SYNTHESIS REPORT

Non confidential & publishable

CONTRACT N°: SMT4-CT95-2019

TITLE: **CHILD RESTRAINT SYSTEM FOR CARS (CREST)**

PROJECT COORDINATOR: Xavier TROSSEILLE

PARTNERS:

Contractors

RENAULT
FIAT
INRETS
PSA
TNO
TUB
RICE
BAST

Associated contractors

GDV
VTI
MUH

REFERENCE PERIOD FROM: 1/1/1996 to 31/12/2000

PROJECT FUNDED BY THE EUROPEAN COMMUNITY
UNDER THE SMT PROGRAMME

CREST

Child Restraint System for Cars

Funded by the European Commission,
Directorate General Research C-RTD

SMT4-CT95-2019 CREST Project

Child restraint systems

The Partners

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FIAT Auto SpA (IT), Safety Center
INRETS, (FR), Laboratoire de Biomécanique et de Mécanique des chocs (L.B.M.C.)
PSA (FR), GIE Peugeot-Citroën
TNO Automotive (NL), Crash Safety Center
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VTI (SE) Crash Safety Group
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Background

Child restraint systems (CRS) for cars are intended to protect children in the case of a car accident.

Protection systems for child passengers in the European Union must comply with ECE regulation 44 which aims at ensuring a good safety level. From the accident protection viewpoint, this regulation consists mainly in a frontal impact test where physical measurements performed on dummies shall not exceed specified limits. Evaluation criteria cover kinematics and acceleration for the thorax.

The analysis of accidents involving children reveals that child restraint systems (CRS) in compliance with European regulations give highly contrasted levels of protection in real-world accidents. The low effectiveness of child restraint systems can partly be explained for the youngest passengers by their greater cervical vulnerability and for the oldest (from 3 to 12 years old) by the morphological immaturity of the pelvis.

The main reasons for this bad situation are on the one hand the lack of biofidelity of the dummies, and on the other hand the insufficient biomechanical knowledge on injury mechanisms and associated physical parameters.

Unlike for the adult, child impact tolerance or behaviour cannot be determined directly by experiments on human bodies. The main sources of data up to now come from child free-fall studies, aircraft field investigations, animal testing, scaling from adults and very few post-mortem experiments on human subjects.

The CREST project was created to develop the knowledge on child behaviour and tolerances, the final aim being to propose new test procedures for determining the effectiveness of CRS using instrumented child dummies.
The method used in this project was to collect data from accident investigations and from reconstruction crash tests in order to determine the physical parameters (forces, accelerations and deformations on the child) which correspond to the various child injury mechanisms. Hence, limits should be prescribed under which injuries could be avoided.

Objectives

The project has to develop new test procedures to determine the effectiveness of child restraint systems for cars using instrumented child dummies. The ultimate aim of the project is to improve the effectiveness of child restraint systems that are used in cars.
This objective can be expressed in three items :

- to determine the physical parameters corresponding to various child injury mechanisms,
- to prescribe limits under which injuries can be avoided,
- to develop new test procedures for determining the effectiveness of child restraining systems for cars, using instrumented dummies.

Workprogramme

Data were collected from accident investigations and from crash tests in order to determine the physical parameters (forces, accelerations and deformations on the child) which correspond to the various child injury mechanisms. Hence, limits should be prescribed under which injuries can be avoided. Frontal and lateral impacts involving child victims were studied in the project. It is expected that side impacts would be particularly important as the few statistics currently available indicate that they account for a high rate of severe and fatal injuries to children. The new test procedures that are developed were applied to market products or prototypes (ISOFIX) in order to evaluate the feasibility for industry and to meet more stringent requirements for child protection.
In order to achieve the objectives, the project was divided in four workpackages :

- WP1 consisted in a detail analysis of traffic accidents involving children using protection systems.
- WP2 consisted in experimental reconstruction of several selected accidents to acquire the biomechanical data necessary for limits to be set for the parameters measured on dummies.
- WP3 consisted in the acquisition of appropriate test tools to conduct the experimental work (WP2), by improving dummies and measurement techniques.
- WP4 intended to propose test procedure improvements and to validate their feasibility.

Results and Achievements

Accident Data Collection (WP1)

405 accident cases involving restrained children were gathered in France, Germany, Italy and Great Britain, according to a common and well defined methodology.
The cases were, wherever possible, in-depth investigations, collected with two aims:

- the analysis of injuries in relation with the use of protection devices,
- the experimental reconstruction.

Figure 1. Accident case collection

For that, all dockets had to include two complementary parts:

- a medical docket including, wherever possible, the description of all occupants with age, weight, position in the car and for all injuries, the typology and level of AIS.
- a technical docket including accident configuration, measurements of car deformations, information on restraining occupant system used and adjustments.

A specific form was developed for this purpose and a database was constructed and filled in with all cases.
This data base in its final version contains 405 accidents involving 430 cars with restrained children. Of these, 312 are involved in frontal impacts and the number of restrained children in this configuration is 460, and 118 vehicles have been involved in side impacts with a total of 168 restrained children.
The reason for the CREST Accident data base not being representative is largely coming from the crash severity in terms of impact severity. For example, more than 83 % of the children involved in frontal impacts are restrained in a car with a Energy Equivalent Speed (EES) over 40 km/h. The EES is the speed of a given vehicle against a rigid barrier to produce the same deformation as in the real impact. For the side impact configuration, more than 86% of the restrained children involved are seated in a car with more than 200 mm of intrusion on the passenger compartment. The severity of these impacts is going to limit the conclusions that can be drawn in the majority of studies from this data base. Nevertheless, the following analysis were performed :

Inappropriate use

The use of a child restraint system was considered as inappropriate when the weight of the child using that CRS is not within the limits of the approval group. When the weight of the child is unknown, then the age is the criteria for the definition of the appropriate or inappropriate use of the CRS.
The **Table 1** has been prepared in order to show the differences of the proportion of children using a non appropriate CRS according the age of the children.

Table 1. Inappropriate use of CRS

Age	Total	% non appr./total
<6 months	26	23%
6-11 months	36	22%
12-17 months	45	4%
18-23 months	39	13%
24-35 months	73	12%
3 years	59	22%
4 years	71	27%
5 years	47	30%
6 years	52	56%
7 years	34	47%
8 years	42	79%
9 years	32	78%
10 years	28	
11-12 years	44	
Total	628	29%

It can be seen from this table that in the CREST accident data base only children of 12 – 17 months and over 10 years can be said to be appropriately restrained. Between 18 and 35 months, less than 15% are inappropriately restrained. Nearly 25% of infants under 12 months are inappropriately restrained, many of whom will be in forwards facing CRS instead of rearward facing ones. The use of inappropriate CRS by children between 3 and 9 years causes concern for different reasons. Children of 3, 4 and 5 years have a lower rate of inappropriate use (22, 27 and 30% respectively) but this group is still very vulnerable to injury, particularly when using the adult 3 point belt as the means of restraining both them and their CRS or just them. The levels of inappropriate use of CRS use amongst the older children increases up to 9 years, and is largely attributable to them no longer using a booster cushion. This is a matter of education and the effects of social and peer pressure, as the children no longer want to use a 'baby' seat and their parents do not understand why they should still be using a booster cushion. Again it must be emphasised that, as the data in the CREST Accident data base is not representative, the situation may be different within the road population at large.

This can also be shown with the repartition of CRS use according to the age of children given on the **Figure 2**. The booster cushion is not used a lot after 7 years old, when its efficiency should be at its maximum.

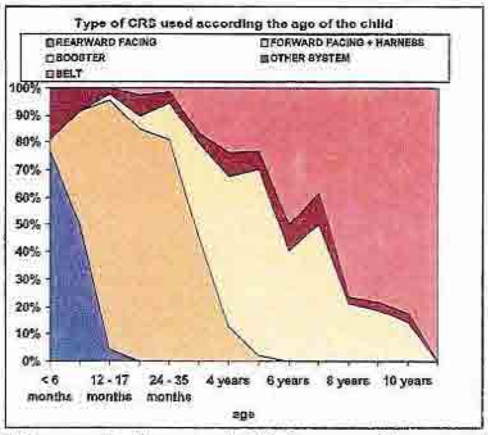


Figure 2. Type of CRS according to the age

Frontal Impact : Comparison between different type of CRS regarding typical severe injuries. Of course before focussing on the injuries of restrained children involved in the CREST accident data base, it has to be said again that it is not representative of the real-world scene, and can be only considered as representative of a selection of very severe accidents. The following study is based on the number of injuries of the restrained children according the body segment on which they occurred. Then a selection is done of the AIS3+ injuries.

Rearward facing infant carrier / forward facing seat
Due to the low number of children restrained with rearward facing devices, the results shown in the **Table 3** cannot be used for statistical analysis, but they can show a tendency of the typical injuries encountered in severe crashes according the type of CRS used. The number of severe head injuries is high and for rearward facing systems can come from an impact of the CRS with the dashboard. However, also important, and shown in **Table 2**, is the number of neck AIS 3+ injuries when children are using group 1 forward facing systems but no neck injuries at all with rearward facing systems. Another interesting point is that the number of limb fractures (upper and lower) is high for both types of CRS. The coding of limb fractures for children is different from the one used for adults which is the reason why very few of them are shown in AIS 3+ injuries analysis.

Table 2. Rearward facing infant carrier / forward facing seat

	Rearward facing		Forward facing	
Number of children with medical information	31		144	
Number of Injuries for:	AIS1+	AIS 3+	AIS1+	AIS 3+
Head	18	5	46	16
Neck	0	0	24	10
Chest	3	0	16	6
Abdomen	1	0	9	3
	AIS1+	fracture	AIS1+	fracture
Limbs	8	4	39	20

Booster cushion + seatbelt / adult seatbelt only:
When comparing the injuries occurring to children using a booster cushion and a seatbelt to those using only the adult seatbelt, in **Table 3** it clearly appears that a lot of abdominal injuries are observed without a booster cushion. The kinematics of the child is then totally different due to a poor positioning of the lap section of the seatbelt.
Interestingly, it is be observed that there are more AIS3+ neck injuries occurring to children on boosters, whilst there are more AIS3+ chest injuries sustained by children using only the adult seat belt. In both cases a lot of limb fractures have been observed.

Table 3. Booster cushion + seatbelt / adult seatbelt only

	Booster cush. + seatbelt		Adult seatbelt only	
Number of children with medical information	108		148	
Number of Injuries for:	AIS1+	AIS 3+	AIS1+	AIS 3+
Head	39	7	44	8
Neck	22	11	25	6
Chest	24	9	45	18
Abdomen	28	9	68	27
	AIS1+	Fracture	AIS1+	fracture
Limbs	53	25	88	38

<u>Side Impact</u> : Severe injuries occurring in side impacts on children from birth to 12 years old.

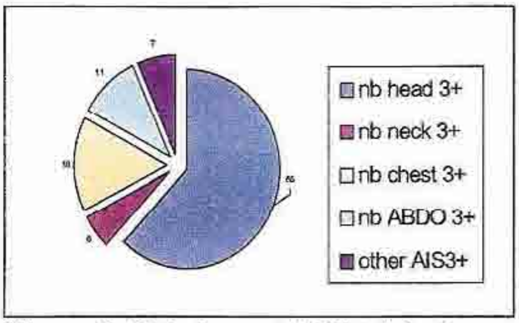


Figure 3. Side impact AIS3+ injuries

The CREST accident data base contains 168 restrained children involved in severe side impacts. Of these, 27 are not injured, and 115 of them have a detailed medical report (including 14 children fatally injured), and the total number of injuries is 424. When focussing only on the severe injuries (AIS 3+), in order to see where effort has to be made in priority to reduce the risk of these injuries occurring, their number is 105. The repartition of the injuries according to the different body segments is given in the **Figure 3**. The head is represented in 62 percent of all the severe injuries recorded in all types of CRS. When comparing the injuries for the different CRS types, severe head injuries always account for more than 50%. Thus, the protection offered to avoid head impacts on the rigid parts of the car or intruding object is currently not sufficient.

Severe injuries also occurred on the chest and the abdomen. They are mainly observed when the child is sitting on a booster cushion or just using the adult belt. For those systems, the chest accounted for 22% and the abdomen 16% of injuries. They have been rarely seen in CRS with a shell, either forward or rearward facing, where the protection of those body segments seems to be more efficient.

The neck appears to be less injured than the other body segments and the injuries noted had mainly occurred on young children using forward or rearward facing child restraint systems and their number is lower. Even though the number of injuries observed is low, it has to be said that each time a AIS3+ injury is observed on the neck in a side impact during the CREST programme, the child has been fatally injured.

Accident Reconstructions and Sled Tests (WP2)

Biomechanical tests with the body of a child are very seldom for obvious cultural reasons. Beside, a child is not an adult at reduced scale and the scaling approach does not allow the transfer of knowledge from adult to child. For these reasons, the crash test reconstruction of an actual accident with a fully instrumented dummy, having a comparable anthropometry, constitutes a right and appropriate methodology to acquire the missing biomechanical knowledge relative to the children. This knowledge is absolutely essential to be able to optimise the design of protection systems for child car passengers.

<u>The objective</u> was to establish correlations between the child injuries observed into the actual accidents and the dummy measurements obtained through the crash reconstructions.
The specific cases for reconstruction were selected according to several criteria:

behaviour and the best prediction of the injury risk to allow enhanced evaluation of the CRS performances: in a first step, improvements of the existing dummies, then development by TNO Automotive of a new series of dummies, called Q dummies, improved for frontal and lateral impacts.
Modifications for frontal impact configurations were made by RENAULT and INRETS; these modifications are described in WP3. A P3, a P6 and a P10 were so modified and used in the subsequent reconstructions (they are called P3M, P6M and P10M). For side impact other modifications were necessary such as reducing the transversal stiffness of the thoracic and abdominal segments and as these modifications were difficult, even impossible on the current dummies, the experts agreed to wait for the new Q dummies for lateral as well as for frontal impact configurations.

For some accidents, these reconstructions were supplemented by a parametric study carried out by means of more simple tests performed on a crash simulator. This made it possible to check the influence of parameters such as the precise position of the CRS (its inclination, its fixation to the vehicle and possible slack in the straps, which cannot be ascertained by the investigation of accident research).

As a whole, 56 full-scale reconstructions and 100 sled tests were achieved. All data from this work were included in a database gathering photos, measurements, criteria, and summary of real accident and allowing row analysis of data. The content of this data base is substantial and unique. However it is still limited, taking into account the number of body segments involved and the different classes of ages of the children.

Synthesis of the analysis from the WPI & WPII databases. A review of all reconstructions was made in order to determine if the results are satisfactory and if the measurements can be used to compare with the injuries. For each case, a form was filled in order to answer the following items:

- shall we consider that the child kinematics is reasonable,
- can we explain injuries,
- do we have to consider the reconstruction for the analysis or
- do we have to consider the sled test and which one.

Thanks to this analysis, it was then possible to select the pertinent measurements and to associate them to the observed injuries, in order to constitute injury risk curves.

Injury risk curves. For head, thorax and pelvis, the analysis was done directly by comparing AIS levels of injuries with measurements (for instance head accelerations or HIC in relation with head AIS). For the neck, a more detailed analysis of injury mechanisms was made in order to associate the good physical parameters to each kind of injury. For instance, a dens fracture was associated to flexion or shearing whereas a spinal cord damage was associated to flexion and traction.

All results of reconstuctions and sled tests were analysed and used to construct injury risk curves. Since accident cases concern several ages, data were scaled to 3 years old, using geometrical and material failure factors.

Figure 5 gives the level of head AIS in relation with the HIC (36ms) value corrected for 3 years old for frontal impact. Only results with Q dummies (and P1 ½ which is closer to Q than to P dummies) were used for the definition of injury risk curve. This latest, which was constructed using the certainty method, is given in yellow for AIS3+. **Figure 5bis** gives the same for Head Acceleration (3ms).

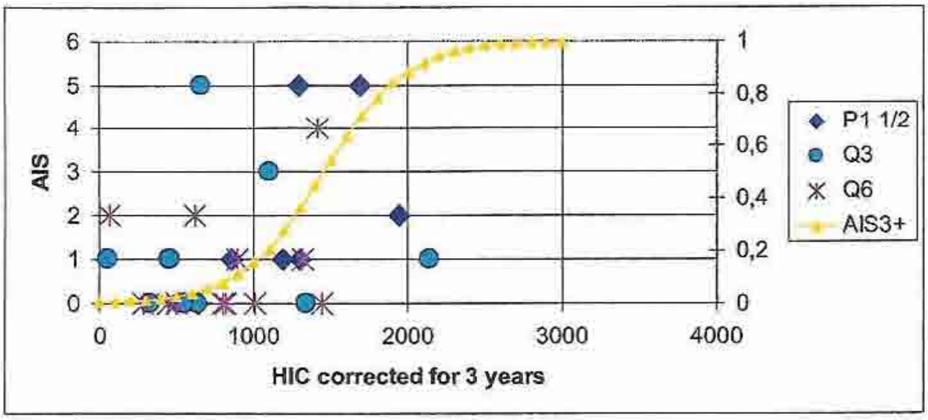


Figure 5. AIS3+ Injury risk curve for HIC (3 years old)

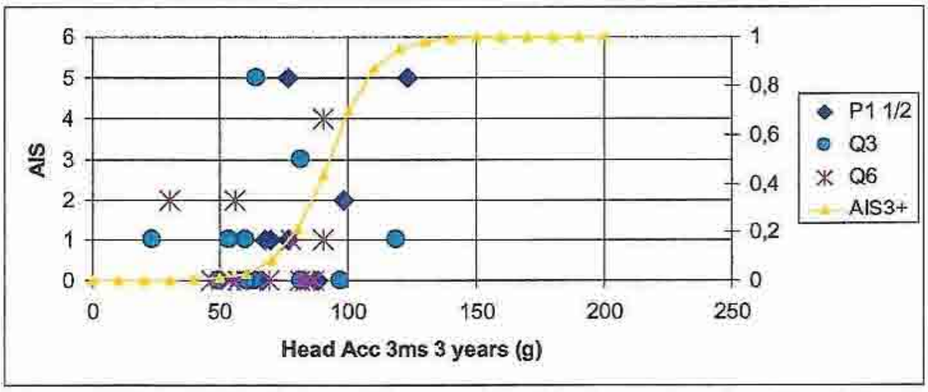


Figure 5bis : AIS3+ Injury risk curve for Head Acceleration (3ms) for 3 year old

Figure 6 gives the level of Neck injury in relation with My corrected for 3 years old. It is obvious in this graph that we are still missing results of the definition of injury risk curves, in particular, cases with injury. It can only be said that a large amount of cases without injury demonstrate My values under 30 Nm and that some unexpected cases with high AIS are observed for low values of My. Results are the same for Fx and Fz parameters where more data are also needed.

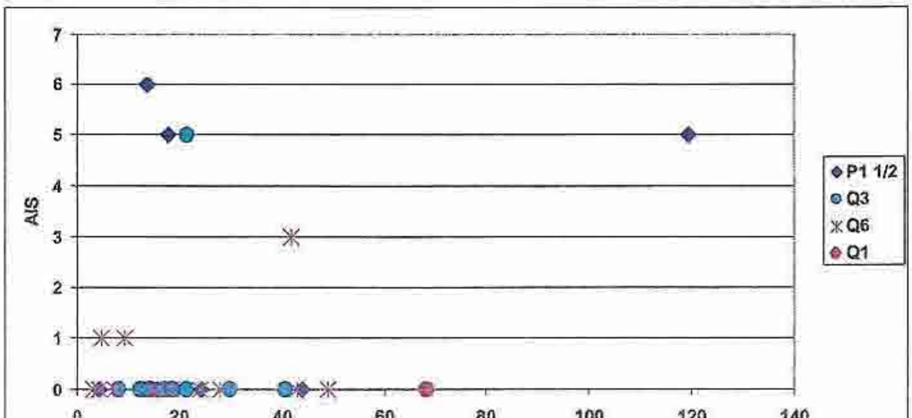


Figure 6. My versus AIS for 3 years old Q dummies

Figure 7 gives the regression curve for AIS2+ injuries to the thorax. This curve was made using a logistic regression with all dummies. **Figure 7bis** gives the same for Q3 and Q6 dummies using the certainty method.

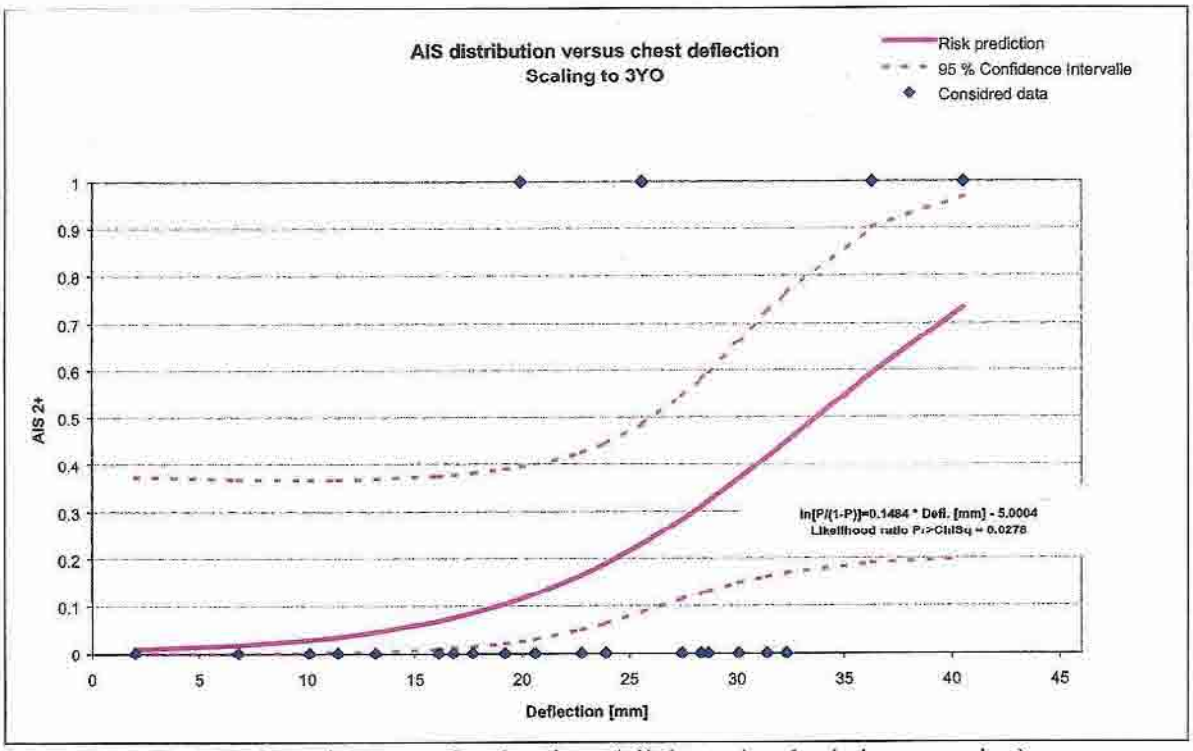


Figure 7. AIS 2+ Injury risk curve for the chest (all dummies, logistic regression)

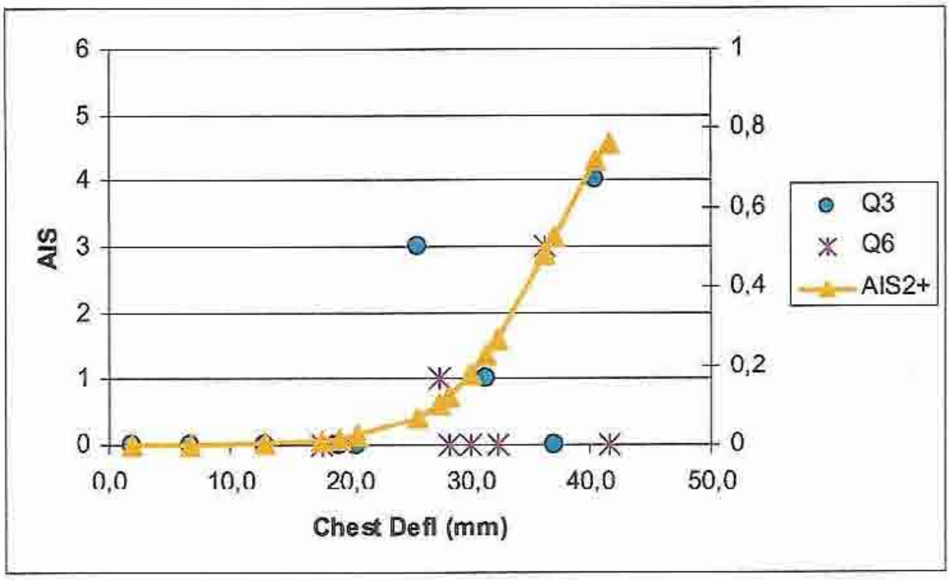


Figure 7bis. AIS 2+ Injury risk curve for the chest (certainty method) for 3 years old Q dummies

Figure 8 gives the AIS2+ injury risk curve for abdomen, measured only on P3M and P6M dummies. No measurements were available on Q dummies and results should not be applied to these dummies.

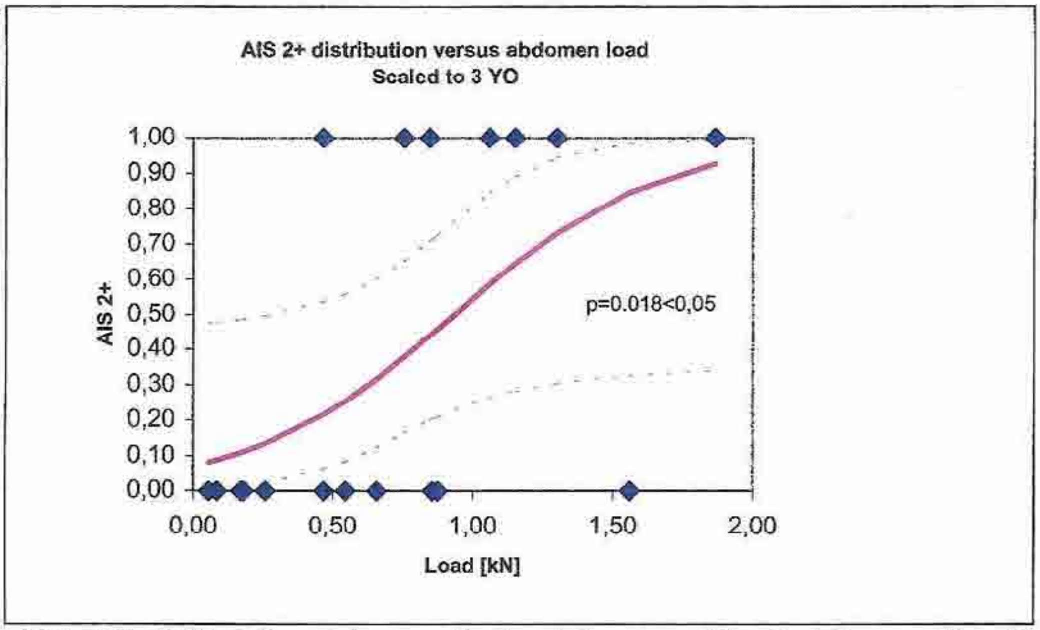


Figure 8. AIS2+ injury risk curve for the abdomen – abdominal force on Pmodified dummies

Figure 9 gives the level of head AIS in relation with the HIC value corrected for 3 years old for side impact. This graph shows a clear limit between injury and no injury. However, more data are needed to confirm these figures, taking into account the uncertainties of reconstructions. **Figure 9bis** gives the same for Head accelerations (3ms).

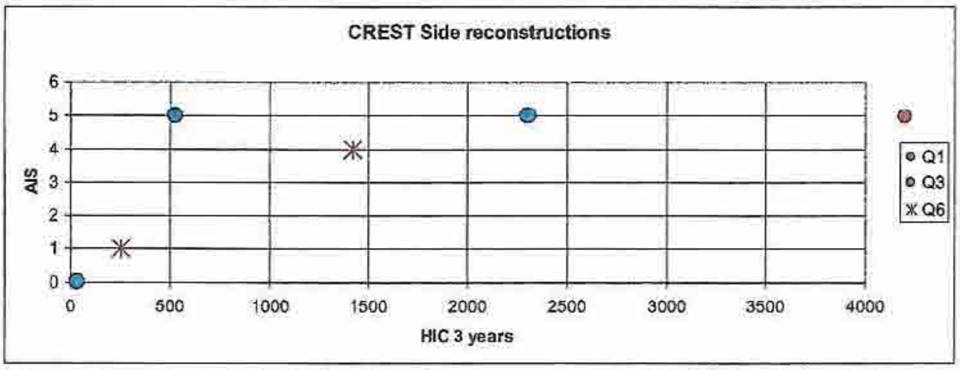


Figure 9 : adjusted HIC data for 3 years versus head AIS (Q dummies)

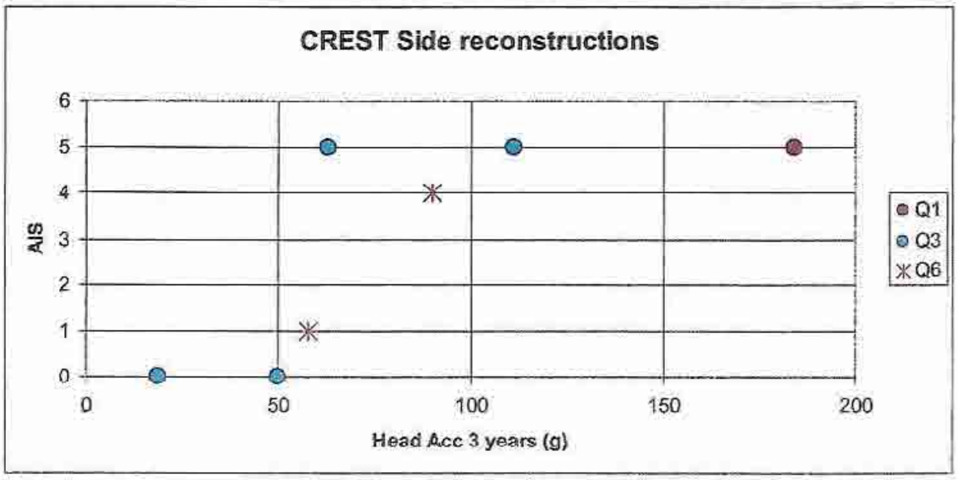


Figure 9bis. 3ms Head acceleration versus AIS (Q dummies)

Dummy Improvements (WP3)

The current child dummies (P-dummies) were developed in the late 1970's and early 1980's. The last two decades the protection offered to children travelling in cars has increased dramatically due to a better understanding of the dynamical behaviour of children and the resulting improvements to child restraint systems. To further improve child safety it seems necessary to replace the P-dummies with child dummies that are not only more advanced, but can also evaluate the protection offered to children in lateral impacts and the interaction of children with deploying airbags. Indeed, P dummies are quite rudimentary and are not able to evaluate the protection in detail.

It was the aim of the WPIII partners to develop a new series of child dummies (Q-dummies), taking into account the latest biomechanical and anthropometrical data knowledge and providing extensive instrumentation possibilities to the users of the dummies. Parallel to the hardware development of the dummies, mathematical models of the new dummies were developed. As the development of new dummies is a lengthy process, modifications have been made to the P-dummies in the beginning of the project to avoid delays in the work of WP2.

In WP3, RENAULT and INRETS have been responsible for the modifications to the P-dummies, TNO Automotive was responsible for the development of the Q-dummies and the TUB has developed the mathematical models of the Q3 and the Q6.

Modifications to the chest, pelvis and abdomen of the P-dummies were carried out and evaluated by Renault and INRETS. In addition to that the instrumentation capabilities of the P-dummies were improved. A new series of child dummies, called the Q dummies, was developed by TNO Automotive. The series now consists of three dummies: Q1, Q3 and Q6, representing respectively a 1, 3 and 6-year-old child. Mathematical models of the Q3 and Q6 were developed by the TUB, with assistance of TNO Automotive.

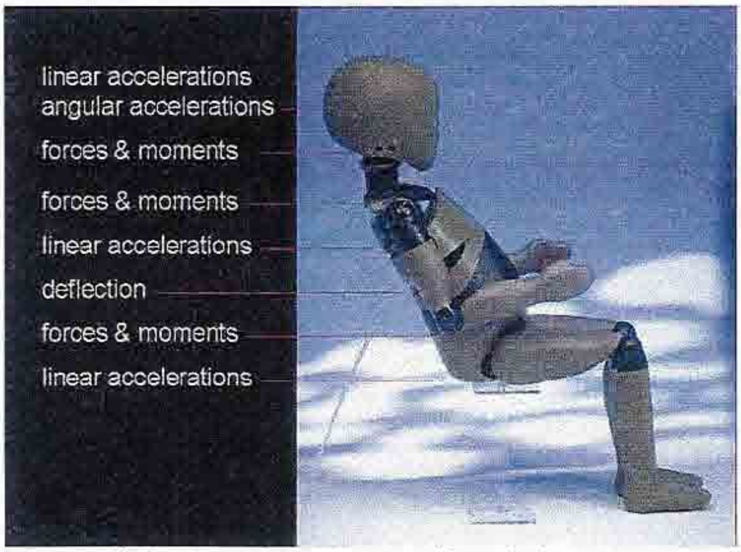


Figure 10. Dummy improvement (Q series)

All dummies were used extensively by partners in more than 56 reconstructions and 301 sled tests. In general, CREST partners were very happy with the Q dummies because they show a significant improvement in comparison with the existing child dummies. During the evaluation of the dummies, CREST partners have expressed some concerns about the belt interaction of the Q dummies, both at the pelvis and the shoulder level. The design of the Q dummies has been modified based on those experiences. A new design for the pelvis area has been made and evaluated. The conclusion of this evaluation is that Q dummies now, show a realistic submarining behaviour. A new flesh representing shoulder part has been made, but has not yet been evaluated by the CREST Partners.

Procedures and Validation

The objective of this workpackage was to include CREST knowledge in procedures and to base improvements on results from CREST activity.

For frontal impact, a complete proposal, from test conditions to evaluation criteria, was set up. The new procedure didn't intend to be a reference for certification, but was made to be representative of the conditions were we found injuries on children and to be closer to modern car environment. It consists on:

- R44 03 basis.
- New pulse corridor based on CREST reconstructions, adjusted to be feasible in current test houses (**Figure 11**).
- Bench shape modification (representative of Renault and Fiat cars and including anti-submarining device)
- Use of Q dummies
- New injury criteria with limits when possible.

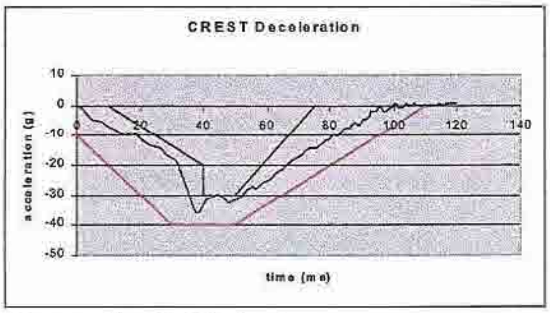


Figure 11. CREST pulse

It was agreed to ask CRS manufacturers to participate and to propose them to test their products or prototypes (like ISOFIX) against CREST procedure. This was decided as a mean to evaluate the coherence of the procedure. Renault contacted about 15 CRS manufacturers, among them 10 accepted to participate.

Hence, 70 CRS were tested with the new CREST procedure for frontal impact (**Figure 12**). The sample of CRS consisted on:

- 19 forward facing seats with harness tested with Q3 dummy (including 2 isofix)
- 6 forward facing seats with shield tested with Q3 dummy (including 1 isofix)
- 17 rearward facing seats or infant carriers tested with Q1 dummy (including 2 isofix)
- 5 rearward facing seats tested with Q3 dummy
- 23 booster cushions tested with Q3 dummy
- 3 booster cushions tested with Q1 dummy

Figure 12. Test procedure evaluation

Results of CRS tests were analysed and ranked with regard to the limits established by WP2 sub-group analysis.
Tests of the 70 CRS in the CREST configuration show that some CRS are only adjusted to the R44-03 regulation but cannot sustain more severe conditions. These tests give the distribution of physical parameters which allows, when compared to the limits proposed by WP2, to evaluate the difficulty to reach CREST specifications and the coherence of the procedure. The distributions of criteria for all sled tests are given in annex 1.

For instance, **Figure 13** gives the distribution of HIC values for the whole sample (including Q1 and Q3). In this sample, only 37% of the CRS tested with Q3 dummy are below HIC=1113, which correspond to about 20% risk of AIS3+ whereas 61% of the CRS tested with Q1 are below 791, which corresponds to the same risk for a 1 year old child.

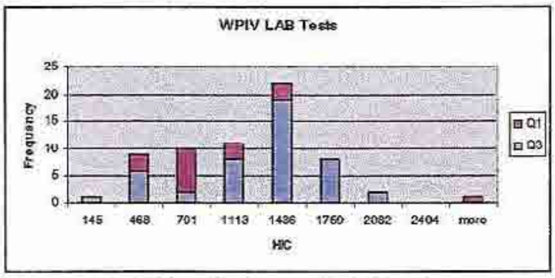


Figure 13. Distribution of HIC values

Figure 14 shows that most rearward facing seats are under the limit whereas only a few boosters pass the criteria for Q3 dummy.

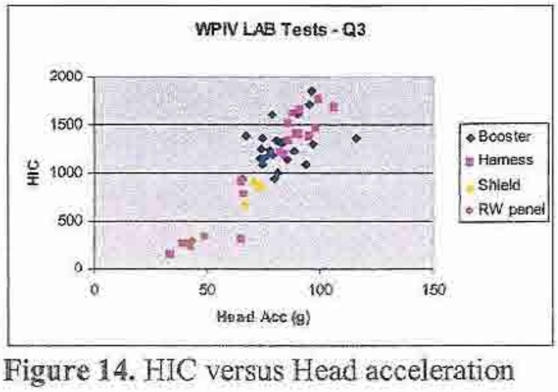


Figure 14. HIC versus Head acceleration

Figure 15 gives My flexion versus Fz traction. This graph shows that rearward facing seats demonstrate low values of My and Fz whereas boosters and 5 point harness seats have large values of Fz, some of them having also high My values.
This analysis shows the ability of the procedure to discriminate between good and not so good seats or concepts.

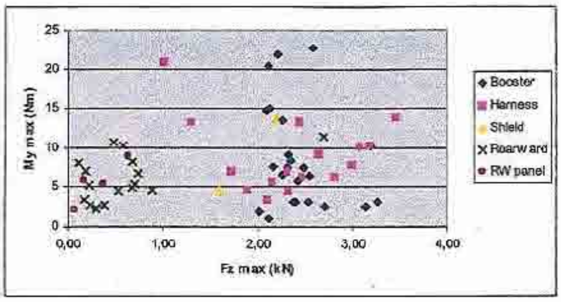


Figure 15. My versus Fz values

These tests allowed also to evaluate the difficulty to handle the tests as regard the pulse and the dummy durability. It was found that no major problems occurred, except weakness of Q3 shoulder and hip, which were also observed in WP2.

The CREST procedure for frontal impact was evaluated thanks to the test of numerous CRS, which can be considered as representative of the European market. It can be assumed that the procedure is coherent, the severity of the pulse and the level of criteria being balanced.

For side impact, current procedures were not mature and it was not possible to propose improvements directly from CREST outcomes. However, recommendations can be made from accidentological findings, reconstruction knowledge, Q dummy experience and first findings on injury criteria.

Conclusions

This research programme is a first step in the improvement of test procedures for assessing child restraining systems. However, still a lot of work is needed to consolidate some knowledge and in particular to address:

- neck or chest injury criteria and limits,
- abdominal tolerances,
- submarining behaviour,
- injury criteria for side impact.

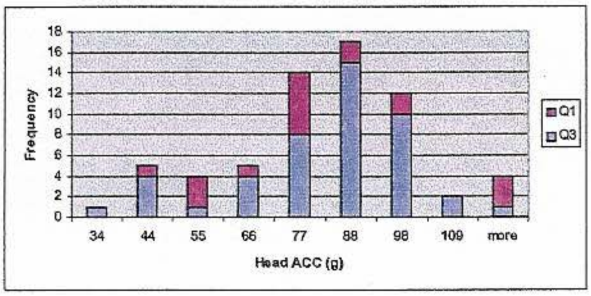
Results have demonstrated the pertinence of such an approach in defining injury risk curves and the need to continue working in this way.
As far as certification is concerned, investigations are needed to improve the representativity of the procedure, in particular dealing with:

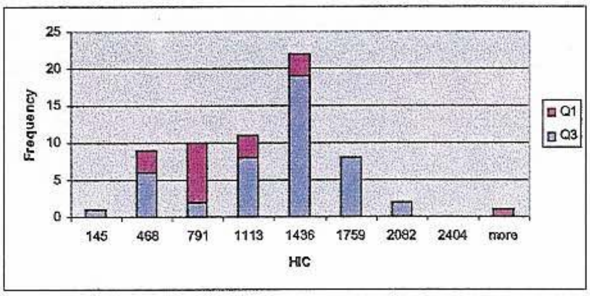
- car environment (bench shape, volumes, anchorage points ...)
- deceleration pulse, assuming the conditions to be considered for CRS evaluation
- child ages

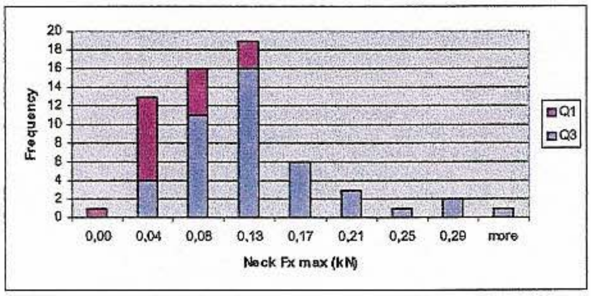
CREST has demonstrated the feasibility of such improvements and a way to deal with them.

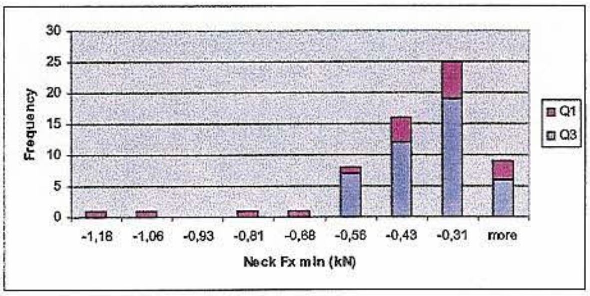
Annex 1

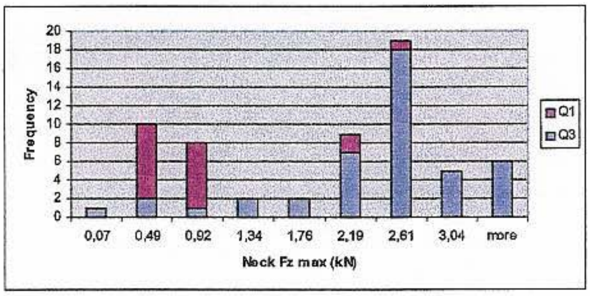
Distribution of criteria for sled tests using CREST procedure

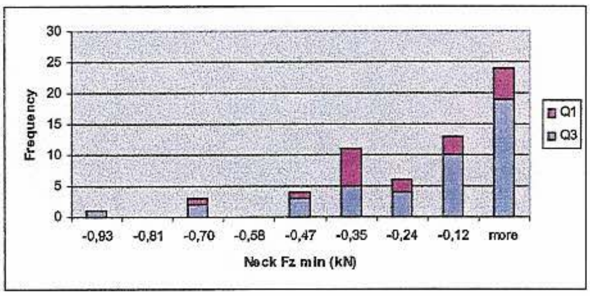


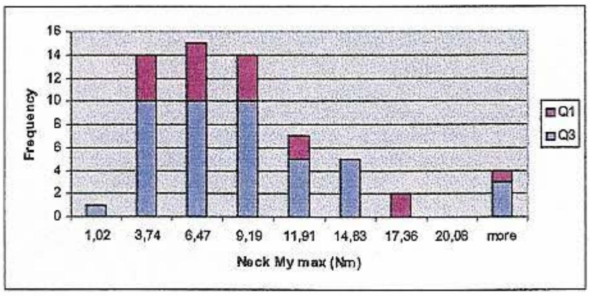


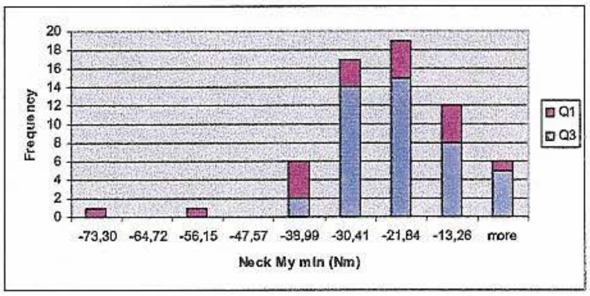


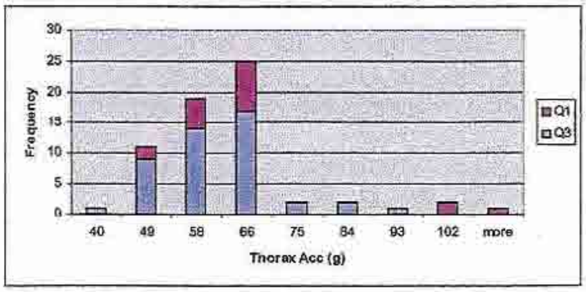


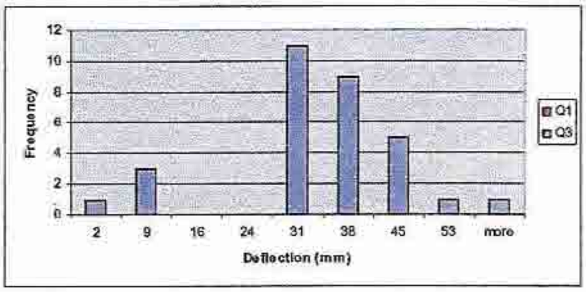


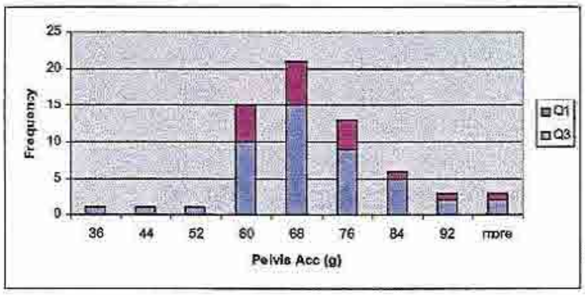


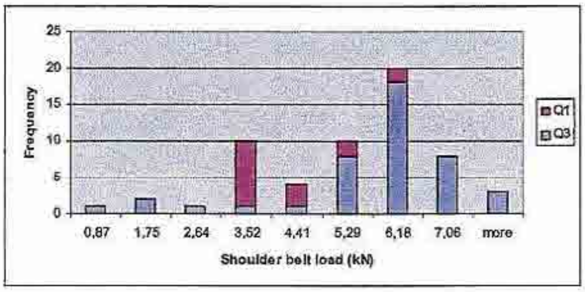


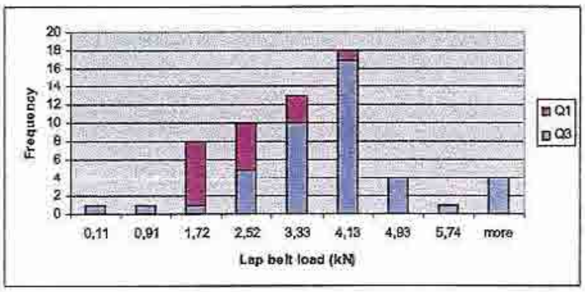



Frequency
Q1
Q3
40 49 58 66 75 84 93 102 more
Thorax Acc (g)


Frequency
Q1
Q3
2 9 16 24 31 38 45 53 more
Deflection (mm)


Frequency
Q1
Q3
36 44 52 60 68 76 84 92 more
Pelvis Acc (g)


Frequency
Q1
Q3
0,87 1,75 2,64 3,52 4,41 5,29 6,18 7,06 more
Shoulder belt load (kN)


Frequency
Q1
Q3
0,11 0,91 1,72 2,52 3,33 4,13 4,93 5,74 more
Lap belt load (kN)