EVALUATION OF PROTECTION CRITERIA ON THE BASIS OF STATISTICAL BIOMECHANICS

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1 METHOD OF THE EQUIVALENT ACCIDENT CHARACTERISTICS

Various systems are examined with the aid of the method of the Equivalent Accident Characteristics (EAC method): the accident occurrence and the imitation of this in the form of mathematical simulation. The input variables of both systems are correlated to each other on the basis of the Equivalent Accident Characteristic, which defines the accident severity numerically as the system input variable. According to [1], this procedure requires that:

- both units of analysis represent complete, separate systems,
- both systems describe the same process,
- both systems are given the same input variable, and finally,
- both output variables describe the same system response function.

These requirements are met in the study described here as follows.

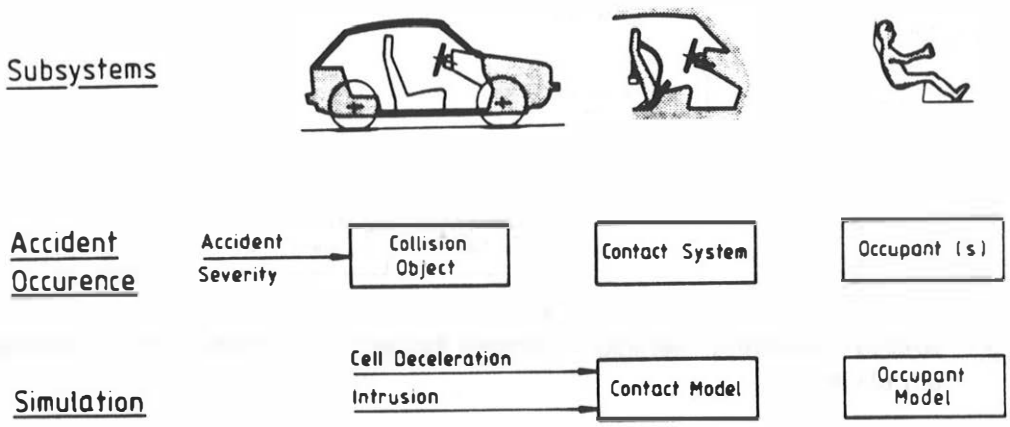


Figure 1: Model of frontal collision for mathematical simulation

The choice of the units of analysis depends on the objective and also on the kind of simulation model used. The actual accident system being analysed consists of the vehicle contact system (seat, belt system, steering system and contact areas) as well as the actual occupant(s) (Figure 1). Here, it is irrelevant whether the passenger vehicle analysed collides with another vehicle or with an obstacle.

In the mathematical simulation, a system reduced to the contact and occupant model is introduced. Input of the cell deceleration not sufficient to imitate the real accident situation, modelling the penetration of interior parts must also be made possible. This applies in particular to the range of greater accident severities.

The severity of an accident cannot be measured directly, but must be determined using various kinds of accident parameters of various degrees of reliability. Since only the contact

system and the occupant are analysed here, the accident severity also includes the deformation characteristics of the colliding vehicles as well as the external accident parameters. This ensures that both systems (accident occurrence and simulation model) are fed with an unclear input variable, but which is nevertheless the same in both cases.

If we neglect material damage, the output variables of the system "accident occurrence" are the injuries, and these can relate to one injured occupant, to an accident (i.e. several injured) or to the sum of all injured persons. The severity of injury is defined using the Abbreviated Injury Scale AIS. With the aid of this scale, both the state of injury to the whole body - this is then termed Maximum AIS (MAIS), and the severity of injury to individual parts of the body can be described. We shall make reference to the latter, since we wish to provide a protection criterion for each region of the body. In the accident system output variables, we are dealing therefore with the severity of injury to individual parts of the body.

The corresponding output variables of the "Simulation" system are the load values incurred by the mathematically described occupant, or to be more accurate, incurred by the modelled parts of the body, these representing the injury mechanisms under biomechanical aspects as accurately as is possible. This ensures that the various degrees of injury severity as well as the load values are the same response functions of various systems, it being possible to correlate these to each other (Figure 2).

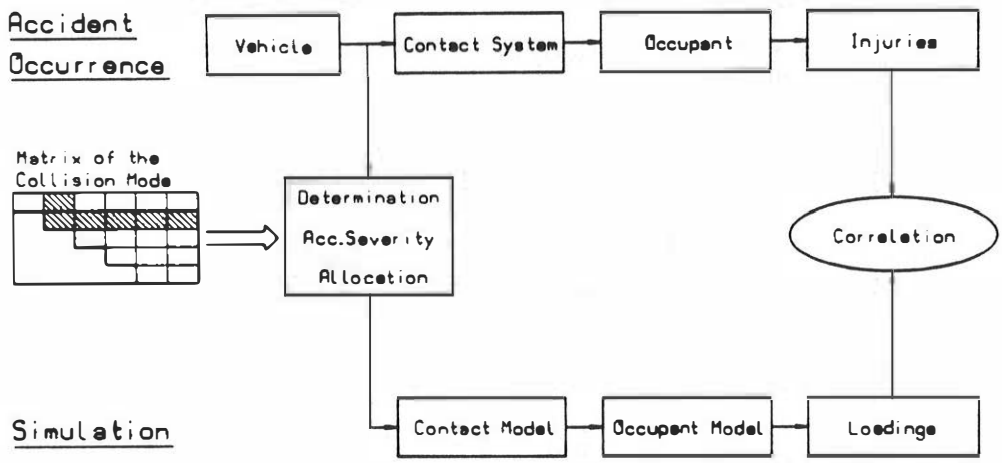


Figure 2: Action sequence "vehicle - contact system - occupant" in an accident and in simulation

The method of Equivalent Accident Characteristics is distinguished by the fact that by eliminating the severity of the accident, the relationship between the severity of injury and the determined load value of the model can be obtained for each region of the body. Using this correlation calculation, a statistical method of checking relationship hypotheses, the protection criteria specific to the individual parts of the body can be deduced from the load values, with the hypotheses to be checked being provided by biomechanics.

2 SEVERITY OF ACCIDENT AND SEVERITY OF ACCIDENT RESULTS

The pre-selected data material used here, which was supplied by the accident research group of the Medical College of Hanover, (Medizinische Hochschule Hannover) covers a total of 1 128 accidents. By limiting the analysis to passenger vehicles colliding frontally with an angle of impact up to 45°, 716 vehicles with 1 288 occupants (55.6 % driver, 25.4 % front-seat passengers and 18.0 % rear-seat passengers) could be evaluated. Of the remaining 1 022 front-seat occupants, 41.2 % used seat belts; they suffered a total of 5 453 individual injuries (belted occupants: 1 944 injuries) of varying severity. To facilitate simulation, only the injuries of the belted occupants are taken into account. The costs resulting from injuries of

sagittally loaded front-seat occupants in frontally colliding vehicles add up to 6.4 billion DM, which comprises approximately 18.2 % of all costs (35.2 billion DM) resulting from injuries, i.e. approximately one sixth of the total costs resulting from injuries incurred in road traffic accidents in the Federal Republic of Germany.

2.1 Accident Characteristic Quantity as Index of the Severity of the Accident

The accident characteristic quantity is meant to characterize the severity of the accident as a numeric value, i.e. the value of the accident characteristic quantity, which is related to the passenger vehicle, should increase with increasing accident severity; in addition, it must include the relevant accident severity parameters. In all, three different statistical procedures were used to examine the following as accident characteristic quantities

- change in kinetic energy,
- the impact momentum
- the change in speed and
- the specific accident power

with regard to their predictability for the severity of injury (MAIS as well as AIS for head, thorax, pelvis, abdomen, arms and legs). On the basis of the accident material used, the specific accident power (SPUL), which can be formulated as

$$SPUL = \Delta v * \bar{a} \quad [m^2/s^3],$$

cannot be confirmed to be the more significant accident characteristic quantity; but neither must it be rejected as unsuitable, due to lack of accuracy, for example. On the other hand, the advantage of the specific accident power over the speed change could be proved quite clearly on the basis of inference statistical analyses based on measured values determined from sled tests. For this reason, it is introduced in the following as an Equivalent Accident Characteristic (EAC) and used as a basis for determining the new protection criteria.

2.2 Severity of Injury upon Sagittal Loading

The distribution of the injury severity as a factor of the specific accident power cannot be directly described with the aid of any distribution density known to statistics. The reasons for this can be seen in the low number of injuries, but also in the natural scatter (depending on the characteristics of the contact systems, on the seat position and on the occupants). The frequency distribution of the severity of injury contained in the data material is shown in the top diagram of figure 3 for the total severity of injury, MAIS. By calculating the mean values, the variance and the skewness from the accident data, this frequency distribution can be approximated using a one-dimensional discrete probability distribution.

For this purpose, the POISSON distribution was chosen due to the good correlation which it can achieve and its relatively simply interpretation. In addition, it had to be ensured that in the calculation of the (M)AIS-class expected values, in which the skewness of the distribution is also expressed, the same form of distribution, together with its description parameters, could be used for all kinds of loading (i.e. for the overall severity of injury, but also for the severity of injury to any individual region of the body).

In the MAIS distribution as shown in figure 3, a less favourable relationship can be seen in comparison to the individual injuries, this being due, in particular, to the low number of injuries.

The lower diagram of figure 3 shows the determined probability, multiplied by the number of injuries per MAIS-class. Along with the compressed frequency distribution, it is noticeable that only a few injuries occur in the lower range of specific accident power, although a high number, at least of injury severity level 0 ought to occur where the accident severity is lower. The reason for underrepresentation of accident severity level MAIS 0 in the lower accident

severity range compared to the total accident occurrence is to be found in the choice of accident data, only those passenger vehicle accidents with at least one injured occupant being taken into consideration.

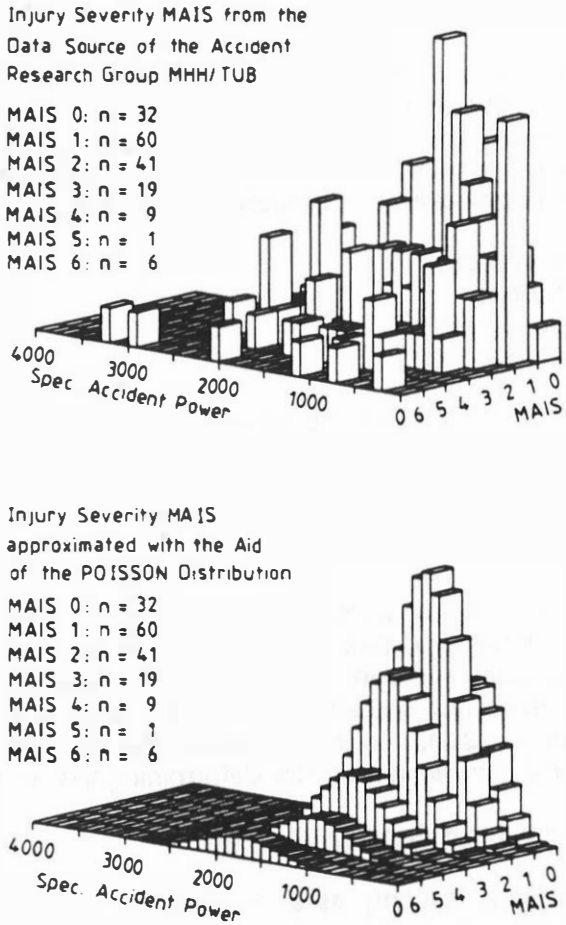


Figure 3: Real and approximated distribution of the overall injury severity MAIS

Upon introduction of the POISSON distribution, the distribution function of the degree of severity of accidents for individual parts of the body provides a consistent, monotonously increasing curve as a function of the specific accident power SPUL. This is exemplified for the head in figure 4. The probability distributions for the degree of accident severity to the head, thorax, upper extremities, abdominal and pelvic regions as well as to the lower extremities show similar characteristics, but of a different kind. For example, the severity of injury to the extremities ranges from AIS 0 to only AIS 4.

3 PROVISION OF LOAD VALUES WITH THE AID OF MATHEMATICAL SIMULATION

Occupant crash mechanics computer models are used to provide the load values required to determine the protection criteria for the mathematically described vehicle occupant. Under the influence of existing model concepts and calculation processes, a new problem-oriented model has been developed for this purpose and formulated as a program. Here it is not possible to give a detailed description of the occupant crash mechanics computer model for frontal collisions (ICMF) used, and in the following only the most essential aspects are explained. A comprehensive description of the model and the programme is given in a research report [2].

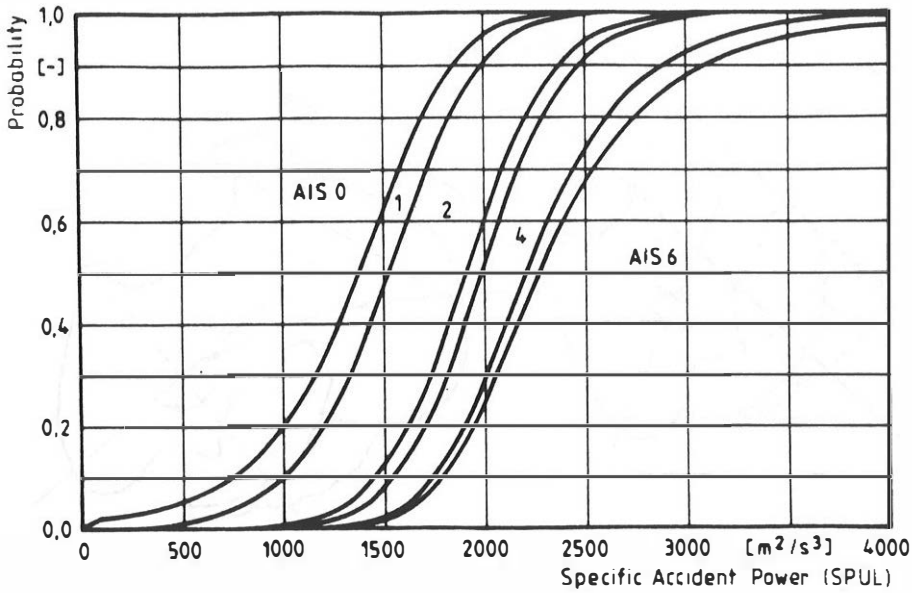


Figure 4: Probability distribution of the severity of injury to the head

The simulation model ICMF is a two-dimensional (2D-) model. The results which can be achieved with this model have proved to correlate well with test measurements, thus confirming the quality of the model, which allows calculation of occupant loads in the form of forces and accelerations. One particular feature of the occupant simulation model in comparison to other existing models is that the neck vertebrae are mathematically described by seven individual elements, thus allowing more realistic simulation of the kinematics and loading of head and neck (Figure 5).

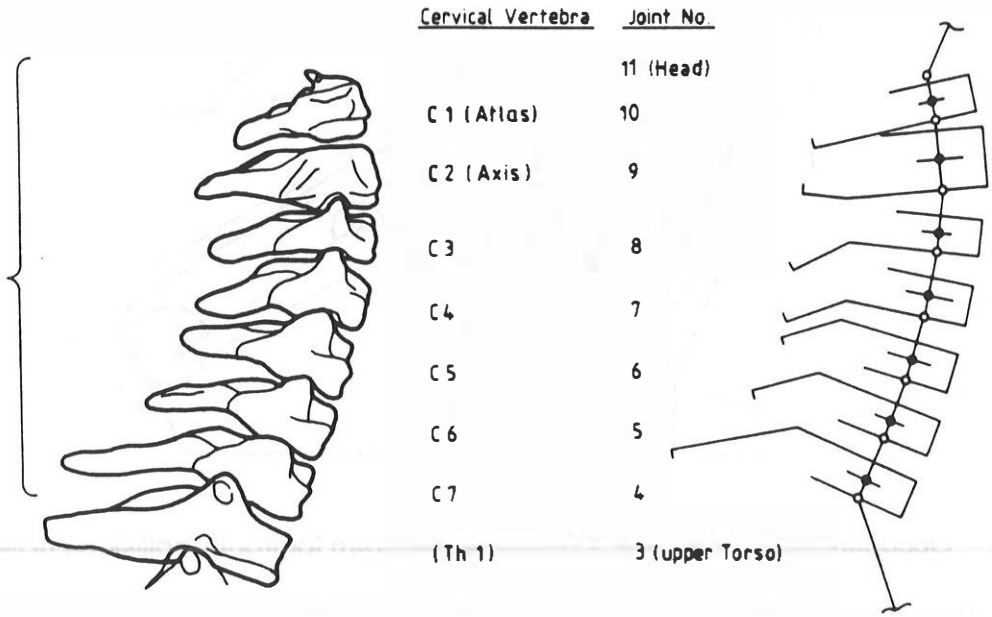


Figure 5: Neck vertebrae and model (ICMF)

Another special feature is that the model is able to simulate submarining effects due to the exact description of the pelvic/abdominal region (Figure 6).

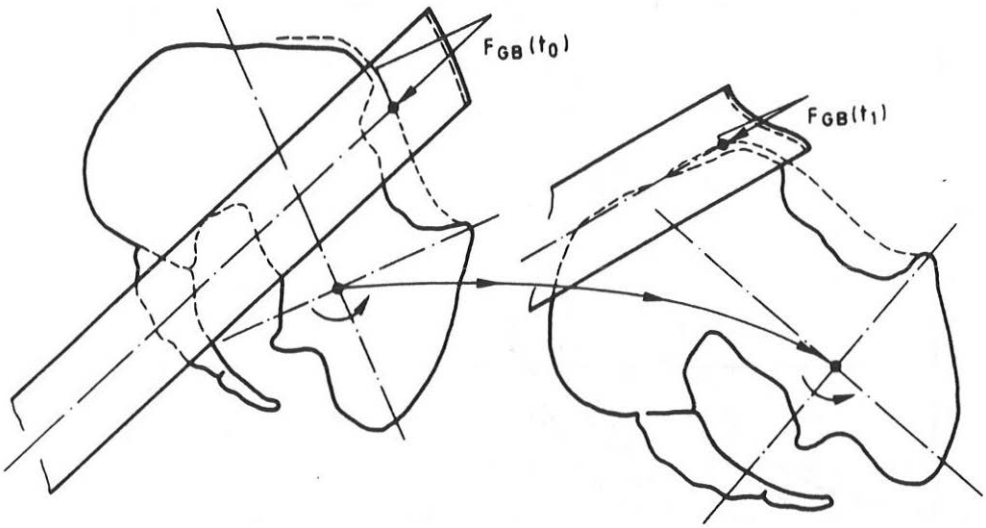


Figure 6: Simulation of the submarining effect

In addition to this, the model includes a spatial description of different types of belt systems (static or automatic belt, also with clamping device as an option, force limiter and pre-loading system). In order to provide realistic forward displacement during the crash, the penetration of the steering system and the intrusion of interior surfaces can also be simulated (Figure 7).

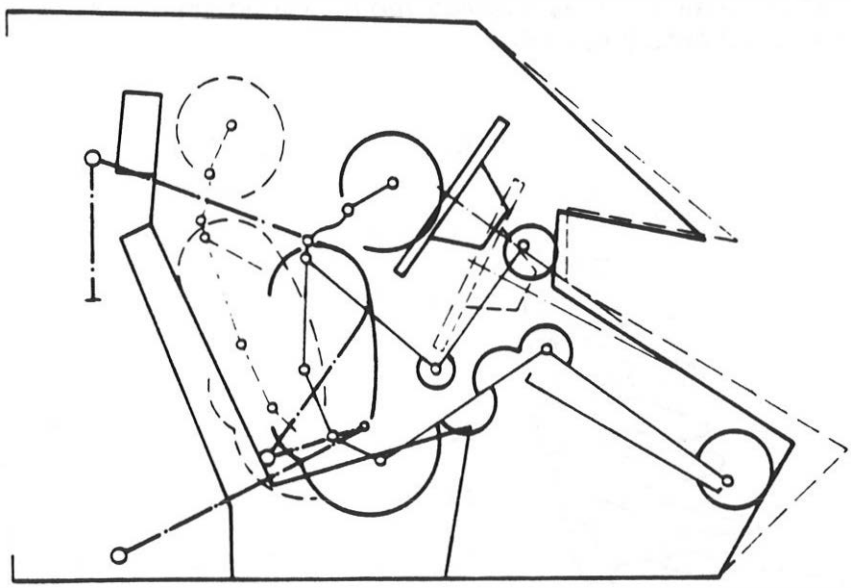


Figure 7: Occupant crash mechanics computer program for frontal collisions (ICMF)

The occupant is described by 15 mass-bound, rigid elements connected by joints, and exhibits 17 degrees of freedom.

The simulation program was adapted with the aid of a total of 22 sled tests at v_1 = 40 km/h and v_2 = 64 km/h. The final remaining deviations between experiment and computer simulation lie within the range of tolerance inherent to the experiment method. The deviations, which may be reduced with great effort, but which cannot be fully avoided, are due to the dif-

ficulty of obtaining an exact, realistic system description, this always being a problem of mathematical simulation.

For simulation purposes, the accident occurrence is depicted in such a way that the parameters relevant to the accident are selected according to statistical aspects and prepared so that the load values determined for the mathematically described occupant can be displayed as a function of the specific accident power SPUL.

If we are to take consideration of both the translational and the rotational loading of the head and the injuries resulting from this, separate analysis of the two kinds of load is inadequate. Whereas skull fractures in connection with a brain trauma can usually be traced back to the effect of blunt force (such as a head impact) and the translational head acceleration would therefore seem adequate as a load value, skull/brain injuries are caused by both translational and rotational relative movements. Numerous publications present the results of corpse and animal tests, for example in [3, 4, 5], in which the rotational accelerations correlate with the brain injuries and were introduced as load values. In [6], NEWMAN suggested the possibility of common evaluation of translational and rotational aceleration in the form of the GAMBIT model (Generalized Acceleration Model for Brain Injury Threshold).

The GAMBIT limit curve, which separates reversible from irreversible injuries, is so determined that the result of the relationship

$$G = \sqrt[n]{\left(\frac{a}{a_c}\right)^n + \left(\frac{\ddot{\varphi}}{\ddot{\varphi}_c}\right)^n}, \quad \text{with } n = 2.5$$

gives the value G = 1 when the threshold values of the two types of acceleration are introduced. Here, the degree of severity of head injuries which seems tolerable is determined in such a way that (taking into consideration a 50 % injury probability) irreversible injuries are out of the question. This means that the tolerance threshold lies between AIS 2 and AIS 3, since with skull/brain injuries at severity level AIS 3, permanent damage which impairs consciousness can already occur [7]. The equivalent accident characteristic which can be allocated to this tolerance threshold is deduced from the injury probability of degrees of severity of head injury.

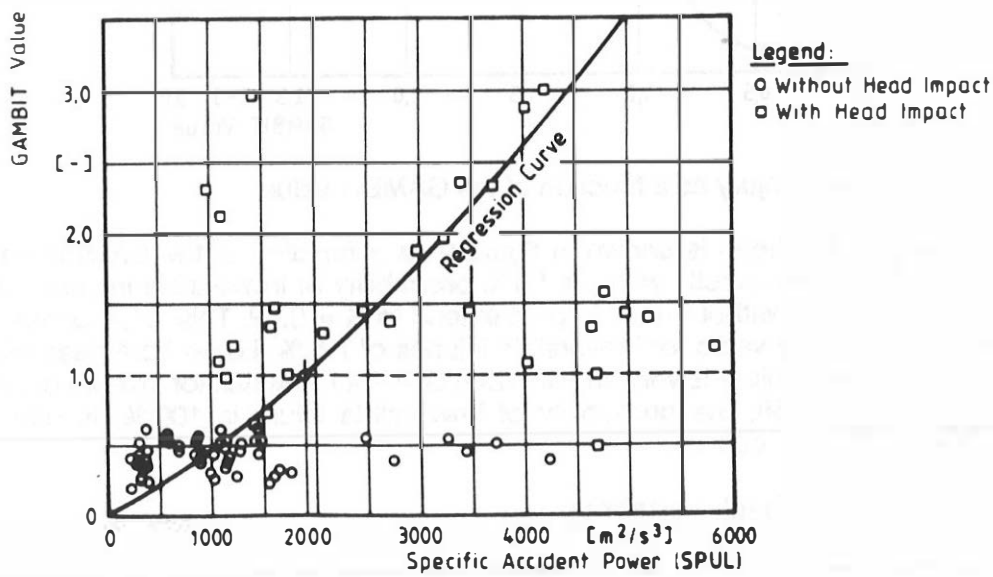


Figure 8: GAMBIT value as a function of the specific accident power

An optimisation calculation (with the aid of evolution strategy), in which the parameters a_c and $\ddot{\varphi}_c$ of the above mentioned GAMBIT equation were varied and the GAMBIT value defined at G = 1.0, provided the threshold values

- for the translational acceleration a_c = 250 g and
- for the rotational acceleration $\ddot{\varphi}_c$ = 25 krad/s².

With the aid of these threshold values, and using the GAMBIT equation, GAMBIT values can be determined for all pairs of max { $a/\ddot{\varphi}$ } values defined by calculation and these can be plotted as a function of the specific accident power SPUL. In figure 8, the head loadings without impact are depicted by circles and those with impact by squares. For those cases with impact, a fitting curve is determined with the aid of multiple regression analysis. This curve presents a progressive rise in relation to an increase in accident severity.

4. RELATIONSHIP BETWEEN INJURIES AND PROTECTION CRITERIA

4.1 Risk of Injury to the Head

The equivalent accident characteristic can be used to establish the relationship between the levels of severity of head injuries (according to the probability distribution in figure 4) and the GAMBIT values shown in figure 8.

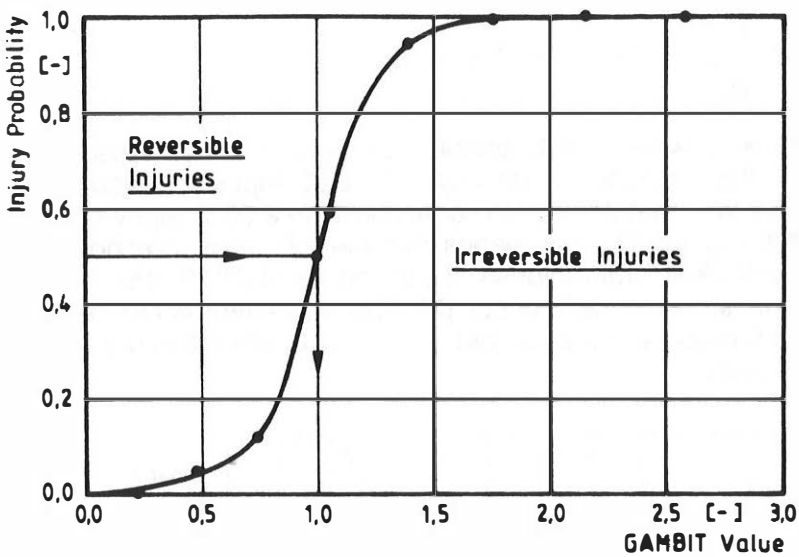


Figure 9: Risk of head injury as a function of the GAMBIT value

The risk of injury to the head is shown in figure 9 as a function of the GAMBIT value. The value G = 1 corresponds exactly with the 50 % probability of irreversible injuries value. The GAMBIT values for loads without head impact extend to G = 0.62. This value corresponds to an occurrence probability value for irreversible injuries of 7.5 %, i.e. without head impact the risk for permanent head injury is very small. When G = 1.41, the risk for irreversible injuries is 95 %, and when G = 2.58, the probability of irreversible injury is 100 %, in other words, reversible injury no longer occurs.

4.2 Risk of Injury to the Neck Vertebrae

The neck injuries resulting from the accident data relate exclusively to fractures and/or luxation of the neck vertebrae. In figure 10 the risk for this kind of injury is represented as a function of the bending moment, the load being independent of the direction (flexion, extension). This would mean that irreversible traumata of the neck vertebrae at injury severity level

AIS > 3 only occurs at a bending moment of approximately 200 Nm or more; the 50 % injury risk lies at a neck bending moment of 370 Nm.

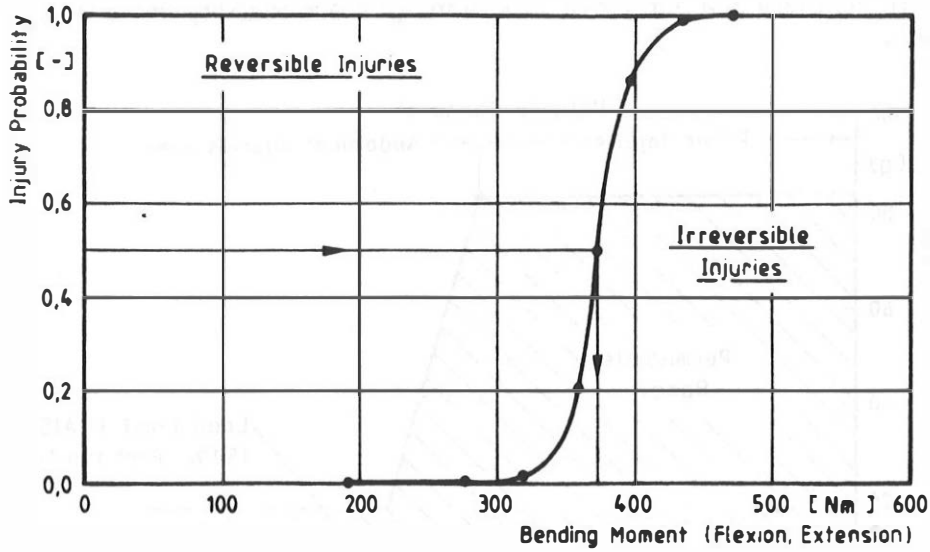


Figure 10: Risk function for injuries of the neck vertebrae as a function of the bending moment

4.3 Risk of Injury to the Thorax

Figure 11 shows the relationship between the risk of injuries to the chest and the load value in the form of chest deformation. Here it can be seen that irreversible chest injury (AIS > 3) start to occur at a thorax compression of around three centimetres. A 50 % risk of irreversible injury can be expected from a thorax compression of 4.0 centimetres or more.

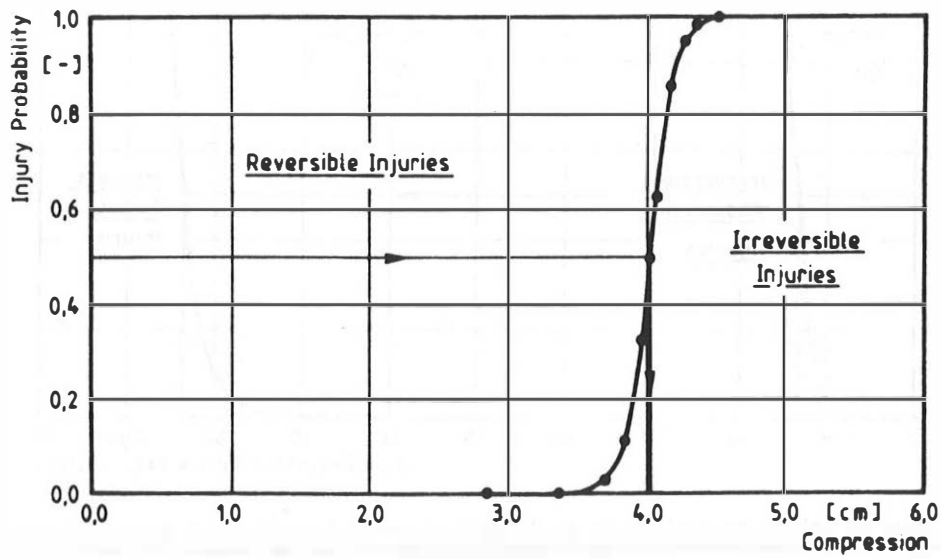


Figure 11: Risk of chest injury as a function of the thorax compression

4.4 Risk of Injury to the Abdominal Region and the Pelvis

The different protection criteria in the form of varying resulting pelvic accelerations which must be applied to injury of the pelvis and abdomen region are separated by the critical pelvic angle of rotation. An exceeding of this critical angle can be regarded as the condition

required for the occurrence of abdominal injuries. This is shown in the model for pelvic and abdominal injury as shown in figure 12: accelerations of approximately 83 g can be absorbed by the pelvis up to a relative pelvic angle of rotation of 20 degrees. At angles greater than this there is a danger of submarining; the loadability decreases and then lies at around 13 g.

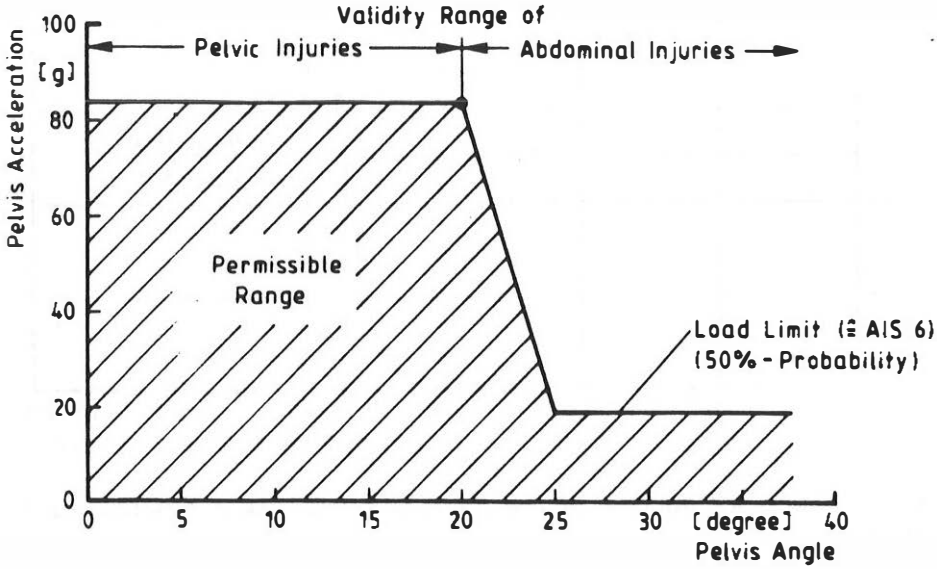


Figure 12: Model for pelvic and abdominal injuries with 50 % occurrence probability using the pelvic angle of rotation criteria

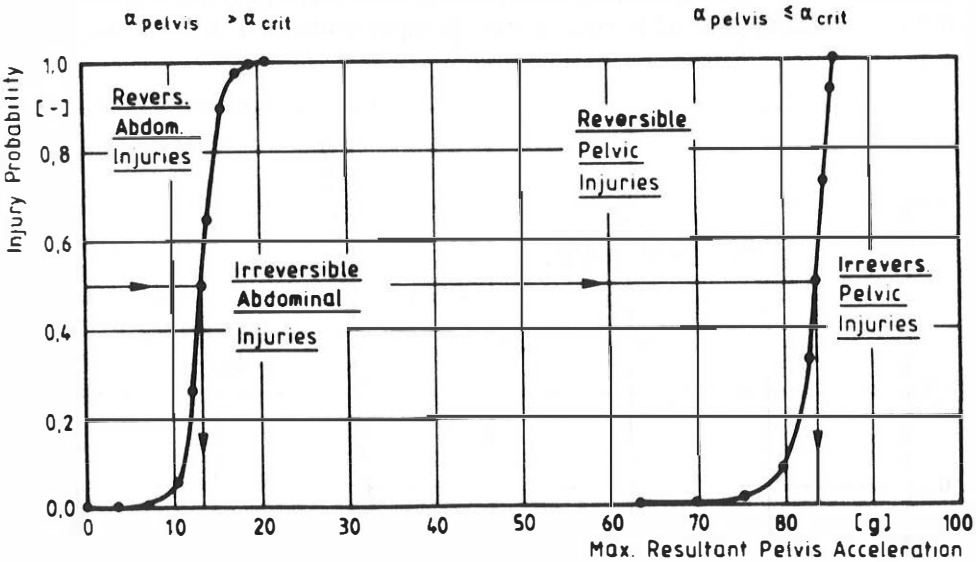


Figure 13: Risk of injury to pelvis and abdomen as a function of the pelvic acceleration taking into consideration the critical pelvic angle of rotation

The combined diagram of the risk function for pelvic and abdominal injuries as shown in figure 13 forms a special case in comparison to those functions presented up to now, since both kinds of loading are shown as a function of a common protection criterion, i.e. the maximum resulting pelvic acceleration, but they are separated from each other by the critical pelvic rotation angle of $\alpha_{crit} = 20°$. This reveals that, at least with loadings around the tolerance threshold, either pelvis injuries (at a pelvic angle of rotation of $\alpha_{pelvis} \leq 20°$) or abdomen injuries ($\alpha_{pelvis} > 20°$) will occur.

4.5 Risk of Injury to the Extremities

The relationship between injuries to the arms and hands and the hand contact force is shown as the risk function in figure 14. Irreversible injuries of the upper extremities, i.e. injuries of severity levels above AIS 2, first occur at hand contact forces of $F_{HC} > 2.0$ kN. At a contact force of $F_{HC} = 3.8$ kN, the risk of irreversible injuries lies at 50 %, i.e. at this loading value, the probability of reversible and irreversible arm and hand injuries is the same.

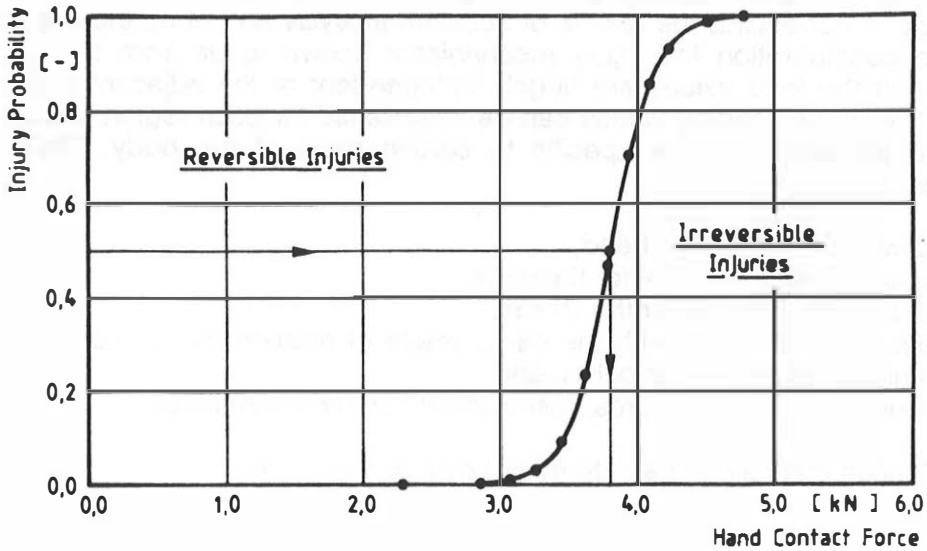


Figure 14: Risk of injury to upper extremities as a function of the hand contact force

In frontal collisions, leg and foot injuries occur more frequently compared to injuries to other parts of the body. The foot contact force provides a better protection criterion than the thigh longitudinal force since it shows a high force even without knee impact and is therefore characteristic of injuries to the lower extremities.

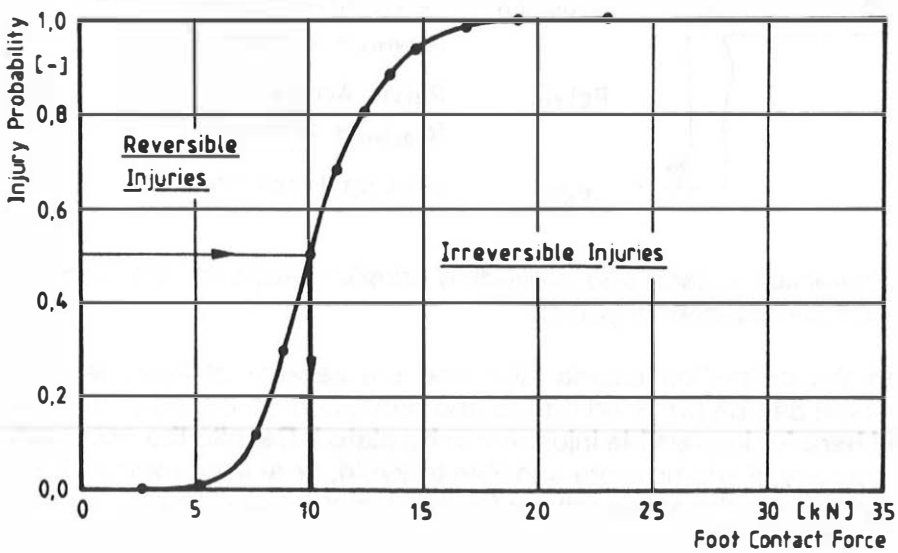


Figure 15: Risk function for injuries to the lower extremities as a function of the foot contact force.

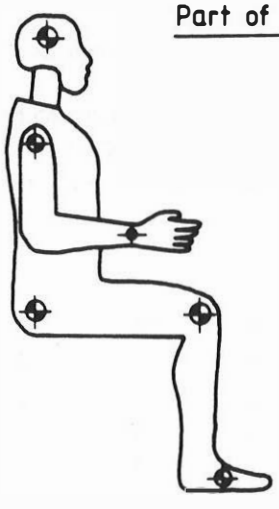
Figure 15 shows the relationship between the risk of injury and the protection criterion in the form of maximum foot contact force in which the tolerance threshold between reversible and irreversible injuries is characterised by the boundary between the severity of injury levels AIS 2 and AIS 3. At a foot contact force of 10.1 kN, the probability of irreversible injuries to the lower extremities is 50 %.

5 SUMMARY

A wide variety of mathematically determined load values are available for all parts of the body for use in correlating the results of accident analysis and of mathematical simulation. Taking into consideration the injury mechanisms known to us from biomechanics, and assuming that the load values are largely independent of the adjacent part of the body, representative model loading values can be established for each region of the body. These provide the protection criteria specific to certain parts of the body. These criteria are (compare to figure 16).

- the GAMBIT value for the head,
- the neck bending moment for the neck,
- the chest compression for the thorax,
- the pelvic acceleration with the pelvic angle of rotation as distinctive feature for the abdominal region and the pelvis, and
- the hand or foot contact force, respectively, for the extremities.

These protection criteria can be determined by measurement.



Part of the Body:	Protection Criterion:	Level:
Head	GAMBIT Value	1,0
Neck	Bending Moment	370,0 Nm
Thorax	Compression	4,0 cm
Arms	Contact Force at Hands	3,8 kN
Abdomen	Pelvic Acceleration (α_{pelvis} > 20 degree)	13,0 g
Pelvis	Pelvic Acceleration (α_{pelvis} ≤ 20 degree)	80,0 g
Legs	Contact Force at Feet	10,0 kN

Figure 16: Protection criteria and protection criterion levels for the occupants of a frontal colliding passenger vehicle

By matching the protection criteria level and the severity of injury level, a reliable injury prediction model can be provided on the one hand, and on the other hand, the risk of injury as explained here for irreversible injuries can be stated. Despite the assumption of any given degree of accuracy, it seems more sensible to avoid, or at least reduce, the factor of impact of parts of the body in the safety criteria for the design of passenger cars, rather than to stay just within the limits of the permissible range of suggested boundary values because of economic aspects. Only in this way can we continue to fundamentally improve the safety level which we have already achieved.

ACKNOWLEDGEMENT:

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