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Adapting Load Limiter Deployment for Frontal Crash Diversity

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ABSTRACT

Objective: Current European restraint systems may not realise their full protection potential in real world frontal crashes because they are highly optimised for specific conditions. This research sought to quantify the potential benefit of adapting seat belt load limit thresholds to a wider range of occupant and crash characteristics.

Methods: Numerical simulations using hybrid III dummies were conducted to determine how varying load limiter thresholds could affect occupant kinematics and injury outcome in frontal impacts. Occupant-compartment models were developed with a restraint system consisting of a frontal airbag, a 3-point belt with retractor, buckle pretensioner and load limiting at the shoulder. Load limiting threshold was varied in five frontal impact scenarios, covering as wide a range of real frontal crash conditions as possible. The lowest simulated thoracic injury risks were converted into injury probability values using AIS 2+ age dependent thoracic risk curves. These values were then applied to a British real-world frontal impact sample to determine the injury reduction potential of optimised load limiting; taking into account occupant seating position, impact scenario, occupant size and occupant age, and assuming an appropriate adaptive system was fitted to all cars.

Results: In low severity impacts, a low load limit provided the best chest protection, without increasing risk to other body regions, for both the 50th and 95th percentile dummy in both front seating positions. In high severity impacts, the low limit was not recommended since it allowed the driver dummy to move into close proximity with the vehicle interior, although there appeared to be some benefit of lower load limiting for the 50th percentile front passenger dummy, due to the increased ride down space in that seating position. Adapting the load limit showed no injury reduction potential for 5th percentile drivers. Utilising the best load limit threshold in real world crashes, could reduce the number of occupants with AIS 2+ chest injury from belt loading from 377 to 251 (a 33% reduction). Correspondingly reducing the number of occupants with AIS 2+ chest injury (from all sources) in the whole frontal impact population from 496 to 370. This is a reduction in injury rate from 6.4% to 4.8%.

Conclusions: The concept of an adaptive load limiter shows most promise in low speed frontal crashes where it could lower the AIS 2+ chest injury risk for most front seat occupants, except the smallest of drivers. Generally, adaptive limiters show less potential effectiveness with increased crash severities. Overall, an intelligent adjustment of load limiting threshold could result in a reduction of at least a third of front seat occupants with AIS 2+ chest injury associated with restraining loads and an overall reduction in AIS 2+ chest injury rate in frontal crashes from 6.4 to 4.8%

Keywords: adaptive restraints, chest injury, elderly occupants, frontal crash, load limiter, real world

INTRODUCTION

There are several different aspects of diversity that can determine the injury severity outcome in a frontal crash. These include crash characteristics, restraint use and type, and age, BMI and gender of occupants (Carter et al. 2014).

Older vehicle occupants are increasing in number. Unfortunately, they are the most fragile and tend to have some of the worst injury outcomes in a crash. The higher rate of chest injury and associated mortality to elderly occupants is reported by several authors (Ekambaram et al. 2019; Kent et al. 2009).

Numbers of female drivers are also increasing. Their gender-specific tolerance to crash loads is different to males (Linder & Svensson 2019). Females are generally underrepresented in fatal and serious motor vehicle crashes (Bose et al. 2011) but despite their lower crash involvement rate, studies have shown that they are most at risk of being killed or seriously injured in a crash (Bose et al. 2011). They are generally smaller in stature and tend to sit closer to the front interior structures (Parkin et al. 1995; Welsh et al. 2003), resulting in an increased risk of serious head, chest and pelvic injury from contact with the airbag and lower facia (Welsh et al. 2003).

Seating position is another important aspect of diversity. Drivers are usually at higher risk compared to front passengers due to lower ride-down distance. However, studies have also found that females and the elderly are more likely to occupy the front passenger seat (Ekambaram et al. 2019). This implies that, at least in Europe, safety systems which are optimised for an average male may not be optimal for the occupants who most often use that seating position. European frontal crash safety tests currently only evaluate the 50th percentile male dummy in the front passenger seat. US regulation and USNCAP do include the 5th percentile Hybrid III dummy, although there are still questions concerning how well its anthropometry and the injury assessment reference values represent a small female (Linder & Svensson 2019).

Diversity is not only limited to occupants; frontal crashes are not all the same. Crash characteristics such as crash speed, impact load distribution and the extent of passenger cell intrusion can all influence severity of injury. Addressing the safety of occupants in high speed impacts is necessary, however it is also important to test crashworthiness in lower speed impacts which occur more frequently. In low speed impacts, traditional restraints may be too rigid and may not fully utilise the available ride down space (Ekambaram et al. 2015, Hynd et al. 2011). Crash severity is also determined by the amount of frontal overlap of the vehicle. A fully overlapping frontal impact will test the restraint system much more severely than a frontal offset impact which has more emphasis on crash structure performance.

Since 1997, the EuroNCAP frontal impact assessment has employed a 40% offset deformable barrier impact at 64 km/h, and modern European restraint systems have been optimised to produce good safety scores in this test. Optimising safety systems for one particular crash type has produced significant safety gains, but these systems may not be as effective when real world frontal crash conditions vary. To address this concern, in 2015, EuroNCAP introduced an additional frontal impact test. One in which the car strikes a rigid barrier with full overlap at a speed of 50 km/h. The limitations of current restraints are shown because cars performing well in the offset impact do not yet demonstrate the same protection in the full overlap configuration. In the near future, EuroNCAP will introduce the THOR frontal impact dummy, which has improved biofidelity and is capable of utilising age dependent injury risk functions. This will be an additional challenge to restraints which deploy at pre-determined thresholds (so-called Single Point Restraints).

The enhancement of crash protection afforded by seat belts is unequivocal. It is estimated that seat belts have saved more lives since 1960 than all other crashworthiness design features combined (National Highway Traffic Safety Administration, 2005). However, in frontal impacts, chest injuries continue to occur despite correct restraint use. In those crashes, the chest is one of the most frequently injured body regions at the AIS 2+ injury level, and the injury mechanism most frequently identified relates to chest restraining loads as the occupant moves into the belt (Hardy et al. 2005). One way to further enhance the capability of the seat belt could be to intelligently modify the restraining force by adapting the load limiter deployment threshold with so-called “adaptive load limiters”. By utilising information such as the occupant age and size, seat position, crash overlap and crash severity, the restraint could be made to vary its deployment parameters to address that diversity.

This study investigated whether chest injuries could be further reduced in a representative sample of real world European frontal crashes, if the best load limiting threshold were selected, taking account of occupant and crash variables. Previous studies have attempted to address this using simulation to investigate the efficacy of restraint adaptation for the 50th percentile male dummy (Ekambaram et al. 2015). The current study has progressed this by considering a wider range of occupant sizes using different seating positions.

METHODS

An occupant compartment simulation model was developed and used to determine the load limiter settings which would provide the lowest chest injury risk in five crash test configurations, representing real world frontal crash conditions where front seat occupants sustained AIS 2+ chest injury and where the injury mechanism was deemed to be related solely to the occupant loading the belt restraint – hereafter described as restraining loads. To cater for the diversity of real world occupants, a range of dummy sizes and seating positions were included in the assessment. The new, simulated injury outcomes were then translated into likely real-world injury severities and applied to the real frontal crash sample, in order to assess overall chest injury reduction benefit.

Real World Crashes

Crash injury data collected between 1998 and 2008 for the UK Co-operative Crash Injury Study (CCIS) were interrogated. The data were statistically weighted to represent the population of UK crashes and injury outcome was recorded using the Abbreviated Injury Scale (AAAM 1990). The study methodology is described by Mackay et al. (1985) and Hassan et al. (1995). The criteria used to select the frontal impact sample are shown below:

- Single frontal impact or two impacts with frontal impact being the most significant in causing injuries
- Principal direction of force (DOF) between -30^{o} and +30^{o}
- Vehicle manufactured after calendar year 1995
- Three point belted front seat occupant $\geq$ 15 years of age
- Frontal airbag, seat belt pretensioner and load limiter
- No under-ride or rollover crashes

This resulted in a sample of 7729 occupants of whom 496 (6.4%) had sustained AIS 2+ thoracic injury. Of those, 377 (76%) were identified where the injury mechanism had been identified as belt restraining loads only. This group of occupants formed our population of interest.

The population of interest was then classified into groups of similar crashes based on front end overlap, Energy Equivalent Speed (EES), passenger compartment intrusion and width of damage. Crashes with overlap above 70% were considered as full overlap and crashes with overlap less than 60% were considered as offset. Crashes with overlap between 60 and 70%, front fascia and/or steering wheel intrusion above 80 mm or impact to narrow objects with diameter <41 cm were included in an unclassified category. The classification resulted in six groups of real world crashes. The groups represented a low pulse offset and full overlap condition, a mid pulse offset condition, a high pulse offset and full overlap condition, and an unclassified condition (Table 1).

Simulated Test Configurations

Crash pulses based on crash test front end overlap and speed were chosen to represent the real crash conditions. Crash pulses and associated restraint deployment thresholds were based on C segment European vehicle platforms with European restraint systems. This proprietary data was provided by a large world OE manufacturer. Five frontal crash test configurations were matched to 298 of the real world crash conditions (representing 79% of the population of interest). Table 1 shows the match and the peak crash pulses, but it should be noted that the rate of deceleration and the onset of the peak pulse differed between full and offset impact types.

Four different seat belt load limiter behaviours were simulated. The constant seat belt load limiter (SBL) threshold was varied between 2, 3, and 6 kN along with a baseline model of 4 kN. Airbag triggering time was set according to the crash pulse severity and was as follows a) Low FRB: 45 ms, b) Low ODB: 38 ms, c) Mid: 28 ms, d) EuroNCAP: 25 ms and e) USNCAP: 15 ms. The analysis was conducted for both driver (DVR) and front seat passenger (FSP) seating positions, resulting in 100 parametric tests.

Occupant Compartment Model

Generic baseline driver and front passenger compartment models using MADYMO software were developed with identical frontal restraints and interiors including the steering system, seat and front fascia (TNO 2013, Figure A 1). The models were representative of a C segment car (also termed a Small Family Car in Europe) and represented the important points of front seat occupant interaction in a frontal impact. The compartment models were developed with an initial baseline restraint system, consisting of a frontal airbag and a 3-point belt with retractor, buckle pretensioner and load limiting at the shoulder. Further details of the restraint system and model validation can be found in the appendix.

The generic compartment models were then adapted to accommodate different dummy sizes. The 5th and 95th percentile dummies were positioned in the far forward and far rearward position respectively. The 50th percentile in the mid track position (Justification for dummy positioning is noted in the appendix).

Selection of Best Load Limiter Configuration

From the simulation results, the best load limiter threshold in each impact condition was selected. This was defined as the load limiter setting resulting in lowest chest injury risk, without increasing injury risk to other body regions. To determine this, a technique used by NHTSA, the joint injury probability (Pjoint) was used (NHTSA 2008). Further details of the procedure are shown in the appendix. Additionally, an excursion limit was also considered to cater for driver dummy movement into a zone where interior interaction became more likely. This was defined as to within 80 mm of the steering wheel hub. Its justification is included in the appendix.

Benefit Quantification

In order to calculate benefits, the best simulated chest injury outcomes first required adjusting for occupant age. This was achieved by using an age-related chest injury risk function developed by Ekambaram et al. (2015) and detailed in the appendix. The real-world injury reduction benefit was quantified by applying the estimated relative chest injury risk reduction obtained from simulations to the matched real-world accident sample according to the occupant seating positions, impact scenario, occupant sizes and occupant age. The procedure for achieving this is explained in the appendix. For those cases which were not matched with a simulated scenario, and including 5th percentile occupants in the passenger seat, it was assumed that varying the load limiter would not have produced any change in the chest injury risk. i.e. ratio of Rbest and Rbase is 1.

RESULTS

Best Load Limiter Configuration

The simulation output used to estimate the 4 kN (baseline) injury risk is provided in Table 2 and Table 3. The relative percentage change in driver and front seat passenger dummy HIC15, chest compression and Pjoint score for SBL settings 2, 3 and 6 kN relative to the baseline 4 kN SBL model is shown in Table A 3 and Table A 4 where the 'best' selected restraint system in each of the crash pulses is represented with an asterisk. An explanation of tables A 3 and A 4 is provided in the appendix. The appendix also contains a more detailed description of the observed dummy kinematics.

50th percentile driver The predicted head, chest and overall injury scores were lowest with the 2 kN SBL in both low pulse tests. In both conditions the limit of dummy excursion also remained more than 80 mm from the wheel, therefore this was selected as the best restraint system in the low pulse impacts. The 2 kN SBL in the mid pulse impact produced best head, chest and overall injury scores, however, the forward displacement of the thorax moved it to less than 80 mm from the steering wheel hub. The 3 kN SBL produced lower injury risks than the baseline model while not displacing the dummy closer than 80 mm and therefore was chosen as the best restraint for mid pulse crashes. In both high crash pulses, the chest excursion with a 2 and 3 kN SBL surpassed the pre-determined limit from the steering wheel while the 6 kN SBL increased the Pjoint and chest injury risk. Therefore the baseline model was chosen as the best restraint configuration in both high pulse scenarios.

5th percentile driver Irrespective of crash pulse and SBL configuration the dummy head had early interaction with the deploying airbag and excursed to less than 80 mm from the steering wheel in all impacts. With the 2 kN SBL in the EuroNCAP impact, the head was even observed to 'bottom out' the airbag. It was considered that varying the load limiter for smaller occupants who tend to sit closer to the steering wheel has limited scope with the restraint system tested. For this reason, the baseline 4 kN SBL was chosen for the small female dummy in all simulated impacts.

95th percentile driver The 2 kN SBL was chosen as the best load limit for both low pulse scenarios because in both, it gave the best chest and overall injury outcome with dummy forward displacement outside of the pre-determined limit. In the mid pulse impact, with a 2 kN SBL, the forward displacing dummy pushed the airbag upwards and rearwards, reducing the amount of airbag between the thorax and steering wheel, and increasing the peak chest accelerations above those of the baseline limiter. The 3 kN SBL was chosen for the mid pulse scenario because it showed some reduction in chest injury risk with acceptable forward movement. In both high pulse impacts, the dummy pushed the airbag upwards and rearwards with the 3 kN SBL, therefore the baseline SBL was retained.

50^{th} percentile passenger The 2 kN SBL produced lowest chest compression scores in both low pulse tests and was chosen as the best SBL. The 3 kN SBL in mid-pulse and EuroNCAP impacts provided the best injury protection without excessive dummy forward movement. Varying the load limiting threshold from the baseline level did not produce any tangible injury reduction benefit for the USNCAP impact.

95^{th} percentile passenger In both low severity impacts, use of a 2 kN SBL produced the best chest and overall injury outcomes. In the mid and both high pulse impacts, employing a 2 kN SBL resulted in the amount of belt fed into the system reaching the maximum modelled amount of 400 mm, abruptly stopping the introduction of belt from the retractor and resulting in greater acceleration forces to the dummy head and chest. This effect was not seen with the 3 kN SBL, although the benefits of that setting were negligible compared to the baseline SBL. Since no injury reduction benefit was predicted by lowering the load limiting, the default SBL threshold of 4 kN was selected as the best option for the mid and high pulse impacts.

Benefit Quantification

The potential benefit of an adaptive load limiter was estimated by matching the best chest injury outcome from simulation to real front seat occupants who had sustained AIS 2+ chest injury from restraining loads. Where simulation was not performed, the chest injury risk was considered to be unchanged. The risk of AIS 2+ chest injury when employing a baseline (Rbase) and best (Rbest) SBL set up is shown in Table A 5**Error! Reference source not found.**, for occupant size, seating position, age and frontal impact configuration. Table 4 summarises the benefits. Older occupants gained most benefit from load limit reduction (AIS 2+ chest risk reduced from 13.1% to 8.6%). However, young and middle aged occupants also benefitted with risk down from 1.3% and 7.6% to 0.9% and 5.0% respectively. If the best load limit threshold had been used in the real world crashes, the number of occupants with AIS 2+ chest injury from belt loading could have been reduced from 377 to 251 (a 33% reduction). In turn, this would have reduced the number of occupants with AIS 2+ chest injury (from all sources) in the whole frontal impact population from 496 to 370. This is a reduction in injury rate from 6.4% to 4.8%.

DISCUSSION

The mitigation of chest injuries using seat belt load limiters has been shown before in cadaver studies (Kent et al. 2001) and also in field studies (Foret-Bruno et al. 1998). However, chest injuries continue to occur in modern European cars, despite almost universal load limiter fitment. This parametric adaptation study set out to answer the question – could an intelligent load limiter (able to adapt to different occupant and frontal crash characteristics) improve chest protection in real world operating conditions? The effect of appropriately varying load limiting values was investigated with simulation, using different sizes of dummy in each front seat, in five simulated frontal impact scenarios representing 80% of real-world frontal crashes which resulted in AIS 2+ chest injury from restraining loads. Belt load limiting was varied between 2, 3, 4 and 6 kN with 4 kN being considered the standard baseline. Results suggested that optimal load limits differ, depending on type of frontal impact and occupant age, size and seating position.

For the 50^{th} percentile driver dummy with low and mid severity impacts, low load limits produced the best chest injury outcome with acceptable dummy forward displacement. However, with high severity impacts, the 2 kN limiter, despite producing the lowest chest deflection, resulted in excessive forward movement. This implies that caution is needed when choosing a low load limit threshold in high severity impacts.

For the 95th percentile driver, in low severity impacts, low load limits also provided the best injury outcome, with acceptable dummy excursions. However, the extra seat belt slack introduced by low load limits resulted in excessive dummy forward excursion in both mid and high severity impacts, resulting in sharp peaks in the chest acceleration response due to contact with the airbag and steering wheel assembly.

The 5th percentile driver dummy demonstrated excessive forward excursion in all impact configurations. In low severity impacts, it was found that deployment time of the airbag was very important for the shorter stature occupant. Later deployment of the airbag induced undesirable dummy-airbag contact resulting in higher peak head accelerations. This suggests that the opportunity for improving small stature driver protection simply by adapting load limits is not as great as it is for average and large drivers. European cars do not currently perform well in the EuroNCAP full overlap frontal restraint test because of the technical difficulties in protecting the small driver with a restraint which is often optimised for the "average" size male in an offset impact configuration. One of the possible solutions to achieve load limiter variability for the short statured occupant is by optimising the airbag trigger time and/or reducing the airbag volume. Simply reducing the airbag volume may have negative effects for larger occupants but adaptive airbags could vary the airbag volume and pressure according to the occupant size. As reported in the literature, this technology could protect the 5th percentile female in the forward seated position (Hynd et al. 2011; Bosch-Rekveldt et al. 2005), without affecting other occupant groups.

Simulations with the 50th percentile male passenger dummy showed that the 2 kN load limiter produced the best chest and overall injury scores in low severity impacts, whilst the 3 kN limiter produced the best injury protection in mid severity and EuroNCAP impacts with stable airbag loading. Compared to the 50th percentile driver, there appeared to be more scope for the use of a lower than baseline load limit in the high pulse EuroNCAP impact. This suggests that different load limiting for each front seat position could be beneficial.

For the 95th percentile passenger in low severity impacts, lowering load limiter deployment to 2 kN predicted low injury risk values. Therefore, similar to the 50th percentile male, a lower than base line limit appeared beneficial for the large occupant. However, with the 2 kN limiter in the mid severity and NCAP impact scenarios, the amount of belt fed by the retractor reached the maximum allowable amount of 400 mm. This belt-spool out resulted in greater head, neck and chest injury risk. A belt system with more belt spool may avoid such an effect, but could increase the dummy excursion, possibly resulting in an unfavourable airbag contact.

In all simulated impacts, the predicted femur load was greater with low load limiting thresholds, but did not reach critical values. If the low limiter thresholds were to be used in impacts with compartment intrusion, there would be a clear need to implement countermeasures such as knee bolsters or knee airbags to ensure that the protection of the lower extremities is not compromised.

The findings reported in this study provide support to the concept that appropriate adaptation of the seat belt load limit has the potential to reduce chest injury risk, but that potential is mainly confined to low severity crashes. In higher severity impacts, and for small stature drivers, any potential benefit appeared to be minimal. These results are consistent with the load limiter adaptation studies reported in the literature (Kitagawa & Yasuki 2013). The result is important, because the real world study indicated that a majority (72%) of real-world frontal crashes resulting in AIS 2+ chest injury from restraining loads were at lower speeds (EES $\leq$ 45 km/h), with little or no compartment intrusion. Applying the simulation results for both seating positions to real world frontal crashes showed that, if all the vehicles had been equipped with load limiters able to adapt to the best setting for crash severity, occupant age, size and seating position, then 33% of the front seat occupants who had previously sustained AIS 2+ chest injury from restraining loads would have sustained a lower chest injury AIS score. This translates to an overall reduction of AIS 2+ chest injury risk (from all injury mechanisms) from 6.4% to 4.8% for belted front seat occupants in frontal impacts. It should be noted that one third of the occupants with AIS 2+ chest injury were elderly. As this segment of the car user population is increasing rapidly, the need for intelligent restraint systems can only increase in the future. Additionally, there is current interest in protecting "out of position" occupants in crashes involving autonomous vehicles. All of this will result in the requirement to identify more crash scenarios for virtual crash testing and the need for even more sophisticated restraint systems.

In this research, the load limiter value was adapted for four discrete settings only. The concept of continuously variable load limiting is one way of achieving more infinite settings (Paulitz 2005). Therefore it is recommended that future work consider this. Field studies have shown adverse consequences from belt load limiters, resulting from increases in excursion and head contact risk (Brumbelow et al. 2007). This current study has also shown that there is a trade-off between chest deflection and occupant excursion. Changing the belt load limit should therefore not be taken lightly (even in an adaptive sense) and future work should also consider potential for adverse outcomes resulting from error in occupant or collision estimations, or factors such as occupant position.

To extend the benefit of adaptive load limiters, a higher degree of adaptiveness for the whole restraint system could be envisaged, with attention also paid to varying airbag and pretensioner parameters. Such a comprehensive adaptable restraint system could cater for a wider range of crash scenarios and would be useful to investigate in future work. It could be argued that US vehicles already exhibit many adaptable features because they are assessed with a wider range of frontal test configurations and dummy sizes than European vehicles (FMVSS 208 frontal compliance barrier and out of position tests, USNCAP full frontal barrier and IIHS high speed offset tests). Technology which includes progressive, digressive and multi stage load limiters already exists, in addition to smart airbags. However, catering for occupant age related fragility and passenger compartment intrusion remains an additional step up in system intelligence.

Any study using human surrogates is susceptible to a number of limitations and must rely to a degree on assumptions. In this study one could question whether the different dummies accurately represent the range of sizes of human that use cars; or whether the multi-body simulation tool is accurate enough when an FE Human Body model (THUMS) may be more biofidelic; Further study might address these issues by utilising the MADYMO parametric dummy models or the parametric human body model. However, the utility of the model is not simply a matter of biofidelity or limited sizes but also the representation of different injury mechanisms and kinematics, which may have substantial impact on occupant protection. For example, recent studies have shown that occupants with different sizes, shapes, ages, and genders sustained very different kinematics and injury concerns in frontal crashes (Hu et al. 2019). The utility of the model is also a matter of the model's sensitivity to changes in restraint design, and this type of sensitivity is rarely assessed for dummies or human body models.

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Table 1 Frontal Impact Classification

Simulated Crashes	Real Crashes	Matched Sample (N)	Matched Sample (%)
full width rigid barrier impact (Low FRB) low pulse 26 km/h 100% overlap (14 g)	EES ≤ 40 km/h full overlap	155	41
offset deformable barrier impact (Low ODB) low pulse 40 km/h 40% overlap (17 g)	EES ≤ 45 km/h offset	116	31
offset deformable barrier impact (Mid) mid pulse 56 km/h 40% overlap (30 g)	EES 46 - 60 km/h offset	2	1
offset deformable barrier impact (EuroNCAP) high pulse 64 km/h 40% overlap (33 g)	EES 61 - 70 km/h offset	0	0
full width rigid barrier impact (USNCAP) high pulse 56 km/h 100% overlap (40 g)	EES 41 - 70 km/h full overlap	25	7
No simulation	Unclassified	79	20
Total		377	100

Table 2 Driver model 4 kN (baseline) simulation results

Dummy size	Crash Severity	Head Acc. (g)	HIC15	Nij	Chest Acc. (g)	Chest Comp. (mm)	Femur Force (kN)	Pjoint (%)
5th	Low FRB	47.7	137	0.19	22.9	28.4	0.7	8.7
	Low ODB	42.2	130	0.18	19.7	29.5	0.4	8.9
	Mid	58.5	291	0.27	34.7	34.2	2.1	13.0
	EuroNCAP	60.5	372	0.27	40.9	35.8	2.2	15.0
	USNCAP	85.1	781	0.26	50.5	35.2	2.6	25.3
50th	Low FRB	134.4	135	0.32	24.2	20.3	1.7	8.7
	Low ODB	71.8	17	0.21	16.6	20.4	1.6	7.3
	Mid	41.8	121	0.42	33.0	34.5	2.1	24.3
	EuroNCAP	49.5	191	0.46	36.3	37.3	2.5	16.8
	USNCAP	55.5	252	0.36	54.0	37.0	4.3	17.0
95th	Low FRB	40.5	124	0.21	23.8	25.7	0.6	8.1
	Low ODB	35.5	106	0.18	19.4	26.3	0.4	7.9
	Mid	65.1	388	0.32	35.2	34.8	1.3	14.9
	EuroNCAP	68.6	469	0.38	40.7	39.2	1.5	19.8
	USNCAP	83.8	790	0.39	47.5	41.2	2.7	30.6

Table 3 Passenger model 4 kN (baseline) simulation results

Dummy Model	Crash Severity	Head Acc. (g)	HIC15	Nij	Chest Acc. (g)	Chest Comp. (mm)	Femur Force (kN)	Pjoint (%)
50th	Low FRB	28.0	35	0.16	22.3	25.8	0.9	7.7
	Low ODB	23.9	38	0.19	18.4	29.2	0.3	8.8
	Mid	44.4	180	0.25	32.5	30.9	1.3	10.4
	EuroNCAP	53.0	375	0.28	38.7	32.8	1.7	13.3
	USNCAP	91.3	844	0.35	48.3	37.2	2.9	29.5
95th	Low FRB	28.3	57	0.24	23.5	27.4	0.7	8.8
	Low ODB	24.0	38	0.20	20.3	26.8	0.4	8.2
	Mid	46.3	210	0.28	34.5	29.2	1.4	10.2
	EuroNCAP	58.7	366	0.34	42.6	32.9	1.4	13.8
	USNCAP	89.5	780	0.36	42.2	35.9	2.8	26.7

Table 4 Actual and estimated (smart SBL) AIS 2+ chest injury risk from seat belt loading for front seat occupants in frontal impacts

Age group	Total No. of frontal Occupants (A1)	Actual No. of AIS 2+ seat belt chest injured (A2)	Actual risk (A2/A1)	Estimated No. of AIS 2+ seat belt chest injured (A3)	Estimated risk (A3/A1)
Young	4108	52	1.3%	38	0.9%
Mid	2713	206	7.6%	135	5.0%
Old	908	119	13.1%	78	8.6%
Total	7729	377	4.9%	251	3.2%

APPENDIX

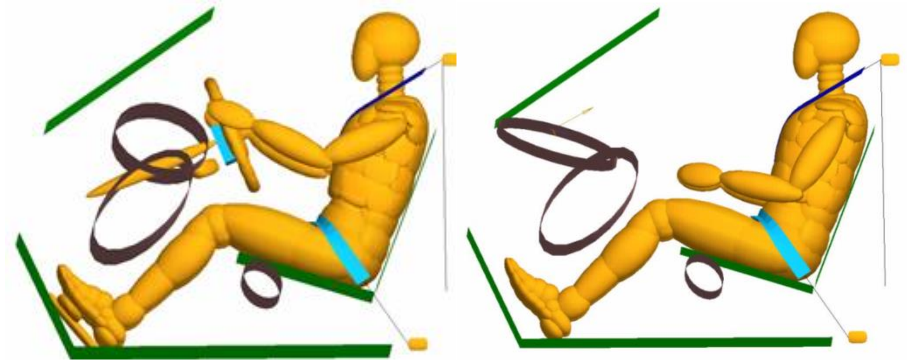


Figure A 1 Baseline Driver (left) and Front Passenger (right) Simulation Models

Table A 1 Baseline dummy positioning measurements in the compartment model

Description	**units**	**Measurements**
Windshield angle	deg	34
Steering wheel angle	deg	67.4
Steering column angle	deg	22.7
Head to windshield distance	mm	556
Nose to rim distance	mm	415
Chest to steering hub distance	mm	320
Rim to abdomen distance	mm	206
Knee to dashboard	mm	145
Pelvic angle	deg	22.9

Table A 2 Real- World Weighting Factors from AIS 2+ chest injured target sample

Age group	Wposition		Wimapct		Wsize	
	Position	Weight	Impact type	Weight	Occupant	Weight
Young	Driver	0.686	26 km/h FRB	0.417	HIII 05	0.109
			40 km/h ODB	0.375	HIII 50	0.723
			56 km/h ODB	0.000	HIII 95	0.168
			EuroNCAP	0.000	**sum**	**1.000**
			USNCAP	0.208		
			sum	**1.000**		
	FSP	0.314	26 km/h FRB	0.818	HIII 05	0.166
			40 km/h ODB	0.091	HIII 50	0.731
			56 km/h ODB	0.000	HIII 95	0.103
			EuroNCAP	0.000	**sum**	**1.000**
			USNCAP	0.091		
			sum	**1.000**		
	sum	**1.000**				
Mid	Driver	0.821	26 km/h FRB	0.634	HIII 05	0.109
			40 km/h ODB	0.313	HIII 50	0.723
			56 km/h ODB	0.000	HIII 95	0.168
			EuroNCAP	0.000	**sum**	**1.000**
			USNCAP	0.052		
			sum	**1.000**		
	FSP	0.179	26 km/h FRB	0.467	HIII 05	0.166
			40 km/h ODB	0.433	HIII 50	0.731
			56 km/h ODB	0.000	HIII 95	0.103
			EuroNCAP	0.033	**sum**	**1.000**
			USNCAP	0.067		
			sum	**1.000**		
	sum	**1.000**				
Old	Driver	0.641	26 km/h FRB	0.349	HIII 05	0.109
			40 km/h ODB	0.556	HIII 50	0.723
			56 km/h ODB	0.000	HIII 95	0.168
			EuroNCAP	0.000	**sum**	**1.000**
			USNCAP	0.095		
			sum	**1.000**		
	FSP	0.359	26 km/h FRB	0.457	HIII 05	0.166
			40 km/h ODB	0.457	HIII 50	0.731
			56 km/h ODB	0.029	HIII 95	0.103
			EuroNCAP	0.000	**sum**	**1.000**
			USNCAP	0.057		
			sum	**1.000**		
	sum	**1.000**				

Table A 3 Driver Simulation Results

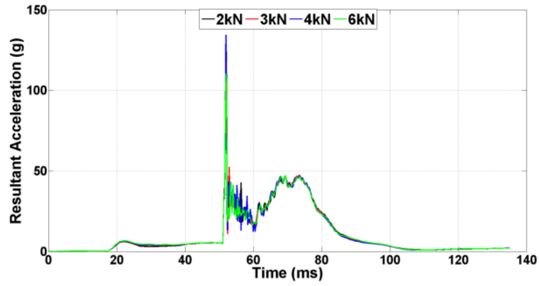
Crash Severity	SBL (kN)	Simulation Results (% change)			
		HIC15	Chest Comp. (mm)	Femur Force (kN)	Pjoint
50th Driver					
Low FRB	2*	-29%		143%	
	3			29%	
	4				
	6				
Low ODB	2*			150%	
	3			50%	
	4				
	6				
Mid	2				
	3*				-19%
	4				
	6	34%			
EuroNCAP	2				
	3				
	4*				
	6		32%		81%
USNCAP	2				
	3				
	4*				
	6				
5th Driver					
Low FRB	2				
	3				
	4*				
	6				
Low ODB	2				
	3				
	4*				
	6				
Mid	2				
	3				
	4*				
	6				
EuroNCAP	2				
	3				
	4*				
	6				
USNCAP	2				
	3				
	4*				
	6				
95th Driver					
Low FRB	2*			102%	
	3			38%	
	4				
	6				
Low ODB	2*		-29%	83%	
	3			46%	
	4				
	6				
Mid	2				
	3*				
	4				
	6				
EuroNCAP	2				
	3				
	4*				
	6				
USNCAP	2				
	3				
	4*				
	6				

*Best Selected Load Limiter Setting. Unshaded bar denotes that the minimum distance between the driver dummy and the steering wheel was less than the selected 80 mm threshold.

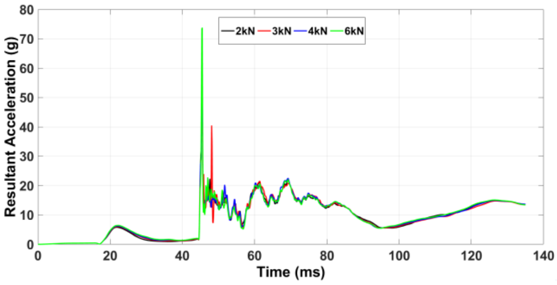
Table A 4 Front Seat Passenger Simulation Results

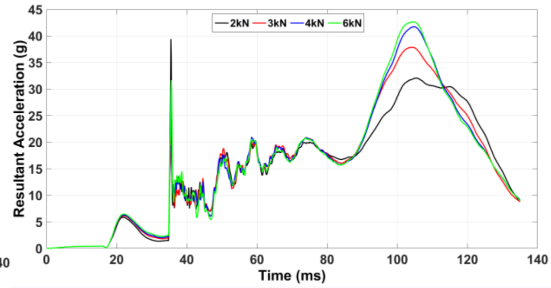
Crash Severity	SBL (kN)	Simulation Results (% change)			
		HIC15	Chest Comp. (mm)	Femur Force (kN)	Pjoint
50th Passenger					
Low FRB	2*			89%	
	3			11%	
	4				
	6				
Low ODB	2*	-53%			
	3				
	4				
	6				
Mid	2				
	3*				
	4				
	6	66%			76%
EuroNCAP	2				
	3*				
	4				
	6				
USNCAP	2				
	3				
	4*				
	6				
95th Passenger					
Low FRB	2*				
	3				
	4				
	6				
Low ODB	2*		-46%	103%	-29%
	3			23%	
	4				
	6				
Mid	2				
	3				
	4*				
	6		40%		
EuroNCAP	2				
	3				
	4*				
	6				
USNCAP	2				
	3				
	4*				
	6				

*Best Selected Load Limiter Setting. Unshaded bar denotes excessive forward movement of the passenger dummy.



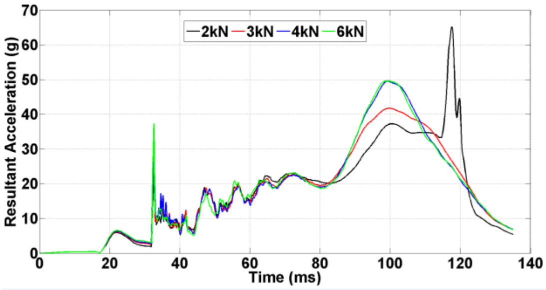
a) Low FRB

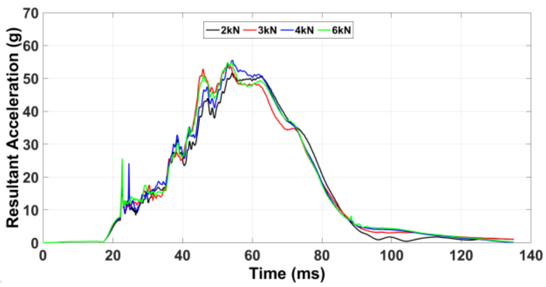




b) Low ODB

c) Mid

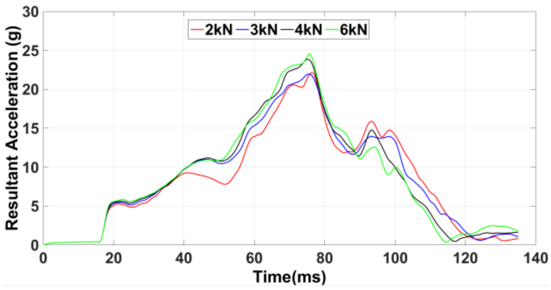




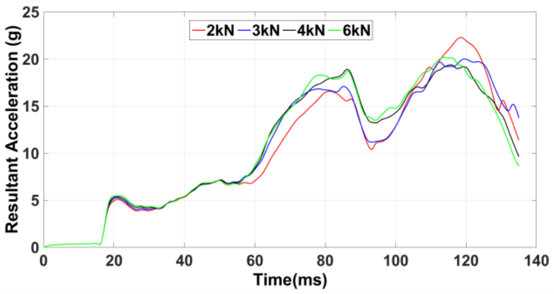
d) EuroNCAP

e) USNCAP

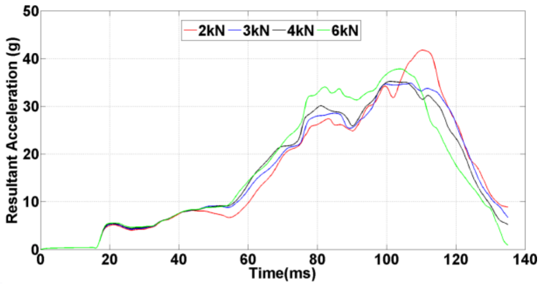
Figure A 2 Head Resultant Acceleration Time History Curves- 5th Percentile Driver



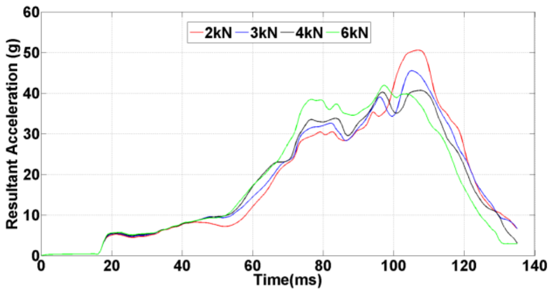
a) Low FRB



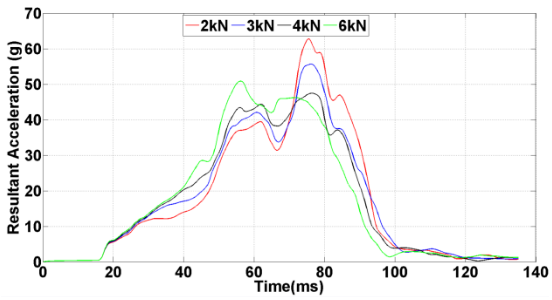
b) Low ODB



c) Mid

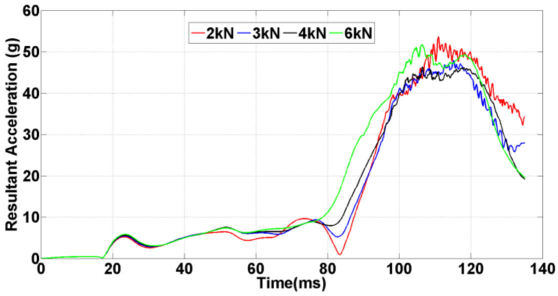


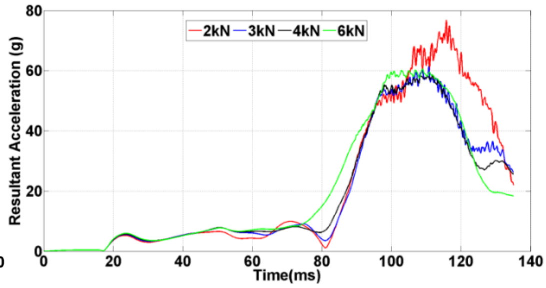
d) EuroNCAP



e) USNCAP

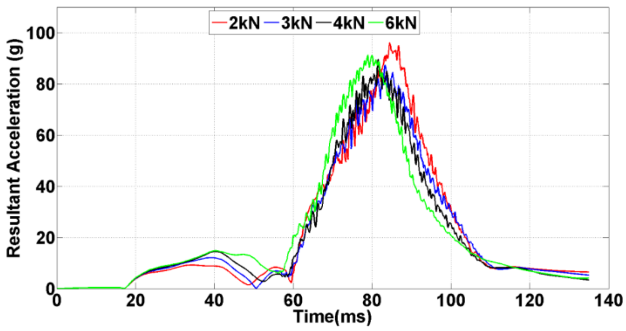
Figure A 3 Chest Resultant Acceleration Time History Curves- 95th Percentile Driver





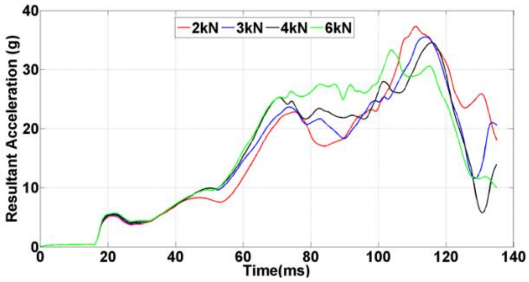
a) Mid

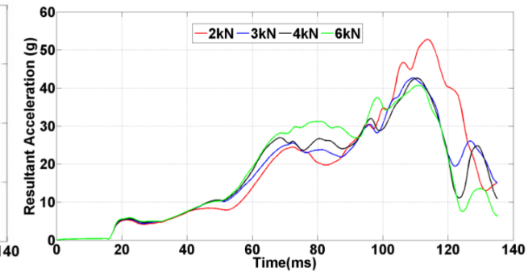
b) *EuroNCAP*



c) USNCAP

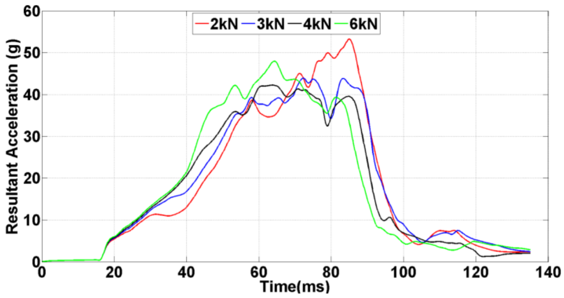
Figure A 4 Head Acceleration Time History Curves- 95th Percentile FSP





a) Mid

b) *EuroNCAP*



c) USNCAP

Figure A 5 Chest Acceleration Time History Curves- 95th Percentile FSP

Table A 5 Estimated AIS 2+ Chest Injury Risk of Baseline and Best SBL Models

		Young(30 y)	Mid (50 y)	Old (70 y)
50th Driver				
Low FRD	Base (4kN)	9%	23%	48%
	Best (2kN)	4%	12%	29%
Low ODB	Base (4kN)	10%	26%	52%
	Best (2kN)	4%	12%	30%
Mid	Base (4kN)	17%	39%	66%
	Best (3kN)	11%	27%	53%
EuroNCAP	Base (4kN)	20%	44%	71%
	Best (4kN)	20%	43%	70%
USNCAP	Base (4kN)	19%	42%	69%
	Best (4kN)	19%	42%	69%
5th Driver				
Low FRD	Base (4kN)	3%	8%	22%
	Best (4kN)	3%	8%	22%
Low ODB	Base (4kN)	3%	8%	22%
	Best (4kN)	3%	8%	22%
Mid	Base (4kN)	17%	40%	67%
	Best (4kN)	17%	40%	67%
EuroNCAP	Base (4kN)	23%	48%	74%
	Best (4kN)	23%	48%	74%
USNCAP	Base (4kN)	22%	47%	73%
	Best (4kN)	22%	47%	73%
95th Driver				
Low FRD	Base (4kN)	6%	17%	39%
	Best (2kN)	2%	7%	19%
Low ODB	Base (4kN)	7%	18%	41%
	Best (2kN)	2%	6%	17%
Mid	Base (4kN)	18%	41%	68%
	Best (3kN)	14%	33%	61%
EuroNCAP	Base (4kN)	27%	53%	78%
	Best (4kN)	27%	53%	78%
USNCAP	Base (4kN)	32%	59%	82%
	Best (4kN)	32%	59%	82%
50th FSP				
Low FRD	Base (4kN)	6%	17%	39%
	Best (2kN)	3%	10%	25%
Low ODB	Base (4kN)	10%	25%	51%
	Best (2kN)	2%	7%	18%
Mid	Base (4kN)	12%	29%	56%
	Best (3kN)	7%	19%	42%
EuroNCAP	Base (4kN)	15%	35%	62%
	Best (3kN)	9%	23%	48%
USNCAP	Base (4kN)	23%	47%	74%
	Best (4kN)	23%	47%	74%
95th FSP				
Low FRD	Base (4kN)	8%	21%	45%
	Best (2kN)	1%	4%	12%
Low ODB	Base (4kN)	7%	19%	42%
	Best (2kN)	1%	3%	9%
Mid	Base (4kN)	10%	25%	51%
	Best (4kN)	10%	25%	51%
EuroNCAP	Base (4kN)	15%	35%	62%
	Best (4kN)	15%	35%	62%
USNCAP	Base (4kN)	20%	44%	71%
	Best (4kN)	20%	44%	71%

Occupant Compartment Model

The retractor was located at the shoulder belt lower anchorage and was locked at 1ms in to each simulated impact. The belt feed from the retractor was restricted when the amount of belt introduced into the system exceeded 400 mm. The driver airbag was adapted from the TNO frontal application model (TNO 2013). It was a standard fold circular airbag with a volume of approximately 43 litres. The passenger compartment contained a generic frontal airbag with a volume of approximately 120 litres, adapted from the European PRISM project (Bosch-Rekveldt et al. 2015). It had a two-stage inflation characteristic, fabric permiability and vent-hole response definition. Both airbags were positioned to provide an adequate representation of dummy interaction with the airbag while deployed. The stiffness characteristics of the vehicle interior components such as the steering column, front fascia and seats were based on those defined for the TNO frontal application model (TNO 2013). The windscreen, floor and toe pan were considered to be rigid.

Models were validated using data obtained from USNCAP frontal barrier test reports of vehicles classified as a small family car according to EuroNCAP, and the baseline predictions for head, chest and pelvic acceleration were compared against measures obtained from a validated model in comparable tests. Full details of the validation procedures can be found in Ekambaram et al (2015). Passenger compartment intrusion was not considered in the numerical simulation because intrusion would limit the scope for injury reduction using variable load limits.

Dummy seat track position is at best an estimate because in the real world this can vary, even with occupants of the same size. However, it is reasonable to assume that a very small driver would adjust the seat to the fully forward position, a tall driver to the rearmost location and an average sized driver would use a mid-range position. The front passenger seat adjustment is less predictable, the small stature passenger probably most of all. It was assumed that a tall passenger might use the rearmost position for more leg room, and the average sized occupant is content with a mid-track position. The small stature front passenger was not evaluated pending confirmatory current positioning data and validation of any corresponding interaction between the dummy and deploying airbag. However, It should be noted that a small occupant in the front passenger seat accounted for only 6% of the real world sample matched with crash pulse data. The following numerical models were therefore developed to conduct a parametric load limiter adaptation study.

- 50th percentile male dummy in driver position.
- 5th percentile female dummy in driver position.
- 95th percentile male dummy in driver position.
- 50th percentile male dummy in front passenger position.
- 95th percentile male dummy in front passenger position.

Selection of Best Load Limiter Configuration

Optimising the restraints to benefit one body region may increase injury risks to other body regions. Therefore, it was necessary to check whether reducing the injury risk to the chest had any detrimental effect on other body regions. The performance of a load limiter configuration in each crash scenario was quantified by employing a method used by NHTSA to determine the joint injury probability (Pjoint). The evaluation combines the injury risk to each selected body region assuming that injury to different body regions are independent events and are expressed as Eq. (1) (NHTSA 2008).

$$\mathrm{P_{joint}} = 1 - [(1 - \mathrm{P_{head}})(1 - \mathrm{P_{neck}})(1 - \mathrm{P_{chest}})(1 - \mathrm{P_{femur}})] \qquad (1)$$

The Phead, Pneck, Pchest and Pfemur are the injury probability of head, neck and chest sustaining AIS 3+ injury and the femur sustaining AIS 2+ injury (NHTSA 2008). The injury responses of 5^{th} and 95^{th} percentile dummies were scaled (normalised) to account for the difference in the biomechanical characteristics with the 50^{th} percentile dummy using Injury Assessment Reference Values (IARVs) (Mertz et al. 2016; NHTSA 2002). It would have been possible to modify the standard Pjoint calculation used by NHTSA, using an AIS 2+ chest injury risk curve. However, this would not have influenced the selection of best load limiter based on AIS 2+ chest injury in this study.

The presence of the steering wheel reduces the ride down space on the driver side. High dummy excursions induced by the low SBL thresholds generally increased the risk of dummy contact with the vehicle interior and unfavourable interaction with the deploying frontal airbag. An excursion limit was therefore introduced to cater for driver dummy movement into a zone where interior interaction became more likely. The best restraint system was selected in the driver test configurations only if the chest injury was reduced without increasing the overall injury risk (Pjoint) and the distance between the dummy chest and steering wheel hub remained greater than 80 mm, an excursion limit suggested by real- world data analysis (Ekambaram et al. 2015). The best restraint system was selected in the passenger test configurations only if there was no excessive forward movement of the dummy resulting in unstable contact with the airbag. This was checked using head and chest acceleration plots and animation video.

Benefit Quantification

In order to calculate benefits, first, the simulated chest injury outcomes required adjusting for occupant age. This was achieved by using an age-related chest injury risk function developed by Ekambaram et al. (2015) as expressed in Eq. (2).

$$P(AIS\ 2+) = \frac{1}{1+\mathrm{EXP}(12.432-0.0562 Age-1.7955 (ChestDefl)^{0.4612})} \qquad (2)$$

The occupants in the real-world sample were classified into young (17 - 39 years), middle-age (40 - 64 years) and old (65+) of whom 35 were young (12%), 165 (55%) were middle aged and 98 (33%) were older occupants. In the AIS 2+ chest injury risk function, the age was set as 30, 50 and 70 years for young, middle-aged and older occupants respectively and is based on the mean value of age categories from the accident sample.

The real-world injury reduction benefit was quantified by applying the estimated relative chest injury risk reduction obtained from simulations to the matched real-world accident sample according to the occupant seating positions, impact scenario, occupant sizes and occupant age. It was assumed that in each of the categorised crash scenarios, the predicted chest injury risk of the baseline model would be representative of the real-world chest injury risk, and by switching to the best load limiter model, the real-world injury risk would reduce relative to the corresponding simulated reduction. The new frequency of AIS 2+ seat belt- related chest injury after employing the adaptive restraint was estimated using Eq. (3).

$$[F_{smart}]_{age} = [F_{actual}]_{age}\left[\sum_{i=1}^{2\ position}\sum_{j=1}^{5\ impacts}\sum_{k=1}^{3\ sizes} W_{ijk}\frac{[R_{best}]_{ijk}}{[R_{base}]_{ijk}}\right] \quad (3)$$

Where,

F_{smart} is the estimated number of occupants to sustain AIS 2+ chest injury with an adaptive system for that particular age group;
F_{actual} is the actual number of AIS 2+ chest injured in the sample for that particular age group;
positions= Driver, Front seat passenger;
impacts = Low FRB, Low ODB, Mid, EuroNCAP and USNCAP;
sizes= HIII05, HIII50, HIII95
W_{ijk} is the age dependent, real world weighting factor, such that W_{ijk} is W_{pos_i} x W_{impact_j} x W_{size_k}
$[R_{best}]_{ijk}$ and $[R_{base}]_{ijk}$ are the AIS 2+ chest injury risk of the best and baseline model respectively for particular seat position, impact severity, occupant size and age group.

Weighting factors used to evaluate EQ 3 are reported in Table A 2**Error! Reference source not found.** which are based on the sample with occupants who had sustained AIS 2+ chest injuries from seatbelt restraining loads. Accordingly, all of the terms of the equation were estimated for each of the age groups. Therefore, three age groups produced three frequency values (F_{smart}). The occupants in the data sample were classified as 5th percentile (≤ 158 cm), 50th percentile (159 - 182 cm), and 95th percentile (≥ 183 cm) based on their height. It was also assumed that all vehicles in the target sample of accident data had a 4 kN SBL (similar to the baseline numerical model).

Explanation of Tables A3 and A4

In each body region column, a bar to the left of the central line denotes a reduction in risk, while a bar to the right denotes an increase in risk. The unshaded bar in Table A 3**Error! Reference source not found.** denotes that the minimum distance between the driver dummy and the steering wheel was less than the selected 80 mm threshold. The unshaded bar in Table A 4 denotes excessive forward movement of the passenger dummy. The 'best' selected restraint system in each of the crash pulses is represented with an asterisk.

In all crash scenarios, reducing the SBL threshold (allowing a greater amount of forward displacement) resulted in higher femur loads. For example, changing the load limiting threshold from 4 kN to 2 kN for 50th percentile driver in Low FRB impact condition predicted increase in the femur force from 0.7 to 1.7 kN (an 143% increase). However, the corresponding AIS 2+ injury risk of femur fracture was low (0.90 % to 1.20 %) having no significant effect on the Pjoint value.

Observed Dummy Kinematics and Best Load Limiter Configuration

50th percentile driver   In all crash pulses, the extra seat belt webbing with the 2 and 3 kN SBL allowed the dummy to displace further towards the steering wheel than with the baseline model. The forward displacement of the dummy in each crash pulse was lowest with the 6 kN SBL. In low pulse tests, the limit of dummy excursion remained more than 80 mm from the wheel with all four SBL configurations. The predicted head, chest and overall injury scores were lowest with the 2 kN SBL and this was selected as the best restraint system in the low pulse impacts. The 2 kN SBL in the Mid pulse impact produced best head, chest and overall injury scores, however, the forward displacement of the thorax moved it to less than 80 mm from the steering wheel hub. The 3 kN SBL produced lower injury risks than the baseline model while not displacing the dummy closer than 80 mm. By changing the SBL value from 4 to 3 kN, the chest compression decreased from 34.2 to 30.0 mm (12% reduction) and the overall injury risk (Pjoint) score reduced by 19%. In both high crash pulses, the chest excursion with a 2 and 3 kN SBL surpassed the pre-determined limit from the steering wheel. In fact, it was less than 40 mm from the wheel with the 2 kN SBL in both high crash pulses, suggesting that any extra forward displacement of the thorax could have induced much harder contact with the steering wheel. In the USNCAP pulse, the forward excursion of the head and chest with the baseline 4 kN SBL was borderline. With the 6 kN SBL, it was well outside of the pre-determined limit but the predicted chest injury risk and overall injury risk (Pjoint) was greater than the baseline SBL. For these reasons, the baseline model was chosen as the best restraint configuration in both high pulse scenarios.

5th percentile driver   Unlike the 50th percentile dummy, the small stature dummy, excursed to less than 80 mm from the steering wheel in all impacts. This was almost certainly due to the fact that the dummy was initially positioned closer (229 mm) to the steering wheel compared to the 50th percentile dummy (320 mm). In the low FRB impact, the airbag was fired late in the simulation (45 ms), resulting in the forward displacing dummy head contacting the airbag during inflation in all four tested SBL configurations. This unstable loading of the dummy head with the airbag resulted in a high resultant head acceleration (>100 g, Figure A 2 a). However, the resultant head acceleration 3 ms exceedance values were well within the European regulatory limit of 80 g. Early interaction of the dummy's head with the airbag, due to the dummy forward seating position, was also noted with other crash scenarios which can be distinguished by initial peaks in the head resultant acceleration (Figure A 2). This was due to the dummy contacting the airbag soon after inflation, whilst the pressure inside the airbag was still high. This interaction seems to be almost independent of crash pulse and SBL configuration. With the 2 kN SBL in the EuroNCAP impact, the head was observed to ‘bottom out’ the airbag. The head of the dummy penetrated through the airbag and contacted the steering hub. The increase in the head acceleration during the period of head-hub loading can be seen with the head resultant acceleration peak at almost 65 g (Figure A 2 d). When the SBL threshold was increased (>2 kN) the head did not strike the steering hub. The 6 kN showed some improvements to chest injury risk, however it was limited. It was considered that varying the load limiter for smaller occupants who tend to sit closer to the steering wheel has limited scope with the restraint system tested. For this reason, the baseline 4 kN SBL was chosen for the small female dummy in all simulated impacts.

95th percentile driver The 2 kN SBL gave the best chest and overall injury outcome in both low pulse scenarios, with dummy forward displacement outside of the pre-determined limit. In Low FRB and Low ODB crash pulses, employing a 2 kN SBL reduced the Pjoint value by 16% and 13% respectively when compared to the baseline model. In the Mid pulse with a 2 kN SBL and NCAP impacts with the 2 and 3 kN SBL, the forward displacing dummy pushed the airbag upwards and rearwards, reducing the amount of airbag between the thorax and steering wheel. This resulted in relatively stiff loading region between the chest and airbag. In those test configurations, the peak chest accelerations were greater than the baseline outcome (Figure A 3). The chest compression in the USNCAP impact with a 2 kN SBL remained within the regulatory limit but the chest acceleration exceeded the US FMVSS 208 limit of 60 g. The overall injury risk predicted with the 2 kN SBL in EuroNCAP and USNCAP pulses were greater than the baseline by 7% and 10% respectively. The results show that the SBL threshold can be reduced to 3 kN in Mid pulse impacts but in high pulse impacts, reducing the SBL threshold from 4 kN may increase occupant injury severity risk.

50th percentile passenger The dummy did not have a hard contact with the vehicle interior in any of the simulated impacts. The HIC outcomes were generally lowest using the 2 kN SBL. The only exception was a higher HIC for the low FRB pulse when using the 2 kN SBL. The 2 kN SBL produced lowest chest compression scores in all impacts. However, a greater forward displacement of the dummy in high-pulse impacts with a 2 kN SBL resulted in higher chest and head peak acceleration. More simulation runs with different adapted dummy postures and crash pulses would be required for a greater understanding of the effect of the 2 kN SBL in such crash scenarios. The 3 kN SBL in Mid-pulse and EuroNCAP impacts provided the best injury protection with stable airbag loading. Varying the load limiting threshold from the baseline level did not produce any injury reduction benefit for the USNCAP impact.

95th percentile passenger In low severity impacts, using a 2 kN SBL produced best chest and overall injury outcomes. In the mid pulse and NCAP impacts, employing a 2 kN SBL resulted in a ‘belt-spool out effect’ i.e. the amount of belt fed into the system reached the maximum modelled amount of 400 mm, abruptly stopping the introduction of belt from the retractor and resulting in greater acceleration forces to the dummy head and chest regions (Figure A 4 & Figure A 5). In fact, the chest acceleration in the NCAP impacts with the 2 kN SBL was above 50 g, however it was less than the FMVSS 208 maximum allowable limit of 60 g. When the SBL threshold was above 2 kN, the belt spool out effect was not noticed. In the Mid and NCAP scenarios, the peak chest acceleration outcome with the 3 kN SBL was higher than the baseline model. The Pjoint value of the 3 kN SBL was almost similar to the baseline, which suggests that employing a 3 kN SBL has no/limited injury reduction benefit in those impacts, despite further forward movement of the dummy. In crash scenarios where no injury benefit was predicted by the low load limiting options, the default SBL threshold of 4 kN was selected as the best restraint model.