ABDOMINAL INJURY RISK TO CHILDREN AND ITS PREVENTION

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ABSTRACT

Several crash investigation studies recently lead to opposing conclusions on the importance of abdominal injury risk to children. This paper deals with an in-depth and synthetic analysis of new accidentological data. In particular, the risk is studied by isolating parameters such as age and crash type, as well as restraining systems.

The abdominal risk appears higher above 2 or 3 years old for children using poorly designed booster-cushions or adult belts alone.

The prevention of such a risk for protected children should be given by a pertinent restraint-system assessment in frontal impact simulation. Unfortunately, the lack of biofidelity of the pelvic-abdominal segment of the current child dummies does not allow this child restraint assessment. Data for the improvement of dummy pelvises and for the definition of an abdominal criterion are provided in this paper.

The authors propose the use of geometrical criteria to differentiate poor and acceptable booster cushions, as a temporary measure, until effective abdominal injury assessment becomes possible.

THE USE OF CHILD RESTRAINING SYSTEMS became mandatory in France at the beginning of 1992. This made it possible to evaluate the effect of restraining systems on child protection. A preliminary analysis of accident cases collected during 4 months in 1992-1993 [Got, 1994] shows some tendencies, but the number of cases was insufficient to allow firm conclusions to be drawn. The gathering of a new sample of cases collected during 4 months in 95-96 [Cuny, 1997] allows in particular the isolation of frontal impacts and the drawing of clear conclusions on the need to improve the abdominal protection provided by booster seats (boosters are restricted to belt positionner systems and exclude shields).

CRASH INVESTIGATION STUDY

A crash investigation study [Got, 1994] was made in 1992-1993 on child passengers under 10 years old and involved in accidents between two cars or cars alone. Cases were collected during May, August and November, 1992 and February, 1993 from all over France by the state police force. This study concerned 1629 children and the main results concerning the abdomen were that if the reduction of risk with boosters is globally significant for AIS ≥ 2 injuries (28% for the age group 4-9 years old), abdomen and pelvis injuries still represent 13% of all AIS ≥ 2 injuries observed with boosters and 17 % of those observed with belts. On the contrary, this study showed that abdominal injuries don't exist with harness seats.

Table 1 : Abdominal Injuries of tbe two studies (1992/1993 and 1995/1996) from [Got, 1994] and [Cuny, 1997]

Child Restraint System (CRS)	Study	Age (years)	Comments on CRS	Maximum AIS	Maximum Abdominal AIS	Height (cm)	Weight (kg)	Comments on Abdominal Injuries	Comments on Pevis Injuries	Sample Size	Effectiveness regarding abdominal Injuries
Lap Belt	92-93	4		3	3			perforation of the small bowell, decease at the 24th hour		55	**Lap Belt / No restraint** Eff = -550% Khi²=13,9
	92-93	5		3	3	128	26	Abdominal contusion with small hemo-peritoneum, large hematoma T11, T12, L1, L2	fracture of the right ischium-pubis arcb.		
	92-93	9	Shoulder belt probably under tbe arm	3	3	134	30	Rupture of diaphragm, 2 lines of skin abrasion on thorax. Rupture of tbe small bowell serous, small spleen laceration, T9 fracture.			
	92-93	7		3	3	124	23	perforation of sigmoïd			
	95-96	4		4	4			Large mesentery laceration with intra-peritoneal hemorrage, small re operltoneal hematoma, rupture of abdominal muscles.			
3point Belt	92-93	8		2	0	120	22		Left hip luxation	254	**3pt belt / no restraint** Eff = -69% Khi² = 0,93
	92-93	8		4	4			Spleen rupture	Left tibia fracture.		
	92-93	8		4	4			Spleen rupture, abrasion of the abdominal skin.			
	92-93	5		5	3	110	20	Liver laceration, spleen contusion, left adrenal hematoma.			
	95-96	5		3	3			Perforation of right colon			
	95-96	7		4	3		27	laceration of small bowel			
	95-96	8		4	4		30	Spleen rupture, probably fracture of 11th rib	Left tibia fracture.		

Table 1 (cont.) : Abdominal Injuries of the two studies (1992/1993 and 1995/1996) from [Got, 1994] and [Cuny, 1997]

Child Restraint System (CRS)	Study	Age (years)	Comments on CRS	Maximum AIS	Maximum Abdominal AIS	Height (cm)	Weight (kg)	Comments on Abdominal Injuries	Comments on Pevis Injuries	Sample Size	Effectiveness regarding abdominal Injuries
No	92-93	7		3	3		25	Liver laceration		501	
	92-93	8	Lying child	3	3	120	33	Perforation of right colon.	Right femur fracture.		
	92-93	9		2	0	140	35		luxation of the left femoral head with bone loose.		
	92-93	9		4	4	143	35	Spleen rupture			
	95-96	3		2	0				Right cotyle fracture and left tibia fracture.		
	95-96	3	Lying child	2	2			Small effusion in Douglas's pouch, desappeared a few hours after accident.			
	95-96	6	Lying child	5	3			Contusion of right kidney with large intra-capsulary hematoma.	Displaced fracture of the right femur.		
	95-96	6	Sleeping child	4	4			Fracture of inferior pole of the right kidney with a large retro-peritoneal hematoma. Contusion of the transverse colon.			
	95-96	7	uncertainty on belt use	5	3		20	Small effusion of left pleura, contusion of the superior pole of the spleen, medium intra-abdominal effusion.	Left leg fracture.		
Booster	92-93	3		4	4	104	18	right hepatectomy		427	**Booster / No restraint** **Eff = -51%** **Khi² = 0,69** **Booster / 3pt belt** **Eff = 10 %** **Khi² = 0,05**
	92-93	3		4	4			Spleen laceration. pancreatitis subsequently.			
	92-93	4	uncertainty on belt use	2	0				Fracture of the left illac wing.		
	92-93	6		2	2			Duodenal and pancreatic contusions with fals pancreatic cyst of 13 mm diameter.			
	92-93	7		3	3			Liver laceration with hemo-peritoneum and hemorrhage shock state.fracture of 2 ribs.			
	92-93	7		3	3			Superficial Liver lacerations. retroperitoneal hematoma, contusion of the left kidney.			
	95-96	4	Booster with or without back	3	3			Hepatic trauma with hemoperitoneum.			
	95-96	4	rocking of the CRS.	4	4			Large laceration of the spleen inferior pole : splenectomy, hemoperitoneum.			
	95-96	4	A dog was in the luggage compartment	2	0	105	12		Displaced fracture of the right femur neck, fracture of left pelvis.		
	95-96	9		5	5			Duodenal rupture,pancreas and liver contusion, fracture of the 10th right rib.			
	95-96	7		4	4	130	29	Bursting and perforation of the right colon, superficial laceration of the transverse colou, hematoma of duodenum, L1 fracture.			

In order to complete this study and in an attempt to find more significant results, another one was performed in 1995-1996 on the same basis. As cases were more numerous, it was then possible to concentrate the analysis on frontal impacts and children more than 3 year old. The data of the two studies are presented in table 1 for frontal impact.

The Effectiveness is calculated as follows (for instance for boosters) :

$$Eff = [\tau \text{ (no restraint)} - \tau \text{ (booster)}] / \tau \text{ (no restraint)}$$

where τ = (Nb of AIS $\geq$ 2 injuries) / (Sample size)

The main results are the following :

- The lap belt increases dramatically the abdominal risk (effectiveness = -550 % relative to no restraint)
- The lap and shoulder belt as well as the booster seems to increase the abdominal risk (effectiveness of respectively -69% and -51%), but the results are not statistically significant (Khi² of respectively 0.93 and 0.69). In any case, the risk does not decrease in the same way as with harness seats [Cuny, 1997].
- Boosters do not show a better performance than 3-point belts. Indeed, one could have expected a large decreasing of injuries. But this doesn't appears here, since there is no significant difference between the two samples (Khi² = 0.05). It is clear that something must be done to improve the protection offered.

The reason for the bad performance of boosters is probably the lack of knowledge and tools to evaluate correctly the effectiveness of boosters in the avoidance of submarining. It is with this goal that a study was conducted to improve dummy design and behavior regarding submarining and child tolerance for the abdomen.

DUMMY DEVELOPMENT

A study was performed in 96 [Chamouard, 1996] to define pelvis shape and dimensions for children from 3 to 6 years old. For dimensions, anthropometric measurements were taken from a sample of 54 children aged between 30 and 148 months. Children were seated on the ground with their back on a vertical plane ; we measured the height of the iliac crest, the distance between the back and the antero-superior iliac spine, the pelvis width, the abdomen thickness and the thigh thickness. The abdomen thickness was the distance between the vertical plane and the anterior limit of the abdomen at the thigh level ; The thigh thickness was the distance between the ground and the superior limit of the thigh at the abdomen level. Figures 3, 4 and 5 give respectively the iliac crest height, the distance between the back and the antero-superior iliac spine and the thigh thickness as a function of child weight.

For the shape, 21 X-rays of 7 children supplied by the child orthopedic surgery ward of the R. Debré Hospital in Paris were analyzed. The side and front views of the pelvis were scaled to reach the mean dimensions of their age group, as defined by the anthopometric study. This provided a database for the development of dummy pelvises. Figure 6, as an example, gives the comparison of our pelvis requirements for 3 year old children and the TNO P3 dummy.

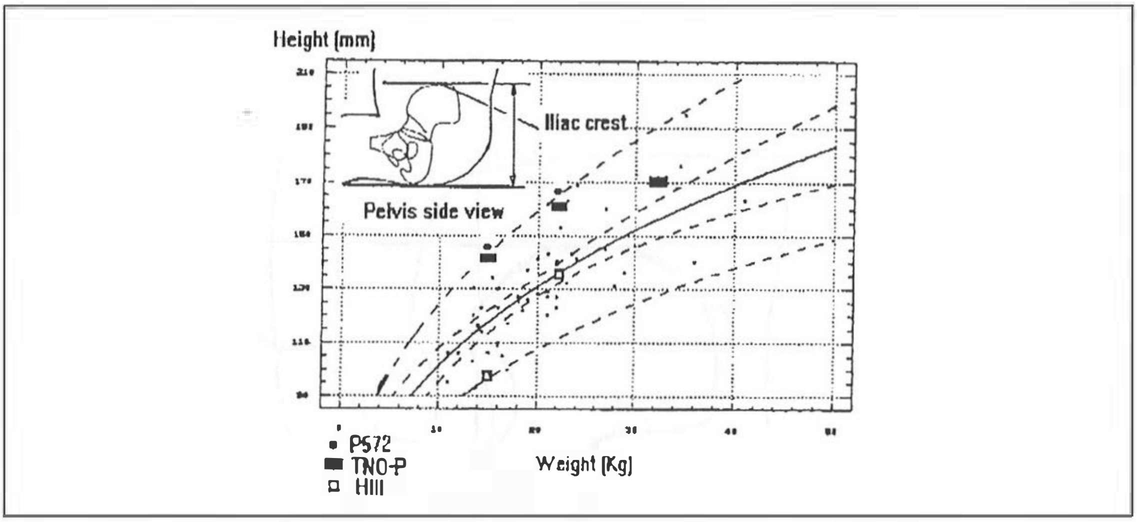

Figure 3 : height of iliac crest as a function of weight [Chamouard, 1996]

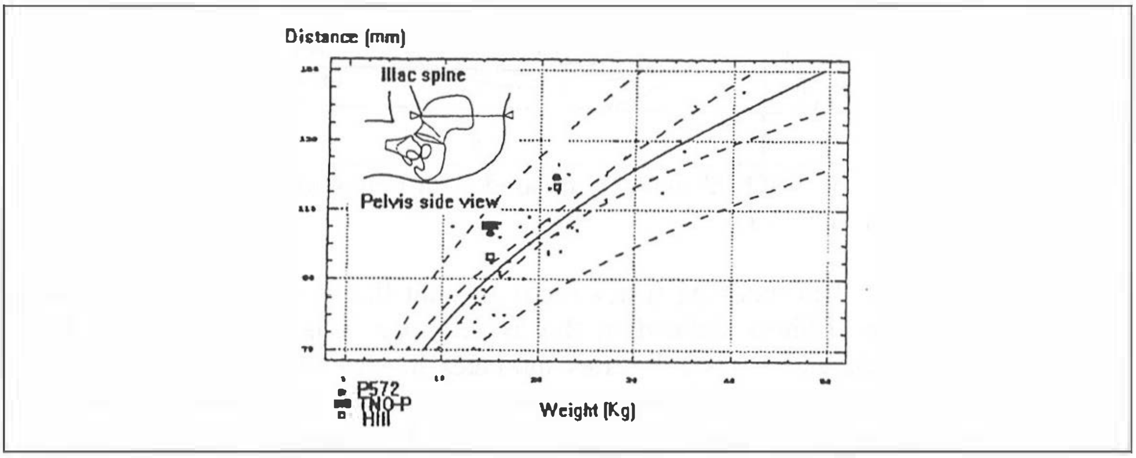

Figure 4 : distance between back and iliac spine as a function of weight [Chamouard, 1996]

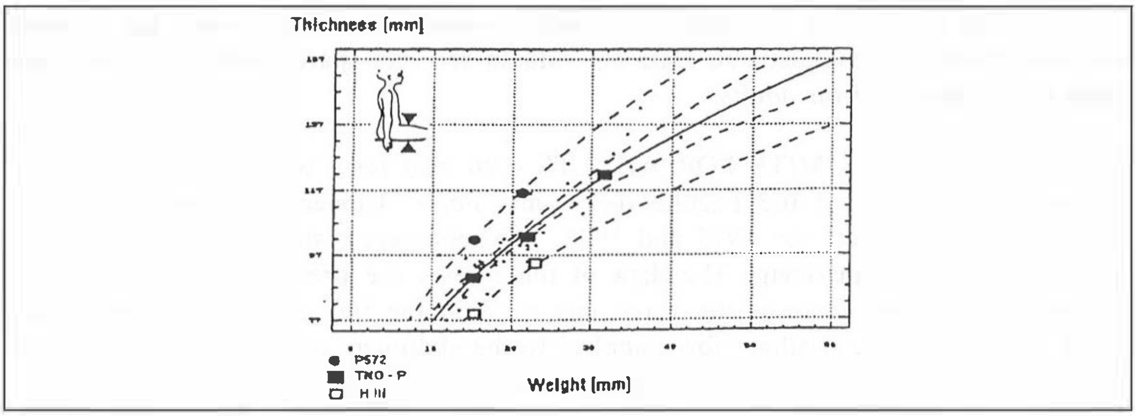

Figure 5 : thigh thickness as a function of weight [Chamouard, 1996]

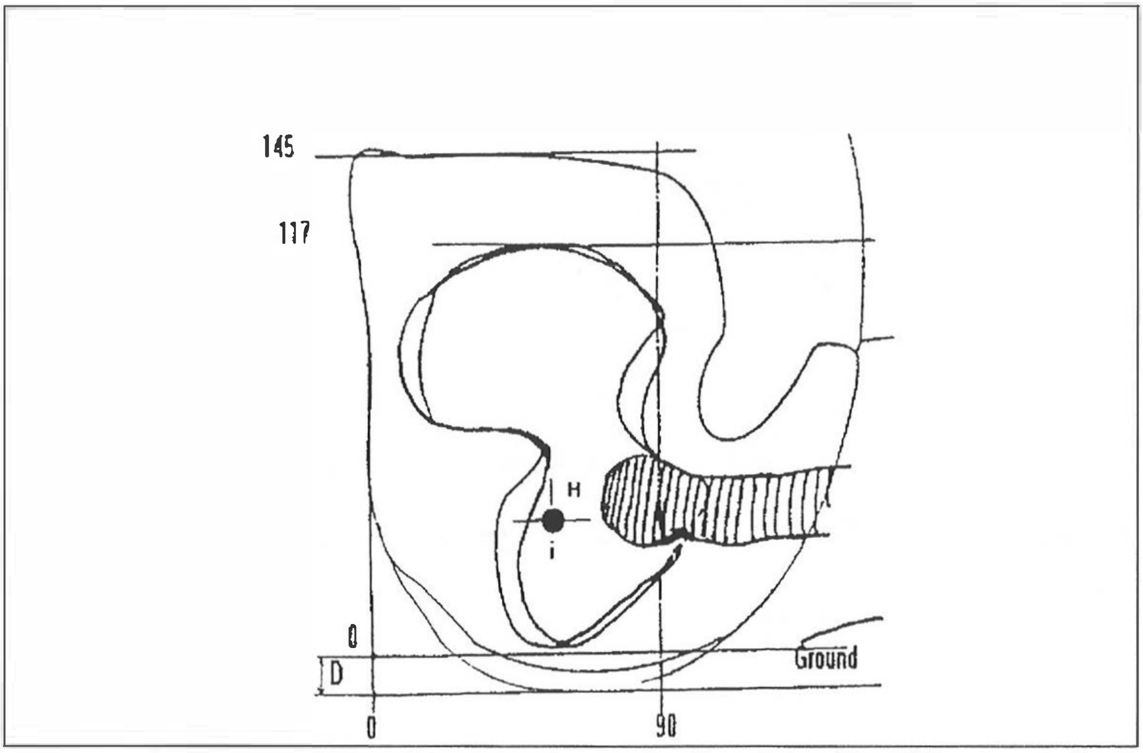

Figure 6 : Side view of TNO P3 pelvis compared with pelvis of 2 children normalized for a standard weight of 15 kg

Dummies were then modified to take into account these requirements, as well as thighs and abdomen stiffness defined in the same study [Chamouard, 1996]. These dummies were compared to TNO P series dummies in sled tests and show a better sensitivity to submarining. An abdominal transducer was also implemented to measure directly abdominal loads to evaluate the risk of injury by belt penetration.

BIOMECANICAL DATA

A good behavior of the dummies regarding submarining is necessary, but requires tolerance limits as a complement. Data on children are very sparce, and a way to define limits is to scale data from adults.

TOLERANCE LIMITS FOR ADULTS - 26 sled tests with cadavers from the Anatomy Laboratory of the Faculté des Saints Pères, University of Paris V, were performed by APR between 1973 and 1988. Subjects were restrained by 3-point belts and experienced submarining. The data of these tests are presented in table 2. The outboard pelvic belt force is the force measured in the belt after submarining. The abdominal force is the resultant force applied to the abdomen, calculated in the plane of the belt, assuming an angle of 56 degrees between the lap belt and the sagittal plane, which is the mean of cadaver tests, as reported by Leung [1981]. As a consequence, Fabdomen = 2*F belt*cos(56°) = 1.118 * F belt.

Table 2 : APR tests with cadavers

NUM	AGE (years)	Height (cm)	Weight (kg)	Abdominal AIS	Outboard Pelvic Belt Force (daN)	Abdominal Force (daN)
16	57	162	62	4	400	447
18	61	167	63	3	430	481
33	51	171	50	0	230	257
34	58	164	61	0	170	190
35	59	0	0	0	200	224
41	60	171	50	0	220	246
54	34	178	60	0	200	224
59	50	0	0	0	250	279
117	60	163	53	3	430	481
123	52	170	75	3	630	704
124	61	162	52	0	320	358
126	51	169	67	4	580	648
126	55	180	95	2	890	995
127	57	159	41	0	400	447
148	65	161	0	0	260	291
148	62	172	0	0	440	492
154	63	171	43	4	730	816
170	58	160	47	3	750	838
182	57	176	62	0	430	481
185	56	159	53	4	700	783
190	39	152	51	0	340	380
231	57	163	49	4	510	570
232	57	163	49	0	340	380
233	60	165	61	0	580	648
243	61	172	74	3	520	581
244	57	165	54	0	220	246
245	56	157	62	3	370	414
246	62	165	52	3	730	816
247	42	163	58	3	850	950
248	66	164	63	0	400	447
255	68	165	56	4	450	503
285	65	165	54	4	970	1084
286	47	170	74	0	480	537
357	66	165	54	4	320	358
358	52	169	68	0	400	447
359	61	170	48	4	220	246
367	57	167	60	4	630	704
368	39	170	79	0	360	402
374	47	173	74	4	290	324
381	65	164	70	0	665	743
386	61	165	76	0	460	514

With this sample, it is possible to plot the probability of serious injury (AIS ≥ 3) as a function of the force in the outboard pelvic belt, using the certainty method described by Mertz [1996] (figure 8).

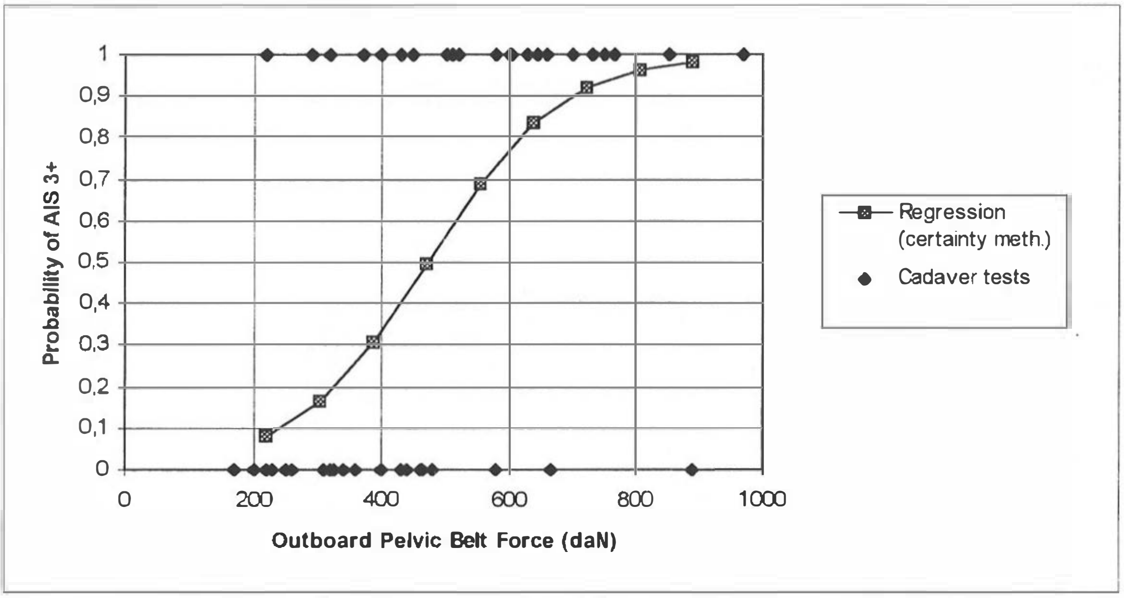

Figure 8 : probability of serious abdominal injury (AIS 3+) as a function of Outboard pelvic belt load.

In the same way, it is possible to plot the probability of serious injury (AIS $\geq$ 3) as a function of the abdominal force, using the certainty method (figure 9).

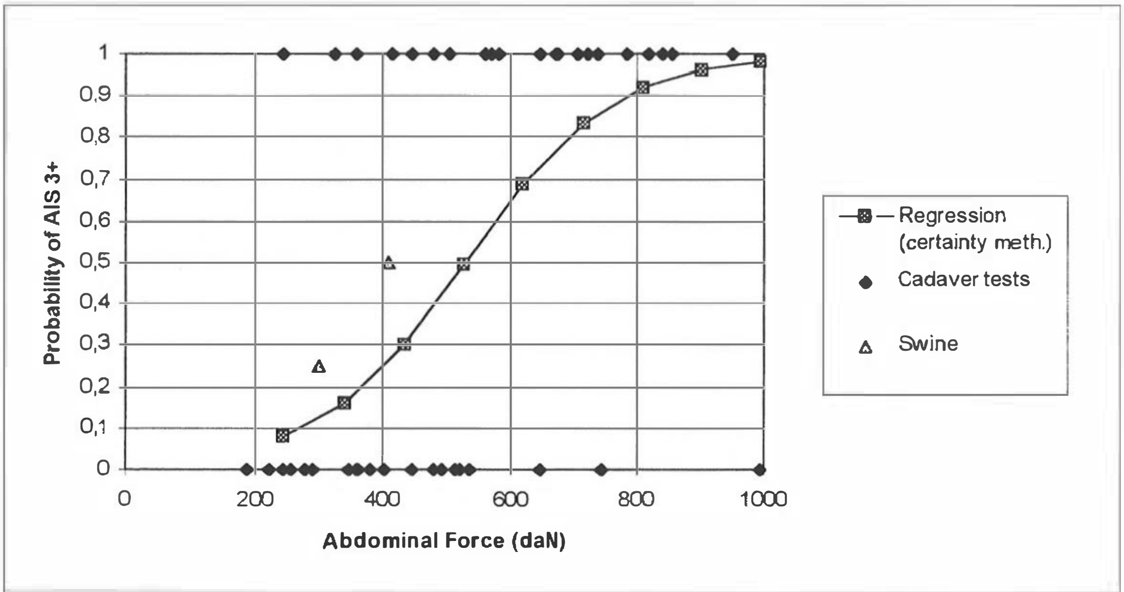

Figure 9 : probability of serious abdominal injury (AIS 3+) as a function of Abdominal force.

DATA ON SWINE - On the base of tests on swine, Miller [1989] found that the peak pressure is well correlated with the probability of AIS3+ : $Khi^2=12.6$, $R=0.668$, $p=0.0003$, ED50=226 kPa, ED25=166 kPa.

If we multiply the belt surface area for adults (5 cm x 36 cm = 180 cm^2), by this limit, we find the total force applied to the abdomen, that is to say F25 = 300 daN and F50 = 410 daN. These values are positioned on figure 9 for comparison with cadaver test results. The two results are not so different if we consider the approximations for the two approaches (angle of the belt for the first one, surface of the belt contact for the second).

SCALING FOR CHILDREN - Assuming thaùt the pressure on the abdomen is a good injury criterion [Miller, 1989], is a way to take into account loading surfaces of different size. In particular for children, this allows to scale the acceptable forces on belts. The belt being the same on adults and children on boosters, the only difference is the length of belt in contact with the abdomen. As a consequence, we can scale in the following manner, based on pelvis width :

Fadult / Ladult = Fchild / Lchild (with L = pelvis width)

We consequently find the following limits for children as a function of age :

Dummy	L (mm)	F abdomen (25% risk) (daN)	F abdomen (50% risk) (daN)
50th percentile male	363	380	525
9 month	166	170	240
3 year	206	215	300
6 year	229	240	330
10 year	255	270	370

ACCIDENT RECONSTRUCTIONS - A first accident case was analyzed in the field of the European CREST program, where a Renault 21 impacted a Volkwagen Scirocco at 115 km/h and with 75% of overlap. In this accident, two children were on rear seat and restrained by 3-point belts. The first one, aged 5 years, had slack in his static belt and sustained a laceration of the small bowel (AIS3). The second one , aged 6 years, had a well adjusted belt and sustained no abdominal injury. He had only a right clavicle fracture. A reconstruction of this case was done with the same cars in the same conditions with TNO P6 dummies. The results are given in the table 3

Table 3 : Results of the case reconstruction (test 4724)

Child	Injuries	Dummy	F lap belt	F shoulder belt
5 years	laceration of the small bowel	TNO P6	148 daN	283 daN
6 years	right clavicle fracture	TNO P6	176 daN	452 daN

In this case, it is possible to associate a force of 148 daN with injury (AIS=3). This result is low compared to scaling from adults (9% probability of injury at this level). This can be explained by the fact that this child had slack in his belt. As a consequence, the angle of the belt in relation to the sagittal plane was rather small and the ratio between the outboard belt force and the resultant force on the abdomen, probably higher than for cadaver tests. This explains the need to use a criteria directly measured in the dummy, in this case a force applied to the abdomen.

DESIGN REQUIREMENTS FOR BOOSTERS

Since dummies are still not available to evaluate boosters, it can be favourable to give some design requirements to improve protection.

As a matter of fact, the prevention of submarining for children aged 3 to 10 years requires the adult belt to be forced to stay at the base of the child's thighs during the impact. This can only be achieved by the use of strap guides which force the belt down at right angles to the thighs and which avoid it's riding up during the impact. Figure 9 shows a diagram of the design requirement : the upper edge of the window should not be above the upper part of the thighs and the rear edge should not be rearward of the iliac spine of a 3 year old child. A procedure for the verification of booster conformity to these design requirements was proposed in [Chamouard, 1996].

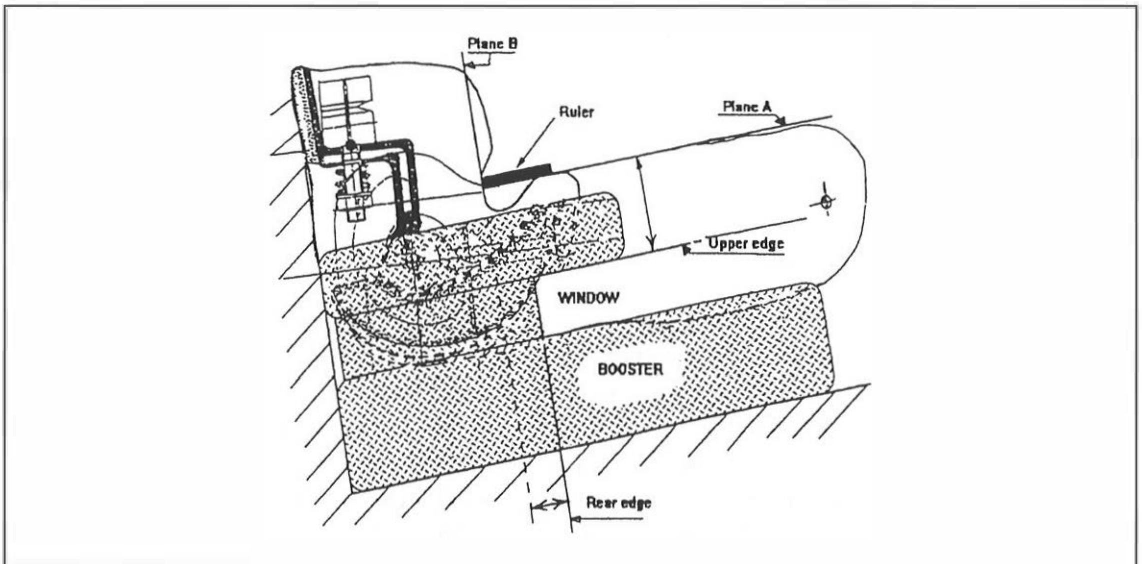

Figure 9 : definition of lap belt guide location zone for boosters [Chamouard, 1996]

CONCLUSION

A crash investigation study was made on more than 3000 accidents involving children. It was concluded that booster cushions do not show any improvement of abdominal protection in regard to 3-point belts in frontal impact.

It can be assumed that this situation would be improved by a better design of booster cushions. But this needs a performing tool to evaluate their effectiveness in the avoidance of submarining. With this goal in mind, design requirements for dummies were established, in particular the shape and dimensions for the pelvis were provided.

Afterwards, tolerance criterion are required for evaluating injury risk on boosters. For that purpose, adult data on abdominal injuries where provided and an injury risk curve was established. Then, abdominal injury risk curve for children was scaled from adult and compared to swine tests and accident reconstructions. The proposed limits are the following for a 3 year old dummy :

Fabdomen = 215 daN for 25% probability of AIS $\geq$ 3

Fabdomen = 300 daN for 50% probability of AIS $\geq$ 3

Limits for other ages including adults are proposed in this paper

Finally, a geometrical criteria to differentiate poor and acceptable booster cushions is proposed as a temporay measure, until performing dummies are available.

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