PHILOSOPHY AND STRATEGY OF NEW CAR ASSESSMENT PROGRAM TO RATE CRASHWORTHINESS

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Paper Number 98-S11-O-14

ABSTRACT

A means of assessing the passive safety of automobiles is a desirable instrument for legislative bodies, the automobile industry , and the consumer. As opposed to the dominating motor vehicle assessment criteria, such as engine power, spaciousness, aerodynamics and consumption, there are no clear and generally accepted criteria for assessing the passive safety of cars.

The proposed method of assessment combines the results of experimental safety tests, carried out according to existing legally prescribed or currently discussed testing conditions, and a biomechanical validation of the loading values determined in the test.

This evaluation is carried out with the aid of risk functions which are specified for individual parts of the body by correlating the results of accident analysis with those obtained by computer simulation.

The degree of conformance to the respective protection criterion thus deduced is then weighted with factors which take into account the frequency of occurrence and the severity of the accident on the basis of resulting costs.

Each of the test series includes at least two frontal and one lateral crash test against a deformable barrier.

The computer-aided analysis and evaluation of the simulation results enables a vehicle-specific overall safety index as well as partial and individual safety values to be determined and plotted graphically.

The passive safety provided by the respective vehicle under test can be defined for specific seating positions, special types of accident, or for individual endangered parts of the body.

INTRODUCTION

In the frame of the research project "Quantification of Passive Safety of Passenger Car Occupants" [1] on behalf of the Bundesanstalt für Straßenwesen (Federal Highway Research Institute), a procedure has been developed, that investigates and assesses the safety of passenger cars on the basis of accident analysis, statistical biomechanics, and crash tests.

In several expert meetings this procedure has been introduced and developed. The test program comprises three different crash tests:

- Frontal crash similar to FMVSS 208 (US-NCAP) (testing restraint systems)
- Offset-test, frontal, similar to 96/79/EG (testing vehicle front structure)
- Side impact according to 96/27/EG with moving deformable barrier (testing restraint systems as well as vehicle structure)

PROCEDURES FOR SAFETY ASSESSMENT

During the last fifteen years, different solution attempts for safety assessment have been proposed and partially have been realized, with basic differences in size of assessment, selection and weighting of criteria, as well as possibilities of application. In principle, the following concepts can be distinguished.

Retrospective Analytical Procedures

Assessment of a specific vehicle type is done by valuation of actual data of available data bases from state and insurance companies, which have been collected and stored over a sufficiently long period of time with statistical certainty. The size of the usable data arises from the frequency of accidents in the survey period. Surveys can be divided into two basic categories. One category is based on the reason of the accident, which mostly considers the pre-crash phase and so is a matter of active safety, while the other category deals with crash and post- crash phase, thus relating to passive safety.

A further distinction feature of retrospective accident analysis is the number of the analyzed accident material and their depth. They are classified as large case studies and in-depth studies.

In large case studies a great number of accidents is being collected, so that these accident data usually do not have the necessary depth for extracting specific statements about severity and mechanism of injury and crash behaviour.

In-depth studies only collect a restricted number of accidents, but they try to analyze the data as exact and in-depth as possible, and so offer the possibility to examine the questions mentioned intensively. Quite often, these data are not representative of the entire accident events, as they usually are collected in local investigations where infrastructural influences of the region of investigation can have a great influence. Additionally, vehicles, which are on the market in only a small number, are not or hardly available in those studies. For this reason, large case studies are used for examinations aimed at ranking the safety of vehicles.

The following institutions judge the passive safety of cars with retrospective procedures:

- Highway Loss Data Institute Report (USA)

- FOLKSAM Report (Schweden)
- Department of Transport Rating System (UK)
- Insurance Institute for Highway Safety (USA)
- Univercity of Oulo [Finnland]
- Monash Univercity (Australien)

Prospective Procedures - Experimental Procedures

To be able to make a statement predicting the state of the passive safety, one cannot proceed by means of retrospective methods with new vehicles. Derivation of the level of safety of the current model from the behaviour of the predecessor model is not possible, as the actual model can be significantly different from the predecessor. Therefore, results from experimental safety tests are used as criteria in relation to the level of protection criteria.

Selection of crash tests determines, which part of the real-world accident events will be covered. At present, the following institutions investigate the safety of passenger vehicles by the use of crash tests:

- ADAC (BR Germany)
- New Car Assessment Program (USA)
- Auto Motor und Sport (BR Germany) [15]
- „European" New Car Assessment Program („Euro" NCAP) (UK)
- Insurance Institute for Highway Safety (USA)
- OSA (Japan)
- NCAP (Australia)

Combined procedures

Combination of experimental safety tests and in-depth accident analysis tries to avoid the conceptually caused disadvantages of retrospective procedures on the one hand and purely experimental procedures on the other hand.

The following procedures are being used or in the development stage:

- Crashworthiness Rating System for Cars (GB)
- Secondary Safety Rating System for Cars (GB)
- Pilot study "Quantifizierung der Passiven Sicherheit" TU-Berlin

Valuation of existing or proposed procedures

Retrospective procedures do not make it possible to make predictions of the passive safety of new vehicles, neither in the real-world accident events nor in the laboratory, as those vehicles are not found in the accident events, when they come to market. Only after several years of presence on the roads, the amount of collected accident data is large enough to make reliable statements about the passive safety, at least this is true for vehicles with a great number of registrations. Therefore it is necessary to investigate the potential of protection in simulated tests, so-called crash tests.

A sole examination of results from crash tests, as done in the prospective procedures, is not sufficient for assessment of passive safety, as they often are only selective assessment attempts that do not reflect the entire real accident events. Moreover, single tests with e.g. very high test speed can lead to an excessive reinforcement of structures, which can have adverse consequences in regard of compatibility in the entire accident events.

Combined procedures try to take into account information from the accident events as well as from constructive design properties of the vehicle. This is done by weighting the results achieved with an additional weighting factor. Assessment of the loading of occupants is carried out by squaring the quotient, according to the "Crashworthiness Rating System for Cars". There is no biomechanical explanation for that. The "Secondary Safety Rating System for Cars" examines the constructive lay-out of the vehicle without subjecting it to a dynamic test. The elements examined are being selected on the basis of data from the accident events. Values attained in every assessment phase become weighted with a factor determined from the accident events. Since a dynamic test is not being performed, no statements can be made about the dynamic behaviour of the structure, the efficiency of the restraint system, etc.

These here introduced procedures contain many good features of a safety assessment. However, none of the assessment procedures mentioned so far shows a clear attempt to build up on the accident statistics. Also the assessment of passenger loadings or further assessment quantities is not or only insufficiently well-founded. An objective, transparent and comprehensible assessment algorithm is not available in most procedures. The attempt of TU Berlin, which was developed in the context of a research project of the German Road Research Institute shows a good basis due to the clear structure and the systematic construction, which will be further extended in the context of this project.

REQUIREMENTS ON A RELIABLE ASSESSMENT SYSTEM

The bandwidth of already existing assessment possibilities of an in principle identical aim, namely the assessment of passive safety, reflects the difficulties and necessary restrictions of such a procedure. Provision of transparent, comprehensible and quantifiable criteria is of basic significance. Following requests and main tasks will build the experimental/analytical attempt of an assessment algorithm:

Table 1:
Specifications for Safety Assessment

Specifications for Safety Assessment of Self and Partner Protection for an Analytical Procedure		
REQUIREMENTS	BASIS	MEASURES
realistic test conditions	data base, in-depth study	accident analysis equivalent accidents
measurement location	data base, in-depth study	accident analysis occupant loadings
assessment criteria, protection criteria	biomechanics, numerical simulation	physical loadings, injury severity/risk function assessment function
limiting value	standards	ECE regulations, FMVSS
relevance factors	data base, in-depth study	data base, relevance factor
statistical confirmation	reference tests, numerical simulation	measurement scatter, statistical evaluation

The specifications for an assessment procedure must contain demands that cover the real accident events under consideration of singular points of view. Doing this, results of accidents related to the occupant in physiological, physical and economic view and the translation of the assessment attempt into a practicable procedure have to be considered.

The following requests to a safety assessment shall be made from these aspects:

- Reproduction of and validation at the real-world accident
- Integration of assessment of self and partner protection
- predictability
- transparency, comprehensability, biomechanical justification
- consideration of measurement scatter
- integration of standards
- modular structure

The necessity to analyze and simulate experimentally the reality as extensively as possible is the dominating of the posed requests. All aspects of vehicle safety with regard to protection of occupants as well as to protection of exterior road-users shall be included. A substantial benefit can be expected if a procedure could be developed which shows a quantitative, reality referring forecast ability. To obtain necessary acceptance of such a procedure, in spite of the variety of the influence parameters, a solution attempt must be worked out which can provide a transparent, comprehensible, checkable consistent procedure. Necessary temporal and financial conditions shall more over allow the realization of the safety assessment. The procedure to be suggested shall make use of frequency and results of an accident event as weighting factor for the experimental test constellation, which is equivalent to the accident. Already existing, legally specified safety test shall also be taken into account when formulating test conditions. These represent a discontinuous assessment measure and play a decisive role due to their compulsory nature for vehicle design. The same holds for the specified protection criteria levels in these tests. The provision of the functional coherence between loading values measured in the tests and injuries of occupants in the form of risk functions is necessary for the striven continuous assessment.

TEST PROCEDURE FOR ASSESSMENT OF PASSIVE SAFETY OF PASSENGER CARS

The newly developed assessment technique combines the methods used so far [2, 3, 4, 5, 6, 7, 8] and provides for inclusion of biomechanics of occupants as well as economic consequences in an experimental-analytical procedure.

Accident Analysis

The main task had to be solved by the accident analysis, based on the data material [9] of the Medizinische Hochschule Hannover (MHH; Medical Highschool Hannover):

- Provision of input data for numerical simulation.

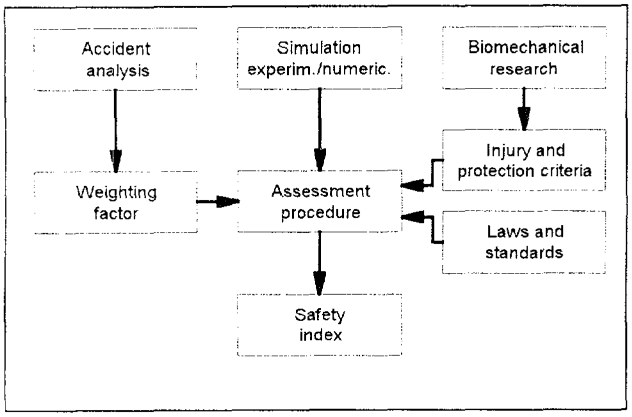

Figure 1: Assessment method

- On the basis of the material of the accident research unit of MHH, an accident data set has been ascertained, that is used as an input data set for numerical simulation. With this accident data set, assessment functions are established in computer simulations.
- Ascertainment of distribution functions of different parts of the body in order to deduce assessment functions [10, 11]. Numerically evaluated functional relations between accident characteristics and load factor on the one hand and distribution functions of injury severity on the other hand are correlated. Correlation is made according to the EAC-method [12], where the result is made mathematically describable by statistic means.
- Determination of relevance factors for weighting measurements at different parts of the body. Relevance factors are used to compare measurements one to another on the basis of injury costs.

Experimental Simulation

When establishing test procedures for the experimental part of the assessment, it was proceeded from the compulsory homologation test similar to FMVSS 208 (a frontal impact against a rigid barrier) [13], an offset test with 40% overlap (a frontal test against a deformable barrier) close to 96/79/EG, and the European side impact test with a moving deformable barrier similar to 96/27/EG [14]. These three 'tests serve mainly as a judgement of self- protection.

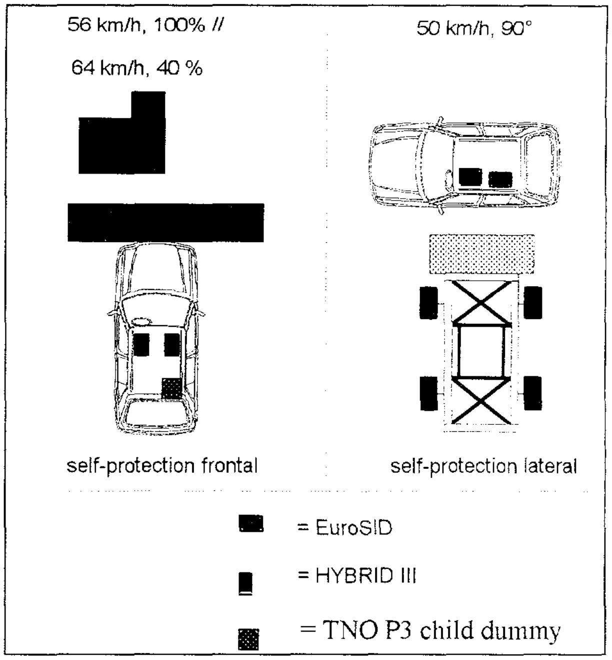

Figure 2: Test-procedure

Instrumentation of the dummies correspond to 96/79/EG and 96/27/EG.

Test Conditions -The following conditions were laid down:

Table 2:Frontal crash similar to FMVSS 208 (US-NCAP)

Collision object	rigid barrier
Impact speed	56 km/h
Impact angle	0°
Overlap	100%
Loading	Hybrid III on driver's and passenger's seat and TNO P3 dummy with child restraint system behind the passenger

Table3: 40%-offset test similar to 96/79/EG

Collision object	deformable barrier
Impact speed	64 km/h
Impact angle	0°
Overlap	40%
Loading	Hybrid III on driver's and in the back behind the front passenger seat

Table 4:Side impact according to 96/27/EG

Collision object	moving deformable barrier (EEVC)
Impact speed	50 -2 km/h
Impact angle	90° left
Impact point	seat reference point
Loading	EuroSID on driver's seat and on the back seat (both struck side)

Measurements and Protection Criteria - Type and position of transducers are in accordance with the customary equipment used with the respective proposed dummies.

For valuation of intrusion into the foot well, use of 5-axial transducers in the lower leg is recommended.

Table 5
Side impact
Transducers in dummy type EuroSID

Body part	Type of measurement	Protection criterion
Head	acceleration 3-axial	HPC 1000
Thorax	deformation and deformation speed	VC 1 m/s
Thorax	deformation of ribs	42 mm
Abdomen	force 3-axial	$\Sigma F_{Abd.}$ 2.5 kN
Pelvis	force in symphysis	$F_{symp.}$ 6 kN

Table 6
Frontal crash
Transducers in dummy type Hybrid III

Body part	Type of measurement	Protection criterion
Head	acceleration 3-axial	HIC_{36} 1000
Head	acceleration 3-axial	a_{3ms} 80 g
Neck	forces	limiting curves
Neck	torque	My < 57 Nm
Thorax	acceleration 3-axial	a_{3ms} 60 g
Thorax	deformation speed	VC 1,3 m/s
Thorax	deformation	< 50 mm
Upper leg	longitudinal force	F_{max} < 10 kN
Lower leg	Tibia Index (TI)	TI < 2 kN

Table 7
Frontal crash
Transducers in child dummy type TNO P3

Body part	Type of measurement	Protection criterion
Head	acceleration 3-axial	HIC_{36} 1000
Head	acceleration 3-axial	a_{3ms} 80 g
Thorax	acceleration 3-axial	a_{3ms} 60 g
Thorax	acceleration z-axial	a_{3ms} 35 g

Rule of Procedure

A finite number of safety tests is necessary to achieve statistically secured test results. However, only one single test is assigned for tests of homologation and type approval, so, the measured value will deviate from the true value with a certain degree of probability.

In order to reduce test expenditures, a rule of procedure takes this into account.

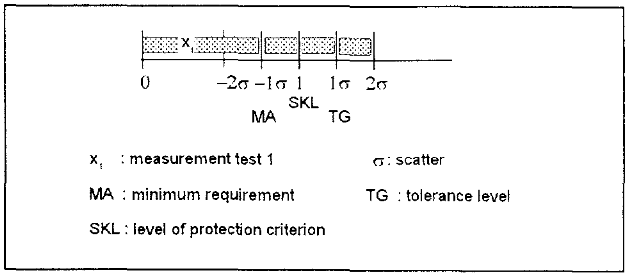

Figure 3: Rule of procedure

The rule includes the definition of a minimum requirement

MA = protection criterion - measurement scatter

and an upper tolerance level

TG = protection criterion + measurement scatter

The relation of the respective loading to these quantities determines whether the values are accepted for assessment, whether one further repeat test with assessment of the mean values is required, or whether the results are excluded from the assessment procedure.

Determination of Assessment Functions

The measurements obtained from a minimum of three or a maximum of six integral safety tests can now be proceeded for assessment.

The physical loading values are first related to the protection criterion, which is the tolerance level of the respective body part. These normalized values are input data to the body part related assessment functions [1].

By combining accident analysis results with those of computer simulation, these functions represent a relationship between the real accident damage and the experimentally deduced loading values.

In the statistical evaluation (figure 4), the severity of the injuries, coded according to the AIS, are plotted for frontal and for lateral collisions (figures 5 and 6) as functions of the equivalent accident characteristics [10, 15], analogous to the values measured by the transducers in the head, thorax, ribs, abdomen, pelvis thighs, and lower legs of the dummy.

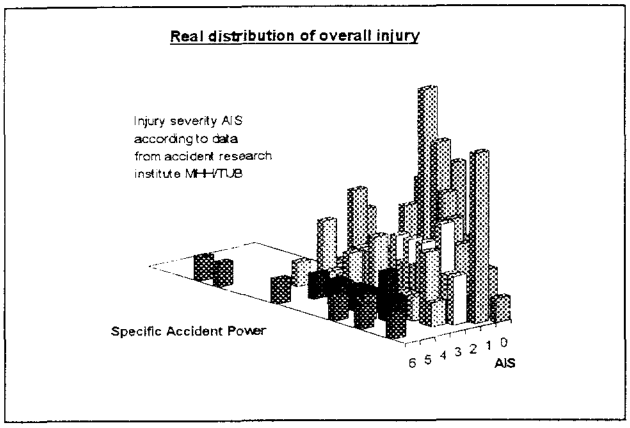

Figure 4: Real distribution of overall injury severity MAIS

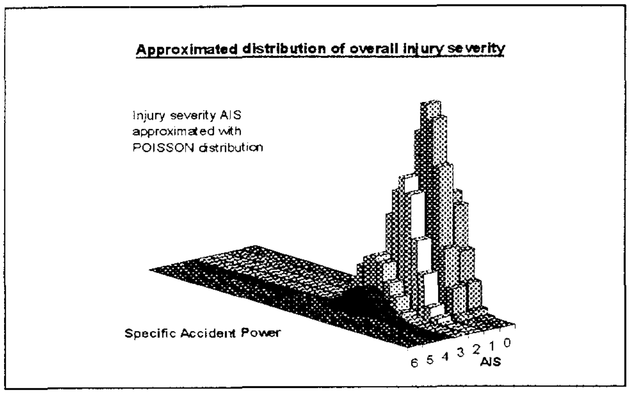

Figure 5: Approximated distribution of overall injury severity MAIS

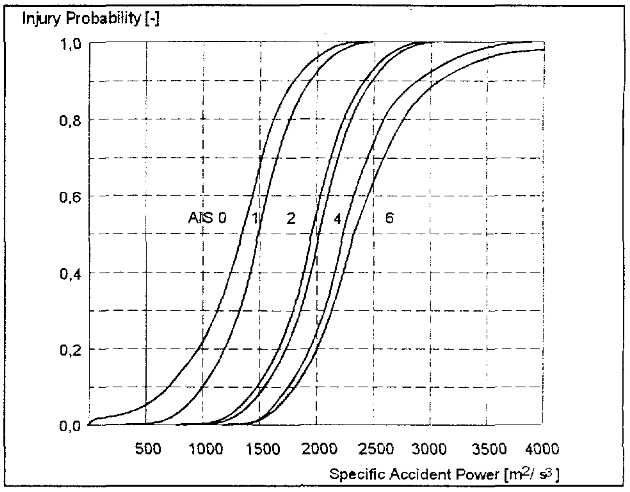

Figure 6: Injury probability of the head (AIS injury scale)

As a result, a distribution function is obtained for the probability of reversible or irreversible injuries to each part of the body in frontal or lateral application of load (figure 7).

The results of this statistical evaluation of real accidents are utilized to determine boundary values as input data for computer simulation, which are to ensure a uniform distribution and to specify the required number of simulation passes.

The physical occupant loading quantities deduced from the equivalent accident characteristics by using occupant simulation models can be correlated to the statistical evaluations. By eliminating the equivalent accident characteristics, which are common to the models, a direct relationship between the loading and the severity of the injuries is established.

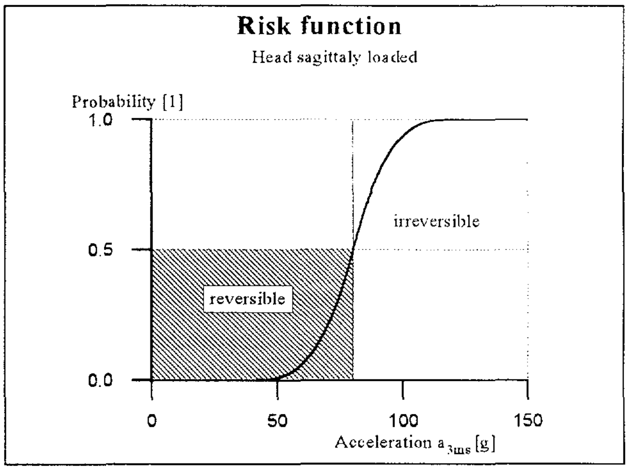

Figure 7: Risk function for occupant loading

Assessment

The assessment function, the central element of the proposed algorithm, provides the ability to carry out a continuous validation of the test results, i.e. the normalized individual measured value is assessed below the protection criterion level within the range defined by the risk function. This degree of compliance with the respective criterion is calculated for every measured value and is weighted with the corresponding relevance factors (figure 8).

The areas of safety assessment described before can be expressed in the following formal relation (figure 9).

The transformation of this method into a computer program [16] enables calculation of both an overall safety index for the whole vehicle and of partial safety indices for the passive safety of the vehicle under test in frontal or lateral collisions. Also, safety values related to seat position and body parts can be established (figure 10).

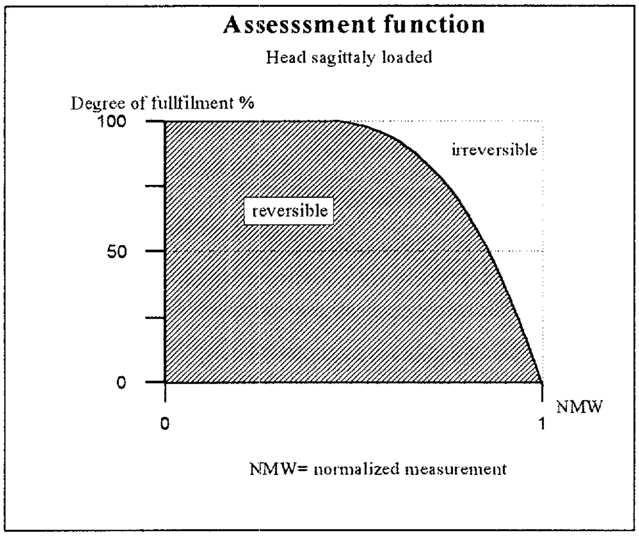

Figure 8: Assessment function

$$\text{Safety index} = \sum_{k=1}^{n}\sum_{j=1}^{m}\sum_{i=1}^{l} RF_{ijk}\left[f_i\left(\frac{MW_i}{SK_i}\right)\right]_{jk}$$

i : point of measurement

j : seating position

k : single test

RF : relevance factor

SK : protection criterion

MW : measurement value

Figure 9: Algorithm for safety assessment [16]

VALIDATION OF THE ASSESSMENT PROGRAM

The philosophy of the validation was to test cars which are on the market for several years to see if there is any correlation between the real world accidents and the results of the crash tests.

The material is the accident database of North Rhine-Westphalia (NRW-data). The BASt performed the accident analysis [20] for those cars which were used in the crash tests with the task to compare these cars with each other regarding the passive safety. The cars which the expert group chose, expecting that these cars were represented in a sufficient number in the accident data material, were the following four cars, which are as well as the results of the two comparisons of passive safety documented in table 8.

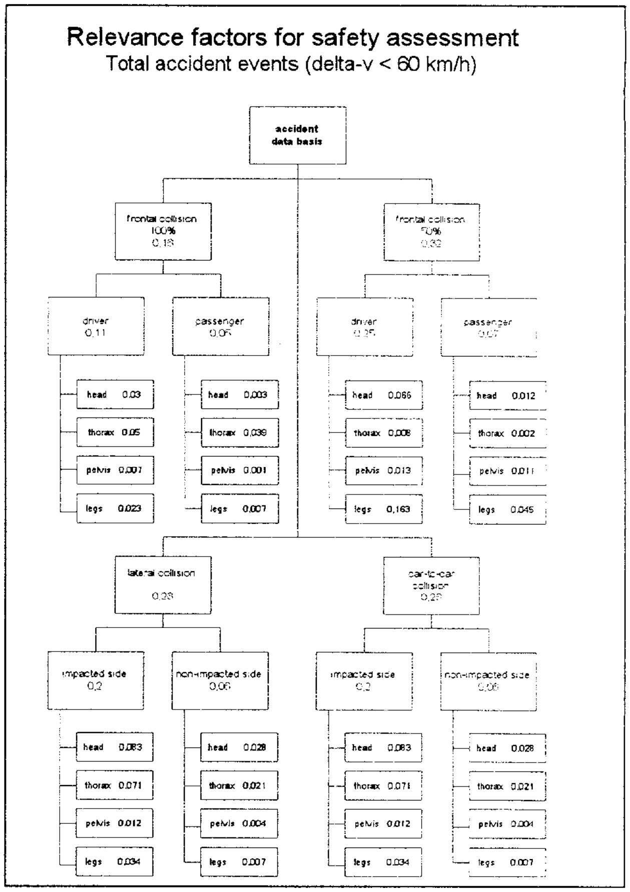

Figure 10: Example of a structure of relevance factors

The safest car both analysis detected was the BMW 5 E34 followed by the VW Golf II, Opel Kadett E, and the FIAT Uno. The comparison on the basis of the NRW-accident data described the value in relation to the medium safe car. This car has the ranking number 100.

Cars with a ranking number greater than 100 are less and lower than 100 more safe than the medium safe car.

Table 8: Comparision between accident and TUB-NCAP ranking

test car	mass class	accident data ranking	TUB-NCAP (SI) ranking
FIAT Uno	sub compact	101	0.1426
OPEL Kadett E	compact class	99	0.2070
VW Golf II	compact class	92	0.3371
BMW 5 E34	large	74	0.5130

The TUB-NCAP algorithm which calculates the safety index (SI) in comparison shows the same ranking. The maximum safety index is 1.0.

At a first glance it seems that the assessment program is working very well.

SUMMARY AND OUTLOOK

Within the scope of this work, the project "Quantification of Passive Safety of Passenger Car Occupants" describes an assessment method for passive safety of cars.

The ranking calculated by the TUB-NCAP is the same as in the NRW-real world accident data analysis of the BASt. This is one more evidence that this assessment program works.

The methodology of validation which is used (that means the comparison between real world accidents and the assessment of the tests) seams to be the only possibility to create a sure assessment program which gives all groups, who are interested in the passive safety of cars, right information about the level of the passive safety of the car. The necessity of repeatability and transparency of the assessment procedure is given by a biomechanically based algorithm.

In this period of validation an offset-crash against the rigid barrier was used. According to the philosophy of this assessment program the new 96/79/EG offset-crash with a deformable element should be used in the future because this test is closer to accident reality. ,Every test which is closer to accident reality makes the validation of this assessment program safer.

For the validation a special attention was given to the assessment of compatibility by means of a car-to-car test. It has to be investigated, wether a less expensive test constellation possibly could give a more complete assessment of the compatibility of passenger cars.

Physical boundary conditions like

- collision speed,
- stiffness of barrier,
- length of barrier at primary impact,
- length of barrier at secondary impact,
- definition of step depth

as well as the behaviour of vehicles of different weight, different front structures and driving concepts have to be investigated.

The EU sponsors two projects which are working on the field of compatibility. The aim of these projects is the development of a test procedure for examination of the compatibility protection potential. On the basis of such a test procedure it should be possible to develop a functional correlation between forces or geometric deformation behaviour of the car and the barrier and the loadings of the dummy to evaluate the compatibility of cars.

Partner protection of the other exterior road users is not included in this procedure at this time. Further research should be done with the view to pedestrians and drivers of bicycles and motorcycles.

For the pedestrian protection an EU working group is developing a test procedure. At this moment the proposal is not validated so that it seems to be necessary to wait for the validation of a suitable test procedure for pedestrian protection.

At this time the assessment algorithm of TUB-NCAP uses only the biomechanical assessment functions for the calculation of the safety index. In the future, functions or assessment criteria will be developed for the opening behaviour of the door, the behaviour of the fuel system (leakage), remaining survival space etc. to put more information into the assessment algorithm. But for all these parameters it is necessary to develop such assessment functions to avoid a subjective assessment which is not reproducible and not transparent.

In this way, the procedure can be optimized concerning the number of necessary crash test and the incidental costs of tests and vehicles.

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