THE EXPECTED IMPACT OF UN REGULATION NO. 137 TESTS ON EUROPEAN CARS AND SUGGESTED TEST PROTOCOL MODIFICATIONS TO MAXIMISE BENEFITS

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ABSTRACT

UN Regulation No. 137 (R137) specifies a 50 km/h, full-width rigid barrier frontal impact test with driver and passenger 50^{th} and 5^{th} percentile Hybrid III dummies respectively. One objective of the regulation is to encourage better restraint systems that protect older occupants and across a wider range of collision severities.

This paper investigates two research questions:

- How much will restraint systems of European cars have to be modified to meet the requirements in R137?
- What level of protection is offered by current European restraint systems at lower impact energies than tested in R137?

Six full-scale crash tests were conducted with European-specification supermini cars. The test configurations used were R137 in standard configuration, at reduced impact speed and with a THOR-M ATD instead of Hybrid III. The crash tests were complemented by an analysis of Road Accident In-Depth Studies (RAIDS) data.

The test vehicles in their European market specification were found to already meet the minimum performance requirements set out in the future R137 at 50 km/h for Hybrid III ATDs. The THOR-M ATD generally predicted greater injury risk than the Hybrid III and in some conditions exceeded the current regulatory limit values (as defined for Hybrid III). At lower impact speeds of 35 km/h, the key driver thorax injury metric measured with THOR-M was found to be only slightly reduced.

The accident data analysis showed that a considerable proportion of casualties sustaining MAIS 2+ or MAIS 3+ injuries occur at impact energies which are lower than currently proposed in R137. It was also found that the thorax was the body region most prone to AIS 2+ or AIS 3+ injuries in low-energy impacts. Older occupants (66 years and older) were markedly over-represented in the low-energy casualty groups.

Under the conditions set within R137, it is likely that many European vehicles will pass without requiring significant changes. Therefore, in its current state, there is no evidence that R137 encourages better driver restraint performance. The results at reduced impact test speeds further indicate that occupants could be more vulnerable than necessary at lower collision speeds.

The accident data further show that there might be a large target population for a low-energy restraint test. The composition of this casualty group indicates that the force limits of current seat belt load limiters might be too high for the reduced biomechanical tolerance of elderly occupants and higher than necessary in low-speed collisions. The accident research is based on UK accident data, which means that the sample size was limited and the results may not be representative of other countries. However, the general trends identified align with previous data from other European countries.

It was concluded that implementation of the THOR-M ATD as a replacement for the current Hybrid III in R137 should be considered at the earliest opportunity in order to deliver tangible benefits. Test and performance requirements could be set to encourage adaptive restraints which provide better protection at lower impact energies.

INTRODUCTION

In November 2015, the World Forum for the Harmonization of Vehicle Regulations (WP.29) adopted the new UN Regulation No. 137 (R137) [1] to test the effectiveness of occupant restraint systems as well as an accompanying amendment providing a schedule for development of the regulation to increase its stringency. R137 specifies a 50 km/h, full-width frontal impact test against a rigid barrier.

The R137 test setup consists of a 50th percentile Hybrid III male in the driver's seat and a 5th percentile Hybrid III female anthropometric test device (ATD) in the front seat passenger (FSP) position. Both ATDs must meet a Thorax Compression Criterion (ThCC) of 42 mm. By 2020, the companion 01 series of amendments [2] is scheduled to reduce the thorax compression limit to 34 mm for the 5th percentile female ATD, which will be the same risk of injury as the 42 mm limit for the 50th percentile male ATD. Note: A full-width rigid barrier test was introduced to Euro NCAP testing in January 2015, although the test setup is significantly different; Euro NCAP tests with a rear seat passenger and 5th percentile Hybrid III female dummy in the driver position.

The main aims of R137 are to:

- Encourage improved restraint systems that will reduce the risk of injury in this loading condition;
- Ensure that restraint systems will protect a range of occupant statures and at a range of collision severities.

However, it has not been demonstrated that the test condition and dummy diversity are sufficiently different to UN Regulation No. 94 (R94) to ensure that restraint systems will have to be modified. Also, the likely effect of the regulation on certain vehicle segments, in particular very small city cars, has not been demonstrated.

This paper therefore investigates two research questions to provide evidence to support the implementation of R137 in Europe:

1. How much will restraint systems of European cars have to be modified to meet the requirements in R137?
2. What level of protection is offered by current European restraint systems at lower impact energies than tested in R137?

METHODS

Crash tests

A programme of six full-scale crash tests was conducted, of which Tests 2 to 6 are relevant for this paper (Table 1). The test vehicles used were Fiat 500 Mk 1, 1.2 Pop, manual transmission, right-hand drive, supermini cars (second-hand). This small-sized car with its stiff front-end design results in a very short stopping distance in a full-width rigid barrier test, and is therefore challenging for the restraint system design.

Table 1.
Test programme of six full-width, rigid barrier crash tests conducted

Test No.	Speed	Driver ATD	FSP ATD	RSP ATD	Comment
1	56 km/h	50M H3	5F H3	–	Replication of US test (FMVSS 208) to compare performance of EU- and US-specification car
2	50 km/h	50M H3	5F H3	–	Baseline at proposed R137
3	50 km/h	50M THOR	95M H3	–	Effect of THOR-M driver dummy (and protection for 95M FSP)
4	50 km/h	95M H3	50M THOR	5F H3	Effect of THOR-M FSP dummy (and protection for 95M driver)
5	35 km/h	50M THOR	95M H3	–	Protection at lower speed
6	35 km/h	95M H3	50M THOR	5F H3	Protection at lower speed

The configuration of Test 2 followed the frontal impact test procedure specified within R137. The objective was to conduct a baseline test to evaluate the performance of the vehicle against the dummy injury limits stated within the regulation.

The R137 frontal impact test consists of a 50 km/h impact into a full-width rigid barrier (Figure 1). Several minimum performance requirements are stated within the regulation in the form of injury metrics recorded by two crash test dummies in the front seating positions of the vehicle. A 50th percentile male Hybrid III (H3) ATD was positioned in the driver's seating position, with the seat in the mid fore-aft and lowest adjustment position. A 5th percentile female Hybrid III ATD was situated in the front passenger's seating position, also with the seat in the mid fore-aft and lowest adjustment position.

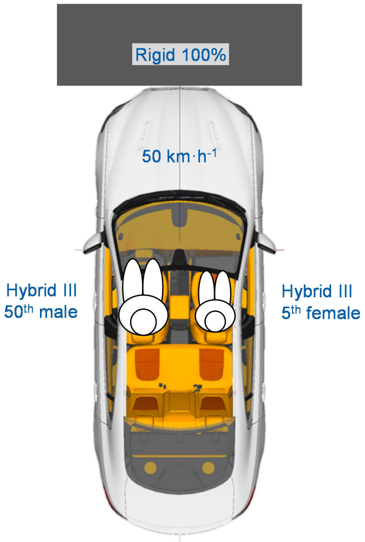

Figure 1. Schematic of UN Regulation No. 137, 50 km/h, full-width impact test configuration (left-hand drive car)

Several dummy position measurements were recorded (such as nose to steering wheel rim distance) in order to ensure consistency with future test setups. Since the test vehicle had been previously used on the road, the front seat cushions were replaced to minimise the chance of differences due to degradation of the seat.

Tests 3 and 5 were conducted at 50 km/h and 35 km/h respectively. In both cases a THOR 50th percentile male dummy occupied the driver position. Tests 4 and 6 were also conducted at 50 km/h and 35 km/h, respectively, with a THOR 50th percentile male dummy in the FSP position. The objective was to investigate the effect of use of the THOR-M ATD on R137 and the effect of reduced test speeds on dummy injury metrics. Note: A Hybrid III 95th percentile male dummy occupied the FSP position and a Hybrid III 5th percentile female dummy occupied the rear seat behind the FSP during some tests to investigate issues not covered in this paper.

Accident data sources

In-depth collision data for the United Kingdom (UK) from the RAIDS database were used to address the pertinent research questions. RAIDS is one of the most comprehensive in-depth collision databases in the world. It contains data from the current Road Accident In-depth Studies (RAIDS) programme that has run since 2012, and four separate historical studies that ran from 1982 to 2010, namely:

- The Co-operative Crash Injury Study (CCIS),
- On-The-Spot (OTS),
- The Heavy Vehicle Crash Injury Study (HVCIS), and
- The Truck Crash Injury Study (TCIS).

The RAIDS Phase 1 programme collected information on approximately 500 collisions per year in two areas of the UK that were specifically designed to represent the demographic and road network of the wider country: The first of these areas is in the south of England, specifically the Thames Valley and Hampshire police force areas and the second in the east midlands, specifically the Nottinghamshire and Leicestershire police force areas. In-depth data are collected at the scene of collisions, and retrospectively, for involved vehicles and people. The data gathered includes detailed assessments of injury causation mechanisms.

The CCIS project collected in-depth collision data from 1983 to 2010, but in a retrospective manner only. Vehicle examinations were undertaken at recovery garages several days after the collision. Anonymised car occupant injury information was collected from hospitals and HM Coroners and questionnaires were sent to survivors.

Collisions were investigated according to a stratified sampling procedure, which favoured cars containing fatally or seriously injured occupants. This means that a relatively large number of fatal and serious collisions were recorded, which are often the most interesting from an injury prevention point of view. This needs to be considered and corrected for when scaling data up to a national level (for example, to determine target populations), which was not necessary for the present study, i.e. the collision data was not weighted. All injury data used was coded using the Abbreviated Injury Scale (AIS) 2005 Update 2008 [3].

For the present project, RAIDS data from Phase 1 (which encompasses collisions collected from 2013 to 2015) and CCIS data from Phases 7 and 8 (which encompasses collisions collected from 2000 to 2010) were used.

Accident data analysis

Table 2 shows the primary selection criteria applied to identify CCIS and RAIDS in-depth accident cases for the present analysis.

Table 2.
Primary selection criteria for RAIDS/CCIS in-depth cases

Category	Selection criteria
Collision	Frontal collision, no underrun/overrun, no rollover CDC side = F CDC principal direction of force (PDoF) = 11, 12 *and* 01 CDC pattern = E, N, S, U *and* W Number of impacts =1 *and* Number of impacts >1, where there is only one frontal impact *and* the frontal impact is the most significant impact *and* where the non-frontal impact CDC extents are <2
Vehicle type	M1 vehicle (passenger car)
Vehicle age	Registered between 2004–2015
Driver	Seat belt: Used *and* suspected use No unbelted rear occupant Gender known Injury severity: MAIS 0 to 6 (known) Frontal intrusion at knee level and above ≤10 cm
Front seat passenger	Seat belt: Used *and* suspected use No unbelted rear occupant Age: 12 years or older Gender known Injury severity: MAIS 0 to 6 (known) Frontal intrusion at knee level and above ≤10 cm
Rear seat passenger	Seat belt: Used *and* suspected use Age: 12 years or older Gender known Injury severity: MAIS 0 to 6 (known)

The main points to note are:

- Only belted occupants in passenger cars (M1 vehicles) involved in single frontal impacts were selected to ensure confounding factors in the analysis such as belt use and the influence of other impacts and rollovers were minimised.
- Children under the age of twelve were excluded because they would likely be using a child restraint system (CRS), which could confound the results of the analysis.
- Only occupants in vehicles compliant with R94 were selected to ensure vehicles with old, non-representative restraint systems were not included in the analysis. This was achieved by selecting vehicles registered 2004 and later (R94 compliance is mandatory for all new M1 vehicles since 1 October 2003).
- Only front seat occupants with injury not influenced significantly by compartment intrusion, such as HGV underrun collisions, were selected to ensure focus of the analysis on the performance of the restraint system. This was achieved by selecting front seat occupants of cars with frontal intrusion less than 10 cm at knee level and above (on any side of the car). This value was chosen on the basis of expert judgement that it should allow sufficient survival space for the restraint system to operate in its designed manner. Applying this intrusion limit reduced the sample size: compared to a casualty sample without this intrusion limit, the reported cases represent ca. 67% of all injured (MAIS 1+), ca. 59% of MAIS 2+ injured, and ca. 39% of those MAIS 3+ injured.

Figure 2 shows the resulting casualty sample size and composition.

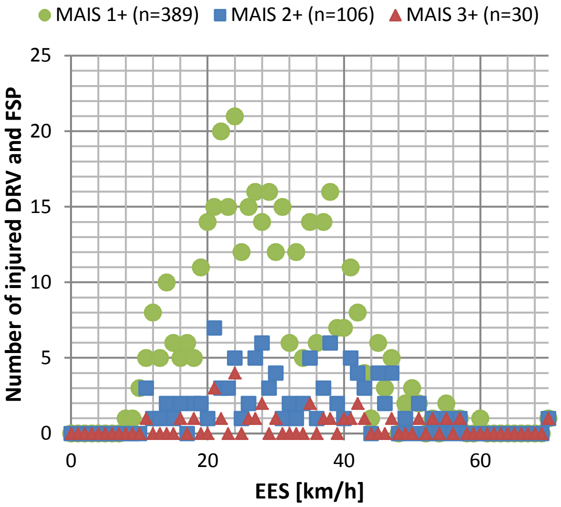

Figure 2. Casualty sample size and distribution across EES range for all injured (MAIS 1+), MAIS 2+ and MAIS 3+ casualties

In the context of this study, the term 'high-energy collision' was defined as a ±10 km/h margin around the R137 test speed (energy equivalent speed (EES) = 50 km/h), and a 'low-energy collision' as an equally wide band below these values, i.e.:

- High-energy collision: EES = 40–59 km/h
- Low-energy collision: EES = 20–39 km/h

RESULTS

Crash test to R137 specification (Test 2)

The configuration of Test 2 followed the frontal impact test procedure specified within R137 (Figure 3). The objective was to conduct a baseline test to evaluate the performance of the vehicle against the dummy injury limits stated within the regulation.

Figure 3. Test 2: Post-test photo, 45-degree view, after 50 km/h, full-width, rigid barrier frontal impact test according to R137

Table 3 summarises the resulting measurements of the driver and FSP Hybrid III ATDs. It can be seen that all parameters recorded were below the limits stated in the proposed R137.

**Table 3.
Test 2: Hybrid III dummy measurements and regulatory limits; colour-coding indicates compliance margin (orange: <10%, yellow: 10-20%, green: >20%)**

Dummy injury criterion	Test 2		R137 limits	
	Driver	FSP	Driver	FSP
	H3-50M	H3-5F	H3-50M	H3-5F
Head				
HIC15	668.50	541.87	–	–
HPC (HIC36)	840.53	807.74	1000	1000
Acceleration Resultant	77.58	70.21	–	–
Acceleration Res. (3 ms)	77.09	69.27	80	80
Neck Upper				
Force Shear Fx+	0.89	0.55	3.1	2.7
Force Shear Fx-	-0.46	-0.55	-3.1	-2.7
Force Tension Fz+	1.55	0.92	3.3	2.9
Force Compression Fz-	-0.02	-0.45	–	–
Moment-OC Flexion My+	23.85	21.74	–	–
Moment-OC Ext. My-	-21.24	-28.44	-57	-57
Chest				
Acceleration Resultant	53.22	55.99	–	–
Acceleration Res. (3 ms)	51.22	51.94	–	–
Deflection (sternum centre/max)	-26.01	-28.66	-42	-42
V*C	0.19	0.33	1.0	1.0
Femur				
Force Tension Fz+ left	0.23	2.46	–	–
Force Compr. Fz- left	-3.87	-0.13	-9.07	-7.00
Force Tension Fz+ right	0.28	1.73	–	–
Force Compr. Fz- right	-2.90	-0.57	-9.07	-7.00

Crash tests with THOR-M driver ATDs and at reduced impact speed (Tests 3 and 5)

Tests 3 and 5 were conducted at 50 km/h and 35 km/h, respectively (Figure 4 shows a photo of the low-speed test). In both cases, a THOR 50th percentile male dummy occupied the driver position. Note: A Hybrid III 95th percentile male dummy occupied the FSP position to investigate issues not covered in this paper.

Figure 4. Test 5: Post-test photo, 45-degree view, after low-speed (35 km/h), full-width, rigid barrier frontal impact test

Table 4 summarises the resulting measurements of the driver THOR-M ATD in both tests. Note: All comparisons with limit values in this paper relate to current R137 limits, as defined for the H3-50M, because equivalent limits (i.e. same risk of injury) have not yet been defined and agreed for the THOR-50M.

It can be observed that:

- During the 50 km/h test, the THOR-M driver HPC and head 3 ms resultant acceleration values were above the limits specified by R137.

- Head loading was much lower at 35 km/h than 50 km/h.
- The change in maximum chest deflection of the THOR-M driver dummy between the higher and lower speed tests was marginal despite a considerable difference in impact energy.

Table 4.
Tests 3 and 5: Dummy measurements; colour-coding indicates compliance margin relative to R137 limits as defined for H3-50M (orange: <10%, yellow: 10-20%, green: >20%)

Dummy Injury Criterion	Test 3 (50 km/h)	Test 5 (35 km/h)
	Driver	**Driver**
	THOR-50M	THOR-50M
Head		
HIC15	859.47	269.35
HPC (HIC36)	1099.32	377.59
Acceleration Resultant	86.10	54.83
Acceleration Res. (3 ms)	84.87	53.50
Neck Upper		
Force Shear Fx+	0.4	0.09
Force Shear Fx-	-0.16	-0.41
Force Tension Fz+	1.73	1.42
Force Compression Fz-	-0.09	-0.17
Moment-OC Ext. My-	-17.16	-7.88
Chest		
Acceleration Resultant	50.9	35.7
Acceleration Res. (3 ms)	50.1	34.4
Deflection (sternum centre/max)	-33.4	-31.8
V*C	0.26	0.2
Femur		
Force Tension Fz+ left	0.06	0.14
Force Compr. Fz- left	-6.30	-4.63
Force Tension Fz+ right	0.22	0.34
Force Compr. Fz- right	-2.60	-1.66

Figure 5 shows the chest deflection experienced by the driver dummy at test speeds of 50 km/h and 35 km/h. The THOR-M driver dummy maximum chest deflections were within 1.6 mm despite the 15 km/h difference in test speed and 50% difference in impact energy. Note: The maximum values were recorded at the left side of the chest during both tests (right-hand drive cars).

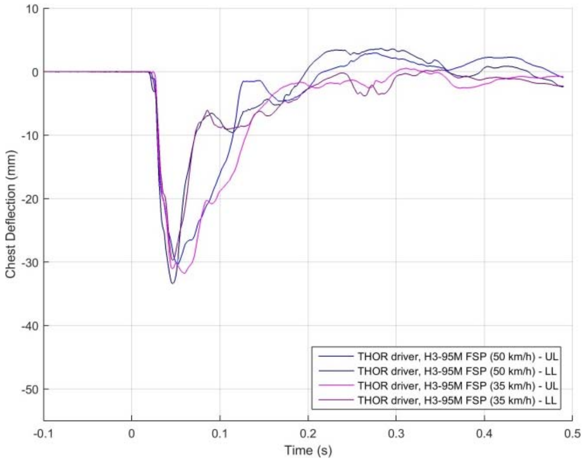

Figure 5. THOR-50M driver dummy chest deflection traces from Test 3 at 50 km/h and Test 5 at 35 km/h; upper left (UL) and lower left (LL) sensor, respectively

Figure 6 and Figure 7 show the corresponding seat belt forces recorded by load cells attached to the driver belt at test speeds of 50 km/h and 35 km/h for the shoulder and lap belt, respectively. It can be seen that the shoulder belt force reached virtually identical levels (load limiter) and only the lap belt force was reduced. This indicates that the shoulder belt part of the restraint system was stiffer than optimal for lower collision severities.

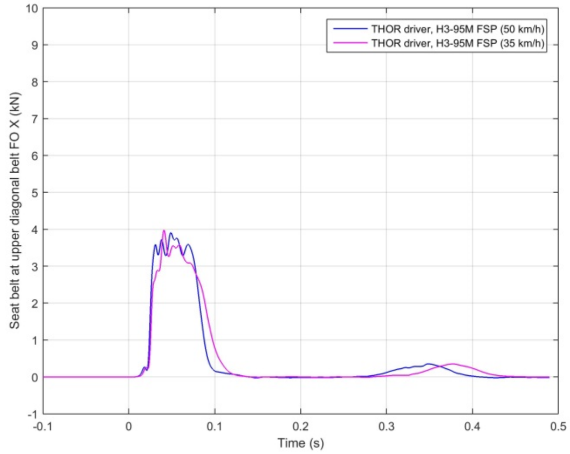

Figure 6. Shoulder belt loads from THOR-50M driver dummy in Test 3 at 50 km/h and Test 5 at 35 km/h

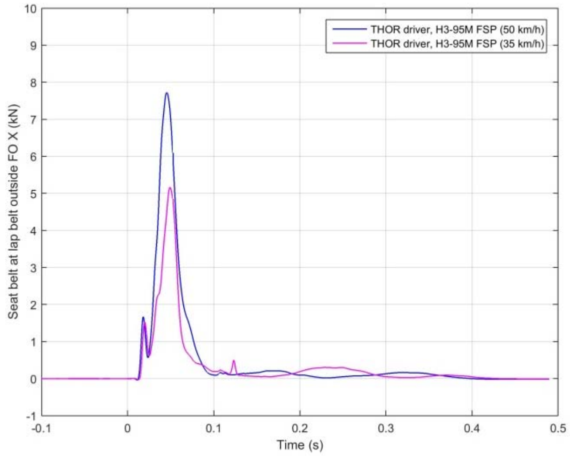

Figure 7. Lap belt traces from THOR-50M driver dummy in Test 3 at 50 km/h and Test 5 at 35 km/h

Crash tests with THOR passenger ATDs and at reduced impact speed (Tests 4 and 6)

Tests 4 and 6 were conducted at 50 km/h and 35 km/h respectively (Figure 8). In both cases a THOR 50th percentile male dummy occupied the FSP position. Note: A Hybrid III 95th percentile male dummy occupied the driver position and a Hybrid III 5th percentile female dummy occupied the rear seat behind the FSP to investigate issues not covered in this paper.

Figure 8. Test 6: Test photo at maximum pitch angle of low-speed (35 km/h), full-width, rigid barrier frontal impact test

Table 5 summarises the resulting measurements of the FSP THOR-M ATD in both tests.

It can be seen that:

- During both 50 km/h and 35 km/h tests, the HPC and head 3 ms resultant accelerations were comfortably below regulatory limits indicating that the head region was well protected.
- The chest deflection of the THOR-M FSP dummy at low speed (Test 6) was of a similar magnitude as the value measured previously for the driver (Test 5). However, the FSP chest deflection at high speed (Test 4) was considerably higher and exceeded the regulatory limit as defined for H3-50M by 24%.

Table 5.
Tests 4 and 6: Dummy measurements; colour-coding indicates compliance margin relative to R137 limits as defined for H3-50M (orange: <10%, yellow: 10-20%, green: >20%)

Dummy Injury Criterion	**Test 4 (50 km/h)**	**Test 6 (35 km/h)**
	FSP	**FSP**
	THOR-50M	THOR-50M
Head		
HIC15	370.93	227.94
HPC (HIC36)	636.52	344.86
Acceleration Resultant	103.18	49.89
Acceleration Res. (3 ms)	59.18	48.87
Neck Upper		
Force Shear Fx+	0.12	0.07
Force Shear Fx-	-0.43	-0.58
Force Tension Fz+	1.69	1.46
Force Compression Fz-	-1.19	-0.02
Moment-OC Ext. My-	-14.60	-7.10
Chest		
Acceleration Resultant	66.3	42.4
Acceleration Res. (3 ms)	62.5	41.2
Deflection (sternum centre/max)	-52.2	-36.2
V*C	0.37	0.32
Femur		
Force Tension Fz+ left	1.93	1.53
Force Compr. Fz- left	-0.50	-0.16
Force Tension Fz+ right	0.46	0.36
Force Compr. Fz- right	-1.20	-1.16

Figure 9 shows the chest deflection experienced by THOR-M FSP dummy over time during the high- and low-speed test. The maximum chest deflections of the FSP were recorded at the right side of the chest during both tests (right-hand drive cars).

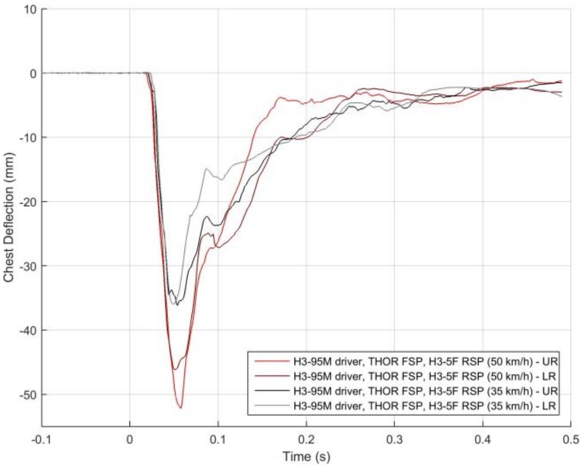

Figure 9. THOR-50M FSP chest deflection traces from Test 4 at 50 km/h and Test 6 at 35 km/h; upper right (UR) and lower right (LR) sensor, respectively

Figure 10 shows the shoulder belt force measured of time during the high- and low-speed test. It can be seen that the maximum force level in Test 4 exceeded the 4 kN load limiter-capped levels observed in the other tests by a considerable margin (Tests 3 and 5, see Figure 6; Test 6).

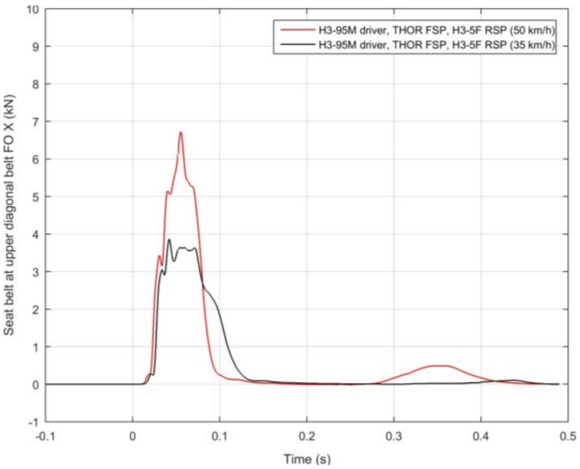

Figure 10. Shoulder belt loads from THOR-50M FSP dummy in Test 4 at 50 km/h and Test 6 at 35 km/h

Figure 11 and Figure 12 show the chest deflection traces for the three occupant sizes in the driver and FSP position, respectively, at a test speed of 50 km/h. It can be seen that THOR-M produced the highest chest deflection values in all positions (noting that injury risk functions and limit values for THOR-M have not yet been defined; see Discussion).

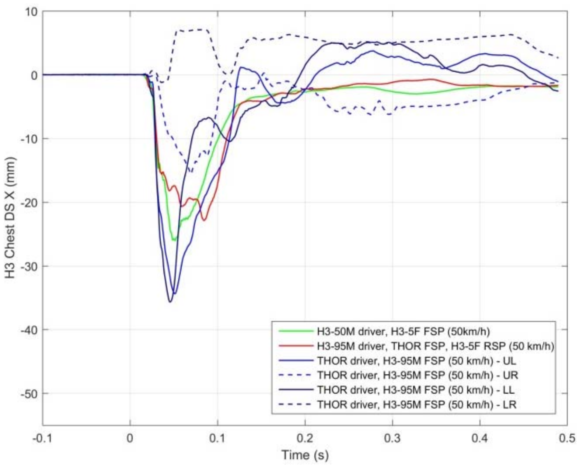

Figure 11. Comparison of the driver dummy chest deflection traces from Tests 2, 3 and 4 measured with H3-50M, THOR-50M and H3-95M, respectively (all 50 km/h)

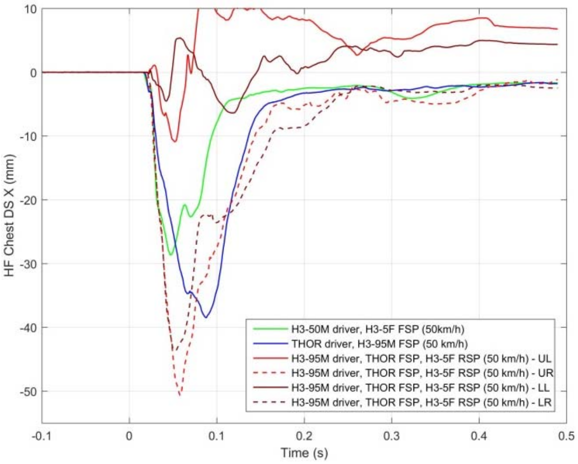

Figure 12. Comparison of the FSP dummy chest deflection traces from Tests 2, 3 and 4 measured with H3-5F, H3-95M and THOR-50M, respectively (all 50 km/h)

Accident analysis: Casualty target populations in high- and low-energy impacts

To examine whether the impact energy level of the current R137 test is appropriate for the casualty target population, the distribution of casualties across the EES range was examined (Figure 13). The median EES, i.e. the EES values below and above which half of the number of casualties in the sample occur, were found to be:

- All injured: $\overline{\text{EES}}_{\text{MAIS 1+}} = 27$ km/h
- MAIS 2+ injured: $\overline{\text{EES}}_{\text{MAIS 2+}} = 30$ km/h
- MAIS 3+ injured: $\overline{\text{EES}}_{\text{MAIS 3+}} = 30$ km/h

EES is a direct measure of impact energy, which allows an immediate comparison with crash tests. This shows that the real-world median EES values are considerably lower than the current regulatory frontal crash tests (EES ≈ 50 km/h).

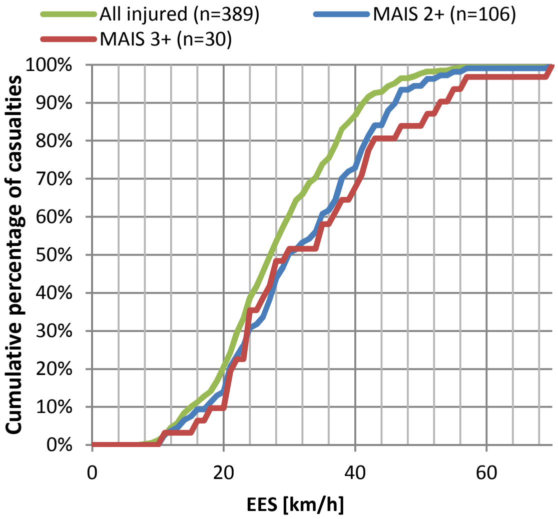

Figure 13. EES levels of injured front seat occupants (cumulative percentages)

In the following analysis the focus was on the more severely injured casualties (MAIS 2+), to explore in what EES range most of the relevant casualties occur (Figure 14). It is evident that the absolute number of MAIS 2+ casualties is fairly stable in the range of EES = 20–50 km/h. (Note: Given a certain variation due to the small number of casualties in each group. The marked dip in the range EES = 30-34 km/h was investigated but no reason could be identified; it is not observed when analysing MAIS 1 injuries, i.e. likely not exposure-related.) It can also be seen that more than half of MAIS 2+ casualties (in frontal impacts without major intrusion) occur within EES = 20–39 km/h. Similar trends can be observed for MAIS 3+ casualties (see Appendix).

It will be seen later on that injury outcome has a tendency to be better at lower EES levels (which can be expected because the impact energy is lower). Nevertheless the number of casualties is similar at low EES and high EES due to higher exposure (i.e. more collisions occurring at lower energy).

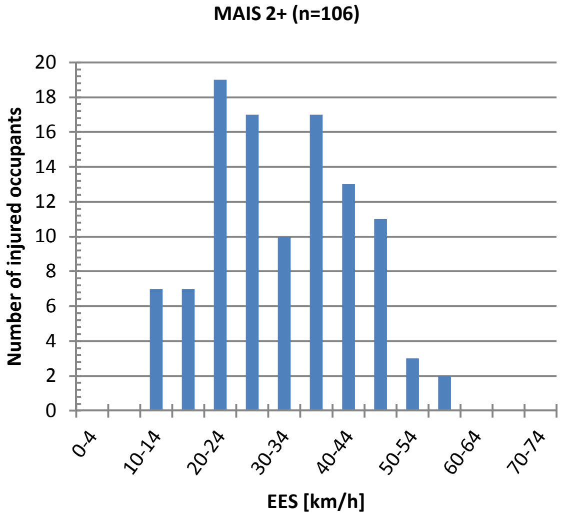

Figure 14. Number of MAIS 2+ injured front seat occupants (absolute casualty numbers) per EES range in 5 km/h intervals

Accident analysis: Injured body regions

The body regions most exposed to forces from occupants' restraints and therefore most relevant when considering potentially restraint-related injuries are thorax, abdomen and pelvis. Figure 15 compares the likelihood of MAIS 2+ injury in each of these three body regions across the EES range.

Note: The 'likelihood of MAIS 2+ injury' is defined here as the proportion of occupants within the casualty sample who sustained MAIS 2+ injuries in a given body region. These values are therefore indications of the severity distribution within a selected sub-section of the casualty sample.

Comparing the three charts shows that the likelihood of sustaining injuries in the thorax region is generally higher than in the abdomen or pelvis region. An exception is the abdomen in the range EES = 55–59 km/h. Examples of AIS 2+ thoracic injuries are fractures of two ribs (AIS 2) sternum fracture (AIS 2), fractures of three or more ribs (AIS 3), or minor lung laceration (AIS 3).

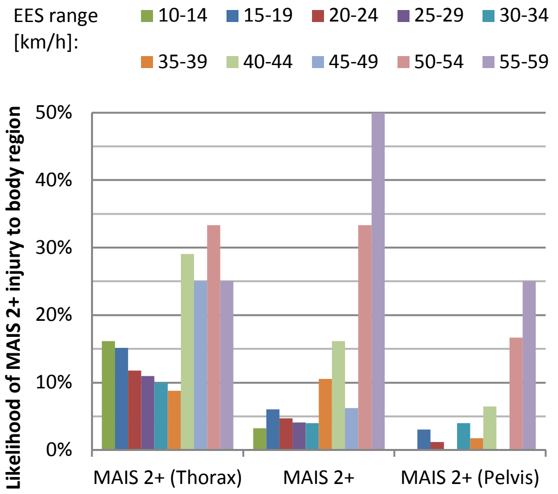

Figure 15. Comparison of the likelihood of MAIS 2+ injury to thorax, abdomen or pelvis between different EES ranges

Reading the individual graphs from right to left, they show that the likelihood of MAIS 2+ injury reduces overall with reducing EES, which is in accordance with expectations due to the lower energy absorbed by the car. The data appears to suggest a rather steep drop in likelihood in the range around EES ≈ 40 km/h for MAIS 2+. Notably, however, with further reduction of the impact energy, the likelihood of MAIS 2+ thoracic injuries does not decrease anymore (even appears to increase in this relatively small sample). A similar trend can be observed for MAIS 3+ casualties (see Appendix).

This indicates that the injuries inflicted to the thorax do not reduce in correspondence with what could be expected from reduced impact energy. Inappropriately high forces of the diagonal seat belt (load limiter levels) acting on the occupant's chest at lower impact energies are a possible explanation for this.

Accident analysis: Role of casualty age

Figure 16 visualises the distribution of MAIS 2+ casualties in the sample between age groups across the EES range. The graphs display a clear tendency that the proportion of elderly casualties, i.e. those aged 66 or older, expands towards lower EES values whereas younger casualties become under-represented. The speed range for which elderly casualties dominate is around EES = 30–34 km/h. A similar trend can be observed for MAIS 3+ casualties (see Appendix).

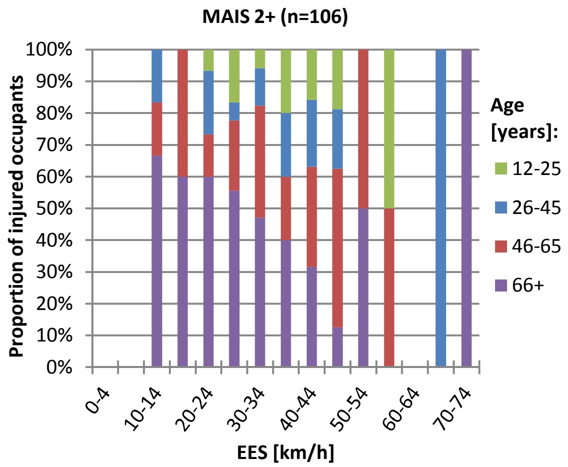

Figure 16. Distribution of MAIS 2+ injured front seat occupants across age groups per EES range. Note: The value at EES = 70–74 km/h is based on a case number of one and therefore not suitable for comparison

Figure 17 and Figure 18 explore this age-related trend between different injury severity levels, based on aggregating the above numbers for low- and high-energy impacts, respectively. Figure 17 shows a stark increase of the proportion of elderly casualties at higher injury severity levels: The proportion of casualties aged 66 years or older in the casualty sample increases considerably when focussing on higher severity levels: from 23% amongst all injured, to 82% amongst those with MAIS 3+ injuries.

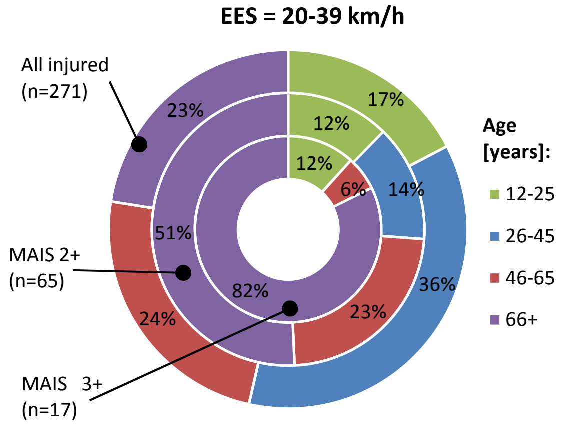

Figure 17. Comparison of age distribution of injured front seat occupants between different injury severity levels in low-energy frontal impacts

Figure 18 shows the same data for high-energy impacts, where the prevalence of elderly casualties also increases with higher injury severity level, but not to the same extent. This indicates that elderly casualties in low-energy impacts are of particular relevance when considering protection against MAIS 3+ injuries.

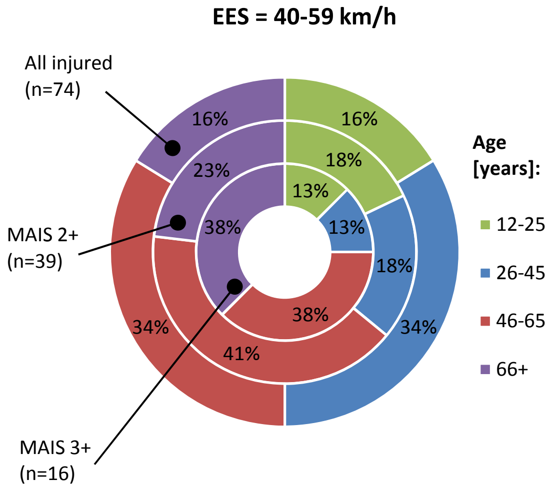

Figure 18. Comparison of age distribution of injured front seat occupants between different injury severity levels in high-energy frontal impacts

Limitations of the accident analysis

The present analysis was performed based on in-depth accident data from the UK. The analysis cannot be transferred in detail to the whole EU because impact typology varies across the member states. The authors have, however, no reason to believe that the general trends observed will differ or that the magnitude of the results would be of a different order.

Collisions with considerable intrusion were excluded from the sample to ensure focus of the analysis on the performance of the restraint system. Because of the positive correlation between extent of intrusion and impact energy (i.e. a tendency of more intrusion at higher EES) it is reasonable to assume that the reported EES levels are lower than in a sample that would include the cases with considerable frontal intrusion.

DISCUSSION

Will R137 encourage adaptations to current restraint systems?

The standard configuration R137 crash test with Hybrid III ATD (Test 2) showed that the tested series production variant of the Fiat 500 was capable of meeting the proposed legislative requirements in a full-width, rigid barrier, 50 km/h test.

All dummy injury metrics measured were lower than the performance limits specified in R137. Most performance requirements had a compliance margin greater than 30%. However, the dummy head injury metrics were close to the regulatory limit. The driver and FSP HPC and the head acceleration metrics were within 20% of the R137 limit, with the driver 3 ms exceedance value being within 10% of the R137 limit.

Although these values met the requirements, the manufacturer may wish to make some modifications in order to comfortably meet conformity of production requirements. When the 5th percentile female FSP chest deflection requirement is reduced to 34 mm (from the current 42 mm, to provide the same risk as for the 50th male ATD) in September 2020, the compliance margin would be reduced to approximately 16%. It is likely that the manufacturer could make minor design changes in order to meet the limits with a greater compliance margin.

These results indicate that the proposed new regulation with Hybrid III ATD in the front seating positions is unlikely to enforce major restraint system design changes to current vehicles. This casts significant doubt whether the test will improve real-world EU road safety; however, it can provide a platform for potential future improvements.

The subsequent tests carried out with THOR-M ATD at the driver and FSP position respectively (Test 3 and Test 4) showed in some cases greater injury metrics: The driver head acceleration (3 ms exceedance) and HPC were both much larger with THOR-M than with the Hybrid III ATD, and both metrics exceeded the R137 performance requirements when assessed with THOR-M. The THOR-M peak chest deflection in the driver's seat was markedly greater than that measured with the Hybrid III, although it would still meet the R137 performance requirement. When placed in the FSP position, the THOR-M chest deflection greatly exceeded the R137 requirement as defined for H3-

50M (52 mm cf. a requirement of 42 mm). Note that the shoulder belt force value in this test exceeded by far the load limiter-capped levels observed in the other tests.

These comments on the chest deflection assume that the chest deflection limit for THOR-M would be identical to that for Hybrid III. Injury criteria and injury risk functions for THOR-M chest deflection are still in development and have not been finalised. However, there is already some indication that the limit would actually be slightly lower for THOR-M (for an equivalent risk of injury), i.e. the THOR-M may be more stringent than indicated by these results.

Overall, the THOR-M ATD was much more stringent than the Hybrid III, both in the driver and the FSP positions, and changes to the design of the vehicle would be necessary in order to meet the performance requirements defined in R137.

Protection at lower impact energies

Reducing the test velocity from 50 km/h to 35 km/h resulted in a general reduction of injury metrics in line with the reduction in test severity, with the exception of chest deflection, which reduced by much less than may be expected: The maximum chest deflection measured by the THOR-M dummy in the driver's seating position only reduced by 1.6 mm (5%, from 33.4 to 31.8 mm) despite a 50% reduction in collision energy.

In the FSP position, a 30% drop in maximum chest deflection could be observed between impact speeds (52.2 and 36.2 mm at 50 and 35 km/h respectively). However, this is not owed to optimised performance at low speeds, but rather to the high chest deflection that occurred at 50 km/h (52.2 mm; shoulder belt force value exceeded the load limiter-capped levels observed in the other tests).

The findings from the accident data analysis show that there are indeed a considerable number of casualties sustaining MAIS 2+ injuries, in particular to the thorax region, at impact energies which are lower than currently tested in legislation (20-39 km/h group). This means there might be a large target population for a potential low-energy restraint test.

The likelihood of MAIS 2+ injury in real-world collisions did reduce considerably when comparing high-energy and low-energy impacts, i.e. the observation is mainly exposure-related (more collisions occurring at lower speeds). However, when EES reduces further (below about 40 km/h), the likelihood of injury reduces only marginally. This is an indication that the potential for improved occupant protection offered by reduced impact energy levels is currently not fully used.

Elderly casualties (66 years and older) were starkly over-represented in the low-energy casualty groups. The reduced biomechanical tolerance of elderly occupants, in particular the more brittle bone structure and calcification of the costal cartilage (making the rib cage less flexible), makes them more susceptible to sustaining injuries. The findings of seat belt-induced rib fractures are an indication that the force limits of current seat-belt load limiters might be too high to effectively protect elderly occupants from thorax injury.

Therefore, in order to increase the likely benefit of R137, it is recommended that further analysis is conducted to determine the benefits of introducing a low-speed test to encourage restraint systems that adapt to accident severity. The data appear to suggest an EES value between 25 km/h and 34 km/h could be most suitable for a low-energy test as it represents approximately the centre of MAIS 2+ injury distributions. However, more detailed collision research with weighted data would be required to substantiate an energy level. Additionally, the test speed selected for the low energy test should be balanced so that it is high enough for the ATDs to remain biofidelic (e.g. >20 km/h), but sufficiently different to the high speed test in order to encourage adaptive restraints.

It may not be possible to reduce the load limit in higher energy collisions because of the risk of bottoming-out the airbag and sustaining serious head injuries, but it is possible to consider the application of lower load limits in lower energy collisions where not all of the available ride-down space is being made use of. This demonstrates the importance of considering the reduced biomechanical tolerance of elderly occupants when defining injury criteria thresholds for a potential low-energy restraint test to ensure that the limits are stringent enough to encourage the desired effect in the real-world.

CONCLUSIONS

Regarding the expected impact of the introduction of R137 on restraint system design of European cars (Research Question 1), the main conclusions from this study are:

1. The tested supermini production car would already pass R137 performance requirements measured with Hybrid III ATD (although some modification may be required to provide a more typical compliance margin). The THOR-M ATD was much more stringent, both in the driver and the FSP positions, and changes to the design of the vehicle would be necessary in order to meet the performance requirements defined in R137 if the THOR-M ATD was implemented.
2. In order to deliver the expected benefits, implementation of the THOR-M ATD as a replacement for the current Hybrid III ATD in R137 should be considered at the earliest opportunity. It is likely that the 50M (average size male) version could be introduced first, followed by the 5F (small female) version when it is available.

Regarding the protection of occupants at lower impact energies (Research Question 2), the following main conclusions were drawn:

3. It appears justified to explore further the potential introduction of a low-energy restraint test, because it might address a large target population.
4. An appropriate energy level for the test might be an EES value between 25 km/h and 34 km/h, based on the collision data reviewed, although other factors such as the suitability of the crash test dummy for use at very low speeds may also need to be considered.
5. The injury criteria thresholds for the test should be adjusted to reflect the reduced biomechanical tolerance of elderly occupants.

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The project used accident data from the current Road Accident In-depth Studies (RAIDS), which is managed by the Transport Research Laboratory on behalf of the UK's Department for Transport (DfT), who funded the programme. Furthermore it used data from the Co-operative Crash Injury Study (CCIS), also managed by the Transport Research Laboratory on behalf of DfT who funded the project along with Autoliv, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Previous sponsors of CCIS have included Daimler Chrysler, LAB, Rover Group Ltd, Visteon, Volvo Car Corporation, Daewoo Motor Company Ltd and Honda R&D Europe (UK) Ltd. Data were collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Vehicle Safety Research Centre at Loughborough University; the Transport Research Laboratory; and the Vehicle & Operator Services Agency of the DfT.

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[1] UN Regulation No. 137. 2016. "Uniform provisions concerning the approval of passenger cars in the event of a frontal collision with focus on the restraint system". https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2016/R137e.pdf

[2] Amendment 1 to UN Regulation No. 137. 2016. "01 series of amendments to the Regulation 'Uniform provisions concerning the approval of passenger cars in the event of a frontal collision with focus on the restraint system'". https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2017/R137am1e.pdf

[3] Association for the Advancement of Automotive Medicine (AAAM). 2008. "The Abbreviated Injury Scale 2005 – Update 2008". Des Plaines, Illinois, U.S.A.

APPENDIX

Additional graphs from accident analysis

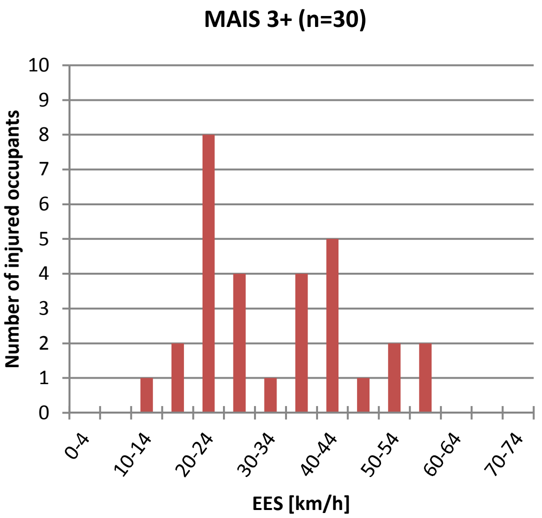

Figure 19. Number of MAIS 3+ injured front seat occupants (absolute casualty numbers) per EES range in 5 km/h intervals

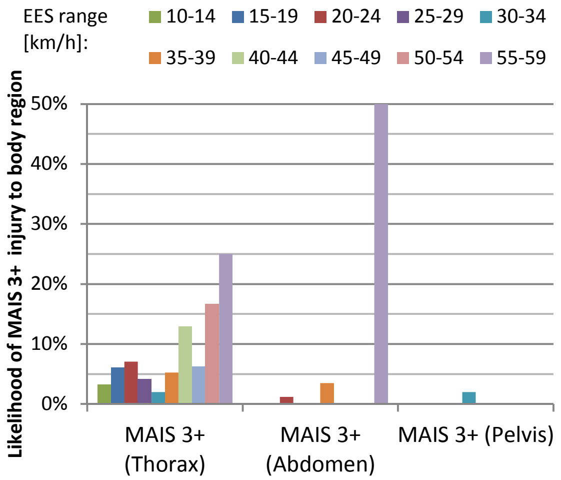

Figure 20. Comparison of the likelihood of MAIS 3+ injury to thorax, abdomen or pelvis between different EES ranges

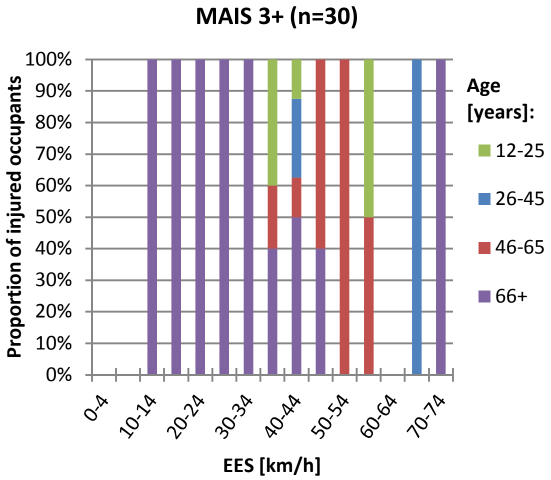

Figure 21. Distribution of MAIS 3+ injured front seat occupants across age groups per EES range. Note: The value at EES = 70–74 km/h is based on a case number of one and therefore not suitable for comparison.