Estimating Q-Dummy Injury Criteria Using the CASPER Project Results and Scaling Adult Reference Values

Heiko Johannsen[1], Xavier Trosseille[2], Philippe Lesire[2], Philippe Beillas[3]

Abstract Based on the results of the CHILD project, injury risk curves for Q dummies for frontal impact were presented in 2007. However, the risk curves for the neck were based only on scaling of adult data. In addition, solid risk curves for the abdomen and chest were missing.

The CASPER project is a successor project of the CHILD project which utilises both its own research results as well as those of the CHILD project. One of the CASPER aims is to provide injury criteria specific to the Q-dummies, combining results of the CASPER project and results of scaling adult Injury Assessment Reference Values focusing on the neck for younger children, the abdomen for older children and the head in the lateral impact condition. Within the CASPER project (similar to the CHILD project), injury criteria are developed pairing the injuries observed in sixty real-life accidents with the crash reconstruction dummy measurements. AIS3+ injury risk curves are drawn for the head, the neck, the thorax and the abdomen using the survival method.

For the assessment of abdominal injury risk the CASPER project prioritized an abdominal sensor from three different options and developed the research solution from the CHILD project to a reliable sensor that is appropriate for product development and assessment of CRS.

Keywords experimental accident reconstruction, child safety, injury risk functions, Q-dummies

I. INTRODUCTION

The EC CASPER (Child Advanced Safety Project for European Roads) project aims at decreasing injuries and fatalities of child occupants. This goal represents a major social and economic benefit for the whole European Community.

CASPER involves a consortium of 15 European partners representing a good balance between industries, medical and technical universities, road state institutes and organisations that specialise in road safety issues for a 38-month project. This project was established under the GA n°218564 of the FP7-SST-2007-RTD-1-program of the European Commission that is partially funding the project. Data from previous European projects CREST and CHILD were used as a basis.

This project has two main objectives that are complementary to improve the real level of protection of children in cars. The first one is the improvement of the rate of correctly restrained children in cars, and the effect of this can be seen in a short-term. This is done through the analysis of the reasons and the consequences of the conditions of transportation of children. The second one is the improvement of the efficiency of child protection which includes tools and test procedures that are used to evaluate the protection of children in cars for regulatory approval and consumer information tests. This second point – even if taking longer before any improvement can be observed in the field – is a necessary and continuous work. It consists of improving existing tools used for the evaluation of protection of children and in the development of the missing ones. Finite element models have been developed for child dummies and for human child bodies and proposals for improvements of the Q-series crash test dummies have been made. The CASPER project has also been evaluating a selection of existing solutions that could be applied to improve child safety in cars, although experts have found that it is sometimes difficult to have solutions that are at the same time scientifically based, approved, acceptable by both parents and children and that improve the ease of use of the restraint system. One major outcome of the CASPER project is the development of missing injury risk functions for Q-dummies.

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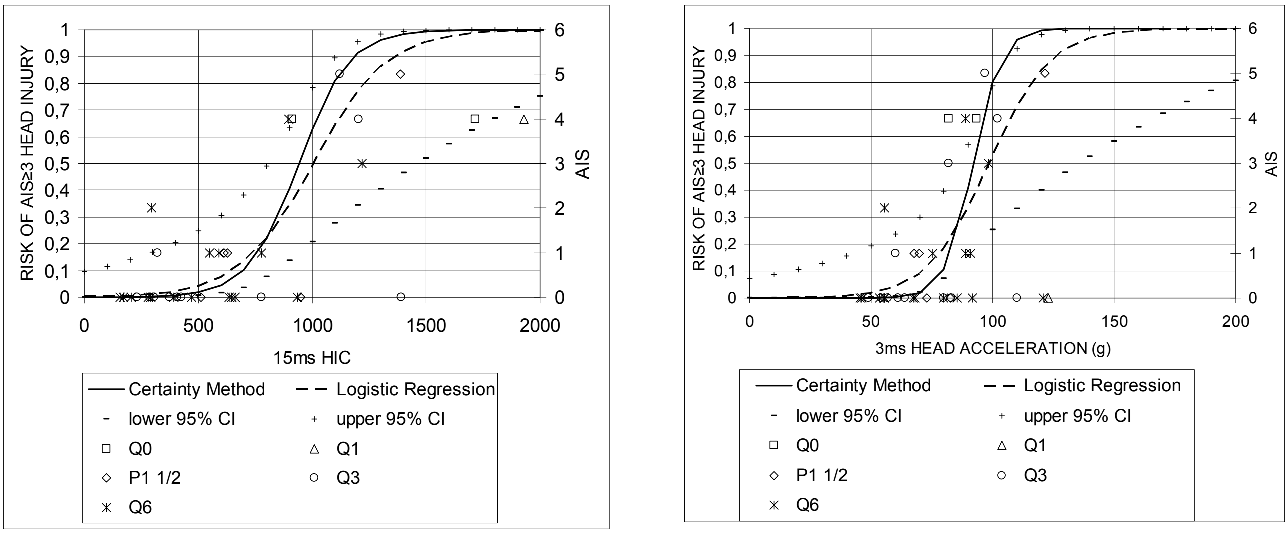
The CASPER project is continuing the earlier research of the CREST and CHILD projects that were reported by Palisson et al [1].

Injury risk functions reported by Palisson et al. [1] were based on accident reconstructions and scaled adult data. While reliable risk curves for the head in frontal impact conditions were computed (see Fig. 1), neck injury risk curves were based on scaled adult data only and for the chest compression both data sources were combined.



HIC15 a_{3ms}

Fig. 1: Q3 head injury risk curves and data dots resulting from the CHILD project [1]

II. METHODS

In order to focus the accident reconstruction on body regions that are considered to be most important for future regulation and consumer information, the injury risks of specific body regions for specific age groups were compared with the number of existing data points. Data from accidentology are used to identify the priorities in terms of protection of children and to evaluate the level of confidence of the existing tools used for the evaluation of CRS and criteria available to predict injuries on the different body segments, see TABLE 1.

Taking into account the specific injury risks and the available data points, it was decided to aim for being able to compute injury risk functions for the following body regions, impact conditions and age groups:

- neck injuries for frontal impact for Q1, Q1.5 and Q3 in forward facing CRS
- chest for frontal impact
- abdomen for frontal impact for booster type CRS
- head for lateral impact

The method used in CASPER is similar to the one used in the previous EC research project in order to be able to integrate data previously obtained in the development of injury risk curves for the Q-series dummies. As there are very few biomechanical data available for children and because post-mortem tests on children are rare and ethically limited in Europe, the methodology is based on injuries sustained by restrained children in cars involved in real accidents and the physical reconstruction of real accidents in crash test laboratories in order to compare injuries with dummy readings.

TABLE 1

Injury risks for different body regions dependent on age for frontal and lateral impact

Frontal Impact

	Head	Neck	Chest	Abdomen	Pelvis	Upper Limbs	Lower Limbs
Newborn							
1 YO							
1,5 YO							
3 YO							
6 YO							
10 YO							
Remarks / Injury pattern	Skull and brain inju-ries, con-cussion, diffuse axo-nal injuries and subdural hematomas	Neck injuries mainly for upper cervical spine (C1 to C4), Injury pattern: fraction, dislocation (w. & wo. cord injury) and cord injury.	Flexibility of thoracic spine to be considered. 1-3YO organ injuries wo rib fracture, 6-10 YO organ injuries with rib fracture	Damage of soft organs (liver, spleen & kidneys) due to penetra-tion of the belt (submarining & oop). No informa-tion for 0-1,5YO	No severe injuries were observed	Fractures, especially in rebound. No data for 3-10YO available	Fractures, especially in rebound. No data for 3-10YO available

Lateral Impact

	Head	**Neck**	**Chest**	**Abdomen**	**Pelvis**	**Upper Limbs**	**Lower Limbs**
Newborn							
1 YO							
1,5 YO							
3 YO							
6 YO							
10 YO							
Remarks / Injury pattern		Unclear but seems to be connected with head injuries.	1-3YO organ injuries without rib fracture, 6-10YO organ injuries with rib fracture	Abdominal penetration of side structure or booster base.	Injuries caused by contacts with pene-trating structure	Shoulder and arm fractures due to in-trusion. No information for 0-1,5YO.	Tibia fractures for 0-1,5YO. Tibia and femur fractures for 3-10YO.

No severe injuries

High risk of injury / high severity

No sufficient information available / see remarks

From detailed accident data, including medical reports, restraint conditions and in depth investigation of cars, experts define the causes of injuries and accident scenarios. It is then necessary to determine if the accident conditions can be properly reproduced in crash-test laboratories using similar vehicles and CRS and child dummies of a size as close as possible to the children involved in the accident. It should be noted that the accidents are selected to be relevant for the development of injury risk functions and therefore are not necessarily representative of European accidents involving children. Selection criteria are that at least one restrained child suffered at least one MAIS 2+ injury or the delta-v exceeded 40 km/h for a frontal impact or the crush exceeded 200 mm in a lateral impact, respectively.

The reconstruction test results are discussed and validated on a case-by-case basis by experts both from accidentology (e.g. similar deformations of the cars, expected structural behaviour) and from biomechanics (e.g. study of the global kinematics of the child dummy and focus on the repetition of the injury mechanisms in the child dummy). A correlation is then made between the level of injury severity of the child and the dummy readings on different body segments. In case of positive result, one point is added to the cloud of existing ones for each body segment. It was necessary to have a large number of reconstructions performed before having injury risk curves for the different sizes of dummies and for different types of impacts. Currently the accident reconstruction database includes 76 valid reconstructions using Q-dummies. The distribution on the different dummy sizes is shown in TABLE 2.

TABLE 2
No. of available reconstructions by dummy size and impact type
Note: the number of cases exceeds the number of reconstructed accidents

Dummy	valid no. of cases frontal impact	valid no. of cases lateral impact
Q0	3	0
Q1	8	4
Q1.5	5	1
Q3	26	10
Q6	27	8
Q10	1	0

Unfortunately injury severity levels were not always known for all body regions. In addition, dummies were not always equipped with all sensors or measurement failures occurred. Therefore the number of existing cases is lower when looking into individual body regions. In addition, this methodology is only valid for injury mechanisms observed in car accidents for restrained children that can be properly reproduced by existing child dummies and in configurations for which their response is sufficiently biofidelic.

A tentative programme of using more simple accident configurations than the one of children in cars has been explored through the analysis and reproduction of domestic accidents such as falls but it seems that dummy response to this kind of impact condition is different to what is known from car occupant conditions. Results of tests from this kind of accident were therefore not included in the risk curves presented in this paper.

Scaling

Reconstructions were performed on dummies from birth to 6 years old. As a consequence, the number of cases for each dummy age is very small and cannot be processed as it is. In order to consolidate these data, it was proposed to scale all results to a given age. This was done using the method proposed by Mertz [2] and applied to the Q dummies by Palisson [1].

TABLE 3
used scaling factors [1], [2]

		Head			Neck			
Scaling factor	$\lambda_{\sigma f}$	$\lambda_{\sigma L}$	λ_{HIC}	λ_A	λ_x	λ_y	λ_F	λ_M
Formula			$\lambda_{\sigma f}^{2,5} \lambda_L^{-1,5}$	$\lambda_{\sigma f} \lambda_L^{-1}$			$\lambda_{\sigma f} \lambda_x \lambda_y$	$\lambda_{\sigma f} \lambda_x^2 \lambda_y$
Q0	0,73	0,69	0,79	1,06	0,65	0,67	0,32	0,21
Q1	0,82	0,92	0,69	0,89	0,95	0,91	0,71	0,67
Q1.5	0,88	0,95	0,78	0,93	0,96	0,95	0,80	0,77
Q3	1	1	1,00	1,00	1	1	1,00	1,00
Q6	1,13	1,03	1,30	1,10	1,11	1,07	1,34	1,49

						Chest Frontal			Chest Lateral			Abdomen
Scaling factor	$\lambda_{\sigma f}$	λ_{Eb}	λ_{ET}	λ_x	λ_y	λ_d	λ_{VC}	λ_{Acc}	λ_d	λ_{VC}	λ_{Acc}	$\lambda_{Pression}$
Formula						$\lambda_y \lambda_{\sigma f} \lambda_{Eb}^{-1}$	$\lambda_{\sigma f} \lambda_{ET}^{-1/2}$	$\lambda_{\sigma f} \lambda_x^{-1}$	$\lambda_x \lambda_{\sigma f} \lambda_{Eb}^{-1}$	$\lambda_{\sigma f} \lambda_{ET}^{-1/2}$	$\lambda_{\sigma f} \lambda_y^{-1}$	$\lambda_{\sigma f}$
Q0	0,73	0,51	0,62	0,63	0,66	0,94	0,92	1,15178	0,91	0,92	1,1088	0,73
Q1	0,82	0,68	0,75	0,80	0,89	1,07	0,94	1,0214	0,97	0,94	0,9232	0,82
Q1.5	0,88	0,77	0,79	0,80	0,93	1,06	0,99	1,10584	0,91	0,99	0,9509	0,88
Q3	1	1,00	1,00	1,00	1,00	1,00	1,00	1	1,00	1,00	1	1,00
Q6	1,13	1,43	1,14	0,99	1,12	0,89	1,06	1,13801	0,79	1,06	1,0107	1,13

This method takes into account geometrical parameters but also material variation through the ages. TABLE 3 gives the scaling factors corresponding to head and neck injury criteria. For instance, if a HIC=1000 is acceptable for a 3 year old child, the acceptable limit for a 1 year old child will be HIC=690.

As a consequence, each individual result has to be divided by the corresponding scaling factor for the 3 year old equivalent value. For instance, if a 1 year old child sustains a given head injury with HIC=690, it is assumed that a 3 year old child would have sustained the same level of injury with a HIC=1000.

Injury risk curve construction

Several methods can be used for drawing injury risk curves. However, it was demonstrated by Petitjean [3] that the survival analysis generally provided the best estimate. Therefore, guidelines for the construction of the injury risk curves were developed and agreed on among ISO experts. These guidelines include several steps:

Step 1: collect the relevant data.

According to the methodology developed in this paper, the relevant data correspond to the real accident case injuries and the dummy measurements from the paired reconstruction.

Step 2: assign the censoring status (left, right, interval censored, exact). Here, all the cases are censored.

Step 3: build the injury risk curve with the Consistent Threshold Estimate (CTE) [4] and check for dual injury mechanism

Step 4:

- If there is evidence of dual injury mechanism, separate the sample into samples with single injury mechanism and return to Step 1
- If there is no evidence of dual injury mechanism, build the injury risk curve with the survival analysis according to the following steps

Step 5: estimate the parameters of the Weibull, log-normal, log-logistic distribution with the survival analysis method

Step 6: identify overly influential observations using the dfbetas statistics. The dfbetas statistic gives an indication on the change of each parameter estimate when deleting one observation of the sample after another. An absolute value of the dfbetas statistic higher than 0.3 indicates that the associated observation was possibly overly influential. These observations are checked for any specificity. If there is no evidence of difference between these observations and the others included in the sample, these observations are kept in the construction of the injury risk curve.

Step 7: check the distribution assumption graphically using a qq-plot or the CTE method.

Step 8: choose the distribution with the best fit, based on the Akaike information criterion (AIC). The AIC criterion is calculated based on the likelihood of the model taking into account the number of variables used in the model (AIC= -2*log likelihood+2*number of variables). The lowest AIC indicates the best fit of the model with the test data.

Step 9: check the validity of the predictions against existing results (such as accidentology outcome), if available

Step 10:

- Step 10.1: calculate the 95% confidence intervals of the injury risk curve with the normal approximation of the error.
- Step 10.2: calculate the relative sample size of the confidence interval (width of the confidence intervals at 5%, 25% and 50% relative to the value of the stimulus at 5%, 25% and 50% of risk respectively).

Step 11: Provide the injury risk curve associated with the quality index based on the relative sample size of the 95% confidence interval. A scale was defined with four categories (“good” from 0 to 0.5, “fair” from 0.5 to 1, “marginal” from 1 to 1.5, “unacceptable” over 1.5).

Step 12: recommend one curve per body region, injury type and injury level.

- Step 12.1: If several injury risk curves can be compared with AIC and if the difference of AIC is greater than 2, then the curve with the lowest AIC is recommended over the others.
- Step 12.2: If an injury risk curve had an “unacceptable” quality index, it should not be recommended.
- Step 12.3: if several injury risk curves were still available for a given injury type and level, engineering judgment is used to recommend one curve over another.
- Step 12.4: The recommended injury thresholds should be provided associated with their quality indexes.

III. RESULTS

Injury mechanisms and injury criteria

The Q dummies can be equipped with the following sensors:
- head - three axial acceleration
- head - three axial angular velocity
- upper neck - six axial forces and moments
- lower neck - six axial forces and moments (only Q3 and Q6)
- chest - three axial acceleration (approx at T4 level)
- chest - sternal deflection or lateral deflection at sternum level
- lumbar spine - six axial forces and moments (except Q0)
- pelvis - three axial acceleration

In order to assess abdominal injury risk in Q dummies, absent from the above, two different sets of abdominal sensors were developed within the CHILD project [5] [6] and then evaluated for future use in the CASPER project. Due to technical shortcomings of the Force Matrix Sensor (FMS) that were impossible to solve, the Abdominal Pressure Twin Sensor system was selected to be proposed as the abdominal sensor system for Q dummies. After this decision was taken, the sensor was optimised to make it more robust.

Based on previous research head a_{3ms} and HIC are suitable criteria for the head in head contact cases. This was also confirmed by Palisson et a. [1] for children. For the cases without head contact, it is currently debated whether or not head a_{3ms} and/or HIC can be used. This discussion is important as the frontal impact assessment of CRS normally takes place without any surrounding interior that the head could contact. Another option could be the rotational acceleration of the head as proposed e.g. by Newman et al. [7] in combination with linear acceleration. For children it is proposed that angular acceleration could be used as an injury criterion for non-contact cases. For contact cases it is believed that the accuracy in accident reconstruction does not allow valid assessment of the loads as the angular velocity is highly dependent on the lever arm (i.e. the correct impact point).

For the neck it is also important to distinguish between head contact and non head contact cases. Neck tension and flexion are the most promising injury criteria for the injuries sustained by children in the database. For lateral impact cases in addition to neck tension, lateral bending moments can be used as well as the combination of neck bending moments and neck Z forces by using the NIJ criterion as used in FMVSS 208. As the main risk for neck injuries was reported for the youngest children in forward-facing CRS (i.e., Q1, Q1.5 and Q3) and no lower neck load cells exist for Q1 and Q1.5, only upper neck was taken into account.

For the thorax in current regulation ECE R44 a_{3ms} is used. For the new regulation proposal it is planned to keep this criterion with the current limit. In addition, sternal deflection (frontal impact), lateral chest deflection at sternum level (side impact) and the viscous criterion VC derived from chest deflection are in discussion. While chest deflection mainly aims at rib fracture risks, VC addresses injury risks for internal organs. Finally, peak abdominal pressure correlated best with injury risk given the selected abdominal sensor based on previous research [6].

Injury Risk Curves for Frontal Impact

The raw data for the head obtained from the reconstructions are presented in Fig. 2. The head accelerations were then scaled to a 3 year old (Fig. 3) and a survival analysis was conducted. The circled data points were found to be overly influential. They were checked for any inconsistency, but nothing was found to be wrong. Therefore, only the red circled data point was removed from the analysis because it was really different from the cloud. Finally, the injury risk curve with its confidence intervals was plotted (Fig. 4). The relative sizes of the confidence interval at 5%, 25% and 50 % of risk were calculated. They were 129%, 47% and 46% respectively. Therefore the error was considered as marginal at 5%, while it was considered as good at 25% and 50%. The values are summarized in TABLE 4.

The HIC values were processed in the same way. However, the AIC were higher and the confidence intervals larger. It should be noted that the HIC should be calculated only in case of impact, which should not happen in a certification test. Therefore, the HIC was not recommended as a criterion for the assessment of child restraining systems in frontal impact.

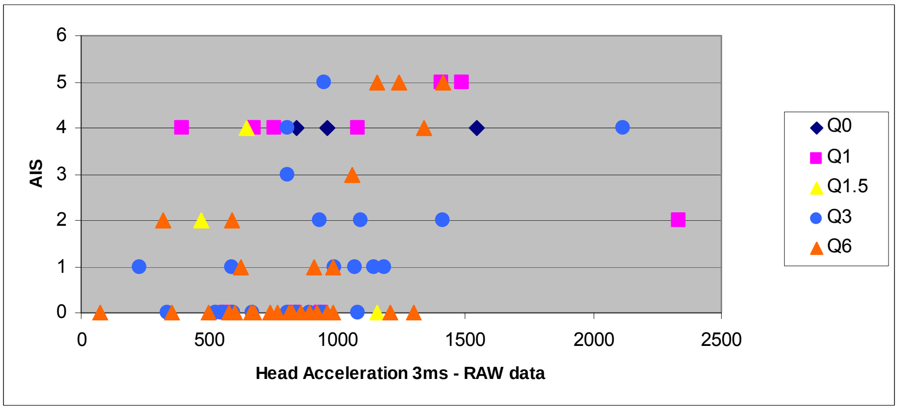


Fig. 2: Head AIS as a function of Head linear acceleration 3ms for frontal reconstructions

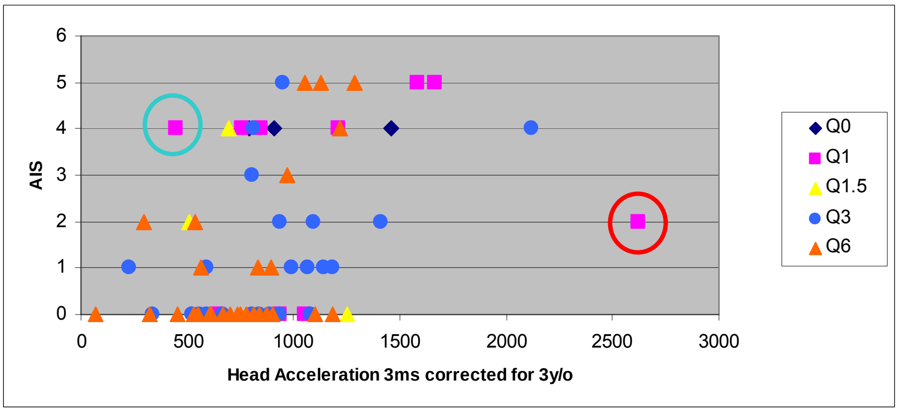


Fig. 3: Head AIS as a function of scaled Head accelerations

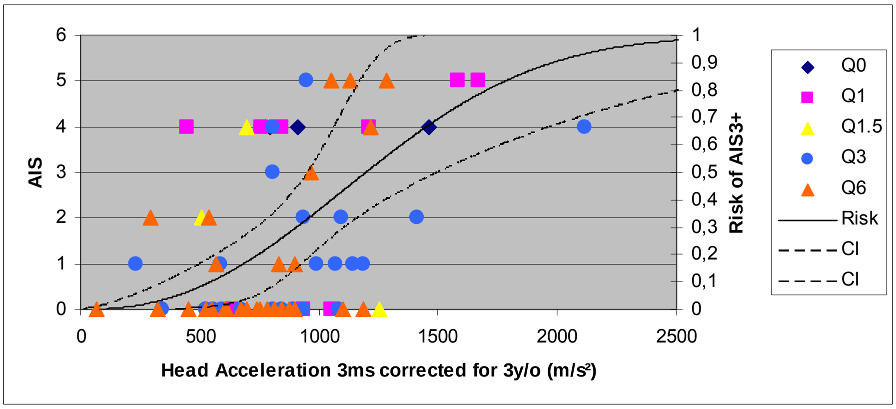


Fig. 4: Head Injury Risk Curve as a function of Head acceleration 3ms for 3 y/o

The neck data points were plotted separately for Q1/Q1.5 and Q3/Q6 dummies since younger children are at particular risk for neck injury in frontal loading. The data points were plotted in Fig. 5 for the Q1 and Q1.5 dummies after scaling at 1 year old. The injury risk curve was constructed. The relative sizes of the confidence interval at 5%, 25% and 50 % of risk were 265%, 130% and 83% respectively. Therefore the error was considered as unacceptable at 5%, while it was considered as marginal at 25% and fair at 50%.It can be observed that no severe injury appeared below 1 kN and that all children sustained a severe injury above 1.3 kN. Neck My data points for cases without head impact do not allow the development of an injury risk curve, see Fig. 6.

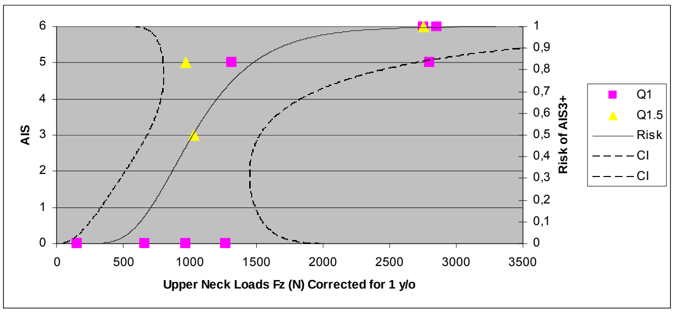


Fig. 5: Neck AIS as a function of Vertical Upper Neck Loads (Fz) corrected for 1 year old

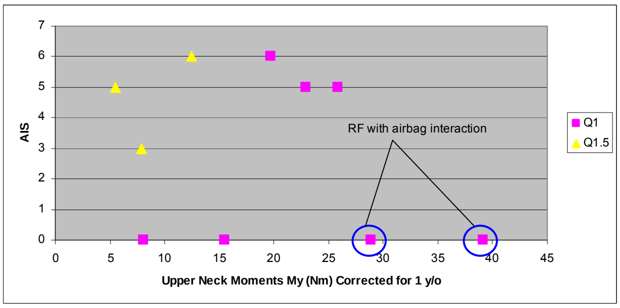


Fig. 6: Neck AIS as a function of Upper Neck bending moments (My) corrected for 1 year old

For Q3 and Q6 dummies, only the cases without head impact were kept. Fig. 7 shows the AIS as a function of the scaled Fz and Fig. 8 the AIS as a function of the scaled My. None of the parameters allowed for the construction of a relevant injury risk curve. A combination of Fz and My was investigated, but did not lead to a more relevant parameter.

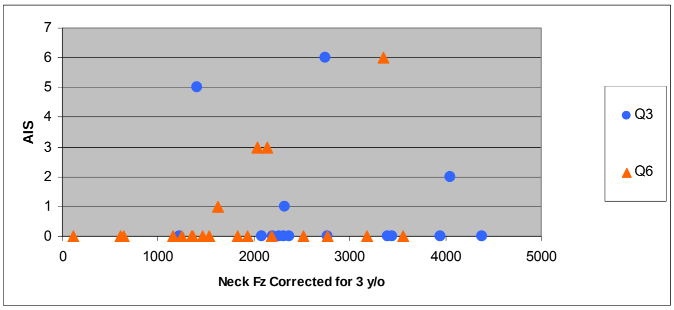


Fig. 7: Neck AIS as a function of Neck Fz corrected for 3 year old

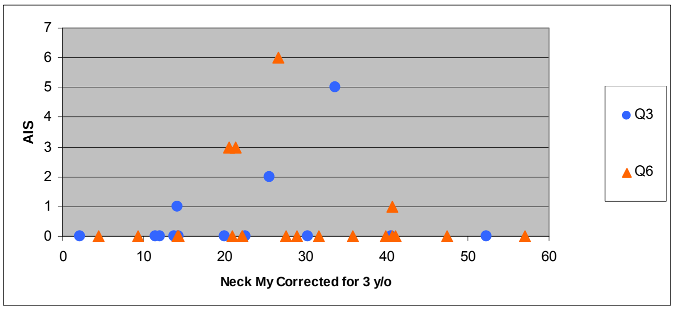


Fig. 8: Neck AIS as a function of Neck My corrected for 3 year old

Chest AIS were plotted as a function of chest deflections (Fig. 9) and accelerations (Fig. 10) corrected for a 3 year old. Cases where the children were restrained by harnesses were separated from cases where the children were restrained by the 3-point belt, with or without boosters, because the response of the chest may differ with the two systems. It can be observed that neither the deflection nor the acceleration was able to predict the risk of AIS3+ injury. The statistical regressions confirm this observation.

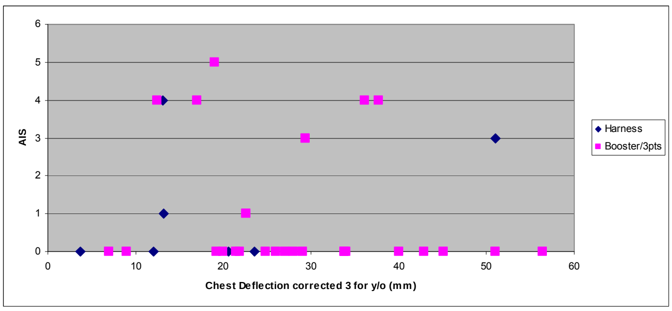


Fig. 9: Chest AIS as a function of Chest Deflection corrected for 3 year old

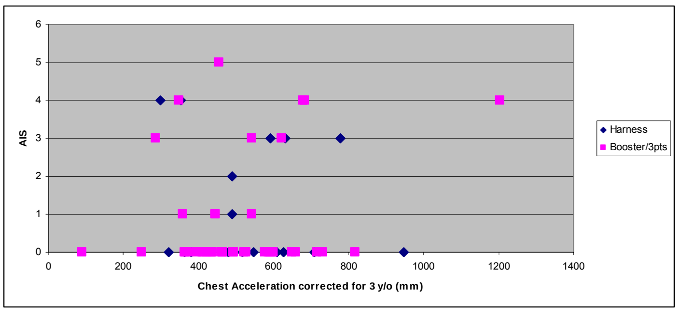
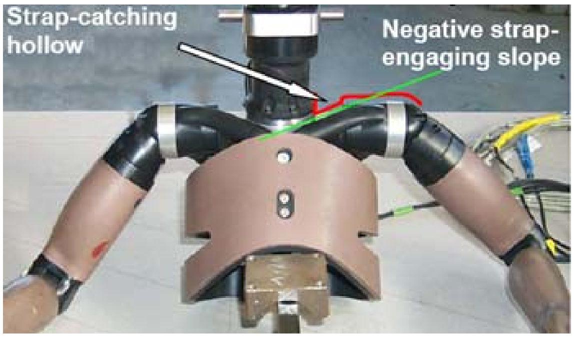


Fig. 10: Chest AIS as a function of Chest Acceleration corrected for 3 year old

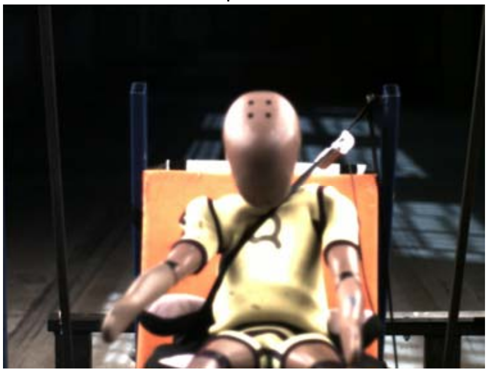
The basis for chest peak deflection and chest VC is the chest displacement measurement using a string potentiometer or an IR-TRACC. It is well known that the accuracy of chest deflection assessment is highly dependent on the positioning of the belt with respect to the location of the chest deflection sensor in H3 adult dummies. In principle the same is true for Q-dummies. Following on that, chest deflection measurement seems to be meaningless for CRS with harness systems as none of the straps will directly interact with the sensor. Furthermore, the problems identified for adult dummies and belt use are more dominant for Q dummies as the shape of the shoulder and thorax leads the shoulder belt to slip away from the sternum, see Fig. 11. In general this leads to an underestimation of the true deflection, which is likely linear, to the measured deflection. However, under specific circumstances which are not yet understood the belt does not move upwards. In addition, in a large number of cases the measured chest deflection was judged to be invalid. In most of the cases it was possible to prove incorrect use of the sensor (e.g., wrong installation direction, incorrect use of IR-TRACC etc.). If chest deflection load limits are to be applied, countermeasures against incorrect use of the sensors are necessary.



negative slope towards neck in shoulder shape

Typical shoulder belt routing before impact (belt is aligned with deflection sensor position

thorax shape from lateral view, slope of the thorax facilitates in addition to the shoulder design upwards movement of the shoulder belt



belt position observed in most of the cases after initial loading (belt moved upwards and is not aligned with deflection sensor)

Fig. 11: problems with frontal impact chest deflection measurement in Q dummies

The abdominal raw data (CFC60) obtained from the reconstructions are presented in Fig. 12 and the data points scaled to a 3 year old are plotted in Fig. 13 together with the injury risk curve. Several data points were found to be overly influential. However since no reason was found to remove them, they were kept in the analysis. However, harness-type CRS cases were removed from the sample. The relative sizes of the confidence interval at 5%, 25% and 50 % of risk were 99%, 60% and 51% respectively. Therefore, the error was considered as fair at 5%, 25% and 50% of risk. The values are summarised in TABLE 4.

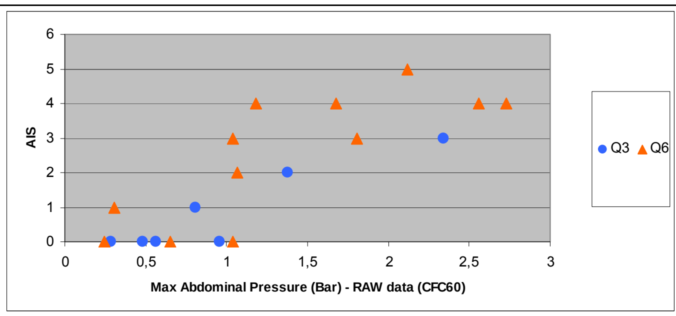


Fig. 12: Abdominal AIS as a function of Abdominal pressure CFC60

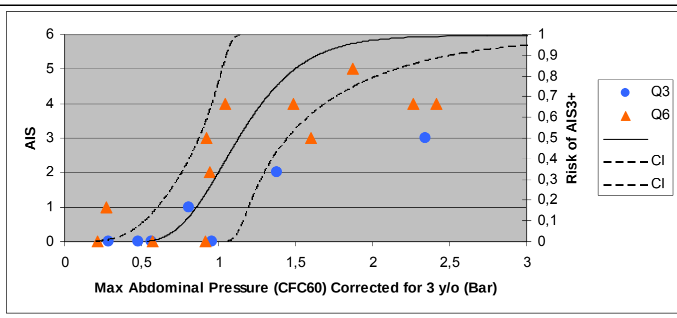


Fig. 13: Abdominal AIS as a function of Abdominal pressure CFC60, corrected for 3 year old.

Injury Risk Curves for Lateral Impact

The head raw data obtained from the reconstructions are presented in Fig. 14 as a function of head acceleration and the data points scaled to a 3 year old are plotted in Fig. 15 together with the injury risk curve. Several data points were found to be overly influential. However since no reason was found to remove them, they were kept in the analysis. The relative sizes of the confidence interval at 5%, 25% and 50 % of risk were 298%, 123% and 64% respectively. Therefore the error was considered as unacceptable at 5%, while it was considered as marginal at 25% and fair at 50%. The values are summarised in TABLE 4. The same process was done with the HIC36ms and HIC15ms. The AIC values were not comparable since some data points were missing for the HIC. However, the sizes of the confidence intervals were higher, leading to unacceptable curves. It was then recommended to use the linear acceleration 3ms and not the HIC. Based on testing experience with the new GRSP IG CRS side impact test procedure GRSP concluded to concentrate on head a_{3ms} instead of HIC because the latter was shown to be less reproducible in this test procedure.

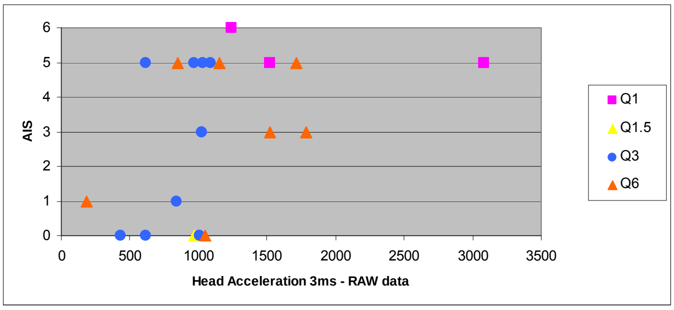


Fig. 14: Head AIS as a function of Head linear acceleration 3ms for lateral reconstructions

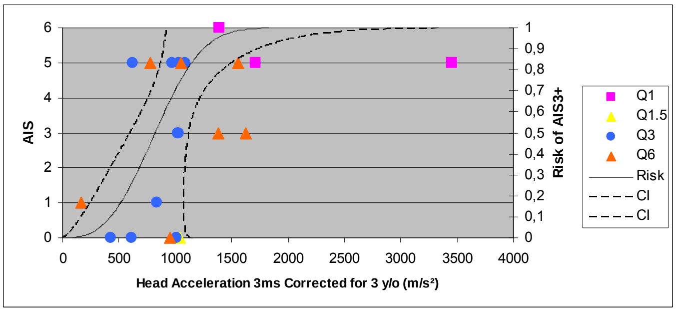


Fig. 15: Head Injury Risk Curve as a function of Head acceleration 3ms for 3 y/o

Chest AIS values were plotted as a function of chest accelerations corrected for a 3 year old (Figure 16). The number of reconstructed accident cases with severe chest injuries in side impact was too small to allow for the definition of thresholds.

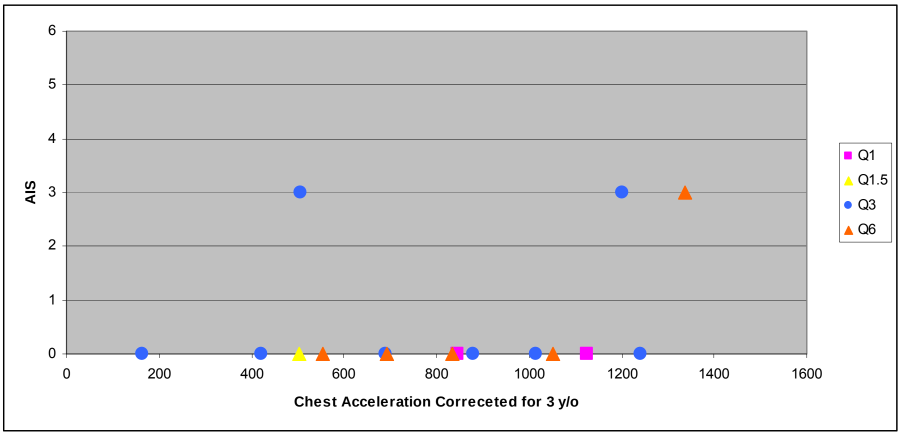


Fig. 16: Chest AIS as a function of Chest acceleration corrected for 3 years old in Side Impact

TABLE 4

Summary of injury assessment values

			5%	25%	50%
Frontal	Head Acc 3ms	Q3	402	827	1196
	Neck Fz	Q1		791	1022
	Abdominal Pressure	Q3	0.70	0.93	1.13
Lateral	Head Acc 3ms	Q3		604	821
good	fair	marginal	unacceptable		
0-50%	51-100%	101-150%	>151%		

Proposed Load Limits

Based on the injury risk curves and the data points for the neck presented above, the following load limits are proposed taking into account the 50% risk for an AIS 3+ injury.

TABLE 5
Proposed load limits

Body region	head (frontal)	head (lateral)	neck	chest	abdomen
Reference dummy	Q3	Q3	Q1	Q3	Q3
Criterion	a_{3ms}[m/s²]	a_{3ms}[m/s²]	FZ [N]	no proposal	pressure [bar]
Proposed limit	1,000	835	1,200	no proposal	1.13

IV. Discussion

First of all it is important to state that the injury risk curves shown above are based on comparing Q dummy readings with injury severity and are therefore only applicable to Q dummies. However, the advantage of this approach is that no scaling between human and dummy is necessary because the curves have been derived using the most appropriate tools available.

One important limitation of the study is the relative small number of cases to be analysed. In order to make up for the small number of cases results of different dummy sizes were scaled to one size, normally the Q3. The used scaling factors were the same that were used to develop the dummy therefore it is reasonable to apply the same assumptions for the development of injury risk functions. It is clear that scaling methods for children rely mainly on assumptions and cannot be accepted as completely validated. In order to address this limitation several approaches were used: for the neck, Q1 and Q1.5 were analysed separately from the other dummy sizes as scaling problems for neck forces were discussed before. In addition data points for different dummy sizes were plotted in different styles in order to allow visual checks of scaling validity and finally statistical analysis supported the indication mentioned above.

TABLE 6
Comparison of load limits proposed by EEVC [8], GRSP IG CRS [9] and CASPER

	Head a_{3ms}	HIC	Neck FZ	Neck MY	Chest a_{3ms}	Chest DS	Abdomen	Head lateral a_{3ms}
Reference Dummy	Q3	Q3	Q1	Q1	Q3	Q3	Q3	Q3
Unit	g	-	kN	Nm	g	mm	bar	g
ECE R1XX	80	800	-	-	55	-	-	80
EEVC	75	780 - 1000	1.2	64	55	36	-	-
CASPER 20 % risk	75	Not recommended	1 (no injuries observed below)	No sufficient data	Generally not recommended but any limit for chest necessary	No sufficient data	0.88	55
CASPER 50% risk	120	Not recommended	1.3 (only children with AIS 3+ injuries above)	No sufficient data	Generally not recommended but any limit for chest necessary	No sufficient data	1.13	85

TABLE 6 shows a comparison between the load limits proposed by EEVC, used by the new regulation for the homologation of CRS and the CASPER results. The comparison shows that in general the EEVC proposals can be confirmed. However, within the EEVC data set for head risk curves the injury cases were mainly based on head contact cases and the risk curve was not valid for injury prediction without contact. With the new data the situation changed as the injury cases were almost equally distributed amongst contact and non-contact cases. The neck load limits proposed by EEVC were based on scaling of adult data. With the CASPER data it is possible to confirm the scaled data at least for Q1 and Q1.5. For Q3 and Q6 it is recommended that limits be defined based on the state of the art of CRS performance in order not to allow worsening of the situation compared to today.

Chest measurement is an issue. Biomechanically, chest deflection is the criteria to be considered but the sensors and the dummy response do not provide results that can be used with confidence.

Except for the head in frontal impact conditions, the risk curves still suffer from a lack of data points. Therefore, further research is necessary to improve the confidence level. This is in particular true for lateral impact.

V. Conclusions

Based on accident reconstructions from CREST, CHILD and CASPER projects injury severity levels were paired with dummy reading results. Especially for the head in frontal impact conditions, a reliable number of data points is available to derive solid injury risk curves using the survival method. For the neck in frontal impact conditions, a trend for the Q1 and Q1.5 dummies can be observed derived from scaled adult data which seem to describe the injury risk quite well. For the chest neither resultant acceleration nor the chest deflection seem to be injury risk predictive; for the chest compression this is likely caused by belt interaction problems of the Q dummies for 3-point belts. The improved APTS abdominal sensor shows good prediction of injury risk although the number of cases is still low. For lateral impact only an injury risk curve for head a_{3ms} was derived. For the other body regions the number of cases with injuries is too low.

VI. Acknowledgement

The authors want to acknowledge EC for funding the research works and CASPER partners for all efforts done to contribute to the construction of injury risk curves

VII. References

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VIII. Appendix

Table A1. Frontal Head Sample

Test Number	Dummy	Head AIS	Lin acc (m/s²)	HIC 36	head contact
CCN_1005 / 1	Q0	4	960,4	673	yes
CCN_1211 / 1	Q0	4	838,6	1149	airbag deployment
CCN_2012 / 1	Q0	4	1542,9	2540	yes
CCN_1185 / 1	Q1	4	1079,2	1215	yes
CCN_2014 / 2	Q1	5	1408,4	5103	yes
CCN_2015 / 1	Q1	5	1487,18	3128	no
CCN_2017 / 1	Q1	4	395,9	204	no
CCN_2053 / 1	Q1	0	568,8	339	soft impact with shield
CCN_2062 / 3	Q1	4	675,4	657	yes airbag deployment
CCN_2094 / 1	Q1	4	752,4	882	yes airbag deployment
CCN_ITF-CRS Case E 2 / 1	Q1	2	2334,8	3391	no
CCT_0038_2 / 1	Q1	0	835,1	1254	no
CCT_0038_2 / 2	Q1	0	939,7	1197	no
CCN_2016_1 / 1	Q1,5	4	646	494	yes
CCT_0011 / 1	Q1,5	2	471,2	343	no
CCT_0068 / 1	Q1,5	0	1158,4	2087	no
CCN0352	Q3	4	808,56	985	no
CCN2059	Q3	2	1410,75	3024	yes
CCN_0002 / 2	Q3	1	588,6	456	chin-chest
CCN_0056 / 2	Q3	0	804,4	637	head-foot
CCN_0123 / 1	Q3	1	229,5	59	likely not, no video
CCN_0182 / 1	Q3	0	523,8	460	likely not, no video
CCN_0323 / 1	Q3	0	557,1	476	no
CCN_0329 / 1	Q3	0	594,5	560	chin-chest
CCN_1067 / 1	Q3	0	937,1		no
CCN_1082 / 1	Q3	0	524,9		chin-chest?
CCN_1119 / 1	Q3	0	1082,6	1522	no
CCN_1148 / 1	Q3	1	1186,6	3067	chin-chest
CCN_1199 / 1	Q3	0	840,6	821	no
CCN_1207-2 / 1	Q3	2	1094,4	2109	no
CCN_2001 / 1	Q3	2	933	1661	yes
CCN_2001 / 1	Q3	1	988,8	1670	no
CCN_2012 / 1	Q3	4	2116,6	7540	yes
CCN_2015 / 2	Q3	1	1142	1837	no
CCN_2016_1 / 1	Q3	0	340,2	167	likely
CCN_2058 / 1	Q3	5	949,8	1380	no
CCN_ITF-CRS Case E / 1	Q3	3	804,4	1107	no
CCT_0022 / 3	Q3	1	1069,3	1693	yes
CCT_1029-sled / 2	Q3	0	890,9	1329	no
CCT_1081 / 3	Q3	0	669,9	719	no
CCN_0002 / 2	Q6	0	578,8	562	chin-chest
CCN2043	Q6	5	1410,75	4233	no
CCN_0089 / 1	Q6	2	321,4	83	likely not, no video
CCN_0225 / 1	Q6	0	1206,6	1028	chin-chest
CCN_0391 / 1	Q6	3	1061,1	2433	chin-chest
CCN_1043 / 1	Q6	1	985	1561	chin-chest?
CCN_1079 / 1	Q6	0	498,2	389	chin-chest
CCN_1104 / 1	Q6	0	1301,1	1755	chin-chest?
CCN_1104 / 1	Q6	0	986,7	1767	chin-chest?
CCN_1148 / 1	Q6	1	912	1924	chin-chest
CCN_1149 / 1	Q6	0	855,7	1306	no
CCN_1215 / 1	Q6	0	602,5	631	chin-chest
CCN_1229 / 1	Q6	0	959,8	2425	no
CCN_2003 / 1	Q6	4	1336,7	3604	no
CCN_2017 / 1	Q6	0	352,4	152	no
CCN_2023 / 1	Q6	5	1239,4	4278	no
CCN_2032 / 1	Q6	0	809,6	1124	no
CCN_2032 / 1	Q6	1	621,5	754	no
CCN_2061 / 1	Q6	0	673,5	1124	no
CCN_2062 / 3	Q6	0	76,5	5	no
CCN_2103 / 1	Q6	0	665	497	no
CCN_ITF-CRS Case E / 1	Q6	2	588,6	785	no
CCT_0022 / 2	Q6	0	824	1129	no
CCT_0038 / 3	Q6	0	922,1	1280	no
CCT_0038_2 / 1	Q6	0	767,6	1167	no
CCT_0038_2 / 2	Q6	0	892,1	1413	no
CCT_0095 / 2	Q6	5	1156,6	2023	yes
CCT_0249 sled tests / 1	Q6	0	735,8	1034	no

Table A2. Frontal Neck Sample

Test Number	Dummy	Neck AIS	Upper Neck (loads) Z [N]	Upper Neck Moments Y [Nm]	head contact
CCN_1185 / 1	Q1	0	662,18	15,45	yes
CCT_0038_2 / 1	Q1	5	2800,855	25,85	no
CCN_2015 / 1	Q1	6	2855,56	19,67	likely not
CCN_2014 / 2	Q1	6	2756,27		yes
CCN_2017 / 1	Q1	0	1268,35	8,1	no
CCN_2062 / 3	Q1	0	151,21	39,14	airbag and RF
CCN_2094 / 1	Q1	0	970,4	28,9	airbag and RF
CCN_2053 / 1	Q1	5	1317,49	22,93	slight contact to schield
CCT_0068 / 1	Q1,5	6	3120,23	14,15	no
CCN_2016 / 1	Q1,5	3	1163,78	8,94	no
CCT_0011 /1	Q1.5	5	1101,27	6,18	no
CCN_0123 / 1	Q3	0	1225	40,6	no
CCN_0182 / 1	Q3	0	2080	14,3	no
CCN_0329 / 1	Q3	0	2200	2,1	chin - chest
CCN_0002 / 2	Q3	0	2310	14,22	no
CCN_1067 / 1	Q3	1	2328	33,7	no
CCN_0323 / 1	Q3	5	1404	12	no
CCN_1102 / 1	Q3	0	2365	30,32	no
CCT_1081 / 3	Q3	0	2268	11,54	no
CCN_1119 / 1	Q3	0	3446	13,82	no
CCN_1148 / 1	Q3	0	4385,65	22,5	no
CCN_1199 / 1	Q3	0	2768,06	52,35	no
CCT_1029-sled / 2	Q3	0	3949,76	19,96	no
CCN_2001 / 1	Q3	0	3398,72	25,52	in rebound
CCN_0352 / 1	Q3	2	4046	61,2	no
CCN_2058 / 1	Q3	6	2742,87	21,4	no
CCN_0089 / 1	Q6	0	2059	33	no
CCN_0225 / 1	Q6	0	1827	6,7	chin - chest
CCN_0225 / 1	Q6	0	1680	70,71	chin - chest
CCN_0002 / 2	Q6	0	820	84,9	chin - chest
CCN_0391 / 1	Q6	0	4770,2	33,1	no
CCN_1043 / 1	Q6	0	3715,09	59,32	no
CCN_1079 / 1	Q6	0	1553	53,37	no
CCN_1104 / 1	Q6	0	2930	41,05	no
CCN_1104 / 1	Q6	0	4262	31,71	no
CCN_1229 / 1	Q6	0	3373,67	30,67	no
CCT_0038_2 / 1	Q6	3	2725,84	43	no
CCT_0038_2 / 2	Q6	3	2875,87	13,95	no
CCN_2061 / 1	Q6	0	1968,78	47,02	no
CCN_2062 / 3	Q6	0	154	60,63	no
CCN_2029 / 1	Q6	0	2596,24	31,22	no
CCN_2103 / 1	Q6	1	2181,73	60,63	no
CCN_2017 / 1	Q6	0	853,82	39,72	no
CCN_2032 / 1	Q6	0	2453,83	21,1	no
CCN_2043 / 1	Q6	6	4502		no
CCN_2032 / 1	Q6	0	1817,37		no

Table A3. Frontal Chest Sample

Test Number	Dummy	Chest AIS	Lin. acc. [m/s²]	Chest deflection front [mm]	CRS
CCN_1185 / 1	Q1	0	389,2	4	5-point harness
CCN_2017 / 1	Q1	4	361,8	14	5-point harness
CCT_0038_2 / 1	Q1	0	723,5		4-point harness
CCT_0038_2 / 2	Q1	0	639,1		4-point harness
CCN_2016_1 / 1	Q1,5	4	331,1		5-point harness
CCT_0011 / 1	Q1,5	1	540,7	14	5-point harness
CCT_0068 / 1	Q1,5	0	572	25	4-point harness
CCN_0002 / 2	Q3	0	480,7		4-point harness
CCN_0056 / 2	Q3	0	598,4		backless booster
CCN_0123 / 1	Q3	0	436,7	7	backless booster
CCN_0182 / 1	Q3	0	373,3		highback booster
CCN_0323 / 1	Q3	0	462,8	20	backless booster
CCN_0329 / 1	Q3	0	319,8	20,55	4-point harness
CCN_1067 / 1	Q3	0	422,8	26	backless booster
CCN_1082 / 1	Q3	0	465,9	34	highback booster
CCN_1102 / 1	Q3	0	494	51	backless booster
CCN_1119 / 1	Q3	3	592,9	51	4-point harness
CCN_1148 / 1	Q3	0	717,3	40	highback booster
CCN_1199 / 1	Q3	0	546,6		5-point harness
CCN_2001 / 1	Q3	2	490,1		5-point harness, harness below arms
CCN_2001 / 1	Q3	0	591	27	highback booster
CCN_2012 / 1	Q3	0	948,4		5-point harness, harness below arms
CCN_2015 / 1	Q3	0	609,31	12	5-point harness
CCN_2016_1 / 1	Q3	4	349,1	17	backless booster
CCN_2058 / 1	Q3	3	631,2		5-point harness
CCN_ITF-CRS Case E / 1	Q3	0	412		highback booster
CCN0352	Q3	0	731	28	highback booster
CCN2059	Q3	3	778,83		5-point harness
CCT_1029-sled / 2	Q3	0	658,5	29	highback booster
CCT_1081 / 3	Q3	5	454,1	19	backless booster
CCN_0002 / 2	Q6	0	559,2		adult three-point
CCN_0225 / 1	Q6	0	414		5-point harness
CCN_0225 / 1	Q6	1	505,7		backless booster
CCN_0391 / 1	Q6	3	707		adult three-point
CCN_1006 / 1	Q6	0	674,2	30	highback booster
CCN_1043 / 1	Q6	0	599,2	19,37	adult three-point
CCN_1079 / 1	Q6	3	324,3		backless booster
CCN_1104 / 1	Q6	0	495,2	30	backless booster
CCN_1104 / 1	Q6	0	465,8	50	backless booster
CCN_1148 / 1	Q6	0	102	22	adult three-point
CCN_1149 / 1	Q6	0	593,8	19	backless booster
CCN_1171 / 1	Q6	3	617,2	26	pillow
CCN_1215 / 1	Q6	0	417,2		highback booster
CCN_1229 / 1	Q6	0	674,3	8	backless booster
CCN_2003 / 1	Q6	4	771,4	32	backless booster
CCN_2017 / 1	Q6	0	283,9	17	backless booster
CCN_2023 / 1	Q6	4	1368,6	33	highback booster
CCN_2029 / 1	Q6	0	738,8	38	adult three-point
CCN_2032 / 1	Q6	0	528,9	40	backless booster
CCN_2061 / 1	Q6	0	491,5		highback booster
CCN_2103 / 1	Q6	1	408,3	20	backless booster
CCN_ITF-CRS Case E / 1	Q6	0	451,3		backless booster
CCN2043	Q6	4	778,83	11	highback booster
CCT_0022 / 2	Q6	1	618		adult three-point
CCT_0038 / 3	Q6	0	932		backless booster
CCT_0038_2 / 1	Q6	0	667,2		backless booster
CCT_0038_2 / 2	Q6	0	682,6		backless booster
CCT_0095 / 2	Q6	0	413		backless booster
CCT_0249 sled tests / 1	Q6	0	657,3		highback booster

Table A4. Frontal Abdomen Sample

Test number	Dummy	Abdomen MAIS	Max Pressure (CFC60)	CRS	Misuse
CCN_0352 / 1	Q3	2	1.38	highback booster	no but shoulder belt guide released during crash
CCN_0323 / 1	Q3	0	0.96	backless booster	shoulder belt under arm
CCN_1102 / 1	Q3	0	0.29	backless booster	no
CCN_1148 / 1	Q3	1	0.81	highback booster	no
CCN_1082 / 1	Q3	3	2.34	highback booster	shoulder belt under arm
CCN_1067 / 1	Q3	0	0.56	backless booster	no
CCN_1207 / 2	Q3	0	0.48	backless booster	no
CCN_0391 / 1	Q6	4	1.68	adult belt only	no CRS
CCN_1171 / 1	Q6	3	1.8	pillow	not a CRS
CCN_1043 / 1	Q6	0	1.04	adult belt only	no CRS
CCN_1149 / 1	Q6	1	0.31	backless booster	no
CCN_1215 / 1	Q6	2	1.07	highback booster	no
CCN_1148 / 1	Q6	0	0.65	adult belt only	no CRS
CCN_2041 / 1	Q6	4	2.56	highback booster	no
CCN_2003 / 1	Q6	4	1.18	backless booster	no
CCN_2017 / 1	Q6	0	0.24	backless booster	no
CCN_2043 / 1	Q6	5	2.12	highback booster	no
CCN_2032 / 1	Q6	3	1.04	adult belt only	no CRS
CCN_2032 / 1	Q6	4	2.73	backless booster	shoulder belt under arm

Table A4. Lateral Head Sample

Test Number	Dummy	Head AIS	Lin. acc. [m/s²]	HIC36	HIC15
CCN_0405 / 1	Q1	5	3080,3	9977	9977
CCN_1048 / 1	Q1	5	1525,5	2065	2065
CCN_1255 / 1	Q1	6	1241,6	9211	3886
CCN_2051 / 2	Q1.5	0	967,3	613	613
CCN_0165 / 1	Q3	0	615,3	37	20
CCN_0196 / 1	Q3	5	1090,9	2300	
CCN_0235 / 1	Q3	0	431,6		
CCN_0255 / 1	Q3	5	620,1	530	388
CCN_1033 / 1	Q3	5	1036,3	826	818
CCN_1037 / 1	Q3	5	972,8	573	541
CCN_1236 / 1	Q3	3	1021,4	669	669
CCN_2006 / 1	Q3	3	1027,2	1011	1011
CCN_2030 / 1	Q3	1	839	385	385
CCN_2095 / 1	Q3	0	1008,8	1351	1316
CCN_0165 / 1	Q6	1	185,2	318	318
CCN_0166 / 1	Q6	3	1785,4	2710	2705
CCN_0168 / 1	Q6	3	1520,5	2044	2043
CCN_0263 / 1	Q6	5	1151,7	1415	1413
CCN_2052 / 1	Q6	5	850,8	1646	921
CCN_2095 / 1	Q6	5	1710,4	18480	18480
CCN_2095 / 1	Q6	0	1046,2	1048	1048