The influence of ASI on injury risk in impacts with roadside safety barriers

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Abstract

Roadside barriers are homologated in Europe to EN1317, which includes tests for containment (resistance to penetration by an impacting vehicle), and accident severity, measured by Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV). Barriers are classed according to ASI measurement. There has been debate as to whether Class C barriers (ASI 1.5 to 1.9) should be considered acceptable from an injury risk point of view, but the debate has been hampered by lack of quantitative correlation between accident severity level and injury risk.This study presents data from three physical crash tests and 50 computer simulations. A small car equipped with crash dummy was impacted into a barrier at a range of speeds and angles, and with variations to the vehicle conditions and occupant positions. Measurements from the crash dummy in the tests and simulations were compared with published injury limits derived from volunteer and cadaver tests and plotted against ASI and THIV.

Results showed that, although ASI did show a correlation with injury risk, the level chosen for the boundary between EN1317 Classes B and C does not provide significant discrimination between higher and lower risk of injury. However, the EN1317 limit for THIV, which applies to all barrier Classes, was found to be a reliable discriminator between acceptable and unacceptable injury risk.

Keywords: Barrier; ASI; Injury; HIC; THIV

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1. Introduction

Roadside barriers save thousands of lives annually, and are an important component of the overall safety of our road system. Barriers are homologated in Europe to the standard EN1317 (British Standards Institute, 1998), which includes tests for containment (resistance to penetration by an impacting vehicle), and accident severity, measured by Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV). Since the introduction to EN1317 of Class C barriers (ASI 1.5 to 1.9), there has been debate as to whether such barriers should be considered acceptable from an injury risk point of view. Lack of quantitative correlation between accident severity level and injury risk has prevented any objective assessment of what accident severity should be considered acceptable.

1.1 Accident Severity definitions

The containment levels and accident severity classes specified in EN1317 are summarised in Tables 1 and 2.

Accident severity is expressed using the Acceleration Severity Index (ASI), derived from the acceleration time-histories measured at the centre of mass of the impacting vehicle:

$$ASI(t) = [(ax/xl)^2 + (ay/yl)^2 + (az/zl)^2]^{0.5}$$

Where $ASI(t)$ is a function of time ; the quoted ASI result is the maximum value of ASI occurring during the crash; ax, ay and az are the vehicle accelerations in the x (forwards) y (lateral) and z (vertical) directions measured in g and averaged over a rolling 50ms period; xl=12g; yl=9g; zl=10g.

ASI provides an indication of the deceleration over a 50 millisecond period compared to tolerance limits for occupants wearing a lap belt only. The criterion and its normalising factors (xl, yl and zl) do not account for the different risks posed by different crash types, nor for impact with hard objects inside the vehicle, nor for the different kinematics experienced by occupants wearing three-point seatbelts. ASI has evolved as a practical means of comparing the rigidity of barriers and is not intended as a direct measure of injury or the potential for injury. ASI should not be confused with Abbreviated Injury Score (AIS). The latter is derived from medical assessment of a victim's injuries and is widely used in studies of the injury outcomes of real world crashes.

A further criterion, Theoretical Head Impact Velocity (THIV), is also calculated from the vehicle motion. It is based on the Flail Space model in which the occupant's head is assumed to undergo free motion inside a cuboid space that moves with the vehicle. The THIV is the velocity with which the head strikes the inside of the cuboid space. The definition of THIV may be found in EN1317.

Table 1. EN1317 Containment Levels

	Mass of vehicle	Impact speed	Impact energy
N1	1.5 tonnes	80km/h	43.3kJ
N2	1.5 tonnes	110km/h	81.9kJ
H1	10 tonnes	70km/h	126.6kJ
H2	13 tonnes	70km/h	287.5kJ
H4A	30 tonnes	65km/h	572.0kJ

1.2 Balancing safety considerations

Various barrier designs are available offering different levels of containment and accident severity. The majority of barriers installed on the UK road network achieve N2 containment, and Class A or B accident severity. Among other options are rigid designs that offer H2 containment or better, and do not require maintenance after an impact – this is a significant safety benefit because maintenance crews are not put at risk, and the disruption to traffic flow during barrier repairs is eliminated. However, such barriers generally have higher accident severity – Class B or C. Since the recent introduction of Class C into EN1317, there has been debate as to whether such barriers should be considered acceptable from an injury risk point of view. It would be desirable to quantify the additional risk posed by the higher accident severity, and compare this against the safety benefits arising from prevention of cross-over accidents and risks to maintenance workers. However, objective assessment is prevented by a lack of quantitative correlation between accident severity level and injury risk for the typical glancing impacts with roadside barriers. The ROBUST project (Anghileri et al. 2005) found an absence of correlation between ASI and Head Injury Criterion (HIC) but the sample included cases in which the occupant's head struck high barriers. If this occurs, injury measurements are disproportionate to the accident severity.

Table 2. EN1317 Accident Severity Classes

Class	ASI	THIV
A	$ASI \leq 1.0$	$\leq$33km/h
B	$1.0 < ASI \leq 1.4$	$\leq$33km/h
C	$1.4 < ASI \leq 1.9$	$\leq$33km/h

Analysis of the Police STATS19 database showed that from 2001 to 2005 on the motorways and A-roads of Great Britain, there were on average 201 cross-over accidents per year, leading to 251 casualties per year. Fatalities and serious injuries are roughly twice as likely in a cross-over accident compared to accidents involving the central reserve barrier in which the vehicle is contained.

Most of the barriers on Britain's roads are designed to N2 containment, and tested with a 1.5 tonne car. Of the vehicles involved in cross-over accidents, 76% were cars and over 90% weighed less than 7.5 tonnes. H2 containment barriers are tested with a 13 tonne vehicle; it is likely that such barriers could prevent a large proportion of the cross-over accidents and the resulting deaths and serious injuries. However, that benefit must be compared against any increase of injuries due to the rigidity of the barrier and hence the higher accident severities.

1.3 Objective

The purpose of this study is to provide a correlation between injury risk and accident severity, and to propose limits at which the risk of injury should be considered acceptable.

2. Methods

The data has been generated using a finite element model of a Suzuki Swift equipped with Hybrid III crash dummy and impacted into a Concrete Step Barrier, Figure 1. This vehicle was selected because injury risks are expected to be highest for occupants of small cars, and because this vehicle is frequently used for testing accident severity to EN1317. The Concrete Step Barrier

(Britpave, 2006) was selected for this study as being representative of rigid, high containment barriers and able to sustain several high severity impact tests without failure or the need for repair between tests. The vehicle model contains 198,284 elements. The dummy is the FTSS Hybrid III 50%ile version 5.1 (FTSS, 2005), which contains 89,953 elements and has been extensively validated against laboratory tests on the physical crash dummy. The barrier was treated as rigid. The model was run using the nonlinear dynamic finite element code LS-DYNA ® (Livermore Software Technology Corporation, 2003).
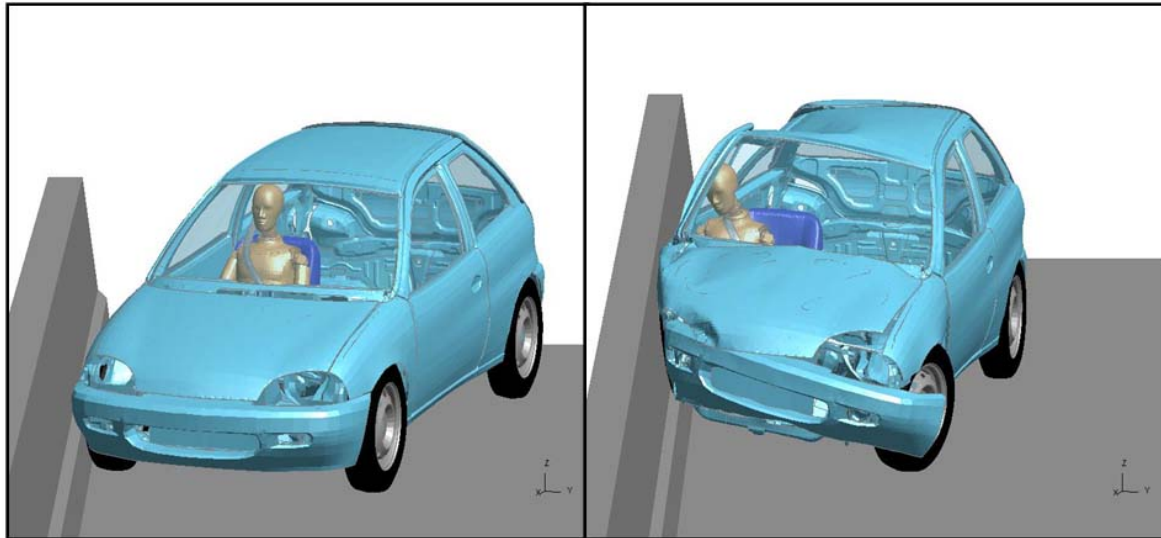

Figure 1. Computer model

Three physical crash tests were carried out to provide data against which the computer model could be validated. Suzuki Swifts equipped with Hybrid III crash dummies were crashed into a Concrete Step Barrier at speeds ranging between 109km/h and 113km/h, and at angles between 15 degrees and 20 degrees. Data from all available channels in the dummy's head and neck was recorded, in addition to a subset of the available data from the chest and pelvis.

After correlating the model against test, 47 further analyses were undertaken to predict the spread of injury results for a range of different accident, vehicle and occupant conditions and a range of accident severities. Parameters were varied as follows:
- o Impact speed: 90km/h to 150km/h
- o Impact angle: 10° to 25°
- o Vehicle strength, simulated by increasing or decreasing the yield stress of critical panels by a factor of 1.5.
- o Occupant lateral position, such that the gap between the head and window varied by 70mm
- o Vehicle B-post position fore/aft within the vehicle, such that the dummy's head impacts the B-post or not
- o Crash dummy Hybrid III (as used in EN1317 tests) or EuroSID (measures chest, abdomen and pelvis injuries relevant to side impact)
- o Seat belt present or absent
- o Friction between the dummy and seat raised from 0.3 to 0.9
- o Failure of suspension joint
- o Different types of seat

Acceleration data is recorded at positions in the finite element model equivalent to the accelerometer positions in the test. These were processed according the protocol of EN1317 to derive ASI and THIV.

The finite element dummy contains instrumentation equivalent to that of the physical dummy, including triaxial accelerometer at the head centre of gravity, and six-axis loadcell at the occipital condyles measuring forces and moments in longitudinal, lateral and vertical directions in an axis system fixed at the top of the neck. Head Injury Criterion (HIC) was calculated using a time period 36 milliseconds. Neck forces and moments were filtered as specified in European New Car Assessment Programme (EuroNCAP) protocol (2004) and the maxima and minima recorded.

3. Results

The impacts modelled resulted in ASI between 1.1 and 2.3, and THIV from 15 to 42km/h. Note that the majority of the crash simulations were performed at speeds in excess of the EN1317 test requirement – the results should not be used to confirm compliance with EN1317. All the injury criteria showed a tendency to increase with increasing ASI and THIV, but the spread of the data indicates that other factors contribute to injury apart from the severity of the impact.

Examination of the results from the crash tests, and initial simulations with Hybrid III and EuroSID dummies, indicated that head and neck injuries would become significant at lower accident severities than injuries to other regions of the body. This is confirmed by real world accident data indicating that the neck is the most likely body region to be injured in collisions with roadside barriers. Therefore injury assessment has focussed on the head and neck. Injury assessment has been performed using several alternative methods.

3.1 Assessment using EuroNCAP frontal impact head and neck scoring protocol

The EuroNCAP protocol sets out a method by which up to 4 points are awarded for protection of the head and neck region, based on HIC, neck forces and neck moments measured during a frontal crash. For the side crash, only HIC is considered. The points awarded for each body region contribute to the overall star rating of the vehicle. By applying the EuroNCAP protocol to the head and neck results from this study, a comparison with the injury risk considered acceptable by EuroNCAP may be obtained. However, it should be noted that the neck region is included in the scoring system only for frontal impact, not side impact. Lateral components of neck force and moment (which are significant in the impacts modelled here) are not included, therefore this assessment method may be non-conservative.

The points awarded for head and neck protection based on EuroNCAP protocol for frontal impact are plotted against THIV in Figure 2. Each computer simulation result is indicated by a cross, while the physical crash tests are indicated by circles. Maximum points are gained for all crashes in which THIV was below the EN1317 limit of 33km/h, suggesting that the EN1317 THIV limit is set at a reasonable level for protection against injury. This assessment method may be non-conservative because lateral neck force and moment are ignored.

3.2 Probability of neck injury using Van Auken's method

Van Auken (2003) proposed a method of calculating a neck injury parameter based on three-dimensional loading of the neck, and provided formulae from which the probability of neck injury could be calculated. Injuries of different severities are classified according to Abbreviated Injury Score (AIS) from 1 to 6 with AIS 1 representing "minor" injury, AIS 2 being "moderate" injury, and so on. Van Auken calculates different coefficients for the statistical models for each injury level, so that the probability of, for example, AIS 1+ injury can be calculated for a given set of neck forces and moments. The statistical data was derived from a study of 565 motorcycle accidents which were subsequently modelled using a rigid body dynamics program to back-calculate the neck forces and moments.
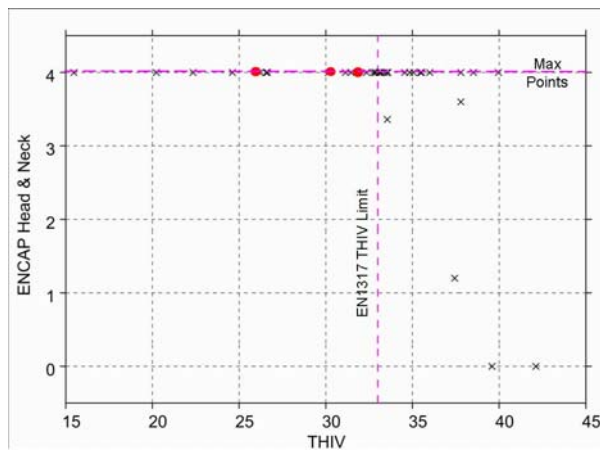

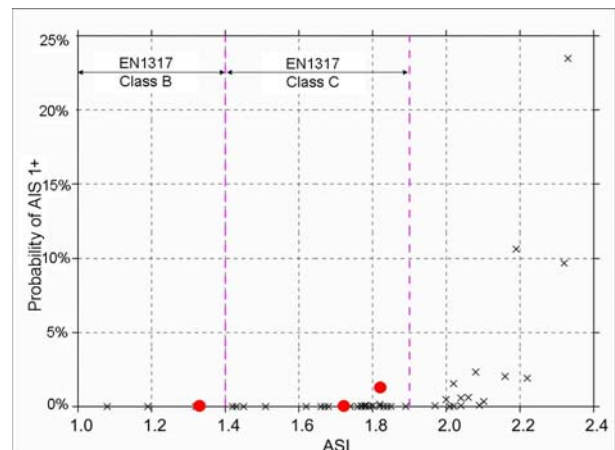Figure 2. ENCAP head and neck assessment vs. THIV

Figure 3. P(AIS≥1+) from Van Auken vs. ASI

The probability of at least minor neck injury (AIS 1+) was calculated according to this method. The data is plotted against ASI (Figure 3) and against THIV (Figure 4). The probability of neck injury of severity AIS 1+ exceeds 10% only for crashes with THIV greater than 39km/h or ASI at least 2.2. This assessment suggests that even minor neck injury is unlikely in crashes of the same severity as an EN1317-compliant crash.

By comparison with the other assessment methods used in this study, the Van Auken method appears to be the least conservative. The method was derived from motorcycle accident data and may be inappropriate to the crash type considered in this study.
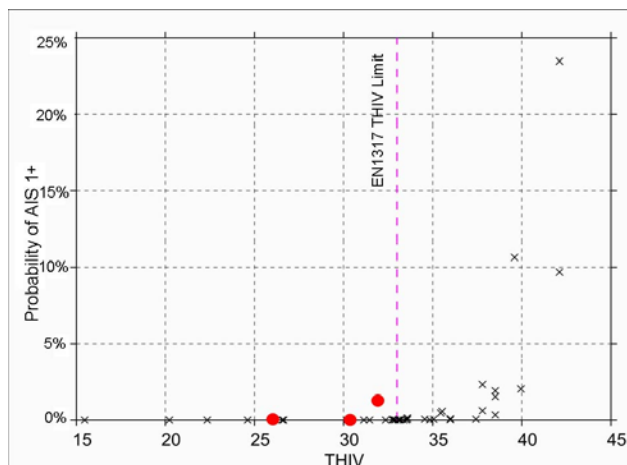

Figure 4. P(AIS≥1+) from Van Auken vs. THIV

3.3 Comparison with Injury Assessment Reference Values (IARVs)

Maxima can be compared against tolerance limits in the literature. Limits have been derived from tests on living human volunteers or on cadavers. In the case of living volunteers, the severity of static or dynamic experiments is gradually increased until the volunteers experience some degree of pain or are unwilling to continue further. Such limits may be very conservative, because the threshold at which injuries occur are not reached and may be well beyond the limits acceptable to the volunteers. In the case of cadaver testing, post-test dissection techniques are used to observe or measure injuries.

The acceptable HIC measurement has been taken as 325, which is half the allowed value for maximum points for head protection in the EuroNCAP side impact protocol. Kuppa (2004) provides head injury risk curves as functions of HIC; the selected HIC of 325 corresponds to less than 10% risk of injury equivalent to AIS 2+.

McIntosh (2007) analyses data from cadaver side impact sled tests and presents an analysis of the neck parameters measured in comparison to neck injury severity. The results are presented in comparison to other cadaveric studies and volunteer studies.

Table 3. Summary of Tolerance Limits

	EuroNCAP maximum points	Acceptable limit	Volunteer data
HIC	650	325[a]	-
Neck Fx (longitudinal)	1900N	-	851N[h]
Neck Fy (lateral)	-	1481N[b]	794N[g]
Neck Fz (tension)	2700N	3300N[c]	1100N[h]
Neck Mx (lateral)	-	122Nm[b]	56Nm[g]
Neck My (extension)	42Nm	57Nm[d]	47.5Nm[e]
Neck My (flexion)	-	190Nm[d]	88Nm[f]
Neck Mz (torsion)	-	54Nm[b]	22Nm[g]

[a]Half the EuroNCAP limit taken as conservative assumption
[b]Mean without injury value from McIntosh cadaver tests
[c]Peak force FMVSS 208 unbelted test
[d]Limit of ligamentous damage from Mertz
[e]Non injurious torque from Mertz
[f]Maximum voluntary moment from Mertz
[g]Volunteer max without injury from McIntosh
[h]Static non injurious volunteer neck strength from Mertz

Mertz (1971) gives static strength data from volunteers for neck tension and compression forces. The results of dynamic tests on cadavers and a volunteer are also presented giving shear force, flexion and extension moments.
Tolerance limits from the literature are summarised in Table 3. Due to scarcity of data it is not possible to offer a set of IARVs from a single consistent source.
Some degree of caution should be exercised when comparing forces and moments measured by the Hybrid III crash dummy to measurements from volunteer and cadaver testing, since the biofidelity of the Hybrid III neck response is questionable.

Figures 5 and 6 show HIC plotted against accident severity, measured by ASI and THIV respectively. HIC falls within the selected limit of 325, for all crashes with ASI less than 2.0 and THIV less than 35km/h. This includes cases in which the head strikes the B-post. In no case did

the dummy's head strike the Concrete Step Barrier. In the most severe impacts (ASI 2.2 to 2.3), contact with the door was noted; the HIC in these impacts was above 1000, indicating a high risk of injury. These cases were 20 degree impacts at 135 & 140 km/h and a 25 degree impact at 120km/h.
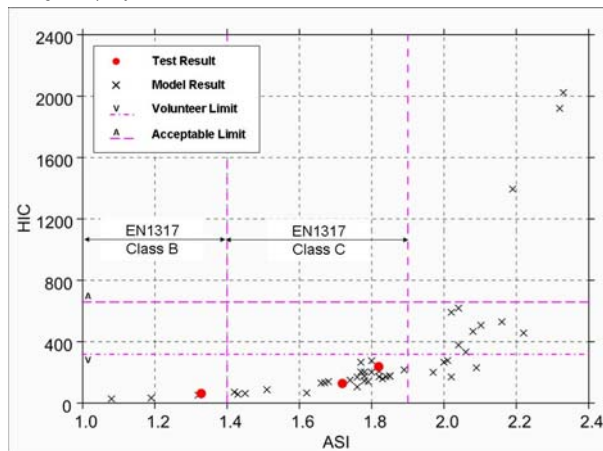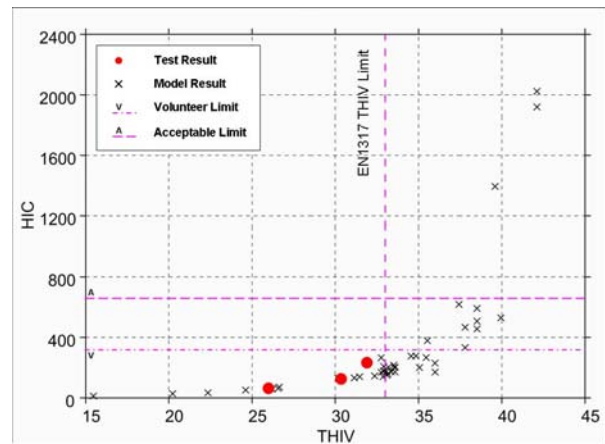

Figure 5. HIC versus ASI

Figure 6. HIC versus THIV

Neck injury results are shown in Figures 7 and 8. Horizontal dashed lines show the "volunteer" and "acceptable" IARVs. The volunteer-derived limits are likely to be less than the forces and moments that would cause injury. All the results fall within the available volunteer-derived limits for all crashes with THIV less than 30km/h or ASI less than or equal to 1.5. It may be concluded that crashes satisfying these criteria do not present any significant risk of neck injury. This conclusion excludes tall barriers that may present a risk of direct contact with the occupant's head.

Neck injuries are within the "acceptable" limits (most of which are derived from cadaver testing) for all crashes with THIV less than 39km/h or ASI less than 2.0. However, there are outlying points in Figures 7 and 8 with ASI and THIV below those values and injury measurements close to the acceptable limits. Extrapolating from these points, it is suggested that ASI of 1.8 and THIV of 33km/h offer reasonable thresholds below which it is unlikely that the acceptable limits will be exceeded.

The results suggest that the THIV criterion of EN1317 is set at an appropriate level to discriminate between crash results that pose some risk of injury from those that do not. However, the ASI limits for Classes B and C do not offer any meaningful discrimination. There is no significant increase in injury risk for crashes with ASI 1.5 compared to those with 1.4, but some crashes with ASI of 1.8 and 1.9, which are within the ASI limits for Class C, showed results indicating a significant risk of injury. However, none of the cases showing significant risk of injury would be considered EN1317-compliant because the THIV values exceeded 33km/h.

Chest compression is also shown in Figures 7 and 8. These showed the largest scatter of any of the measured injury parameters. The chest compression measurement system in the Hybrid III dummy measures chest compression only in the sagittal plane. Only one crash (with ASI 2.0) showed chest compression above the limit for maximum points in EuroNCAP, this was an unbelted case.
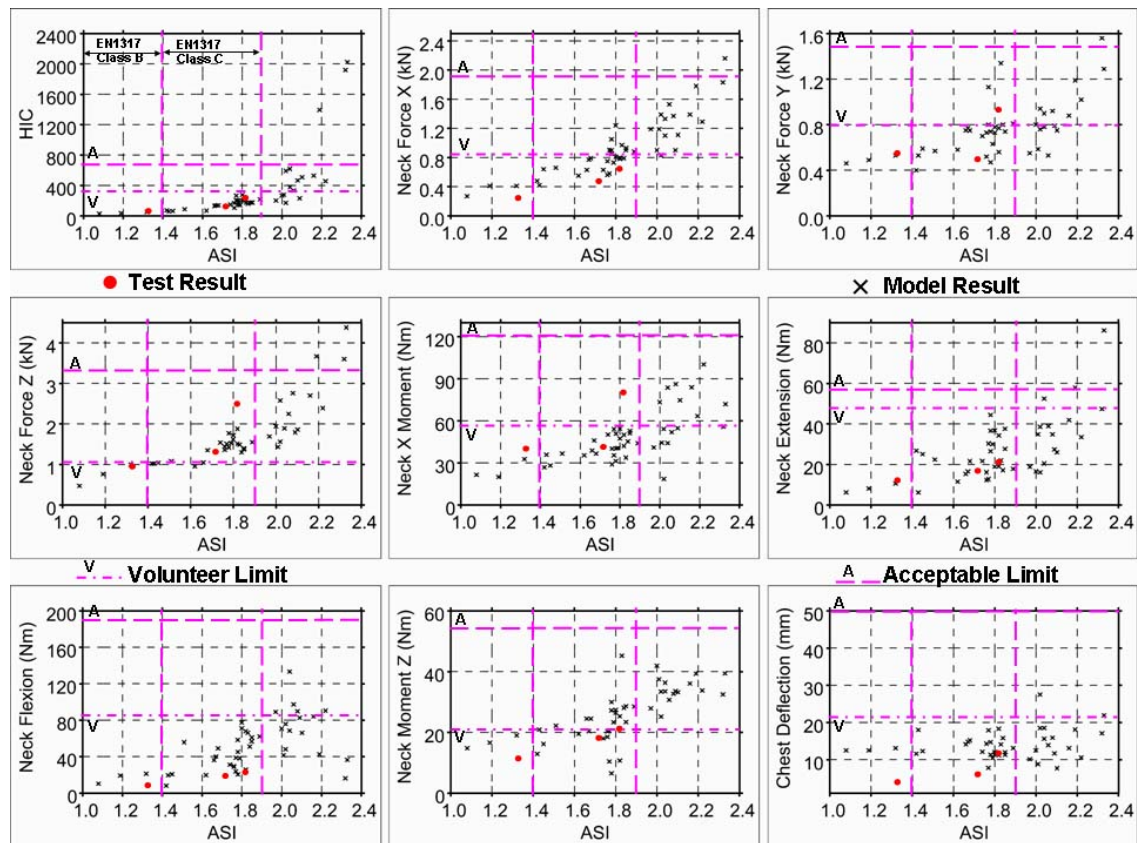
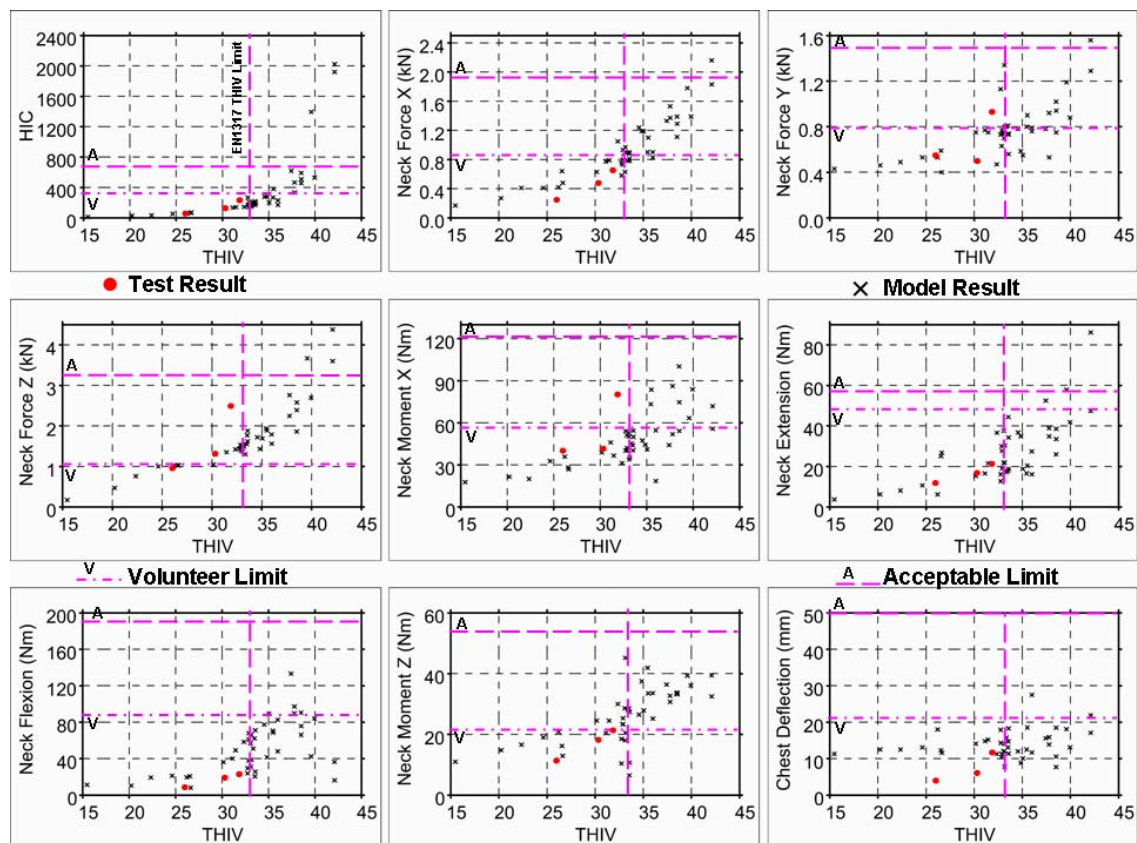Figure 7. HIC, Neck Injuries & Chest compression vs. ASI

Figure 8. HIC, Neck Injuries & Chest Compression vs. THIV

3.4 Assessment using EuroNCAP Side Impact protocol

The glancing impacts studied here combine aspects of frontal and lateral impacts. The Hybrid III dummy is primarily designed for frontal impact. To check for any risk of injury due to lateral impact effects (for example, lateral compression of the thorax following contact with the door), further analyses were carried out with the EuroSID side impact dummy. The injury measurements from the dummy were assessed using the EuroNCAP protocol. A maximum of 4 points can be awarded for protection to each of the body regions head, chest, abdomen and pelvis. These results are plotted against ASI in Figure 9 and against THIV in Figure 10. Different symbols are used for each body region. As accident severity increases, the chest is the first criterion to exceed the limit for maximum points in the EuroNCAP side impact protocol. This occurred at an ASI of 2.0 and a THIV of 35. It is concluded that significant injuries due to lateral impact on the chest, abdomen and pelvis are unlikely in impacts that comply with the requirements of EN1317 for Class B or C barriers.
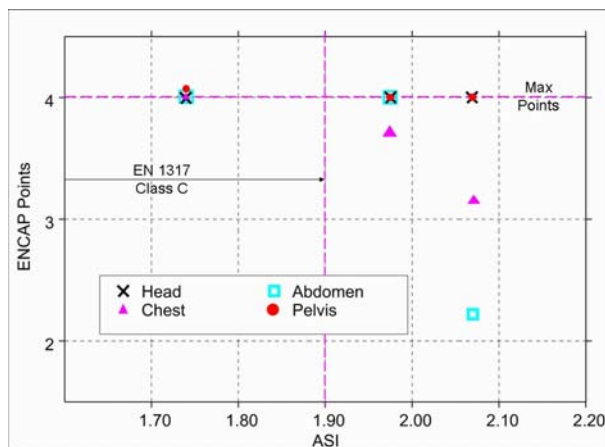
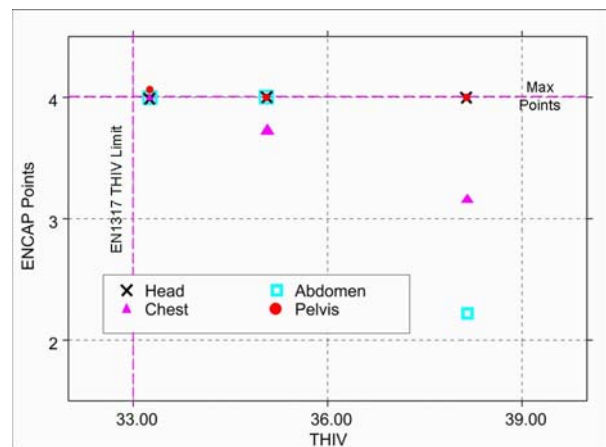Figure 9. EuroNCAP Side impact points vs. ASI

Figure 10. EuroNCAP Side impact points vs. THIV

4. Conclusion

Injury measurements have been correlated against accident severity as measured by ASI and THIV for 50 computer simulations and 3 physical crash tests against a Concrete Step Barrier. It should not be assumed that the conclusions below would also apply to other barriers.
There is a correlation between head and neck injury measurements and accident severity, as measured by both ASI and THIV.
The neck is the body region most likely to be injured in the type of glancing impact considered here.
For the head and chest, injury measurements were found to be within acceptable limits for impacts with ASI below 2.0 and THIV below 35km/h. For the abdomen and pelvis, none of the crashes studied resulted in unacceptable injury measurements.
For the neck, two accident severity thresholds have been identified. For crashes with ASI up to 1.5 and THIV up to 30km/h, neck injury measurements were found to be below the limits derived from volunteer testing. These limits are expected to be significantly lower than the levels at which injuries may occur. For crashes with ASI up to 1.8 and THIV up to 33km/h, neck injury measurements above the tolerable thresholds for injury are considered unlikely. Unacceptable injury measurements were recorded in crashes with ASI above 2.0 and THIV above 38km/h.

The boundary between Class B (ASI up to 1.4) and Class C barriers (ASI 1.5 and over) in EN1317 does not correspond to any significant increase in injury risk.

The existing requirement in EN1317 for THIV to be below 33km/h represents a reasonable threshold below which significant injury is unlikely, provided that no additional risk factors are present such as the barrier being high enough to be struck by the occupant's head.

The EuroNCAP front impact protocol for scoring injury to the head and neck is only partially relevant to the crash type considered in this study, but results from this assessment method do not contradict the above conclusions.

Van Auken's method of assessing neck injury was found to be the least conservative of the methods used.

Many vehicles (including all that achieve EuroNCAP 5-star rating) are fitted with inflatable head protection devices such as curtain airbags, which will drastically reduce the loads on the head and neck during typical impacts with roadside barriers. As the proportion of such vehicles on Europe's road increases, the importance of barriers achieving low ASI will reduce.

When selecting a barrier for a particular site, safety criteria such as the ability to contain larger vehicles, and the need for maintenance after an impact (with consequent exposure to danger of personnel), should be considered, as well as accident severity. There is a risk that overall safety may be compromised if ASI is used as the sole safety criterion for barrier selection.

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