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Limitations of the European barrier crash testing regulation relating to occupant safety



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ABSTRACT

The safety of roadside restraint systems in Europe is ensured by the EN 1317 regulation. The ability of the barrier to mitigate injury to the occupants of vehicles is tested according to two occupant injury metrics: Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV). Both metrics aim to predict occupant head injury from vehicle kinematics, despite the potential to easily measure actual head kinematics from instrumented Anthropomorphic Test Dummies, a non-instrumented version of which is already required according to the regulation. Retrospective data provided by AISICO S.r.l. for 33 certificated barrier tests, where acceleration of the dummy's head had also been recorded, were re-analysed. ASI and THIV were compared with Head Injury Criterion (HIC₁₅) and Neck injury Criterion (N_{ij}), as well as corresponding Real Head Impact Velocity (RHIV) values. Three barriers presented HIC₁₅ values above the threshold used in crashworthiness testing, two of which corresponded to fatal injury according to the Abbreviated Injury Scale. One barrier presented an N_{ij} value corresponding to a 30% risk of neck injury. RHIV values were above the regulation threshold in 15% of tests, but were not significantly different from the corresponding THIV values. It was concluded that vehicle kinematics do not accurately predict head kinematics during barrier testing. The presented data indicate the current EN 1317 regulation was not capable of detecting all potential dangerous outcomes, with the potential to underestimate occupant risk. Further investigation is necessary to devise suitable indices based on actual head and neck data. These data would be obtained from a dummy instrumented with both a head accelerometer and neck load cell and, possibly, a gyroscope. To consistently test the true worst-case scenario, the tested side window should be closed and non-reinforced.

1. Introduction

The World Health Organization estimated that 1.2 million people are killed in road crashes each year and 50 million are injured (European Commission Report, 2018). In Europe, there were 25,300 fatalities, from a total 10 million road accidents involving personal injury in 2017 (European Commission Report, 2018). Hence, one of the main objectives in road transport is to provide users with an adequate level of safety. Safety in this context is pursued through two

approaches: active (primary) safety, which seeks to prevent accidents through vehicle characteristics such as anti-lock braking systems; and passive (secondary) safety, which aims to attenuate the severity of an occurring accident, particularly relating to the initial deceleration of the head. This is usually achieved by distributing stresses over longer durations, thus decreasing the acceleration peaks of the body segments involved (Seiffert and Wech, 2003). Road Restraint Systems (RRS) are an important passive safety feature of today's roads. RRSs are responsible for containing and redirecting the vehicle in a controlled

Abbreviations: AIS, Abbreviated Injury Scale; ASI, Acceleration Severity Index; ATD, Anthropomorphic Test Dummy; CFC, Channel Frequency Class; FMVSS, Federal Motor Vehicle Safety Standard; G_{3ms}, Head acceleration 3ms after its maximum; HIC, Head Injury Criteria; MASH, Manual for Assessing Safety Hardware; NHTSA, National Highway Traffic Safety Administration; N_{ij}, Neck Injury Risk; RHIV, Real Head Impact Velocity; RRS, Road Restraint System; TBI, Traumatic Brain Injury; THIV, Theoretical Head Impact Velocity; THIV_{man}, Theoretical Head Impact Velocity man; VCDI, Vehicle Cockpit Deformation Index

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manner, whilst minimising the deceleration peaks of the vehicle and its occupants. Ultimately, RRSs aim to reduce the risk of injury and death to those involved in automotive crashes (Gabauer and Gabler, 2008).

In Europe, the ability of RRSs to mitigate the risk of injury is regulated by part 1 of the EN 1317 “Compliant Road Restraint Systems” regulation (UNI EN 1317-1:2010 Road Restraint Systems - Part 1: Terminology And General Criteria For Test Methods, 2010). Applying this regulation requires data obtained from a specific crash test type (TB11), whereby a vehicle weighing 900 (\pm 40) kg impacts the tested RRS at 100 km/h, at an angle of 20 deg. The vehicle is equipped with a triaxial accelerometer and gyroscope, close to its centre of mass, and an Anthropomorphic Test Dummy (ATD) placed on the collision side. This data is used to compute two injury metrics describing the potential for the impact to cause head injury; 1. Acceleration Severity Index (ASI), which considers the deceleration of the vehicle in all directions during impact, relative to normalised thresholds of human tolerability; 2. Theoretical Head Impact Velocity (THIV), which estimates the velocity of the occupant’s head during an assumed theoretical impact with the interior of the vehicle. The head is modelled as a freely moving object which, when the vehicle decelerates during contact with the RRS, continues its motion until contacting the vehicle interior, modelled as an imaginary box. The purpose of crash testing according to threshold values is that, during real life crashes, similar to the testing conditions, a certificated RRS can be demonstrated to prevent serious injury to the occupant (Ren and Vesenjajk, 2005). However, this is only possible if the injury metrics and crash test protocols are representative of real life injury. Unfortunately, there is limited evidence to suggest this is the case (Montella and Perneti, 2004).

Injury metrics must be characterised, at least in part, according to the related injury mechanism(s). Several mechanisms of traumatic brain injury (TBI) have been proposed in recent years; however, it is assumed that in real life accidents, TBI is resultant of a combination of linear and angular acceleration and/or local deformation of the skull (Mellander, 1986; Blennow et al., 2012). The relative contributions of linear/ angular head motion to TBI are unknown, however it seems likely that particular head kinematics lead to specific injuries (O’Connor et al., 2011; Takhounts et al., 2013). For example, rotation is thought to lead to diffuse axonal injury (O’Connor et al., 2011). Nevertheless, the majority of the literature focuses on metrics describing TBI in general terms, presumably due to the high incidence of TBI-related deaths resulting from traffic incidents (2.37/100,000, in the European Union, Majdan et al., 2016; third leading cause of death, 19%, in the United States of America in 2013, U.S Department of Health and Human Services, 2017). One such metric is the Head Injury Criterion (HIC), which sums the absolute linear accelerations experienced by the head centre of mass during either 15 or 36 ms of the total impact duration (HIC₁₅ and HIC₃₆ respectively), although most literature focuses on HIC₁₅ (Hodgson and Thomas, 1972). HIC was derived from Gadd’s interpretation of the Wayne state tolerance curve (Gadd, 1961; Lissner et al., 1960), which assumes translational acceleration to cause pressure gradients in the area of the brainstem resulting in shear/strain induced brain injury. In light of more recent TBI literature (Post and Hoshizaki, 2012; Young et al., 2015; Deakin et al., 2017), this is certainly reductionist and potentially an entirely incorrect explanation of the TBI mechanism. However, HIC is still the most widely used index in automobile safety (Gong et al., 2008) and appears to be the best indicator of real life injury, despite failing to account for any rotational component (Mueller, 2015; Takhounts et al., 2013). Consequently, HIC₁₅ is currently used in the European motorcyclist RRS technical specification (UNI CEN/TS 1317-8:2012, 2012) and in Appendix G on side impact test and evaluation procedures for RRS crash tests in the American regulation for vehicles, Manual for Assessing Safety Hardware (MASH) (AASHTO, 2016) superseding the NCHRP Report 350 (Ross et al., 1993).

Although TBI is more prominent in the literature, the cervical spine is the most likely region of the body to sustain an injury following a

glancing impact (Sturt and Fell, 2009) such as that in the TB11. Cervical spine injury, usually manifesting as whiplash (Yeung, 1996), is unaccounted for in the EN 1317-1 regulation. However, the American Federal Motor Vehicle Safety Standard (Hollowell et al., 1998) and the European Technical Specification for motorcyclists (UNI CEN/TS 1317-8:2012, 2012) utilise the Neck Injury Criterion (N_{ij}) which addresses the four possible neck injury mechanisms (tension-extension, compression-extension, tension-flexion and compression-flexion). This metric combines axial forces with moments for a composite neck injury indicator, in order to provide criteria for predicting neck injury probability. The probability of neck injury risk is calculated by a curve (presented by Mertz and colleagues (1997) and compared with the National Automotive Sampling System database) in which N_{ij} values of 1.0 and 1.4 corresponded to a 15% and 30% risk of an Abbreviated Injury Scale (AIS) score \geq 3 injury.

Quantitative information is available for real-world occupant injury risk associated with current MASH criteria, as obtained from crash tests performed with instrumented ATDs (Silvestri-Dobrovoly et al., 2016). However, there exists limited empirical evidence supporting the use of ASI and THIV, such as relatively weak correlations with head (Gabauer and Thomson, 2005; Shojaati, 2003) and neck injury (Sturt and Fell, 2009). Further, there are serious issues regarding their use as indicators of occupant safety (Gabauer and Gabler, 2008). Namely, unlike crash-worthiness testing, where data are obtained from instrumented ATDs, both the aforementioned metrics are derived from data from an accelerometer placed as close as possible to the vehicle’s centre of mass. This data would only be predictive of real head acceleration if the occupant was rigidly bound to the vehicle at all points during impact. In reality, factors such as plasticity of vehicle seats, restricted lateral belt function and varying degrees of belt looseness mean the occupant is experiencing different accelerations to that of the centre of mass of the vehicle (Gabauer and Gabler, 2008; Shojaati, 2003). Vehicle kinematics are used in preference to head kinematics for practical reasons such as affordability (Shojaati, 2003) and variability of ATD responses between identical testing scenarios (Ray and Hiranmayee, 2000; Roque and Cardoso, 2013), especially for oblique movements occurring during redirection of the vehicle from the RRS (Ross et al., 1993). THIV assumes contact with a theoretical box surrounding the head, representing the vehicle interior. From vehicle kinematics alone, it is impossible to predict the distance from the head at which a real impact will occur, what inside or outside the vehicle it will impact with, and, in fact, whether it will impact anything at all. ASI assumes that increasing the duration of the deceleration phase is entirely positive. However, its value is not only influenced by the deformation of the RRS, but also the deformation of the vehicle. If this deformation spreads to the vehicle interior, there is the potential to crush and/or trap the occupant, whilst also increasing the likelihood of a head impact. Moreover, vehicle deformation does not necessarily reduce the head acceleration due to the non-rigid bond with the vehicle. It may, in fact, increase the likelihood of the head translating outside of the vehicle and impacting directly with an outside obstacle, likely to be the RRS.

The aim of this study was to highlight the limitations of the EN 1317 regulation in determining occupant safety during impacts with roadside restraint systems. To achieve this aim, the relationship between occupant risk determined according to EN 1317 criteria and ATD injury metrics will be investigated, with both a statistical approach and selective case by case analysis. Indices will be obtained from retrospective data from thirty-three TB11 crash tests, performed with instrumented ATDs, for which both EN 1317 injury metrics were below threshold.

2. Methods

2.1. Experimental set up

Data were taken from TB11 crash tests carried out from 2002 to 2018 across two different facilities directed by AISICO S.r.l. (Facility 1: Anagni,

Italy, 2002–2013, Facility 2: Pereto, Italy, 2013–2018) in accordance with the version of the EN 1317-1 regulation in place at the time of testing. The company, whenever possible, used an instrumented ATD for research purposes, therefore we selected tests, performed using an instrumented ATD, for which both ASI and THIV injury metrics were below safety thresholds. The TB11 tests entailed using a vehicle with a mass of 860 to 940 kg (including the ATD), undergoing a gliding impact at 20 deg at 100 km/h. All vehicles were equipped with a triaxial accelerometer (ECGS-100, Entran Devices, Fairfield, NJ, USA; full scale range 1000 m/s², acquiring at 10,000 samples/s), to measure longitudinal, lateral, and vertical accelerations, and with a triaxial gyroscope (MEAS 610, Measurement Specialties, Inc., Hampton, Virginia, USA; full scale range 12,000 deg/s, acquiring at 10,000 samples/s), using the angular velocity to take into account the vehicle orientation in space when representing its acceleration in a coordinate system fixed with the ground. Both were rigidly mounted at a single point as close as possible to the vertical projection of the centre of mass of the vehicle (Fig. 1). The yaw angle was measured, within a tolerance of ± 4 deg, by integration of the yaw rate.

For each TB11 test, an ATD representative of the 50th percentile of a male adult (02020911, Denton, Milan, Ohio) was placed in the front seat of the vehicle on the impact side and secured with the vehicle safety belt. The ATD was instrumented with a triaxial accelerometer (7267a, Endevco, Irvine, California; full scale range 15,000 m/s², acquiring at 10,000 samples/s) positioned inside the ATD’s head at the centre of mass level and, for Facility 1, with a six-component load cell (1716 J, Denton, Milan, Ohio; full scale range F_{x,y}: 0–8.9 kN; F_z: 0–13.3 kN; M_{x,y,z}: 0–283 Nm acquiring at 10,000 samples/s) positioned on the neck (Fig. 2).

Data taken from vehicle and ATD sensors were simultaneously acquired with an A/D system (Kidau-advanced type K3880C, Kistler, Winterthur, Switzerland).

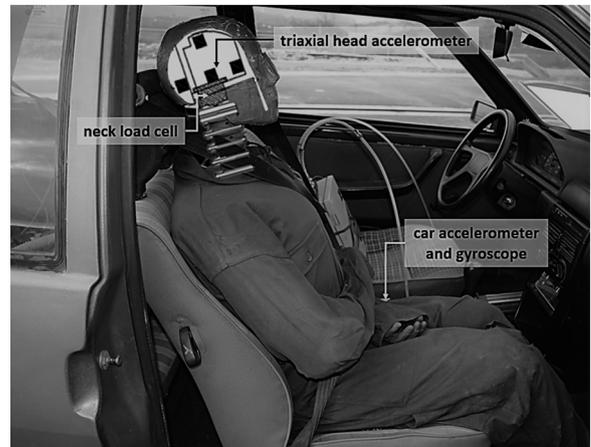


Fig. 2. The Anthropomorphic Test Dummy positioned in the vehicle on the side of the impact, depending on the crash facility set-up, according to EN 1317-1 regulations. Instruments used in this study are also depicted.

2.2. Data analysis

All acquired data were processed through Matlab (version R2018a, The MathWorks Inc., Natick, MA, USA). Data were analysed in a 2 s window from the instant of time at which the vehicle impacted the RRS, defined as the instant immediately before the crash event at which the acceleration variation (taken from the vehicle accelerometer) exceeds 5 g. The acceleration of the vehicle was represented in the global co-ordinate system using the yaw angle derived from the vehicle gyroscope. Both data were low-pass filtered according to the EN 1317-1 regulation (UNI EN 1317-1:2010), using a fourth order phaseless

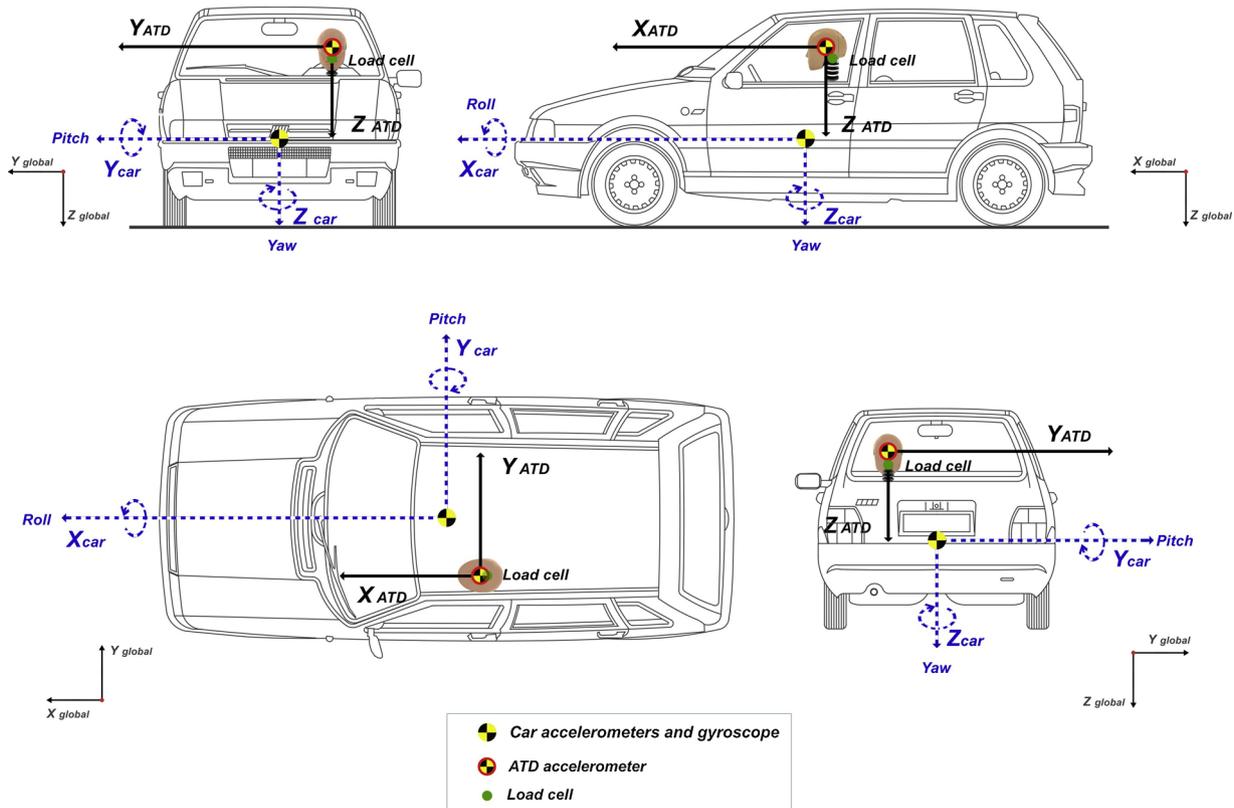


Fig. 1. Reference systems of retrieved data: C_{global}: global coordinate system (black, fixed); C_{car}: car accelerometer and gyroscope coordinate system (blue dashed, centred in the car centre of mass and moving with the car); C_{ATD}: Anthropomorphic Test Dummy (ATD) accelerometer coordinate system (black, centred in the ATD head - in red - and moving with the ATD), C_{load cell} : ATD load cell coordinate system (black, positioned in the neck - in green - moving with the ATD) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Butterworth digital filter (as described in *ISO 6487: 2015*), with a cut-off frequency of 180 Hz (Channel Frequency Class: CFC180). To compute ASI, data were further low-pass filtered, according to the EN 1317-1 regulation in place at the time of testing. Specifically, a moving average filter with a 50 ms window was used for Facility 1 tests (*UNI EN 1317-1:2000*), and a fourth order phaseless Butterworth digital filter, with a cut-off frequency of 13 Hz, for Facility 2 tests (*UNI EN 1317-1:2010*). The ATD acceleration data were filtered according to the regulation used for vehicle accelerations and angular velocities (CFC180). The ATD neck load cell data were low-pass filtered with a CFC600 and a CFC1000 for moments and forces, respectively (*Eppinger et al., 2000*).

The Vehicle Cockpit Deformation Index (VCDI) was computed according to the regulation (*UNI EN 1317-1:2010*).

2.3. Injury metrics

The following injury metrics were then extracted:

2.3.1. Acceleration Severity Index (ASI)

According to EN 1317-1 test procedures (*UNI EN, 1317-1; 2010*), ASI is defined as the following:

$$ASI(t) = \max \left[\left(\frac{a_{car\ x}}{\hat{a}_x} \right)^2 + \left(\frac{a_{car\ y}}{\hat{a}_y} \right)^2 + \left(\frac{a_{car\ z}}{\hat{a}_z} \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

where $a_{car\ x}$, $a_{car\ y}$, and $a_{car\ z}$ are the acceleration values measured with the car accelerometer, and \hat{a}_x , \hat{a}_y , \hat{a}_z the corresponding limit acceleration values ($\hat{a}_x = 12\text{ g}$; $\hat{a}_y = 9\text{ g}$; $\hat{a}_z = 10\text{ g}$). ASI is calculated to at least two decimal places, reported with one decimal place by mathematical rounding, and compared to threshold values: an ASI below 1 is recommended and corresponds to “light injury if any” (*UNI EN, 1317-1; 2010*), classified as ASI A. Values ranging $1.01 \div 1.4$ and $1.41 \div 1.9$ are still acceptable and classified as ASI B and ASI C, respectively.

2.3.2. Theoretical Head Impact Velocity (THIV)

According to EN 1317-1 test procedures (*UNI EN, 1317-1; 2010*), THIV is defined as the following:

$$THIV = [v_{bx}^2(T) + v_{by}^2(T)]^{\frac{1}{2}} \quad (2)$$

where v_{bx} and v_{by} are the velocities of the theoretical head with respect to the car, in the longitudinal and transverse directions of the car coordinate system, respectively. T, referred to as Time of Flight in EN 1317-1, is the instant of time from the initial contact with the RRS, T_0 , at which the theoretical head has been displaced either $\pm 0.6\text{ m}$ in the x direction or $\pm 0.3\text{ m}$ in the y direction. The velocity \mathbf{v} is computed assuming that, at T_0 , vehicle and theoretical head have the same horizontal velocity, v_0 , and that the vehicle motion is purely translational on the horizontal plane, both at T_0 and after the impact, while the car rotates about the vertical axis Z_{car} of a yaw angle ψ (*Fig. 3*).

To determine time T, the displacement the theoretical head is computed with respect to the car coordinate system, C_{car} , from the displacement of the vehicle relative to an inertial car-fixed coordinate system, C_{CAR} , which moves at constant velocity and remains parallel to C_{global} . Therefore, the analysis is concerned purely with velocity changes relative to v_0 , whose value does not enter into the calculations. Initial conditions are assumed to be zero for all variables.

Car acceleration with respect to C_{CAR} , \ddot{X}_C and \ddot{Y}_C , is:

$$\begin{cases} \ddot{X}_C = a_{car\ x} \cos\psi - a_{car\ y} \sin\psi \\ \ddot{Y}_C = a_{car\ x} \sin\psi + a_{car\ y} \cos\psi \end{cases} \quad (3)$$

Head displacement within the cockpit, x_b and y_b in *Fig. 3*, with respect to the original position with respect to C_{CAR} , x_0 and y_0 , is obtained as follows:

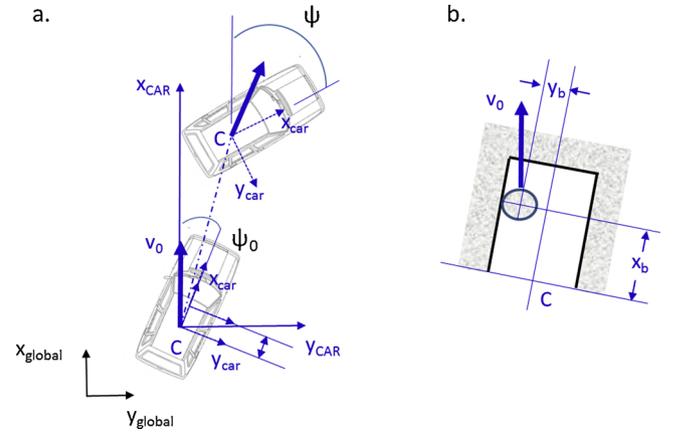


Fig. 3. a. Coordinate systems of the car used to compute Theoretical Head Impact Velocity: C_{car} , car coordinate system; C_{CAR} , inertial car-fixed coordinate system moving at constant velocity and parallel to C_{global} . The relative yaw angle ψ and the initial velocity v_0 are also depicted. b. Theoretical box and theoretical head and their relative displacement along C_{car} , x_b and y_b .

$$\begin{cases} x_b = (x_0 - X_C) \cos\psi - (y_0 - Y_C) \sin\psi \\ y_b = -(x_0 - X_C) \sin\psi + (y_0 - Y_C) \cos\psi \end{cases} \quad (4)$$

where X_C and Y_C are the car displacements computed by double integration of eq.3. Head velocity within the cockpit is then obtained through integration:

$$\begin{cases} v_{bx} = \dot{x}_b = -\dot{X}_C \cos\psi - \dot{Y}_C \sin\psi + y_b \dot{\psi} \\ v_{by} = \dot{y}_b = -\dot{X}_C \sin\psi - \dot{Y}_C \cos\psi - x_b \dot{\psi} \end{cases} \quad (5)$$

THIV is calculated to at least one decimal place and reported with zero decimal places by mathematical rounding. A typical signal measured from the car accelerometer is reported in *Fig. 4*.

2.3.3. Theoretical Head Impact Velocity man (THIV_{man})

The same procedure as THIV (eqns. 2–5) is repeated using the acceleration measured at the ATD’s head. A typical signal measured from the ATD accelerometer is reported in *Fig. 4*.

2.3.4. Real Head Impact Velocity (RHIV)

The relative accelerations of the ATD’s head with respect to the car are first obtained by summing the ATD and the car accelerations, assuming that no relative rotation occurs between them. The head velocity at impact is then obtained by integrating this relative acceleration from T_0 to the instant in which the acceleration increases abruptly due

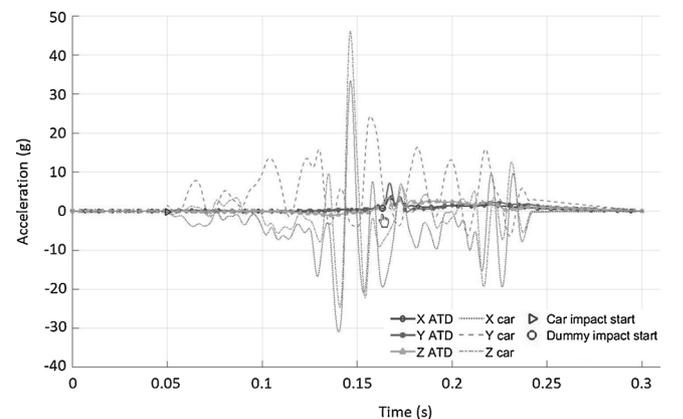


Fig. 4. Profiles of dummy and car acceleration. Car and dummy impact instants of time are also depicted. The cursor exemplifies the manual selection of the instant of time of the dummy impact used to calculate RHIV.

Table 1

Crash test information including: RRS containment class, location, type, Vehicle Cockpit Deformation Index, and the main injury metrics. Experimental tests not for certification are declared as such instead of providing the Vehicle Cockpit Deformation Index. Data are ordered according to time of testing, clustering separately guardrail and new jersey types.

Facility	RRS			VCDI	ASI	THIV	THIV _{man}	RHIV	HIC ₁₅	HIC ₃₆	N _{ij}
	class	location	type								
Facility 1	H3	side edge for ground	guardrail	LF 0001000	1.1	31	30	30	1	1	< 15%
Facility 1	H2	side edge for ground	guardrail	LF 0000000	0.8	25	30	18	18	28	< 15%
Facility 1	H4b	for bridge	guardrail	LF 0001100	1.3	33	33	28	174	219	<i>no data</i>
Facility 1	H2	side edge for ground	guardrail	LF 0002102	1.2	31	30	30	104	208	< 15%
Facility 1	H4a	for bridge	guardrail	LF 1001121	1.1	30	35	22	77	92	<i>no data</i>
Facility 1	H2	side edge for ground	guardrail	LF 1012100	1.2	30	34	17	2213	1439	< 15%
Facility 1	H3	for bridge	guardrail	LF 0001010	0.9	28	33	14	1634	505	< 15%
Facility 1	N2	side edge for ground	guardrail	LF 0001001	0.7	24	30	17	24	22	< 15%
Facility 1	H2	side edge for ground	guardrail	LF 0000000	0.6	23	26	28	20	20	< 15%
Facility 1	H2	for bridge	guardrail	LF 0000000	1.0	25	35	17	24	34	< 15%
Facility 1	H2	side edge for ground	guardrail	LF 0000000	1.3	32	35	36	57	65	< 15%
Facility 1	H4a	for bridge	guardrail	LF 0010000	1.4	33	34	33	75	108	< 15%
Facility 1	H2	side edge for ground	guardrail	LF 0001000	1.0	26	32	22	69	43	< 15%
Facility 1	H4b	for bridge	guardrail	LF 0022000	1.5	33	37	52	615	294	30%
Facility 1	H4a	for bridge	guardrail	LF 0001000	1.3	33	34	25	136	147	< 15%
Facility 1	H4b	double side double line	guardrail	LF 1001100	1.2	33	40	30	616	277	<i>no data</i>
Facility 1	H2	side edge for ground	guardrail	LF 0001000	0.7	23	33	17	42	65	< 15%
Facility 1	H4b	side edge for ground	guardrail	LF 0000001	1.0	32	34	30	29	38	< 15%
Facility 1	H3	side edge for ground	guardrail	<i>no data</i>	1.4	25	36	22	93	78	< 15%
Facility 1	H4b	double side double line	guardrail	LF 0000000	1.0	30	39	28	72	52	< 15%
Facility 2	H2	side edge for ground	guardrail	LS 0110000	0.8	27	53	31	422	228	<i>no data</i>
Facility 2	H3	for bridge	guardrail	RF 0101000	1.3	33	39	27	34	35	<i>no data</i>
Facility 2	H1	side edge for ground	guardrail	RF 0100000	0.8	22	32	16	71	95	<i>no data</i>
Facility 2	L4b	for bridge	guardrail	RF 0101000	1.2	30	50	24	172	139	<i>no data</i>
Facility 2	H3	side edge for ground	guardrail	RF 0110000	0.9	25	30	62	510	210	<i>no data</i>
Facility 2	H1	side edge for ground	guardrail	RF 0101000	0.7	24	38	29	20	23	<i>no data</i>
Facility 2	H2	side edge for ground	guardrail	RF 0110000	0.8	25	33	34	22	29	<i>no data</i>
Facility 2	L4b	double side	guardrail	RF 0111000	1.3	32	39	42	1836	586	<i>no data</i>
Facility 1	N2-H4	new jersey for bridge	new jersey	Exp	1.5	33	35	20	33	73	<i>no data</i>
Facility 1	H4b	new jersey double line	new jersey	Exp	1.3	23	26	23	21	39	<i>no data</i>
Facility 1	N2-H4	new jersey double side	new jersey	Exp	1.1	25	31	15	60	86	<i>no data</i>
Facility 1	N2-H4	new jersey english type	new jersey	Exp	1.6	31	32	31	175	291	<i>no data</i>
Facility 2	H2	side edge for ground	new jersey	LF 0110000	1.2	26	30	25	100	125	<i>no data</i>

Abbreviations: VCDI: Vehicle Cockpit Deformation Index, Exp: experimental tests, THIV: Theoretical Head Impact Velocity, THIV_{man}: Theoretical Head Impact Velocity man, RHIV: Real Head Impact Velocity HIC₁₅: Head Injury Criteria 15, HIC₃₆: Head Injury Criteria 36, N_{ij}: Neck Injury Risk. Values above their respective thresholds are presented in **bold**, THIV, THIV_{man}, and RHIV: 33.4 km/h. Acceptability boundaries are also depicted in **bold**, HIC₁₅: 700; HIC₃₆: 1000; N_{ij}: 30%, and in *italic or bold italic* for ASI B (1-1.4) and ASI C (1.41-1.9).

to impact, T_i, as manually selected on the a_{ATD} graph.

$$RHIV = \left[\left(\int_{T_0}^{T_i} (a_{ATD_x} + a_{car_x}) dt \right)^2 + \left(\int_{T_0}^{T_i} (a_{ATD_y} + a_{car_y}) dt \right)^2 + \left(\int_{T_0}^{T_i} (a_{ATD_z} + a_{car_z}) dt \right)^2 \right]^{1/2} \tag{6}$$

2.3.5. Head Injury Criteria (HIC₁₅ and HIC₃₆)

The Head Injury Criteria is defined as proposed by the National Highway Traffic Safety Administration (NHTSA) (Hodgson and Thomas, 1972):

$$HIC = \max \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_{ATD} dt \right)^{2.5} * (t_2 - t_1) \tag{7}$$

where a_{ATD} is the ATD's head acceleration magnitude. For a time interval of 36 ms, HIC₃₆ is obtained which should not exceed a threshold value of 1000. HIC₁₅ is obtained when integration occurs over an interval of 15 ms; its threshold value is 700.

2.3.6. Head acceleration 3 ms after its maximum (G_{3ms})

Since the ATD's head acceleration should not exceed a threshold value of 80 g for more than 3 ms to avoid brain injuries (Seiffert and Wech, 2003), G_{3ms} was computed, along each axis of C_{ATD}, as the a_{ATD} value 3 ms after its maximum:

$$G_{3ms_i} = a_{ATD_i}(t_{max} + 3ms) \text{ i} = x, y, z \tag{8}$$

2.3.7. Neck Injury Risk (N_{ij})

The Neck Injury Risk (N_{ij}) is defined as proposed by the NHTSA and included in the Federal Motor Vehicle Safety Standard, FMVSS 208 (Hollowell et al., 1998). N_{ij} is a linear combination of axial forces and moments of flexion and extension, normalized with critical values (Kleinberger et al., 1998) specific to Hybrid III 50th percentile ATDs, such as the one used in the study:

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \tag{9}$$

where F_{int} (compression/tension) = ± 4500 N; M_{int} (flexion) = -310 Nm; M_{int} (extension) = 128 Nm. This criterion equals creating a limit area that the acquired signal must not exceed, outside of which it is assumed that the head does not impact anything and the neck is strongly stressed. The limit value of 1 carries a neck injury risk probability below 15%, while a value higher than 1.4 entails at least a 30% risk.

2.4. Statistical analysis

All statistical tests were carried out using SPSS (version 22, IBM Corp., Armonk, NY, USA) and results were considered statistically significant at α < 0.05. Use of the Shapiro-Wilk test determined that all

data were non-normally distributed ($p < 0.05$). Descriptive statistics of selected quantities were obtained using the five-number summary technique (minimum, lower quartile, median, upper quartile, maximum); data were represented using box-plots. Lower and upper quartiles were used to calculate the inter-quartile range (IQR). The Wilcoxon signed rank test was deemed appropriate to compare THIV with THIV_{man} and THIV with RHIV due to the non-parametric and matched nature of the data. One disadvantage of this test is that no magnitude in effect can be determined, however simply demonstrating discrepancies between the measures is still of value. THIV and THIV_{man} values were compared using the Wilcoxon signed rank test in order to determine whether placing the accelerometer on the head made a significant difference to the measured value as to when placed at the car's centre of mass. THIV was then further compared with RHIV using another Wilcoxon signed rank test to determine if there was a significant difference between the measured velocity of the head when using the real impact of the head with the car cockpit (RHIV), and the impact of the modelled head with the theoretical box (THIV).

3. Results

Data are reported for all tested RRSs, alongside RRS class, location, and type (Table 1). ASI median [IQR] value was 1.10 [0.43], with 14 RRSs with ASI A, 15 with ASI B, and 4 with ASI C. The head velocities at impact, as obtained using THIV, THIV_{man} and RHIV, are reported in Fig. 5. The head indices, HIC₁₅ and HIC₃₆, had median [IQR] values of 71 [146] and 82 [175], respectively.

Inferential statistics demonstrated that THIV_{man} was significantly higher than THIV ($U = 183$; $p = 0.000$), while no significant difference was found between RHIV and THIV ($U = 416$; $p = 0.09$), although RHIV was above threshold in 15% of cases. HIC₁₅ is plotted against ASI (Fig. 6) and THIV (Fig. 7), highlighting disagreement between HIC₁₅ and the EN 1317-1 injury metrics. RHIV presents a similar level of disagreement (Fig. 7). Nine percent of RRSs (3 out of 33) had HIC₁₅ values over threshold, while this was the case for only one RRS according to HIC₃₆. One RRS exceeded the N_{ij} threshold (Table 2).

4. Case by case analysis

4.1. Test n.1

The HIC₁₅ in this case corresponds to very serious injury or death according to the related AIS thresholds (Prasad and Mertz, 1985). This may be related or due to the fact the window of the car was broken

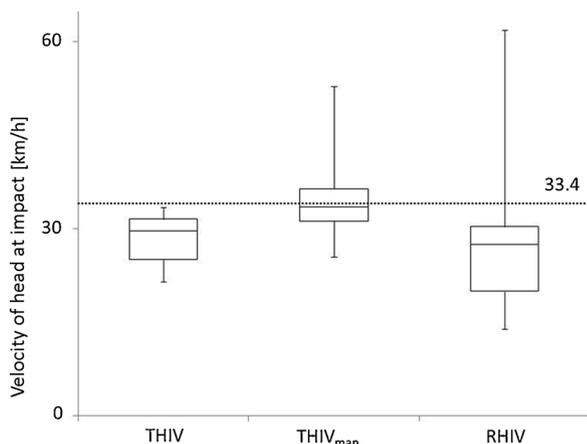


Fig. 5. Boxplot of the velocity at head impact calculated according to Theoretical Head Impact Velocity (THIV), Theoretical Head Impact Velocity man (THIV_{man}), and Real Head Impact Velocity (RHIV). The EN 1317-1 threshold value of 33 km/h (true value 33.4 km/h) is highlighted.

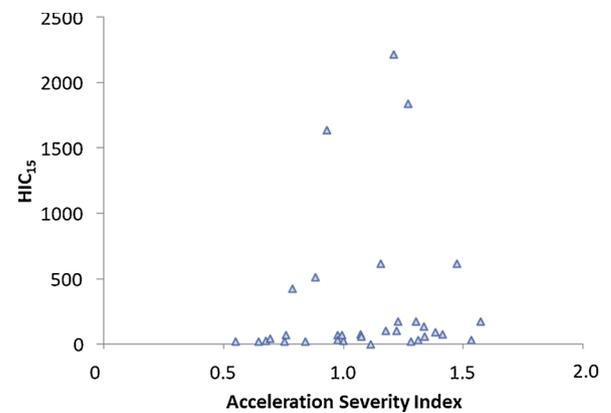


Fig. 6. Acceleration Severity Index (ASI) values compared with corresponding Head Injury Criteria 15 (HIC₁₅) values.

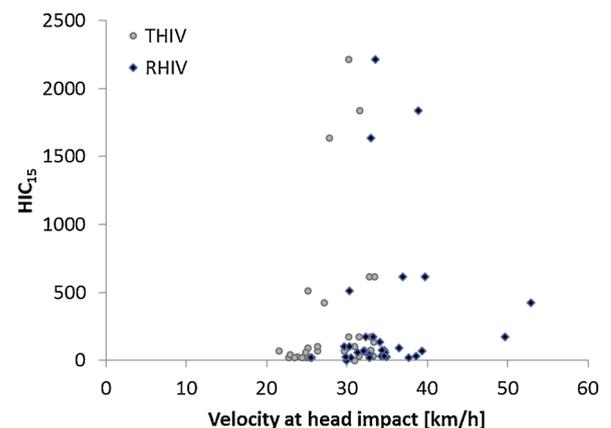


Fig. 7. Theoretical Head Impact Velocity (THIV) and Real Head Impact Velocity (RHIV) compared against their corresponding Head Injury Criteria 15 (HIC₁₅) values. Note: for every HIC₁₅ value, there is a corresponding THIV and one RHIV value.

upon impact, resulting in the head displacing outside of the chassis and impacting directly with the RRS post (Fig. 8). Moreover, the car was deforming during its interaction with the RRS, which usually contributes, alongside deformation of the RRS, to reduced relative decelerations and, therefore, ASI. This index does not take into account that, when the car frame deformation spreads to the cockpit, the head is more likely to impact the cockpit, the distance between the RRS and the head decreases, and the occupant may be crushed and/ or trapped. Cockpit deformation is roughly described in the current regulation with the use of the VCDI index, however, surprisingly this has no bearing on certification.

4.2. Tests n. 2 and 3

It is not possible to determine whether or not the head impacted the RRS (Fig. 9), although in both tests the broken window on the ATD side and the high HIC₁₅ values indicate this is plausible. THIV is approaching the 33 km/h threshold and RHIV is comparatively low, demonstrating the potential for these metrics to drastically underestimate the severity of an impact.

4.3. Test n.4

This test (Fig. 10) presented a high RHIV (52.5 km/h) and a neck injury risk of 30%, which indicates an AIS level of 3, i.e. a serious injury, as classified using the Abbreviated Injury Scale (Wong and Kunz, 2016). Values for ASI, THIV and HIC₁₅ were within, but close to, the

Table 2
Injury metrics for Case-by-Case Analysis.

Test n.	RRS		ASI	THIV	THIV _{man}	RHIV	HIC ₁₅	HIC ₃₆	G _{3ms}			N _{ij}
	class	type		[Km/h]	[Km/h]	[Km/h]			x [g]	y [g]	z [g]	[%]
1	L4b	double side	1.3	32	39	42	1836	586	93	86	225	<i>no data</i>
2	H2	side edge for ground	1.2	30	34	17	2213	1439	292	30	35	< 15%
3	H3	for bridge	0.9	28	33	14	1634	505	86	22	22	< 15%
4	H4b	for bridge	1.5	33	37	53	615	294	87	44	46	30%

Abbreviations: THIV: Theoretical Head Impact Velocity, THIV_{man}: Theoretical Head Impact Velocity man, RHIV: Real Head Impact Velocity HIC₁₅: Head Injury Criteria 15, HIC₃₆: Head Injury Criteria 36, G_{3ms}: Head acceleration 3 ms after its maximum, N_{ij}: Neck Injury Risk.

Values above their respective thresholds are presented in **bold**, THIV, THIV_{man} and RHIV: 33.4 km/h. Acceptability boundaries are also depicted in **bold**, HIC₁₅: 700; HIC₃₆: 1000; G_{3ms}: 80 g; N_{ij}: 30%, and in *italic or bold italic* for ASI B (1-1.4) and ASI C (1.41-1.9).



Fig. 8. Image displaying the car-RRS interaction of test n.1.



Fig. 10. Image displaying the car-RRS interaction of test n.4.

boundaries of their acceptability, despite the possibility of a serious neck injury. A relationship may exist between N_{ij} and RHIV, although due to inevitable rotation of the dummy's head, but it is impossible to explain the head acceleration and velocity without gyroscopic data.

5. General discussion

This retrospective study provided evidence that the current EN 1317-1 regulation is not capable of detecting all dangerous scenarios during RRS testing. The velocity at which the head impacts the cockpit or RRS seems to be estimated poorly without the use of an accelerometer at the head level. Nevertheless, when computed from such an accelerometer, the presented data suggest that the potential for actual head impact velocity to describe impact severity is limited. ASI appears to be kept within class A criteria in part by the deformation of the vehicle as well as the RRS. Therefore, the current regulation may characterise a potentially fatal event as positive behaviour of the RRS.

The striking differences in both magnitude and data spread between THIV, THIV_{man} and RHIV provide evidence for two key conclusions: 1) THIV does not adequately estimate the real head impact velocity; 2)

RHIV in isolation is not particularly useful in determining impact severity, and therefore RRS safety. Although not supported by current findings, further investigations may identify potential applications for the use of head impact velocity metrics in the context of TBI.

Based on our inclusion criteria, all tested RRSs presented passable occupant safety according to the current EN 1317-1 regulation. However, 3 out of 33 RRSs presented HIC₁₅ values above acceptability boundaries, which corresponds with dangerous head kinematics (Prasad and Mertz, 1985). In addition, one RRS, N_{ij} indicated a high risk of neck injury. As opposed to Sturt and Fell (2009) and Shojaati (2003), the HIC₁₅ values above acceptability boundaries were obtained in correspondence with acceptable ASI values, not supporting the hypothesis of their exponential relationship. Ultimately, these findings suggest that the current EN 1317-1 regulation has the potential to certificate unsafe RRSs.

These results should be considered in light of the fact that the sample was relatively small and not stratified, thus the RRSs tested in our sample are not necessarily representative of those used across Europe. The data were also taken from only two crash testing facilities. Further, the author's recognise that using HIC as a form of gold

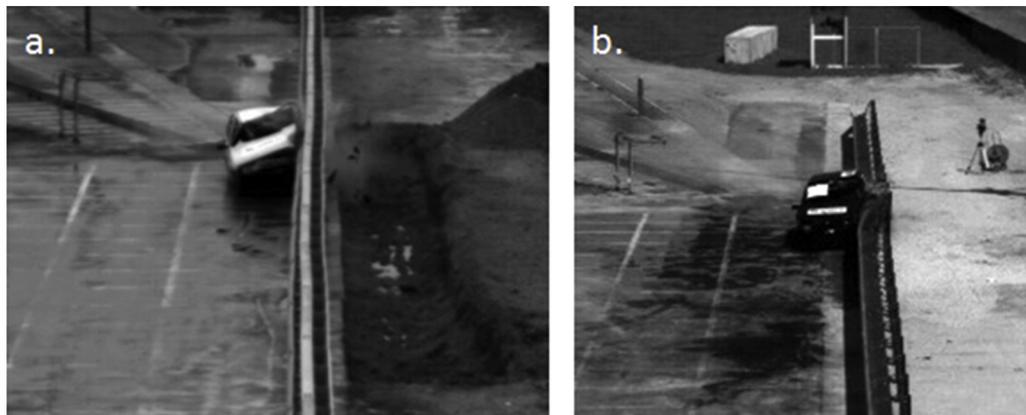


Fig. 9. Images displaying the car-RRS interaction of tests n.2 (a) and n.3 (b).

standard for comparison is controversial, given its flawed background, however this choice was made due to the current lack of better alternatives.

The EN 1317 allows the testing use of older vehicles, than those currently used on today's roads. Specifically, changes in vehicle structural geometry and increases in cockpit stiffness from the early 2000s may significantly modify barrier performance at impact. Consequently, the outcome of tests using older vehicles may not be representative of real impacts entailing a modern vehicle. It is clear that, in order to ensure the safety of Europe's roads, some changes must be made to the current regulation, in parallel with the ongoing activities towards the transformation of the technical specification *UNI CEN/TS 1317-8:2012* into a full European standard to properly test RRSs for motorcyclist safety (García et al., 2009), and towards incorporating motorcycle protection systems such as steel guardrail barrier systems with posts (Atahan et al., 2018) to decrease one of the prime reasons for motorcyclist fatalities (Delhaye and Marot, 2015).

The main limitations of the regulation, based on: the presented data and case studies; a critical analysis of the available literature (points a, e, g); and of extensive experience or knowledge of technological advancement (points e, f, g, and h), are listed. Each point includes a corresponding suggestion for improvement which we hope will be taken into account when defining the new European road safety framework for 2020–2030, and planning practical measures contributing to safer roads in revising the European rules (European commission Report, 2018).

- a. Computing head kinematics from vehicle kinematics using THIV is not only ineffective (Fig. 5), but unnecessary with current technology.
Suggestion: Use an ATD instrumented with an accelerometer in the head, allowing direct measurement of head acceleration, as previously suggested (Roque and Cardoso, 2013).
- b. The actual velocity of the head (RHIV) during its impact with the cockpit does not appear to be useful in isolation when describing the occupant safety risk during glancing RRS impacts (Fig. 7).
Suggestion: Complement head velocity at impact with suitable indices based on actual head acceleration data. HIC₁₅ is a potential alternative as the best current correlate with real life injury data. Eventually, an index relating to the rotational component of head injury, as well as other potential injury mechanisms, should be included.
- c. There may be tests, particularly with high RRSs (as case study in par. 4.1), in which low ASI values are the product of upper cockpit deformation. This potentially dangerous event may result in the occupant impacting the cockpit or obstacles outside of it, both events being undetectable by the current regulation.
Suggestion: Using the above-mentioned instrumented ATD, events such as the head impacting the cockpit, or obstacles outside of it, may be detectable, allowing for substitution of ASI as severity index.
- d. Head kinematics cannot be fully understood without a measure of the head's orientation in space (as evidenced, for example, by the low head velocity at impact corresponding to an overwhelming HIC for case study in par 4.2).
Suggestion: Instrument the test ATD with a triaxial gyroscope.
- e. Neck injury is not accounted for, although it may occur causing a serious AIS (Wong and Kunz, 2016) even for certified barriers (case study 4, par 4.3).
Suggestion: Instrument the test ATD with a neck load cell and include a neck injury risk criterion with threshold values not to be exceeded, such as N_{ij} (Mertz et al., 1997)
- f. There is currently no requirement to include a camera to track head motion inside the vehicle to facilitate interpretation of the crash events.
Suggestion: Equip all vehicles with a camera positioned to track the movement of the ATD within the vehicle.

- g. The potential rotational component of traumatic brain injury is not considered.

Suggestion: There is not currently an obvious solution to this as there is no adequate rotational brain injury criteria in the literature that correlates with real life injury (Mueller, 2015; Takhounts et al., 2013). However, in using a gyroscope the data will at least be available for future retrospective analysis.

- h. No clear indication is provided on the window type (reinforced\ non-reinforced) and condition (open\ closed).

Suggestion: Standardize the type of window used for testing, excluding the reinforced type, and keep it closed. This will allow for consistent testing of a true worst-case scenario.

6. Future developments

Development of the regulation should properly consider factors affecting the severity of the injury and comprise testing conditions truly indicative of real life incidents. Severity factors are multiple and include age, gender, accident dynamics, impact severity, osteoarticular conditions, among others (Abu-Zidan and Eid, 2015; Yoganandan et al., 2014). Although not analysed in the current study, reconsidering impact speed and angle conditions as derived from real data would also be beneficial (Abraham et al., 2016). Testing true worst case scenarios would be protective of those vehicle occupants at greater risk of injury due to decreased awareness, such as fatigued drivers (Paterson and Dawson, 2016; Stutts et al., 2003), distracted young drivers (Bingham, 2014; Lee and Abdel-Aty, 2008), or passengers not actively involved in driving (also the case for occupants in self driving cars).

Further data, eventually gathered through a multicentre approach, are required to reinforce presented evidence and to form the basis of testing for the efficacy of alternative indices. The ability of the indices analysed in this work, or of others, in predicting real injuries related to glancing RRS impacts must be assessed through research that investigates the relationship between real incident characteristics and injury information, based on real data obtained from police and hospital databases and musculoskeletal modelling (Roque and Cardoso, 2013), enabling the production of appropriate thresholds for the selected indices. Eventually, the production of new indices, to be used in conjunction with existing ones, will be essential in order to progress further. Specifically, the linear and angular components, and their respective contribution to TBI must be accounted for.

Declaration of Competing Interest

C.E. Brandani and S. Frascetti are employed by AISICO Crash Test Centre who supplied crash test data, videos and photos anonymously, without any possible references regarding companies, customers and RRSs. This was in compliance with the confidentiality constraint that the laboratory must respect. The remaining authors declare that they have no affiliations with, or involvement in, any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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