PROTECTION FOR THE SMALLEST OCCUPANT – STATUS QUO AND POTENTIALS CONCERNING THE DEVELOPMENT OF CHILD RESTRAINT SYSTEMS

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ABSTRACT

The use of proper child restraint systems (CRS) is mandatory for children travelling in cars in most countries of the world. The analysis of the quantity of restrained children shows that more than 90% of the children in Germany are restrained. Looking at the quality of the protection, a large discrepancy between restrained and well protected children can be seen. Two out of three children in Germany are not properly restrained. In addition, considerable difference exists with respect to the technical performance of CRS. For that reason investigations and optimisations on two different topics are necessary: The technical improvement of CRS and the ease of use of CRS.

Consideration of the knowledge gained by the comparison of different CRS in crash tests would lead to some improvements of the CRS. But improvement of child safety is not only a technical issue. People should use CRS in the correct way. Misuse and incorrect handling could lead to less safety than correct usage of a poor CRS. For that reason new technical issues are necessary to improve the child safety AND the ease of use. Only the combination of both parts can significantly increase child safety.

For the assessment of the safety level of common CRS, frontal and lateral sled tests simulating different severity levels were conducted comparing pairs of CRS which were felt to be good and CRS which were felt to be poor. The safety of some CRS is currently at a high level. All well known products were not damaged in the performed tests. The performance of non-branded CRS was mostly worse than that of the well known products.

Although the branded child restraint systems already show a high safety level it is still possible to further improve their technical performance as demonstrated with a baby shell and a harness type CRS.

INTRODUCTION

The project "Optimisation of CRS" was funded by BASt and was finalised at the beginning of 2007. The use of Q-dummies for these crash tests allowed the assessment of a variety of dummy readings. However, for a complete assessment of the safety level of child restraint systems the interpretation of dummy readings and dummy kinematics from high speed video analysis is necessary. There is a high variation in the safety level between different types of CRS.

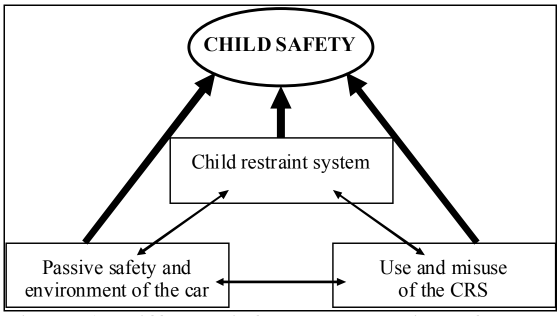

Figure 1. Different influences on child safety.

The safety of children travelling in cars is not solely dependent on the CRS used (Figure 1). Field studies published in the last years [LANGWIEDER, 1997; LANGWIEDER, 2003; FASTENMEIER, 2006] show that there is a high percentage of misuse of CRS. "Misuse" stands for all failures of handling and insufficient use of CRS. For that reason 3 different factors are responsible for child safety in cars:

- the technical behaviour of the CRS
- the use of the CRS
- the car around the CRS

Altogether these 3 factors help to define the level of safety for children in cars. It is necessary to improve all of the above factors affecting child safety at once and not just one at a time.

STATISTICAL INFORMATION

The analysis of the statistical information is focused on Germany. Corresponding to the German legal requirements, "children" means children from 0 up to the age of 12 years.

The good news is that the number of children killed in road accidents has decreased over the years

(Figure 2). The bad news is that the number of children killed as car occupants is still higher than the number of children killed as cyclists or pedestrians.

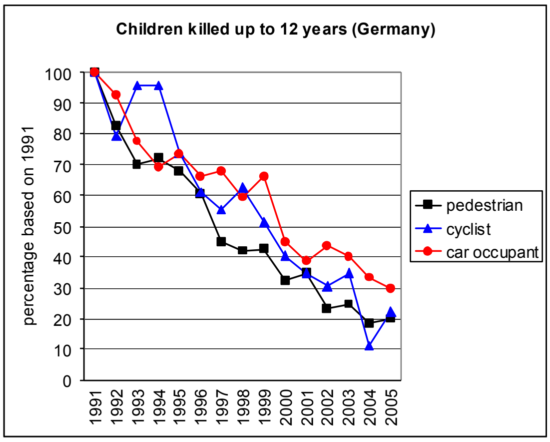

Figure 2. Children killed in road accidents in Germany in the last years [STATIS, 2006].

In comparison to the unprotected pedestrian and cyclist, the car is able to absorb energy and protect the child against outside objects. Therefore, travelling inside of a car should be the safer form of transportation.

In 2005 in Germany 24,247 children up to the age of 12 years were involved in road accidents. 38% of them were injured in the road accidents as car occupants, 28% as cyclists and 29% of the children injured were pedestrians (Figure 3).

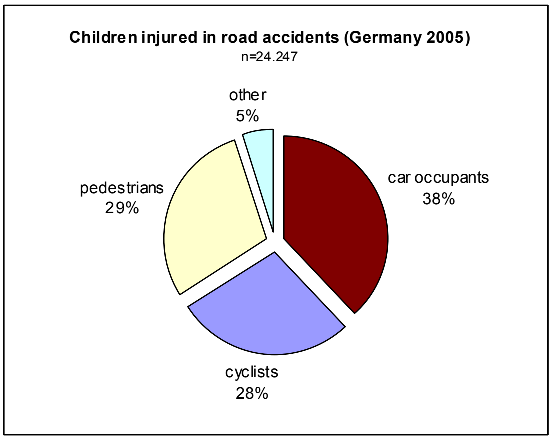

Figure 3. Children injured in road accidents in Germany in 2005 [STATIS, 2006].

102 children died due to road accidents in Germany in 2005. Almost half of them died within a car, one third died as pedestrians and 16% as cyclists (Figure 4).

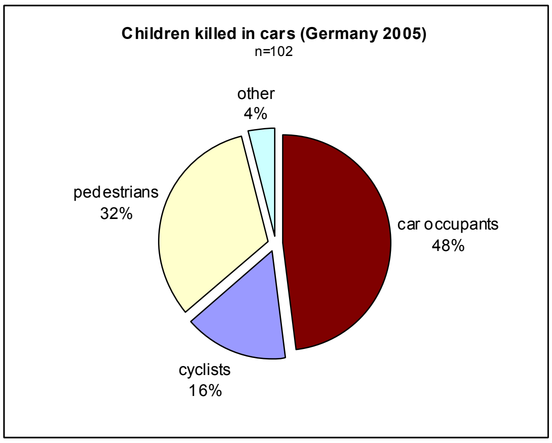

Figure 4. Children killed in road accidents in Germany in 2005 [STATIS, 2006].

The high number of children killed in cars is most likely due to the higher collision speeds in car accidents, the higher kinetic energy, inappropriate CRS and last but not least, misuse and non-use of CRS.

BIOMECHANICAL BASICS

Children are different from adults in:

- body shape (mass, proportions, inertia, size)
- anatomy (bones, ligaments, muscles)
- mental issues

These differences lead to the well known sentence: "Children are not miniature adults." This means that it is not possible just to scale down the size of an adult to have the correct child proportions (Figure 5).

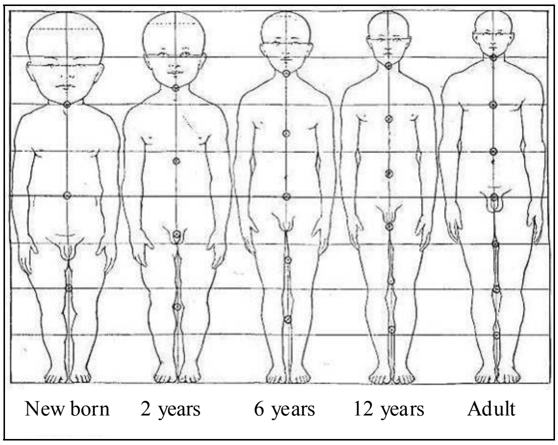

Figure 5. Proportions of the body of a new born baby up to an adult [HUELKE, 1992].

The average size of an adult is about 1.5 to 2.0 meters. Therefore, most of the belt and airbag systems are developed for these sizes. Children's body parts are not able to withstand the loads

applied by a normal car restraint system during a car crash: The iliac wing in children is not able to support the belt, causing the belt to override the pelvis and to penetrate the abdominal area. Here the internal organs are located and severe injuries could occur. The belt has to be adjusted to the height of children otherwise the contact between the neck and the belt could lead to injuries. Due to the proportions of a child – influencing the high centre of gravity – children tend to turn out of the standard 3-point-belt in case of a crash/accident. Therefore the belt placement should be adapted to the child. For that reasons it is necessary for children to use a CRS to prevent injuries.
For the development of CRS it is necessary to take all of these facts into account.

ANALYSIS OF DATABASES

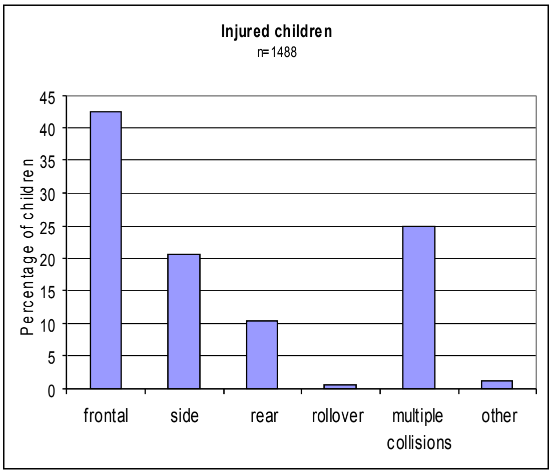

Figure 6. Injured children of car accidents vs. type of collision [OTTE, NOT YET PUBLISHED].

Figure 6 shows the percentage of 1,488 children involved in car accidents as car occupants in different types of collision from 1985 to 2004 from the German In-depth Accident Study database (GIDAS). These accidents are collected from the areas around Hannover and Dresden. They are meant to be representative for Germany.
Most occupants (more than 40%) were injured during frontal accidents. 25% of all children were injured in accidents with multiple collisions. After these kinds of accidents side and rear impacts follow. The number of single rollover accidents was irrelevant.

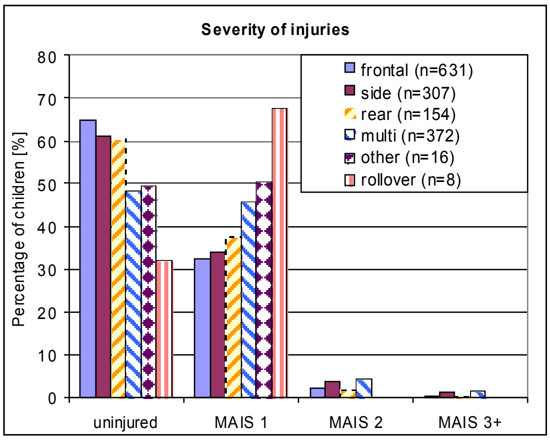

Figure 7. Injury severity vs. type of collision [OTTE, NOT YET PUBLISHED].

During side impact and multiple collisions with more than one severe impact the severity of injuries of children were much higher than in frontal collisions (Figure 7). The CRS should be tested in these configurations as well, today only the frontal test configuration is mandatory.
For the following study it was not possible to use the whole GIDAS information. Some special restrictions (accidents not before 1994, children are restrained in CRS) and additional cases from GDV (association of the German insurance institutes) and the "Unfallforschung Greifswald" (accidentology teams of the University in Greifswald, Germany) lead to a data set of 280 children in 205 accidents.

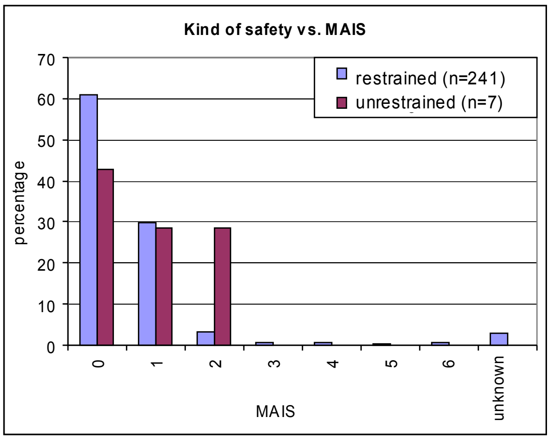

Figure 8. Consequences of the kind of safety to the severity of injuries (GIDAS, GDV, UfoGw).

Figure 8 shows the differences between restrained and unrestrained children with respect to injuries. Restrained children were more often uninjured than unrestrained children. The relative share of MAIS 2+ injuries is much higher in unrestrained children than in retrained ones. The number of investigated accidents was small; therefore only a tendency is visible.
Different dummies are required for the mandatory dynamic tests of the CRS groups. The features of

these dummies and the height and the weight are exactly described. The dummy should represent an average child of the age group of the dummy.

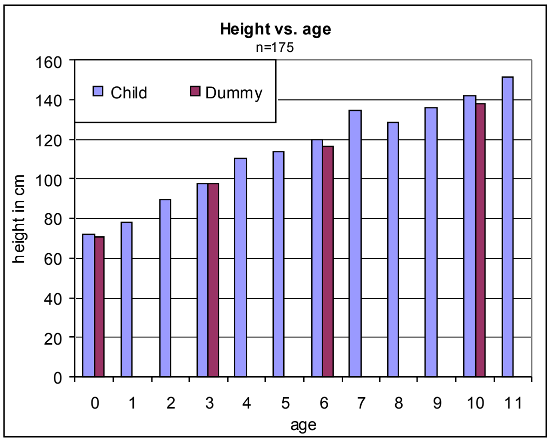

Figure 9. Height comparison of child vs. dummy (GIDAS, GDV, UfoGw).

In most of the cases the height of children involved in the accident is given. In Figure 9 the height of the dummies is compared to actual children. The height of the dummies is within the same range as the height of the children. Therefore, there is today no need to change the height of the dummies.

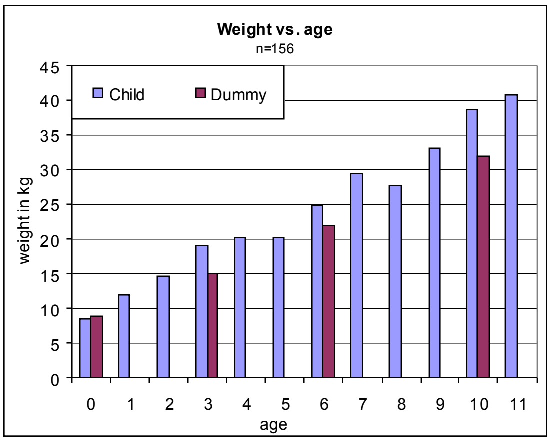

Figure 10. Weight comparison of child vs. dummy (GIDAS, GDV, UfoGw).

When comparing the difference in weight between dummies and actual children, the results are different compared to the dummy height.
Today's children are heavier than the dummies used. Therefore two issues have to be altered: the dummies and the ECE classes of CRS.
Because of the weight of the child and an insufficient CRS size some parents switch to a higher class of CRS too early. The safety level in the lower class CRS is higher for children and depends more on the height than on the weight.
The use of an appropriate CRS is mandatory for children up to the age of 12 years or the height of 1.5 m in Germany. Unfortunately there are some children smaller than 1.5 m, under 12 years old and weighing more than 36 kg. In these cases, they still have to use a CRS but due to the approved weight limit of 36 kg of CRS there is an unclear situation leading to children without any CRS. The car belt has a lower safety level for children than an appropriate CRS. Therefore it is necessary to update the regulation and CRS to the size of today's children.

SINGLE CASE INVESTIGATIONS

Probable reasons leading to death	**Number**
CRS (Misuse/failures of design)	**5**
children without any safety device	*4*
Severely destroyed car	**3**
No possible explanations (50/50)	**4**
Not enough information	**1**

Figure 11. Sample of 13 children killed in Germany 2006 (TUB).

Figure 11 shows the result of a small case study. This study was performed from July 2006 until December 2006. During this time many web sites and newspapers were reviewed. In cases of children that were killed in car accidents in Germany the police were called for more information.
Approximately half of all the accidents during July-December 2006 in Germany were studied. This study does not represent all accidents in Germany but it shows the high occurrence of misuse.
The car was completely destroyed in one quarter of all cases at the seating place of the child. That means that there was a limited chance to survive independent from the CRS usage.
In 4 out of 13 cases it remained unclear whether inappropriate use and/or use of a poor CRS or the accident severity lead to the death.
One third of the children killed in the car crashes died without a CRS or safety device or due to using a CRS incorrectly.
This study already indicates the high risk of misuse and non-use. In addition several very severe accidents were published by databases or newspapers showing children with minor injuries properly using a CRS. Misuse dramatically reduces the safety level of CRS.

During an accident the lives of children could depend on two issues:

- The use of an appropriate CRS reducing the risks of dying due to an accident
- Misuse decreasing the safety level of a CRS

TEST PROCEDURES

World wide there are many different types of test procedures for CRS. It is not clear, which is the best one. In the EU one test procedure is mandatory for a CRS before it can be put on the market. This is the ECE-R44 [ECE-R44]. In this regulation a frontal and a rear test procedure is described. The frontal tests are performed at a standardised test bench. The collision speed is equal to 50 km/h. The deceleration pulse is mandatory. For this test P-dummies have to be used. For any CRS the ECE-R44.04 gives only the minimum requirements. If CRS fail it, they are not approved for the market. But this test configuration has not been changed for some years - regarding the test configuration the last change was 1995. At the moment there is no side impact test procedure included. Regarding accident data there is a need to improve this regulation.

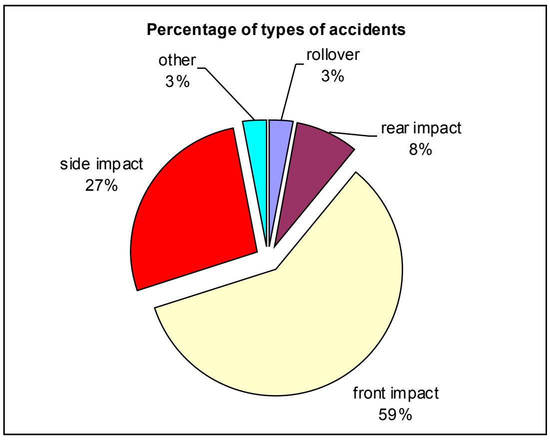

Figure 12. Percentage of all types of accidents for all occupants [DETER, 1996].

In Figure 12 only single collisions are included. However, in real world a large number of accidents are multiple collisions. Side impact occurs only in one quarter of all accidents.

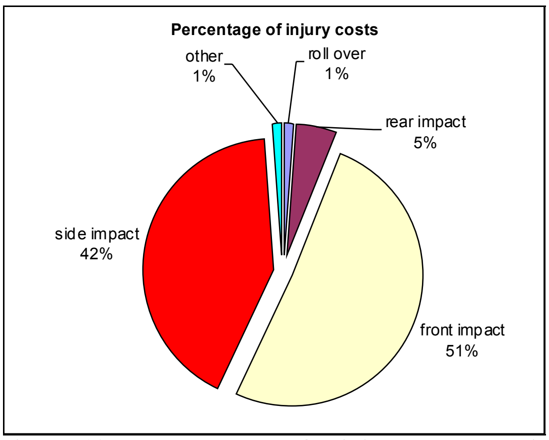

Figure 13. Percentage of injury costs in different types of accidents for all occupants [DETER, 1996].

Side impact accidents cause more than 40% of the injury costs, so the injuries are more severe than in other types of accident. Side impacts and multiple collisions lead to a high injury severity for children, too. For that reason new test procedures should be developed to include all kinds of accidents. To define new test procedures it is necessary to analyse real accident situations first. Test procedures have to replicate most of the real configurations. Acceleration, intrusion and kinematics should be replicated as best as possible.
Consumer test procedures make higher demands on CRS. They test CRS under more severe conditions and not only in frontal tests but include side impact tests. The side impact test is very important for the safety level of a CRS because in most cases side impacts lead to higher injury severities.
But there are too many test procedures with different assessments of the CRS and parents could ask: Which test procedure is the correct one? At the moment the answer is not clear but NPACS (New Programme for the Assessment of Child Restraint Systems) proposed test procedures which are harmonised and under further consideration by technical experts from governments in Europe.
For a deeper look inside the technical development of the side impact test procedure please see ESV Paper (Number 07-0241: Review of the development of the ISO side impact test procedure for CRS [JOHANNSEN, 2007]).
The assessment of NPACS is divided into frontal and side impact ratings. The test procedures for CRS are technically described. The assessment of the CRS is focussed on different body parts of the Q-dummies. The preliminary measurements and the maximum scores in the frontal tests are [NPACS, 2006]:

- Head acceleration (120-51 g) 55 points
- Head excursion (600-270 mm) 55 points
- Chest acceleration (65-33 g) 20 points
- Chest compression (50-6 mm) 20 points
- Neck moment (35-7 Nm) 20 points
- Neck force (3000-900 N) 20 points
- Pelvis acceleration (90-24 g) 10 points
    - Max. 200 points possible

In the side impact the preliminary measurements and maximum scores are [NPACS, 2006]:

- Head acceleration (160-50 g) 30 points
- Head containment (contained/marginal/not contained) 80/20/0 points
- Chest acceleration (100-41 g) 20 points
- Chest compression (39-6 mm) 20 points
- Neck moment (35-10 Nm) 20 points
- Neck force (1900-200 N) 20 points
- Pelvis acceleration (120-40 g) 10 points
    - Max. 200 points possible

The overall assessment is calculated by the addition of the single scores of the different body parts. The lower score of the frontal or side impact rating will be used for the entire assessment of the CRS.
This proposal of scoring for CRS was used for the tests. The technical procedures were not absolutely identical with the described NPACS procedures. For that reason the differences in the scoring between the test procedures are not sensible to predict the difference in the safety level of the CRS. The requirements in these tests are too different.

RESULTS OF SLED TESTS

To compare different test procedures for different CRS classes, several sled tests were conducted at TUB. The selected CRS should not only be assessed in one of today's test procedures, for that reason they were tested in four different procedures taking into account different severity levels for frontal and lateral impact. Q-dummies were used, because they are more biofedelic than P-dummies.
For frontal tests the ECE-R44 test procedure was chosen. Additionally a more severe test procedure was introduced, based on a real accident from the (EC funded) CHILD project. The test bench was the ECE-R44 bench but the deceleration pulse was increased from 21 g to 40 g. The test velocity was increased from 50 km/h to 61 km/h. This test configuration comes from a real accident, included in the database of the CHILD project. With this new test velocity, almost 100% of all accidents inside towns and almost 66% of accidents outside towns are covered (Figure 14).

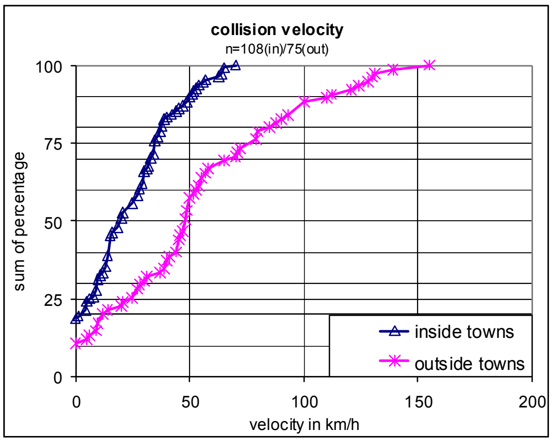

Figure 14. Collision velocity of accidents inside and outside of towns (GIDAS, GDV, UfoGw).

Two different side impact test procedures were used. The first procedure is called TUB-SIPCRS. It was developed at TUB. The test bench is comparable to the ECE-R44 one. To reproduce the loads during a side impact using just the deceleration is not effective. In addition a hinged door is used to represent intrusions according to ECE R95 tests. The test velocity represents an accident with 50 km/h.
The second test procedure is built up like the ADAC side impact test of CRS, using a body-in-white of a Golf-IV equipped with a fixed door.
The results of more than 100 sled tests with CRS were analysed.
For the assessment of the test results the preliminary NPACS rating was used. The ratings were published in 2006 [NPACS, 2006], but changes may occur until the end of the NPACS validation phase. For this assessment different loads were measured: Head, chest and pelvis acceleration, neck moments and forces and chest displacement. With regard to the NPACS protocol the measurements were assessed and points were given.
Detailed investigations at the crash facility of TUB showed differences between good and poor CRS. In tests with higher loads to the CRS than in the ECE-R44 test procedure the measurements of dummy loads were higher and this means the level of safety for children was lower. Also in the side impact test procedures bad results were achieved.
The next two figures show the results of the sled tests. The entire comparison of all CRS is not possible because different types of CRS or different dummies were used and different assessments of the measurements exist. Only a similar couple of CRS should be assessed and could be compared.

		Frontal test						
		ECE-R44					Highspeed	ADAC Frontal
		Q0	Q1	Q1,5	Q3	Q6	Q3	Q3
0+	A	108						
	B	109		117				
	C			110				
1	D		45					
	E		80		70			65
	F				67			66
	M						26	
	N						22	
2/3	G				48			
	H				73			
	J					66	21	23
	K					49		
	L					55		20
	O						17	

Figure 15. Results of sled tests (frontal impact).

In every test the more expensive CRS show better results.
All CRS have to be tested in ECE-R44 conditions before they go on the market. That is the reason for the minor differences between these tests.
If the test conditions are more severe, design problems become visible. The highlighted fields show critical structural problems. In all of these cases non branded CRS were damaged. The design of these CRS is only developed to comply with the ECE-R44 targets.

		Side impact test							
		TUB SIPCRS					ADAC Seite		
		Q0	Q1	Q1,5	Q3	Q6	Q1,5	Q3	Q6
0+	A	110		20					
	B	135		115			158		
	C						55		
1	D							71	
	E		109		114			145	
	F		121		117				
	M								
	N								
2/3	G							50	45
	H							157	153
	J				114	63			
	K								42
	L				22	38			
	O								

Figure 16. Results of sled tests (side impact)

Also during the side impact tests design problems became visible. Again the highlighted fields show critical structural problems and again all of this damage occurred on non branded CRS. The side impact is not addressed by ECE-R44. The design of these CRS is only developed to reach the ECE-R44 targets, not to protect children against side impact.

In addition to the dummy readings the high speed movies were analysed. The following pictures show screenshots of the kinematics during a test.

Figure 17. Baby shells during tests according to ECE-R44.

The left picture shows the Q1,5 in a badly performing class 0+ CRS. The dummy does not have sufficient head support. The loading to the dummy's neck and head are high.
In the right picture the CRS has a good safety level.

Figure 18. CRS of class 2/3 during tests according to TUB-SIPCRS.

The left picture (Figure 18) shows a CRS with insufficient side protection devices. The dummy has contact to the door panel. This would lead to severe injuries.
To be sufficient during a side impact, a CRS has to protect the head. The best side impact protection is to have a shell around the whole child to avoid any contact between the child and the door. Most of the good CRS have head and pelvis protection devices. Some of them have also chest protection devices.

Figure 19. Different severe damage on non branded CRS.

During the tests some non branded CRS were severely damaged. Figure 19 shows examples of severe structural damage of the tested CRS. The damage ranged from small deformation, to destroyed parts of the CRS, up to the destroyed shell itself. For expensive CRS no visible damage occurred.

PROPOSALS FOR OPTIMISATION OF CRS

Two different approaches are possible to improve CRS. First of all testing during the development phase is today's state of the art. Prototypes with different properties could be used in test procedures. The results could lead to some direct improvements at the prototype. This needs time and money to build up several prototypes. Sometimes the prototype materials have other properties than the later CRS. Therefore the results may be not valid.
Numerical simulation is a helpful tool to improve CRS. It is possible to investigate different possibilities to improve a CRS without prototypes. Small changes, e.g. stiffness of belt systems, or simulations without slack in the belt system are quickly possible. For the simulation it is necessary to analyse and validate the CRS, the dummy and the test procedure.
At TUB both tools were used. First in the numerical simulation different measures were proved. After that, some measures were used to build up prototypes for testing.

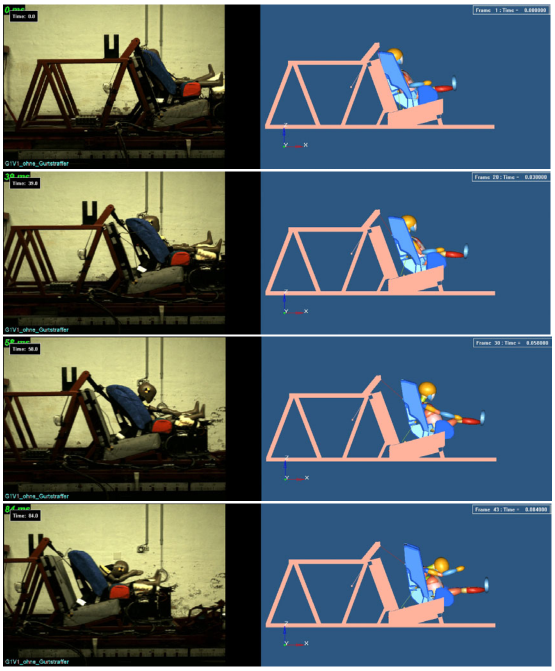

Figure 20. Validation process of numerical simulations by testing [NAAMANE, 2005].

Both (testing and numerical simulation) lead to the following measures to improve child safety in cars:

- Belt routing: The belt should be on the middle of the shoulder going over the chest to the pelvis and belt routing devices. If there is any contact between the belt and the neck in the normal seating position, severe injuries can be expected in case of an accident. The 3-point-belt should only be used on taller children.
- Rigid connection between CRS and car (ISOFIX)
- The car-belt should be as tight as possible (tensioning devices at the CRS)
- Structure of CRS should be able to absorb energy without damage
- Belt routing of car belt should be exact, so that no slipping is possible in loading conditions
- The CRS-belt should be as tight as possible
- Reduction of rotation around the Y-axis

The next Figure 21 shows the benefit of the two last points. The basis model is compared with the two different optimisations. First the rotation around the Y-axis is blocked by a top tether. In the second CRS the slack in the harness is reduced to a minimum before the test started.

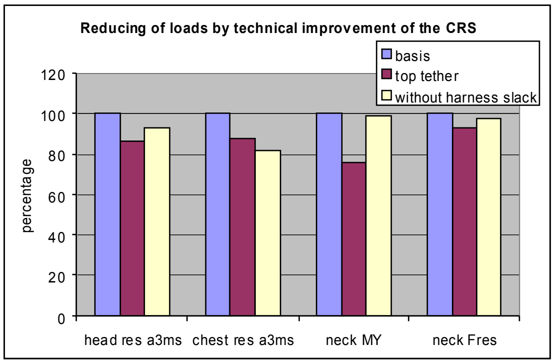

Figure 21. Technical improvements of the CRS and the benefit.

The anti-rotation device significantly reduced the loads on the head and on the neck. The loads also decreased if the slack in the harness was minimised. A combination of these and/or the other named optimisations leads to improved CRS and a high safety level for children.

Sled tests with different types of belt systems were used to investigate the influence of the different devices. For that investigation three belt systems were used:

1. standard belt system
2. belt system with load limiter
3. belt system with load limiter and pretensioner

The used CRS were:

1. Group 2/3, child and CRS were installed together by the 3-point-belt
2. Group 1, the CRS was installed by the belt system, the child used the internal 5-point-belt system of the CRS for securing
3. no CRS, just the belt system
4. Group 3, booster
5. Group 1, like number 2 but rearward facing
6. Group 1, like number 2 but installed with a pre-tensioned belt system

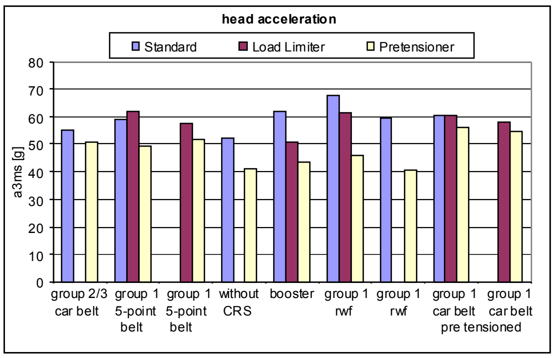

Figure 22. Influence of different belt systems on the head acceleration.

The measurement in Figure 22 show decreased loads when using load limiters and pretensioners. If only load limiters were used the benefit is not clearly visible. That comes from the force level of 4 kN, which is seldom exceed in the performed tests.
The use of additional belt devices could reduce the head acceleration up to 30%.

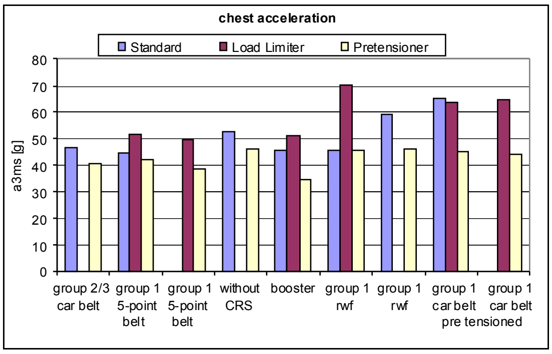

Figure 23. Influence of different belt systems on the head acceleration.

The same influence is visible in Figure 23 for the chest acceleration. The use of load limiter and pretensioner decreases the values of acceleration.

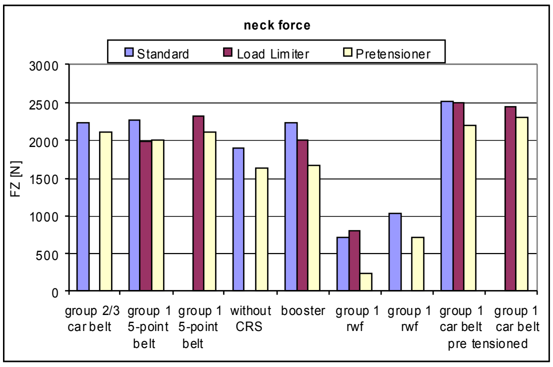

Figure 24. Influence of different belt systems on the head acceleration.

The neck forces were also reduced by the load limiter and pretensioner. In Figure 24 the advantage of rearward facing CRS is visible. The neck forces are about 200 N in this configuration while in the 5-point harness the forces are more than 2000 N. The risk for neck injuries is less for rearward facing CRS.
In the end it is clear that belt systems with additional tensioning devices, as developed for the safety of adults, increase the safety of children too. The same results were found in [BOHMAN, 2006].

RECOMMENDATIONS ON THE RATING PROCEDURE

With respect to the preliminary NPACS ratings (but also generally for CRS ratings) the following thoughts could be discussed in the future:

- In the side impact rating it is possible to have the same number of points as in the frontal impact rating. Taking into account the injury severities in the different accident types it is sensible to emphasise the need for side impact protection by the scoring.
- The assessment of 55 points for the head excursion leads to an advantage for CRS without back rest, because of the measurement between a fixed point of the test bench and the head excursion.
- The present state of the art does not measure the head excursion online during the test. The value is read from high speed videos afterwards or calculated. Some optical errors are the reason for wrong results. New configurations (like online distance measurements) should be used.

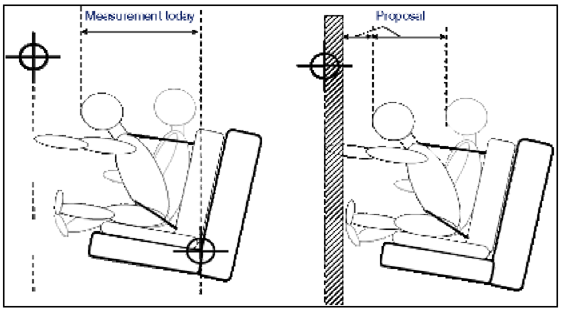

Figure 25. Today's measurement (left) and proposal for independent measurement (right) of the head excursion.

The left picture (Figure 25) shows the most recent measurements of head excursion. It starts on a fixed point (CR-Point) at the bench. This is an advantage for CRS without any back rest - but these CRS have considerable disadvantages, especially in lateral impacts.
The most important target it to avoid any head contact. But in every car there is different space between the seating rows or the passenger seat and the dashboard. For that reason an assessment for the head excursion should be given by the special combination of CRS and car. Here it would be possible to assess the real excursion.
Another solution could be to measure the relative displacement of the head (Figure 25, right). But for this configuration it is necessary to define a global maximum (e.g. 550 mm). The head of the dummy is not allowed to contact a defined safety zone in front of this maximum. If the measurement is higher it is necessary to reduce the overall assessment of the CRS.

SUMMARY AND OUTLOOK

The risk of a child to be injured or killed in car accidents is still high. From the safety point of view two different types of CRS are available: CRS with good protection in some accident configurations and CRS without protection other than the mandatory ECE regulation. But the effectiveness of CRS depends on more than one topic: not only technical issues are responsible for children's safety. Use and handling of CRS should be easy and understandable. In all CRS-groups some improvements are possible to reduce the loadings.

ISOFIX is the best basis for new investigations. It reduces misuse compared to CRS which use the car belt for installation. The rigid connection between the ISOFIX-CRS and the car, especially when supported by an anti-rotation device, leads to decreased loads to the dummy. Starting at this point the CRS could be developed and improved for different accident situations to absorb energy on a high safety level. Numerical simulation should be included in the design process of CRS at an early stage.

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