EVALUATION OF CHILD SAFETY SYSTEMS ON THE BASIS OF SUITABLE ASSESSMENT CRITERIA

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The safety standard of various child safety systems has been the subject of extensive public discussion, as well as of various expert circles in the past few years, but it was not possible to provide an effective instrument for the evaluation of child safety systems to date.
Research work carried out at the Institute for Automotive Technology (Institut für Fahrzeugtechnik) of the Technical University, Berlin has led to the development of assessment criteria which enable the evaluation of child safety seats with various means of restraint.
The proposed assessment criteria are based on the legal groundwork for the testing of child safety seats, but they also call for further bio-mechanical information.
The safety level of four different child restraint principles was examined using several series of experimental tests based on the Uniform Conditions Concerning the Approval of Restraint Device for Child Occupants in Power-driven Vehicles (ECE-R44), but with realistic vehicle deceleration functions. Using the assessment criteria developed at the institute, a preference scale of the level of child protection provided was formulated.
This preference scale, however, only relates to the principle of the restraint system, in form of the 3-point belt system, 4-point belt system, the impact upholstery system and the reboard system, and, to avoid the problem of competition, does not include a comparison of systems produced by various manufacturers. This study made it possible to determine the most suitable child restraint principle for children of various age groups, taking into account the kinematics and the loading of the various occupants, and thus to formulate comprehensive evaluation criteria.

1 INTRODUCTION AND PROBLEMS INVOLVED

In the Federal Republic of Germany, approximately 12 000 children are involved in accidents every year, 2000 of these children suffer serious injuries and 100 even suffer fatal injuries. The percentage of child automobile passengers using restraint systems is almost 60% in the Federal Republic of Germany; of these, about 50 % were protected by special children's restraint systems. This means that about 40% of all children travelling in automobiles are not strapped in, i.e. they are unprotected [1]. These figures clearly illustrate that the legislative powers are called upon to enforce the use of seat belts for children of all ages, in the same way as was already done, years ago, for persons over 12 years of age.

In the currently-used test standard ECE-R44, the child safety seat is clearly described with respect to its protective effect, however, the criteria set down in this standard do not protect the child from the risk of injury adequately. This standard, at least in the dynamic part of the test, describes the criteria shown in figure 1.1.

- No complete or partial separation of any laod bearing structural element
- Limit for the resultant acceleration to the chest: $a_{3ms} = 55$ g
- Limit for the vertical acceleration between head and the chest: $a_{3ms} = 30$ g
- Limitation of the occupant excursion
- Limit for maximum of slack: s = 25 mm
- test dummy: 50 th-percentile test dummy
  - 3/4 year old
  - 3 year old
  - 6 year old
- Calibation of the dummies after each test

Figure 1.1: Criteria in the dynamic test according to ECE-R44

However, if we now consider the parts of the body of children injured in real accidents, and who were strapped in, we obtain the injury distribution shown in figure 1.2.

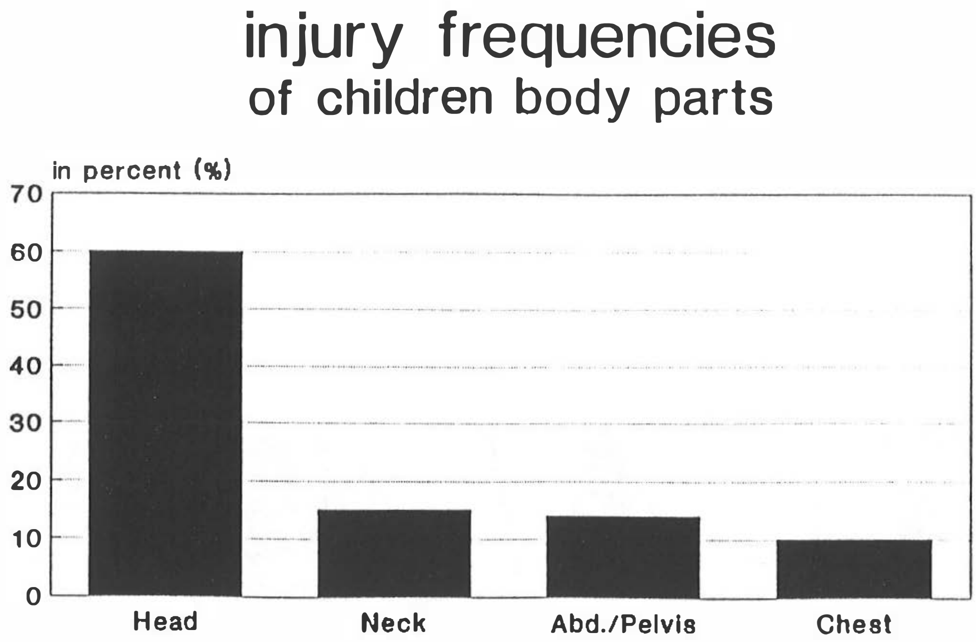

Figure 1.2: Percentages of injured parts of the body [2]

As can be seen, the standard does not provide any criteria to describe the loading to the head, neck or in the abdominal/pelvic region. In order to make reliable statements on the protective effect of child restraint systems, it is necessary to have information both on the loads exerted on the aforesaid parts of the body and also on suitable protection criteria. It is precisely this lack of knowledge of the protection criteria that makes further research in this field urgently necessary. One possible method could be provided by statistical biomechanics, as developed in [3] and applied in [3] and [4].

As a further criticism, it must be remarked that the prescribed range within which the deceleration impulse of the test sled has to lie is an insufficient model of real vehicle deceleration behaviour. In this respect, attention must be paid to the fact that the trend to engines with increasingly larger displacements and a multitude of non-deformable auxiliary devices reduces the available deformation zone and thus increases the vehicle deceleration.

2 EXPERIMENTAL STUDY

For the user of child restraint systems it is both desirable and necessary to select the most suitable system from the wide variety of restraint systems on the market with respect to weight, size and age of the child.

To do this, it is first of all necessary to examine the restraint principles with regard to their suitability for children of different ages. This is particularly the case for children between the age of 9 months and three years, since children of this age can already be transported in a sitting position. On the other hand, their neck vertebrae are not sufficiently developed to be able to absorb large forces. Apart from this, particularly in this age group, the head is disproportionately large in comparison with the torso.

For these reasons a research project with the aim of examining the safety potential of various restraint principles (see figure 2.1) was carried out. The seats of various manufacturers were tested in accordance with ECE-R44 (figure 2.2).

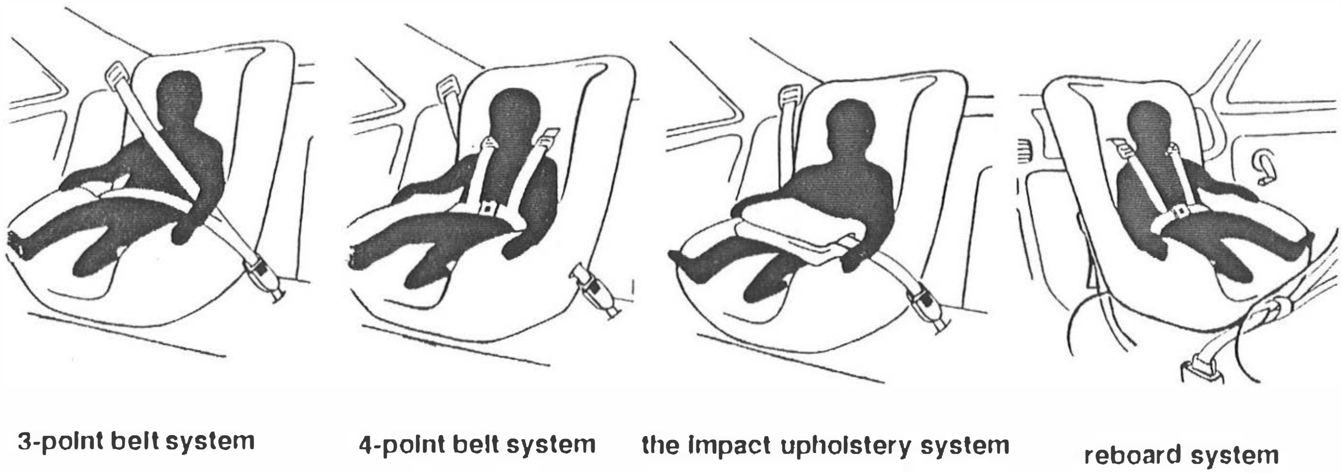

Figure 2.1: Restraint principles [5]

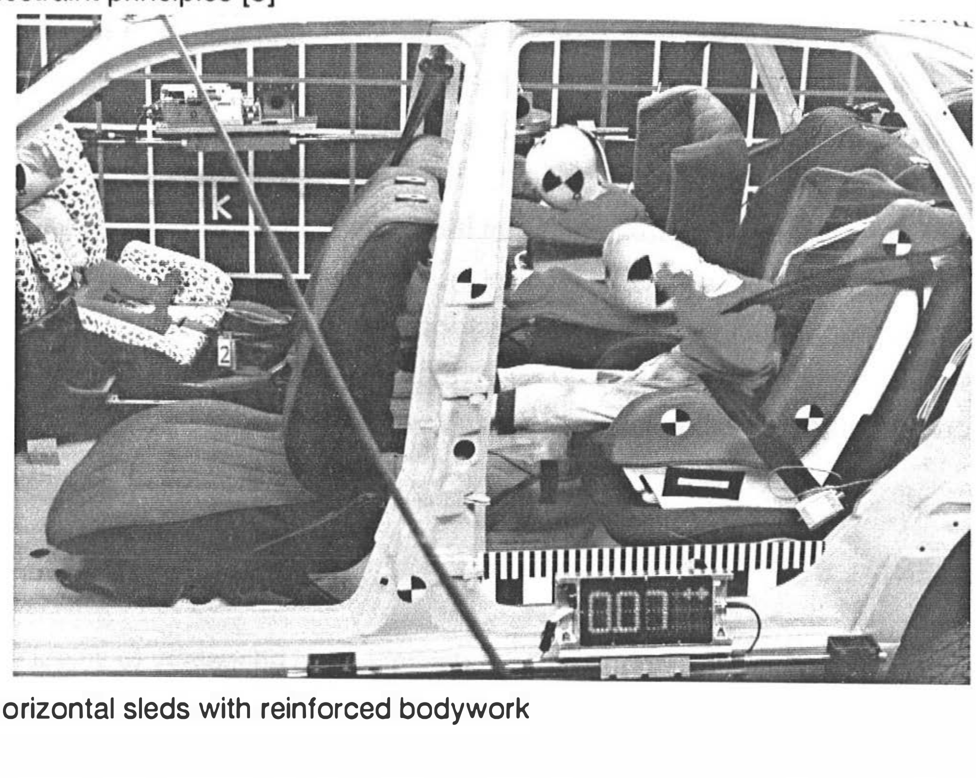

Figure 2.2: Horizontal sleds with reinforced bodywork

The test conditions were defined on the basis of ECE-R44. In order to obtain results as close as possible to reality, complete reinforced car bodies were mounted on the horizontal sled system.

Vehicle deceleration:

Three different vehicle deceleration curves, one of which lay within the ECE range, were obtained using a three-stage strap brake and appropriate material selection.

Type of impact:
Frontal impact with an impact speed of 50 km/h at an angle of 0°.

Dummy:
In accordance with the ECE-R44 regulation, the TNO P3/4, the TNO P3/4, the TNO P3 and the TNO P6 dummy were used.

Seat position:
Outer right-hand and left-hand rear seats with three-point belts or special belts supplied by the manufacturer of the child safety seat.
Middle rear seat with lap belt;
Front passenger seat with three-point belt and/or special belts supplied by the manufacturer of the child safety seat.

In order to ensure a sound statistical assessment of the results, 30 tests were carried out with nine different seats, three seat positions being occupied in each test. The measured (or deduced, where necessary) loading values are summarized in table 2.1. Film document material provided by three accompanying cameras (1000 frames/s) were used for the evaluation of the motion sequence.

Head:	
- resultant acceleration:	$a_{,max}$, a_{3ms}
- Head Injury Criterion:	HIC
- acceleration:	a_{xmax}, a_{ymax}, a_{zmax}
- maximum of Head excursion:	s_{max}
Chest:	
- resultant acceleration of the chest:	$a_{,max}$, a_{3ms}
- Severity Index:	SI
- acceleration:	a_{xmax}, a_{ymax}, a_{zmax}
Bodywork/Horizontal Sled:	
- sled acceleration:	a_{xmax}
- impact velocity:	v_{max}
- deformation length:	s_{max}
- belt forces:	F_{max}

Table 2.1: measured loading value

Measurement of the loading in the neck and abdominal area has not been carried out up to now since, at present, there are no standardized and generally accepted measuring systems. Apart from this, no safe findings on the maximum tolerable loading limits for these parts of the body exist, so that only a relative scale of preference can be determined on the basis of the loading values and on an assessment in relation to a certain absolute test limit value.

3 ASSESSMENT CRITERIA FOR CHILD RESTRAINT SYSTEMS

In evaluating the results, the a3ms acceleration limit value for the head was assumed to be 80 g, this being known as the protection criterion for the resulting acceleration to the head of the 50% dummy (male adult). The limits for loading of the thorax is defined in ECE-R44, and was also used here.

The geometric conditions described in the ECE regulation for the maximum displacement range of the head in the vehicle in a longitudinal direction merely serve to describe the amount of free movement available to the restrained child and in this study had no effect on the evaluation.

Examination of the high-speed films is of special importance for evaluating non-quantifiable descriptors of the kinematics.

As a new assessment quantity for evaluating the safety potential of different child restraint principles, the RIDE-DOWN-EFFECT [6] was used for the first time for child safety seats.

The RIDE-DOWN-EFFECT (figure 3.1) states the percentage of the vehicle's deceleration which is shared by the child restraint system. It is described by the following formula:

RDE: Ride-Down-Effect

$$RDE = \frac{s_{ad} - s_{anl}}{s_{ad}} * 100 \, [\,\%\,]$$

s_{ad} : maximum outer deformation path of the vehicle

s_{anl} : deformation path of the vehicle up to the time the restraint system comes into effect.

In order to determine the RIDE-DOWN-EFFECT, the resulting thorax deceleration is required as well as the time function of the deformation path which can be determined by double integration of the vehicle deceleration function (figure 3.2).

In order to be able to determine the time, t_{anl}, at which the slack in the belt has been taken up, a tangent is placed on the rising curve of the resulting thorax acceleration. The slope of the tangent is chosen to provide as good an approximation of the deceleration curve as possible, i.e. so that the shaded areas above and below the straight line are equal (figure 3.2).

$$RDE = \frac{s_d^a - s_{nl}^a}{s_d^a} * 100 \; [\%]$$

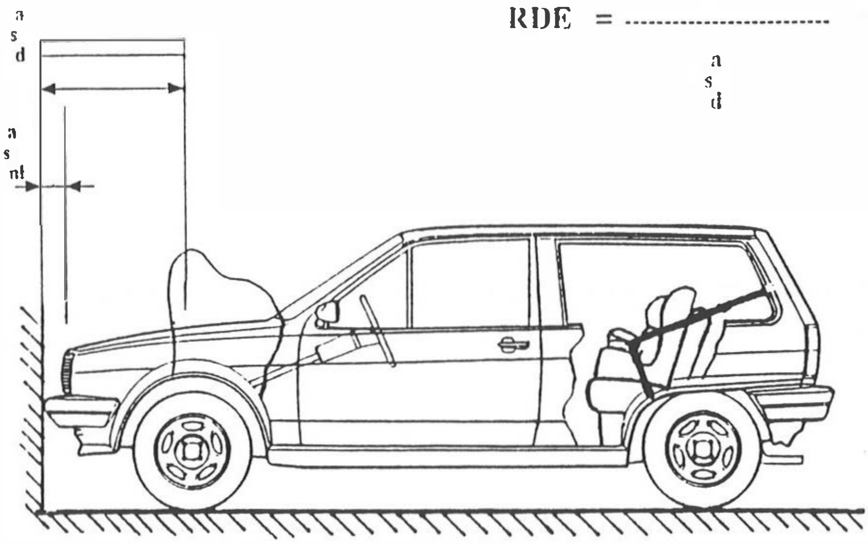

Figure 3.1: RIDE-DOWN-EFFECT in child restraint systems

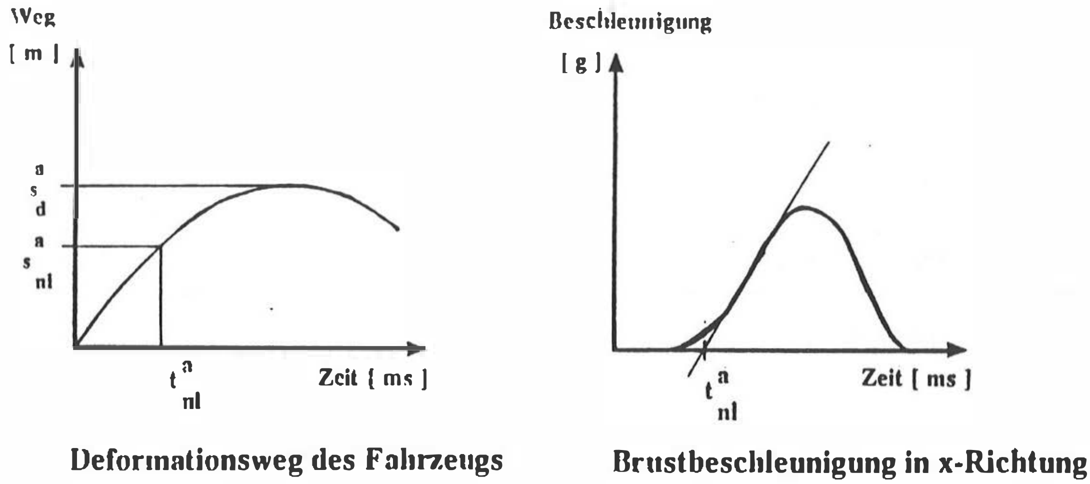

Figure 3.2: Determination of the RIDE-DOWN-EFFECT for child restraint systems

The intersection with the abscissa (time axis) marks the point in time from which the restraint system takes effect. At this time, the vehicle has already passed through a deformation path of s_{anl}. This path is set in relation to the maximum dynamic deformation path and thus describes the percentage of the vehicle deceleration shared by the restraint system.

According to this:

- RDE = 1.0 restraint system is activated immediately, without belt slack
- RDE = 0.0 restraint system is not activated until the maximum dynamic deformation path has been reached, if it is activated at all.

4. EVALUATION OF THE RESULTS

The four different restraint system principles; 3-point belt system, 4-point belt system, impact upholstery system and reboard system, are evaluated by means of the criteria described above.

4.1 3-point belt system

For this restraint principle, the following average loading values were determined:
As a rule, the limiting values are exceeded. The Ride-Down-Effect is high in comparison to other restraint principles, i.e. the system responds at a relatively early stage. The dummies twist free of the belt, so that the head often strikes the thigh. When this happens, the shoulder belt presses into the abdominal region, thus presenting a high risk of injury.

resulting head acceleration	over 100 g
resulting thorax acceleration	70 g
thorax acceleration in z-direction	45 g
Ride-Down-Effect	45%

The arrangement of the shoulder belt, which is designed for adult passengers, is problematic since, on the one hand, an unguided shoulder belt lies directly on the child's neck, and, on the other hand, if guides exist, these are often fixed to the upholstery and do not assume any predictable position during a crash.

4.2 4-point belt system

The following table gives a summary of the average loadings:

resulting head acceleration	over 100 g
resulting thorax acceleration	60 g
thorax acceleration in z-direction	35 g
Ride-Down-Effect	25%

In spite of having lower average values, the 4-point system achieves the highest acceleration values. The limiting values are exceeded. The Ride-Down-Effect and the response characteristics are not very effective due to the double belt slack (belt fixing seat to vehicle and the belt system of the seat itself). The relative velocity between the vehicle and the occupant becomes very high and is not reduced until much later. Due to this, the accelerations experienced by the occupant are usually greater. Accordingly, the high relative velocity is also the cause of the high head acceleration, and also because of the strong thorax fixation exerted by the 4-point belt, of the large stresses on the neck vertebrae which are the connecting link between the head and the torso.

4.3 Impact upholstery system

The average loadings determined on the dummy in the impact upholstery system are summarized in the following table:

resulting head acceleration	over 80 g
resulting thorax acceleration	45 g
thorax acceleration in z-direction	25 g
Ride-Down-Effect	45%

The head loading values exerted on a child passenger in a impact upholstery system are evenly distributed about the limiting values. The thorax loading remains distinctly below the limiting values.

The motion pattern of a child in this seatig system depends very much on the age of the child. Whereas the restraint system shows a "harmonic" wrap-around motion of the torso around the cushion when used with a dummy of a three-year-old, it displays similar effects to those of a 4-point belt system when used with a dummy of a 3/4- year-old. The cushion covers almost the whole torso and the induced kinematics of the head and neck vertebrae are harmonic, with little rotational acceleration and lower head accelerations than those of the dummy of a 3-year-old.

4.4 Reboard system

The reboard system provides the highest protection potential. The resulting acceleration and the efficient Ride-Down-Effect are both due to the small amount of play and slack of the backward-facing occupant.

resulting head acceleration	over 70 g
resulting thorax acceleration	50 g
thorax acceleration in z-direction	20 g
Ride-Down-Effect	50 %

Because the shell of the seat immediately supports the entire body, the deceleration of the vehicle is transferred to the body at a very early stage. The accelerations remain below the limiting values. Because of the low relative motion between the head and the torso, the neck vertebrae are only subjected to low loads in the reboard system, as opposed to seats which face forwards.

Consequently, this principle is especially suitable for children of up to two years of age, i.e. at ages when the neck is not strong enough to withstand greater loads.

5. SUMMARY AND CONCLUSIONS

The object of this study was to establish an order of preference for child restraint systems, taking into consideration the age of the children. Upon reviewing the results, it becomes evident that further research work is necessary in order to obtain a comprehensive assessment of restraint systems.

The order of preference shown here must be regarded as a suggestion. It takes into consideration all the possible restraint systems for the respective age group in question.

Group 0: Restraint system for babies
(0 to 9 months, weight up to 10 Kg)

For this age group, reboard systems, baby baskets, baby carriers and pram-tops are available on the market. The latter three systems are only suitable if they are sturdy enough and are designed to absorb energy, since the child's head usually strikes the restraint system in the case of impact.

The restraint system must be fixed to the vehicle by belts which, as a rule, will also prevent the child from being flung out of the restraint system e.g. when the vehicle overturns.
Reboard systems, so-called baby shells, provide a high degree of protection; on the one hand this is due to the fixation of the head during the deceleration phase and, on the other hand, to the fact that the neck load is reduced to a minimum. In order to achieve a high protection potential, the following requirements must be fulfilled:

- seat and belt design must be suited to the occupant,
- adequate mechanical strength of the seat shell,
- padded seat shell, and
- secúre connection to the vehicle during impacts from all relevant directions.

Group I: Restraint systems for infants
(9 months up to 3 1/2 years, weight 9 kg up to 18 kg)

We suggest that this age group is divided into two sub-groups in order to take into account the special physiological and biomechanical characteristics of these children.
Reboard systems should be used for children of up to 3 1/2 years in order to ensure the best possible protection of the child against injury. To achieve this, the same structural design features must be provided as for group 0. For children of over two years, impact upholstery systems may be used as an alternative to reboard systems. In these systems, there is still scope for reducing the acceleration of occupant acceleration by further optimization of the cushion with respect to its shape and compressibility in the areas where head and thorax impacts may occur. Although excessive loading of the neck vertebrae cannot to be excluded in this system, the loadings are consideraly lower than those experienced with four-point belt systems [5] - however accident analysis does not show the necessary relevance for this restraint system.

Group II: Restraint system for pre-school children
(3 to 7 years of age, weight 15 kg to 25 kg)
and

Group III: Restraint system for children of school age
(6 to 12 years of age, weight 22 kg to 36 kg)

Groups II and III describe an age range of almost nine years. To meet the requirements of this age spectrum, a variety of seat cushions must be used in conjuction with the car's safety belt system. For smaller children of up to approximately 7 years of age this is done by modifying the impact upholstery system. The protection system used is the same as that of impact upholstery systems

for age group I. For children over 7 years of age, seat cushions which optimize the position of the shoulder belt should be introduced.
Neither the use of 4-point belt systems nor the direct strapping-in of children under 7 years of age with the vehicle's built-in shoulder belt seems to be advisable.
The acceleration of the head and of the thorax, as well as the Ride-Down-Effect were taken as assessment criteria. The results of the research show that the following additional loading values and test conditions are required and can be realized:
The rotational and linear acceleration of the head must be measured and the GAMBIT - value [3] with yet to be determined protection criteria levels for children must be introduced as a protection criterion.

The loading on the neck vertebrae must be determined by measuring the bending moment exerted on the neck [3], whereby it will be necessary to determine limiting values for child passengers here, too.

It is necessary to make statements on the loading on the abdominal region in submarining cases, a method for doing this was developed in [3]. A meaningful criterion can then be provided when a protection criterion level for children, which still has to be determined, becomes available.

Furthermore, it is necessary to extend ECE-R44 by including rear and lateral collisions with movable barriers, a realistic seat environment, modified dummies (abdominal region, neck vertebrae), as well as by introducing new measurement techniques on the dummy

These essential measures can contribute to the improvement of the safety of child car passengers and serve to develop child restraint systems effectively.

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