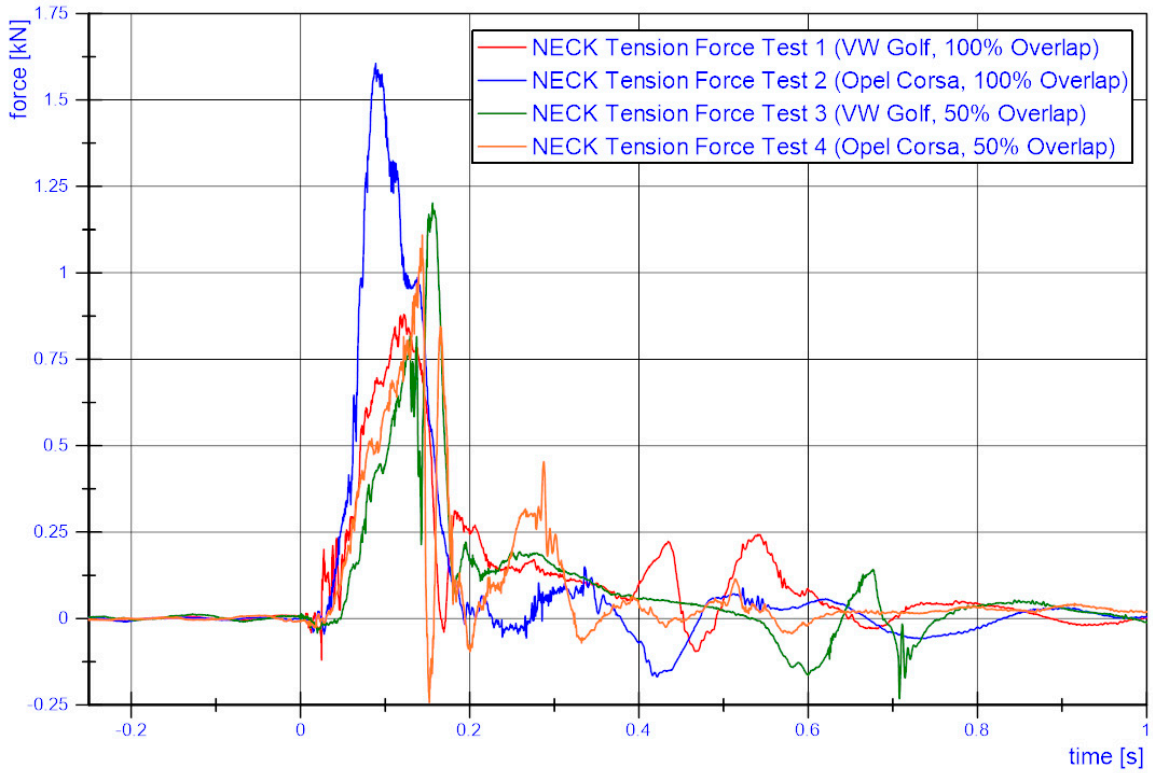

Figure A7. Neck tension force time history.

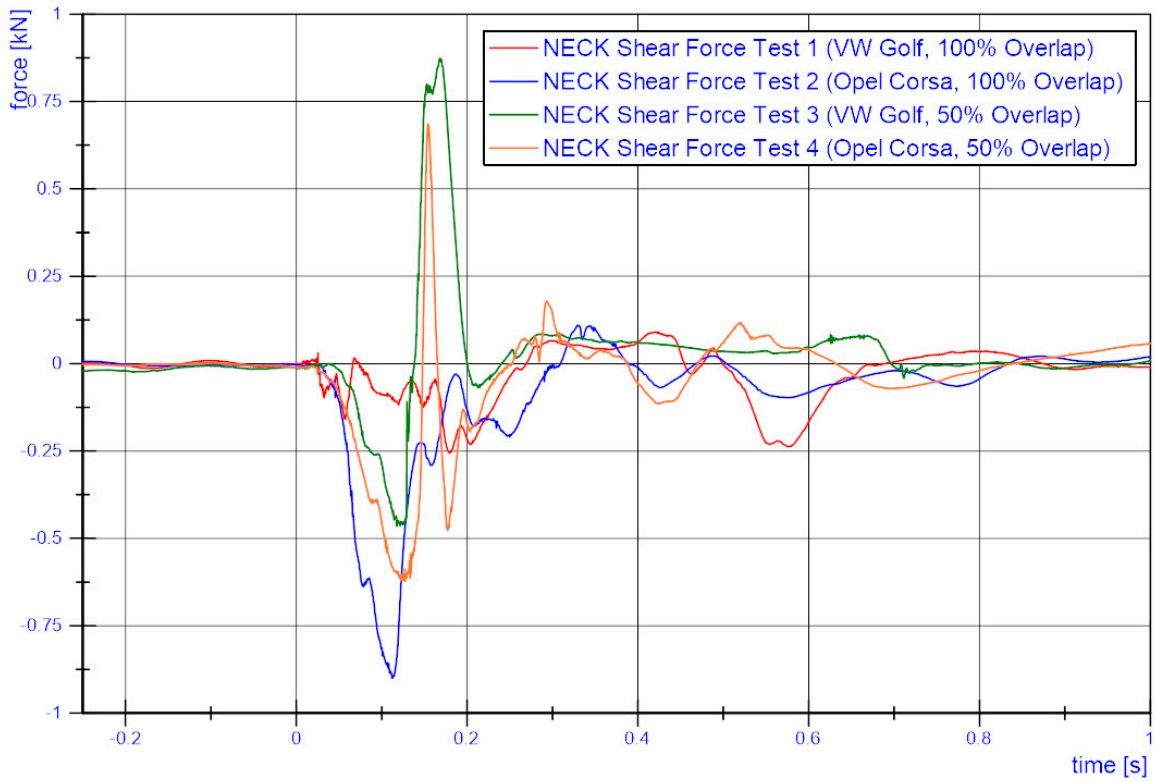

Figure A8. Neck shear force time history.

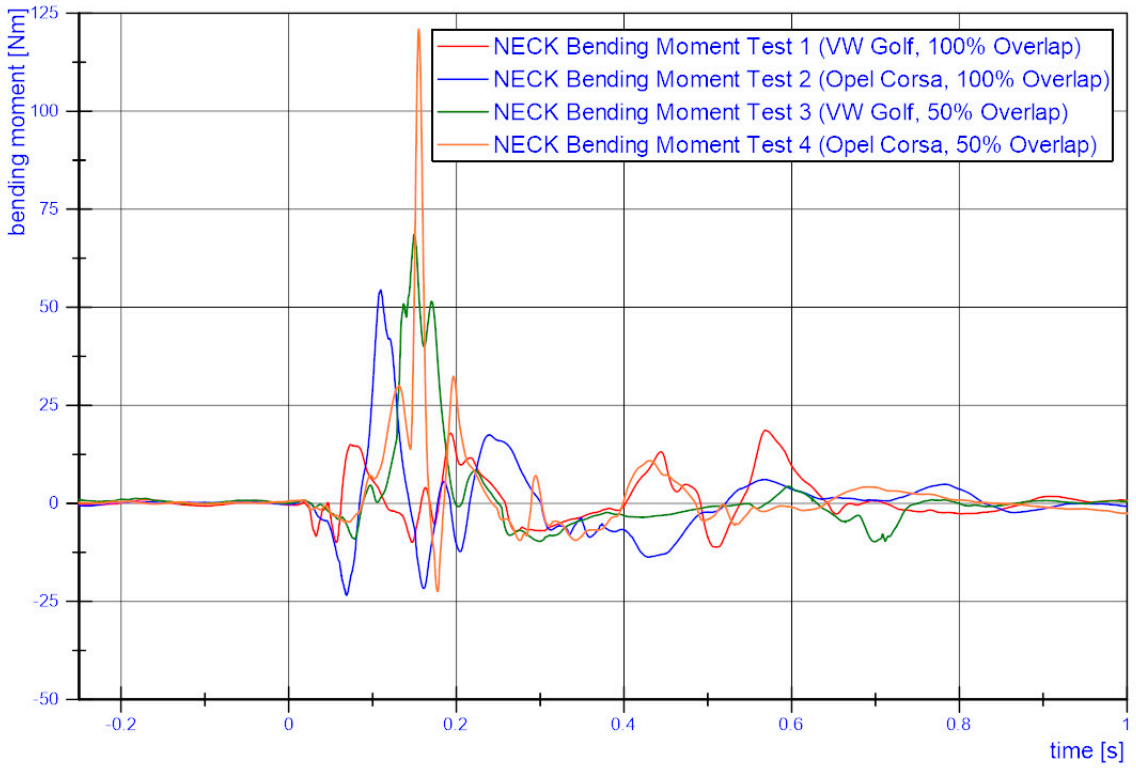

Figure A9. Neck bending moment time history.

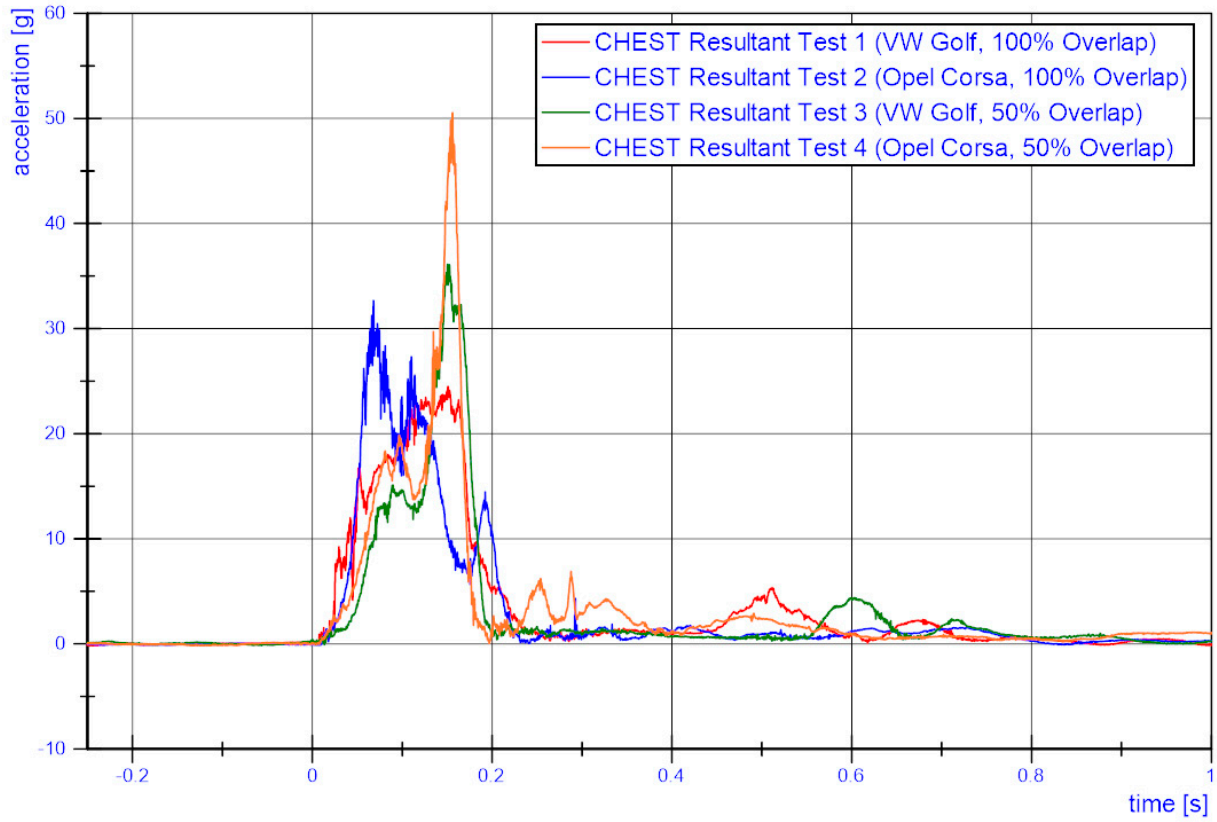

Figure A10. Resultant chest acceleration time history.

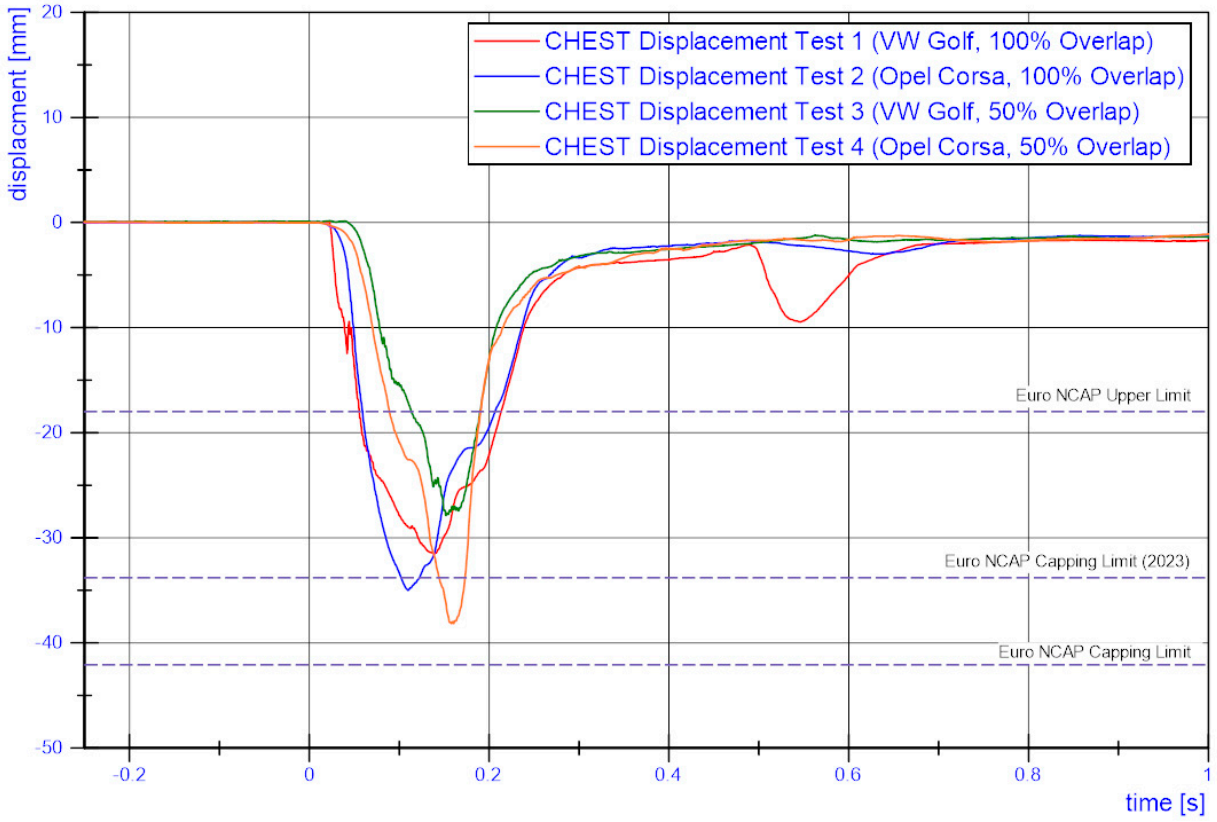

Figure A11. Chest displacement time history.

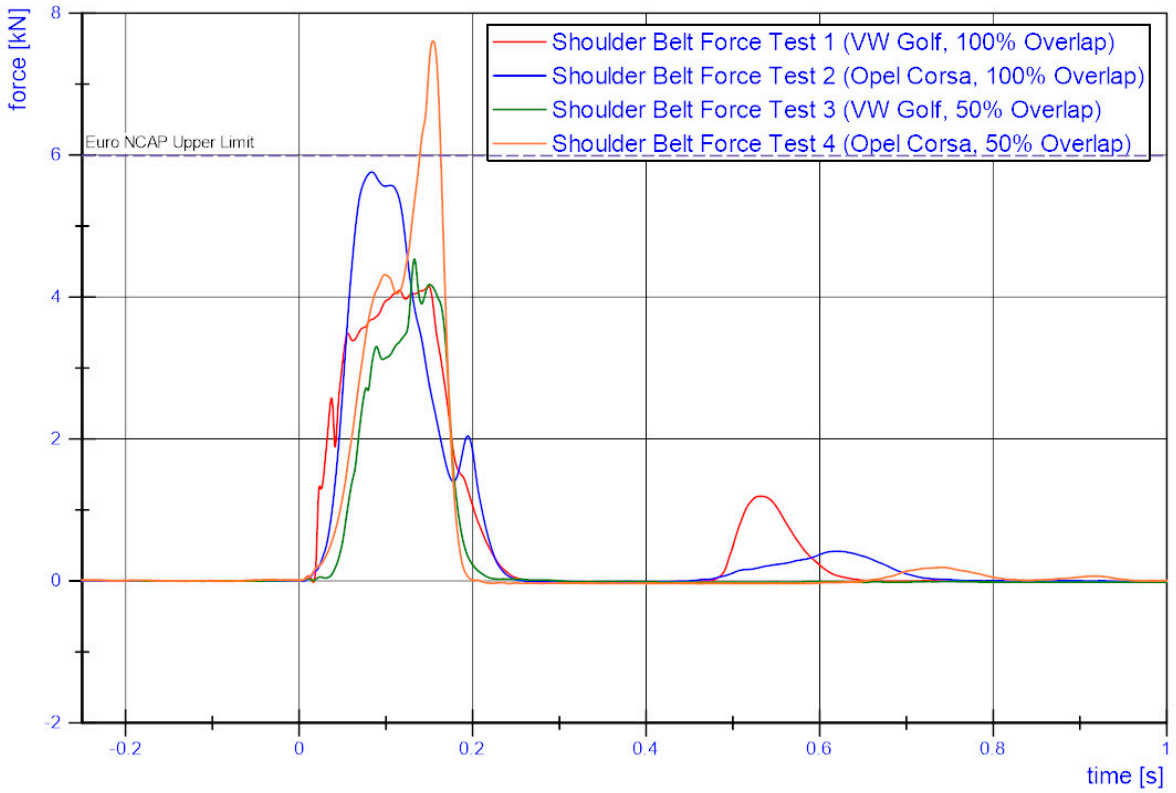

Figure A12. Shoulder belt force time history.

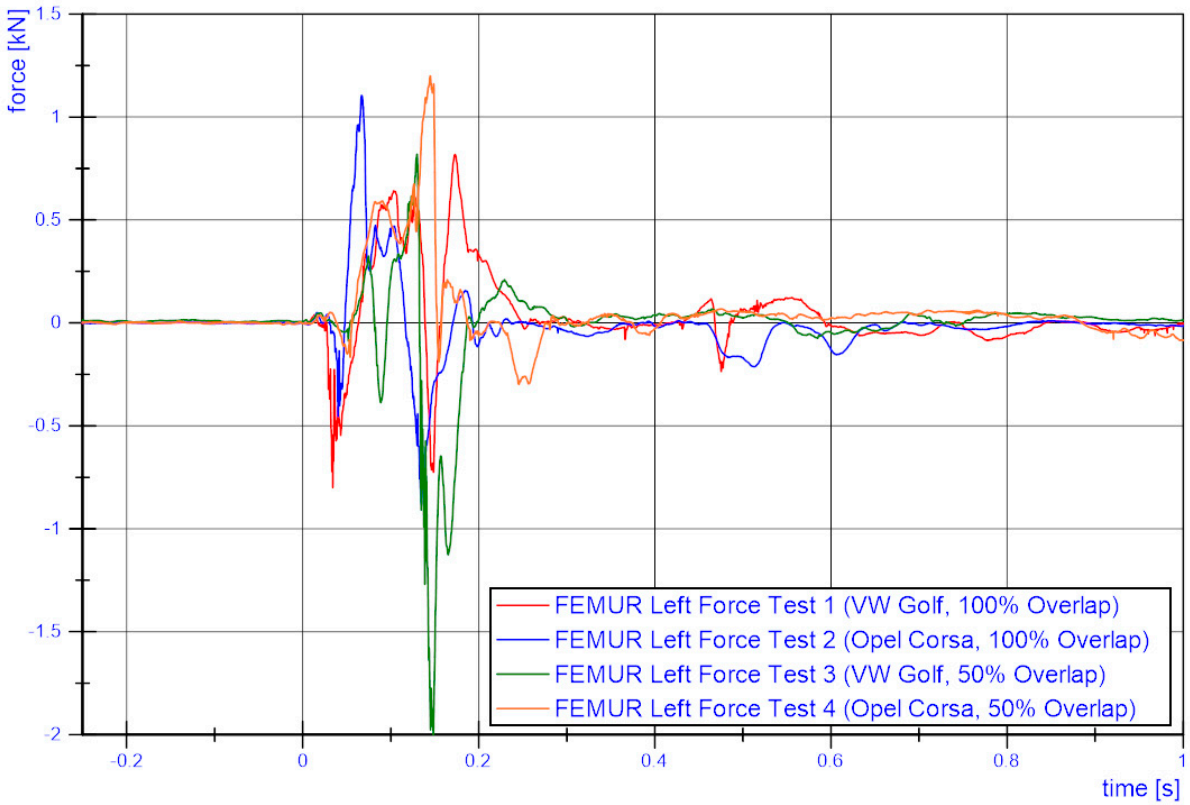

Figure A13. Femur force time history (left).

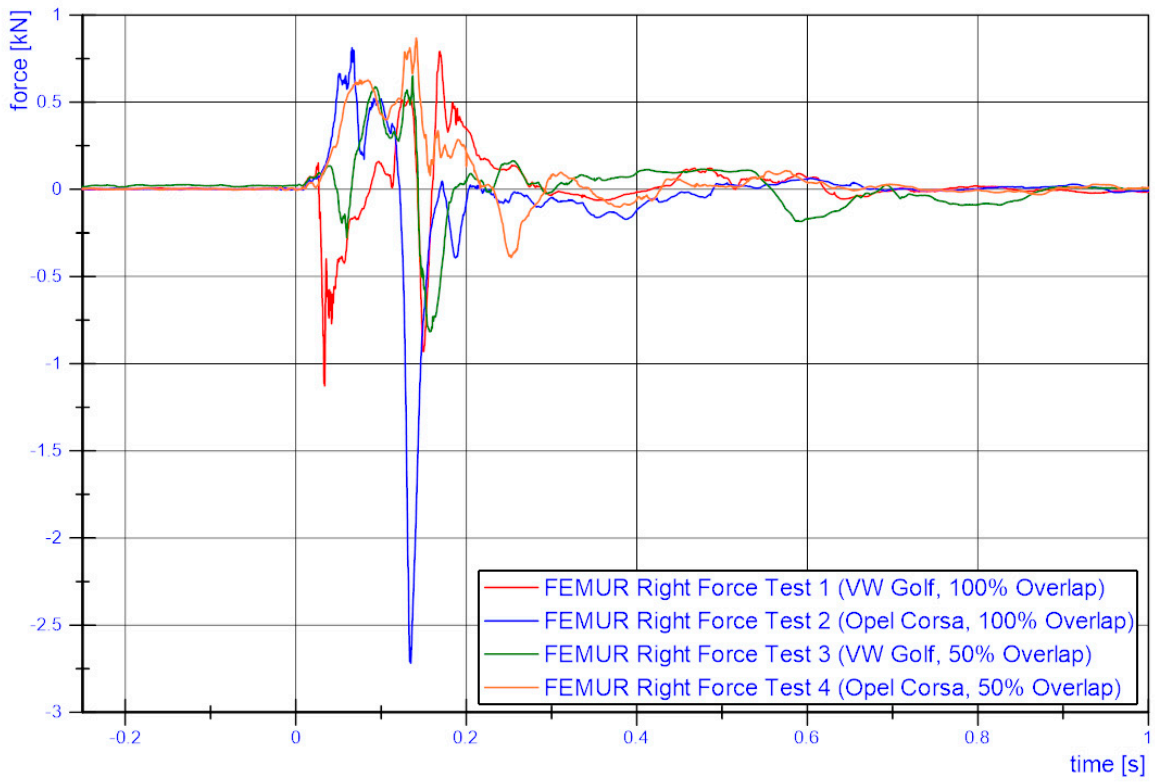

Figure A14. Femur force time history (right).

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