ASSESSMENT OF THE SAFETY OF AUTOMOBILES

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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, as well as one lateral crash test between two vehicles of the type being tested, thus taking into account both self-protection and protection of the other involved party.

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" on behalf of the Bundesanstalt für Straßenwesen (German Federal Road 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.

At least, the procedure comprises four different crash tests:

- Frontal crash according to FMVSS 208 (testing restraint systems)
- 50%-offset-test, frontal, 50 km/h (testing vehicle front structure)
- Side impact according to EEVC-proposal with moving deformable barrier (testing restraint systems as well as vehicle structure)
- Vehicle-to-vehicle crash test (testing compatibility and self-compatibility)

TEST PROCEDURE FOR ASSESSMENT OF PASSIVE SAFETY OF PASSENGER CARS

The newly developed assessment technique tries to combine 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.

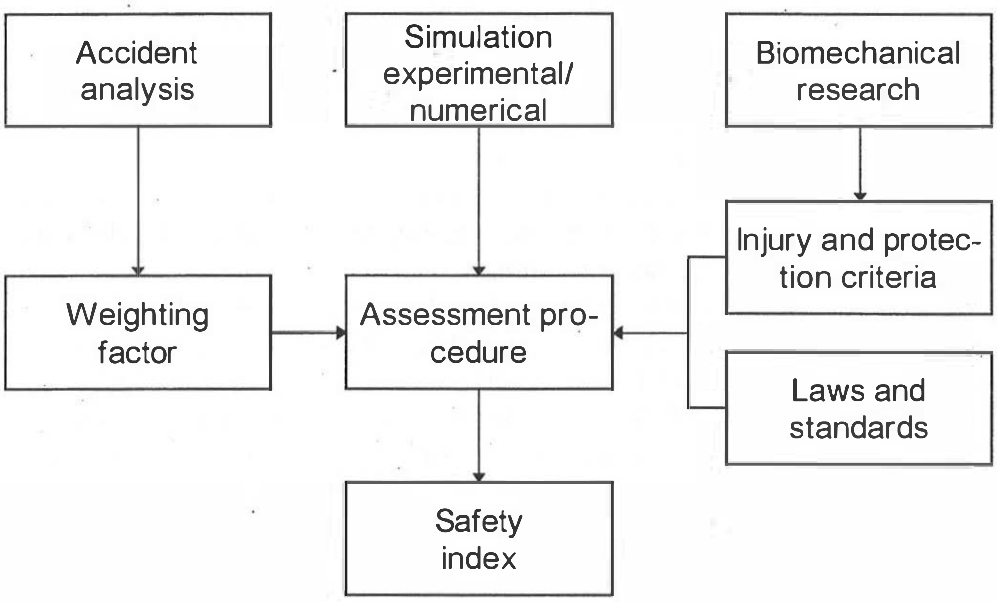


Figure 1: Assessment method

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.
- 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, in computer simulations assessment functions are established.
- 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 according to FMVSS 208 (a frontal impact against a rigid barrier) [13], an offset test with 50% overlap, and the proposal for a European side impact test with a moving deformable barrier [14]. These three tests serve as a judgement of self- protection.

Partner-protection is paid regard to by an additional side impact test with two vehicles of the type to be examined.

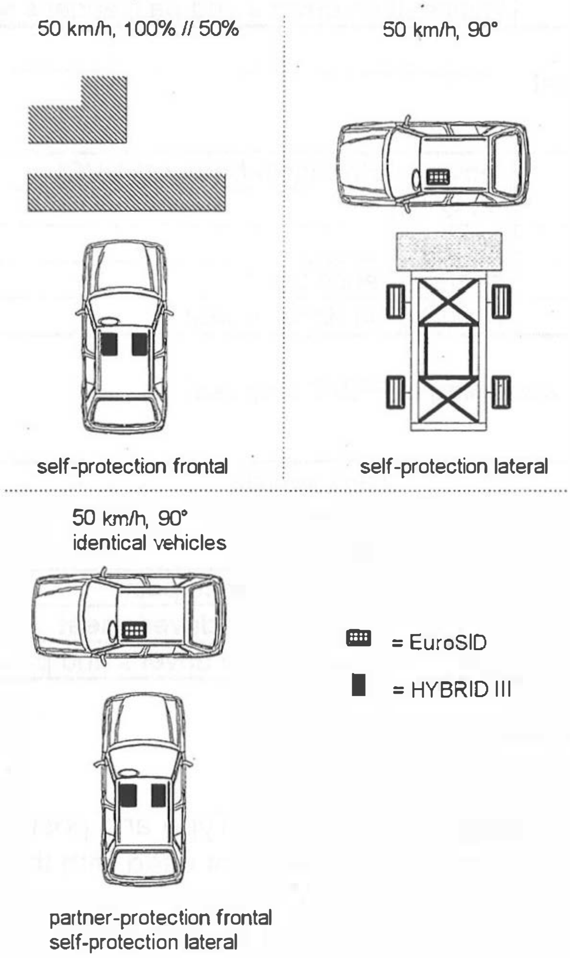


Figure 2: Test-procedure

Instrumentation and loading correspond to ECE-R94 and ECE-R95. Test speeds for all tests are 50 km/h under an angle of 0° and 90°, respectively.

Test Conditions -The following conditions were laid down:

Collision object	rigid barrier
Impact speed	50 km/h
Impact angle	0°
Overlap	100%
Loading	Hybrid III on driver's and passenger's seat

Table 1: Frontal crash according to FMVSS 208

Collision object	rigid barrier
Impact speed	50 km/h
Impact angle	0°
Overlap	50%
Loading	Hybrid III on driver's and passenger's seat

Table2: 50% offset test

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

Table 3: Side impact according to EEVC-proposal

Collision object	test vehicle
Impact speed	50 km/h
Impact angle	90° left
Impact point	seat reference point
Loading of struck vehicle	EuroSID on driver's seat
Loading of striking vehicle	Hybrid III on driver's and passenger's seat

Table 4: Compatibility test (car-to-car test)

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, the calculation of the Tibia Index on the basis of the loadings of the lower legs is used.

Body part	Type of measurement	Protection criteria	Level
Head	acceleration 3 axial	HPC	1000
Thorax	deformation and deformation speed	VC	1 m/s
Thorax	deformation of ribs	rib deflection	42 mm
Abdomen	force 3 axial	$\Sigma F_{Abdominal}$	2,5 kN
Pelvis	force in symphysis	$F_{Symphysis}$	10 kN

Table 5: Side impact, Transducers in dummy type EuroSID

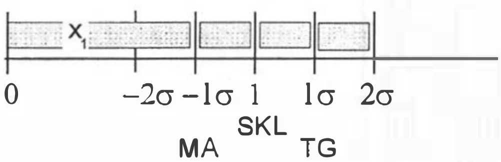
Body part	Type of measurement	Protection criteria	Level
Head	acceleration 3-axial	HIC_{36}	1000
Head	acceleration 3-axial	a_{3ms}	80 g
Thorax	acceleration 3-axial	a_{3ms}	60 g
Thorax	acceleration 3-axial	a_{3ms}	60 g
Upper leg	longitudinal force	F_{max}	10 kN
Lower leg	forces, torques	Tibia Index	1,3

Table 6: Frontal crash: Transducers in dummy type Hybrid III

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.



x_1 : measurement test 1

σ : scatter

MA : minimum requirement

TG : tolerance level

SKL : level of protection criterion

Figure 3: Rule of procedure

The rule includes the definition of a minimum requirement (MG)

MG = protection criterion - measurement scatter

and an upper tolerance level (TG)

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 test, 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 normalised 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, pelvis, and legs of the dummy.

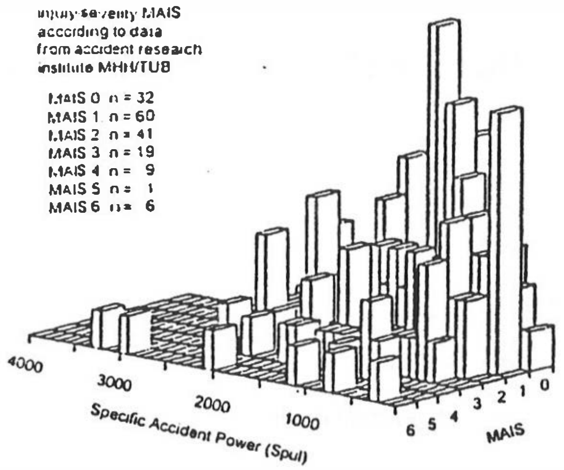


Figure 4: Real distribution of overall injury severity MAIS

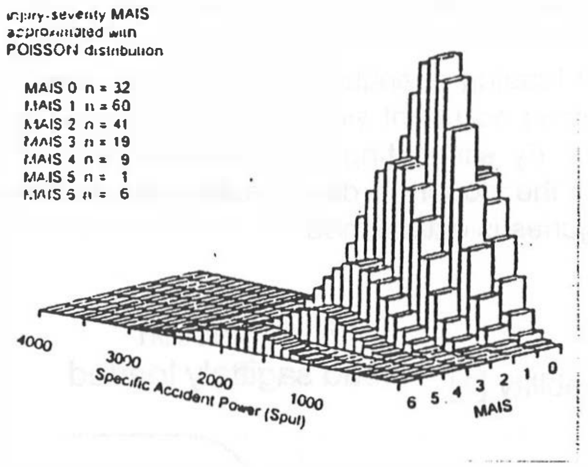


Figure 5: Approximated distribution of overall injury severity MAIS

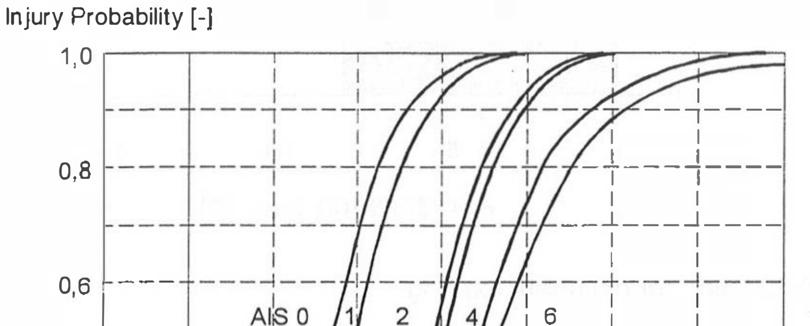


Figure 6: Injury probability of the head (AIS injury scale)

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 utilised 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.

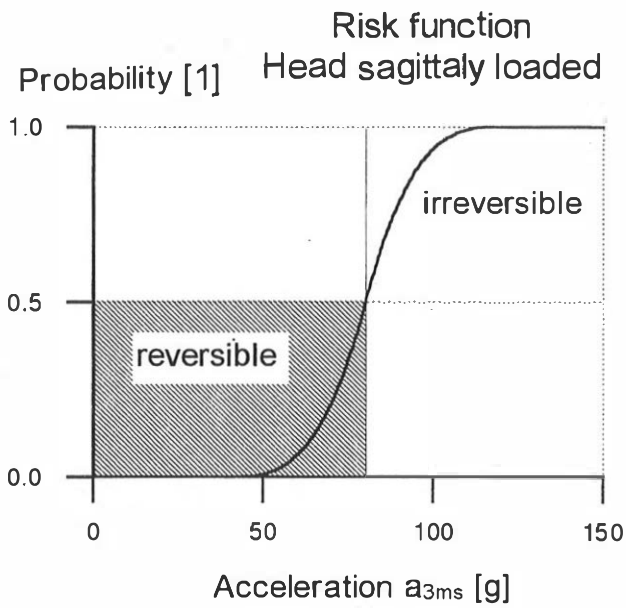


Figure 7: Risk function for occupant loading

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 normalised 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 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).

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

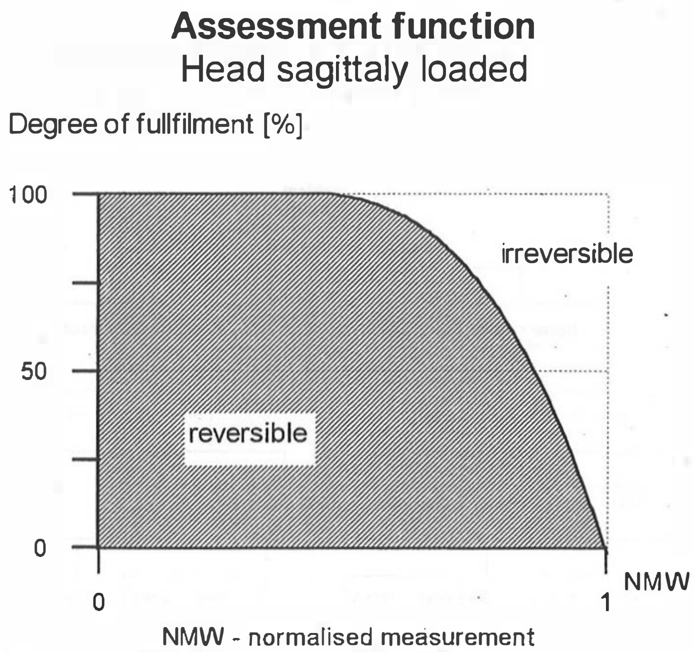


Figure 8: Assessment function

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

MW: measurement value
i : point of measurement
j : seating position
k : single test
RF : relevance factor
SK : protection criterion

Figure 9: Algorithm for safety assessment [16]

Relevance factors for safety assessment

Total accident events (delta-v < 60 km/h)

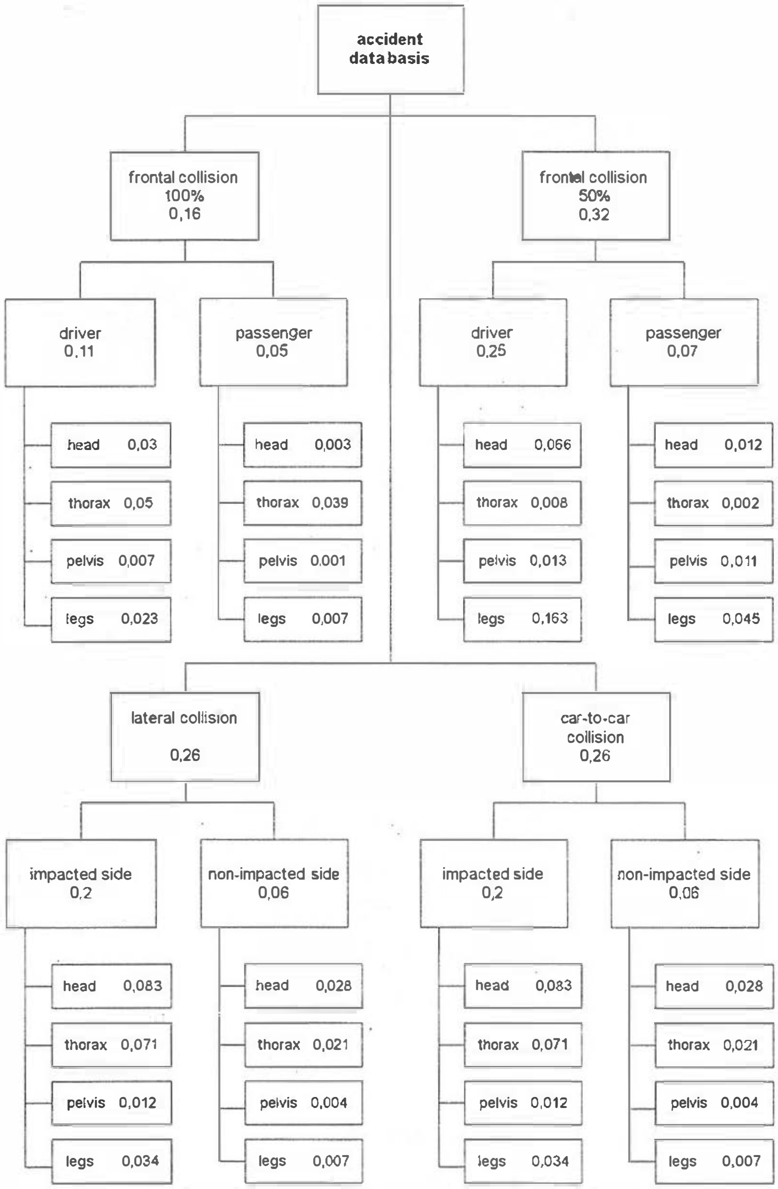


Figure 10: Example of a structure of relevance factors

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 Rine-Westphalia (NRW-data). The BASt performed the accident analysis [26] 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 choose, expecting that these cars were represented in a sufficient number in the accident data material, were the following four cars :

FIAT Uno	sub compact class
OPEL Kadett E	compact class car
VW Golf II	compact class car
BMW 5 E34	large car ?

The results of the two comparisons of passive safety are documented in the following table.

As the safest car both analysis detected 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.

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

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

At a first glance it seems that the assessment program is working very well. But there were several problems:

1. The cars which were used all are cars of old generations. That is caused by the necessity of being present in the real world accident data with a sufficient amount of cases.
2. These cars are not designed specially for the car to car collision and the ECE-R95 side impact crash.

For these reasons, more than 50% of the tests were not passed by the cars, but this is a special problem of the methodology of making this kind of validation by using actual tests and their conditions for old cars.

MODEL FOR EVALUATION OF PASSIVE SAFETY OF PASSENGER CARS

In this section a procedure for determination of influence of certain parameters for passive safety of passenger vehicles will be presented.

The consequences of passenger car accidents can be described in terms of

- injuries of the occupants and
- damages at the vehicles and environment.

In a system based view, the output parameters (accident results) are related to several input parameters and boundary conditions (figure 11).

With the model presented, the relations between input and output parameters can be investigated. The methodology used for these investigations is shown in figure 12.

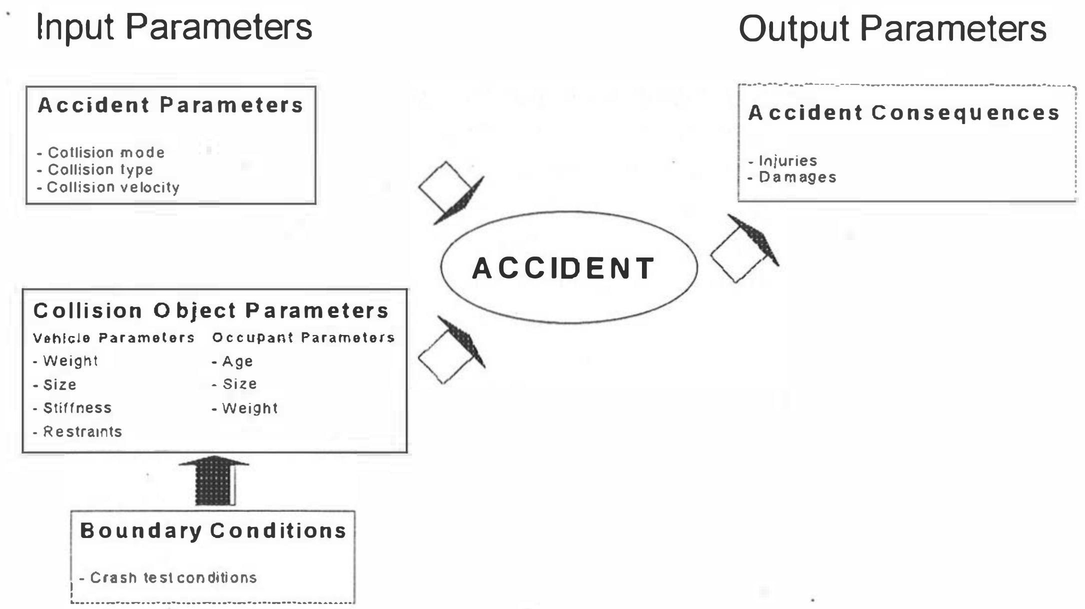


Figure 11: Accident in a system based view

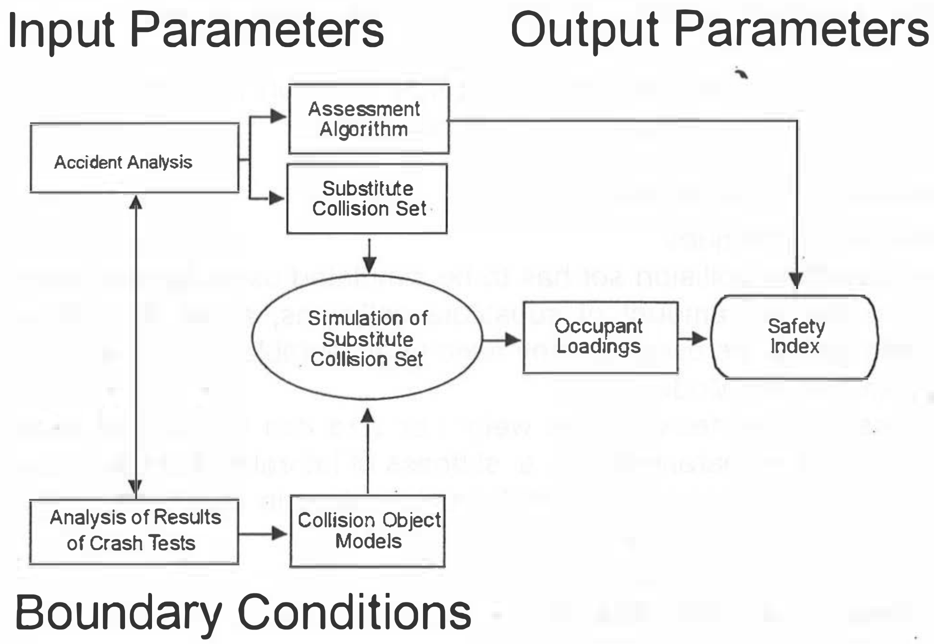


Figure 12: Methodology for derivation of safety index

INPUT PARAMETERS

Accident Parameters

With a detailed accident analysis, there can be obtained important data like

- collision mode
  The collision mode describes, which collision objects are involved in the collision
- collision type
  The collision type describes the position of the collision objects before crash
- collision velocity
  The collision velocity is the before crash speed of each collision object.

Collision Object Parameters

Collision object data, like vehicle and occupant parameters are treated, as input parameters as well.

- Vehicle Parameter
  The most simple parameter for description of vehicle is the crash weight. This parameter has a big influence on the crash performance, as has been shown in different publications [17,18]. There are other parameters like body style, engine power, average travel distance per year and so on which have an influence, too, but these parameters will not be taken into account.
- Occupant parameters
  The robustness of human beings against harm depends on there age. I. e. demineralisation processes reduce the tensile strength in the bones [19]. For

this reason, the age of occupants is also treated as input parameter. Occupants height and weight can be taken into account, as well.

With this set of parameters, a substitute collision set can be built up which describes the most relevant real world accidents.

BOUNDARY CONDITIONS

- Modelling techniques
  The substitute collision set has to be simulated using lumped mass models. Due to the big amount of substitute collisions, about 300, finite element models cannot be used, as they need unacceptable CPU time.
- Collision Object Model
  The main characteristics like weight or size can be derived from accident analysis. Other parameters, i. e. stiffness of lateral or front structure, have to be determined by using results of public domain crash tests. These crash tests are
  - AMS (55 km/h, 50%, 15°)
  - ADAC (50 km/h, 40%, 0°)
  - FMVSS (50 km/h, 100%, 0°)
  - NCAP (56 km/h, 100%, 0°) [20, 21 23]

  Additionally, several low speed tests, pole crashs and car-to-car-tests have been used as a validation database. The results have been analysed statistically. In this way it is possible to assign certain structure parameters to one vehicle class.
  For the described crash tests, certainly not all data needed to built up collision object models are available. For this reason, the lumped mass collision object models are used to simulate these crash tests. A parameter variation leads to multy body system models which have the same behaviour as the vehicles used in the tests. Using several test results, the collision object models can be validated in several collision severities and types.
  The set up of the models has been chosen in a object orientated way. Interfaces between different collision object models are stiff contact surfaces. Bringing together different collision object models to a collision model is easy in that way.
  The collision models are validated in several points, most of them in single vehicle crashes. It has to be assumed, that validation of collision object models in this matter leads to usable models for car-to-car-collisions as well.
- Simulation of Substitute Collisions
  With the presented collision object models, a complete substitute collision set can be simulated.

OUTPUT PARAMETERS

Assessment of Output Parameters

Simulation of the whole set of substitute collisions leads to a big amount of output data. For extracting the relevant data, the QUPASI assessment algorithms are used.

However, the QUPASI algorithms have to be expanded for evaluation of influence of occupants age. So, an age depending risc function has been developed for each body part (figure 13).

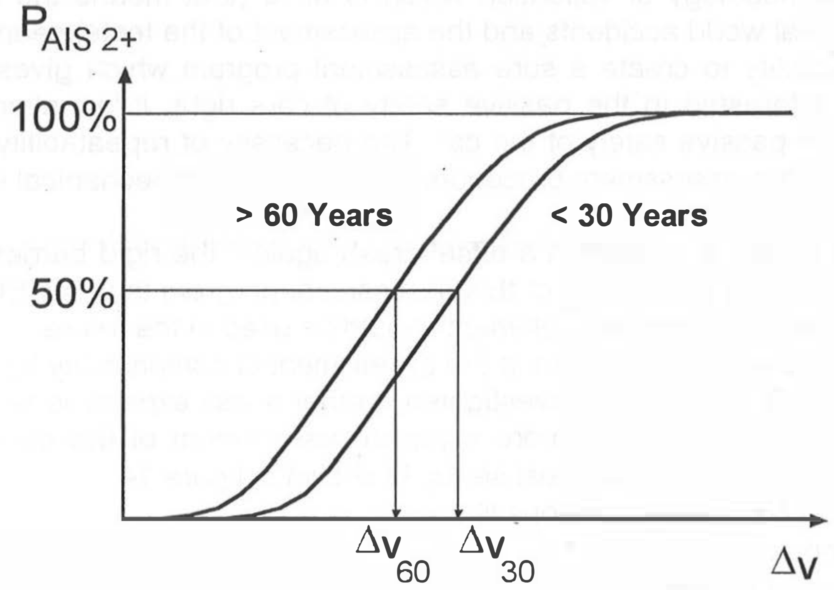


Figure 13: Risc function depending on occupant's age

The application of QUPASI assessment algorithm leads to a safety index for the simulated set of substitute collisions.

APPLICATION OF THEMODEL

The presented model can be used to evaluate i.. e. the influence of changes of vehicle's structure due to modified crash test conditions. For this investigation, the MBS models have to be adapted not to the formerly published test results, but to the fictive, new test conditions. After a new simulation of the substitute collision set, the new safety index can be compared to the basic safety index.

Another application is the evaluation of new or modified occupant protection systems. In this case, the occupant protection system in the collision object model has to be modified. A renewed simulation of substitute collision sets leads to a new safety index, also.

To evaluate the influence of occupant's age, there is no need to re-simulate the whole substitute collision set. It is sufficient to repeat the assessment procedure to obtain a new safety index.

SUMMARY AND OUTLOOK

Within the scope of this work, the assessment method "Quantification of Passive Safety of Passenger Car Occupants" was used at that first time to validate this assessment program for passive safety of cars.

The problems of the validation were the problems of the cars which did not pass all tests. However, the ranking calculated by the TUB-NCAP is the same as in the NRW-real world accident data analysis of the BASt.

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 biomechanical based algorithm.

In this period of validation a offset-crash against the rigid barrier was used. According to the philosophy of this assessment program the new ECE-R94 offset-crash with a deformable element should be used in the future.

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. A possible test set-up is shown in figure 14.

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

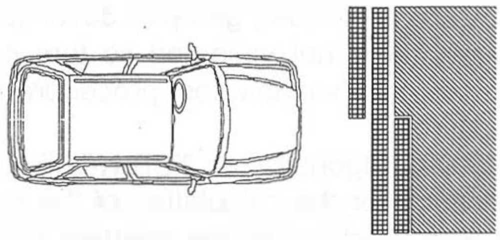
as well as the behaviour of vehicles of different weight, different front structures and driving concepts are investigated by means of an FEM model with the test situation "impact against a non-moving deformable barrier".

Set-up of such a procedure is currently being investigated at ISS Automotive Engineering, first test have been performed [24].

It will be analysed, whether statements can be made about aggressivity of mass and stiffness of the vehicle as a whole as well as about the aggressivity of members of the front structure, deduced from the deformation characteristic.

It seems possible, that such a test procedure could substitute 0°-test and offset test as well as car-to-car test under the premise of realistic test conditions.

Check quantities are results of frontal tests (0°-test and offset test).



Characteristic:
Barrier: fixed,deformable stepped barrier
Collision speed: V_{koll} >> 50 km/h
Overlap 40%-50% // 100%

Aim of the test:
Investigation of self- and partner-protection

Dummies:
2 HYBRID III-dummies (driver and passenger)

Measurement points on the dummy:
Head, thorax, pelvis, upper leg
(and contact force of the feet)

Measurement points on the vehicle:
Vehicle acceleration in the center of gravity

Deformation behavior:
Vehicle : static deformation before and after crash
Barrier : Determination of proportionate deformation energy
Determination of mean deformation length
Determination of maximum deformation length

Assessment quantities
self-protection : measurements on the dummy
partner-protection : vehicle deceleration and deformation behavior of vehicle and barrier

Figure 14:Safety test for evaluation of self- and partner-protection

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

Measurement of forces induced into the rigid barrier with a platform of force transducers was investigated too, but the deformation behaviour of the front structure becomes unrealistic [25].

The EC 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 pedestrian 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 moment the assessment algorithm of TUB-NCAP used only the biomechanical assessment functions for the calculation of the safety index. In the future we will develop as well function for the opening behaviour of the door, the behaviour of the fuel system (leakage), remaining survival space etc. to give more information into the assessment algorithm. But for all these parameters it is necessary to develop such assessment function to avoid a subjective (emotional) assessment which is not reproducible and transparent.

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