## ABDOMINAL AND PELVIC INJURIES OF VEHICLE OCCUPANTS WEARING SAFETY BELTS INCURRED IN FRONTAL COLLISIONS - MECHANISM AND PROTECTION -

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## ABSTRACT

On the basis of an analysis of accident data for frontal collisions, injury patterns and the mechanism of injuries to the abdominal region and the pelvis of motor vehicle occupants wearing safety belts are described.

With the aid of experimental and mathematical simulation, the respective section of the accident occurrence which is of interest is reproduced, making it possible to trace the mechanism of the origins of the injury.

The correlation between the loading values obtained from simulation and the actual injuries incurred in the accident makes it possible to deduce the critical angle of pelvis rotation, which can then be used as the distinguishing characteristic for abdominal and pelvic injuries. In this way, pelvic acceleration attains new importance as a protection criterion for preventing injuries both of the osseous pelvis as well as of the abdominal region. Due to the good measurability of these two loading quantities, the angle of rotation and the acceleration of the pelvis can be determined relatively easily in safety tests.

#### THE ACCIDENT DATA MATERIAL

Data material supplied by the accident research group of the Medizinische Hochschule Hannover [9] was used for the present study. It covers a total of 1 128 accidents. By limiting the analysis to passenger cars colliding frontally with an angle of impact up to 45° and to belt-wearing front-seat occupants, a total of 1 944 individual injuries of varying severity, to 421 persons was reviewed. This target group accounts for approximately one sixth of all costs resulting from road traffic accidents in the Federal Republic of Germany.

#### INJURIES TO THE ABDOMINAL AND PELVIC REGIONS

In the abdominal injuries studied, the lap belt is the most frequent cause of injury, accounting for almost 60 % of all injuries. These are submarining injuries which are caused by the pelvis slipping under the lap belt loop. The next most frequent type of injury, accounting for a proportion of 21 %, may be traced back to steering-wheel impacts.

Traumatisms of the abdominal region mainly comprise low-severity injuries to the exterior abdomen (45%) and injuries to organs (42%) the latter usually being severe or critical. The incurred fractures, which were coded with AIS 2 [13], are compression fractures or luxations of the lumbar vertebrae. In spite of the shorter forward displacement of the driver, abdominal injuries to front-seat passengers occur more frequently than their percentage share in the total number of cases examined would lead us to expect. However, due to the small number of cases involved, it was not possible to conclusively determine whether this is a characteristic result. The relatively high proportion of female occupants with abdominal injuries (63% as opposed to an overall proportion 35% of occupants suffering injuries) is similarly problematic. It can be assumed that the driver's more specific sitting posture helps to prevent abdominal injuries, and that the passengers' application of safety belts, especially with respect to the position of the lap belt, is more careless than in the case of the drivers. The

abdominal injuries, and that the passengers' application of safety belts, especially with respect to the position of the lap belt, is more careless than in the case of the drivers. The disproportionally high proportion of injuries to female occupants, who were passengers in most cases, also speaks in favour of this thesis. The even distribution of injuries with respect to age allows us to rule out any relationship between age and injuries to the abdomen.

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 reason 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. For this porpose, the POISSON distribution was choosen due to the good correlating which it can be achieve and its relatively simple interpretation. In a ddition, it had to be ensured that in the calculation of the AIS-class expected values, in which the scewness 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 maximum severity of injury, but also for the severity of injury to any individual region of the body) [5].

The probability distribution of the severity of abdominal injuries (Figure 1) describes a total of 38 injuries. The narrow range of light-to-medium injuries of severity codes AIS 1 to AIS 3 is remarkable here, implying that the bones of the pelvic girdle have a protective function. This range of transition to severe injuries already occurs at low accident severities (probability of 50 % for around SPUL =  $1\ 800\ m^2/s^{3}$ ).

In the pelvic region, there was a total of 25 injuries, which are to the largest part (64 %) recorded as being excoriations and laceration injuries. Apart from one totally shattered pelvis with a partial severance from the torso (coded with AIS 6), the evaluation of the data showed fractures of the pelvic girdle, of the ilium and of the upper shell of the acetabulum, all coded with AIS 2 or AIS 3. The probability distribution of the severity of pelvic injuries is shown in Figure 2. This is characterized by a narrow transition range between AIS 0 and AIS 4 (or 6).



Figure 1: Probability distribution of the severity of abdominal injuries.

<sup>\*)</sup> SPUL =  $1800 \text{ m}^2/\text{s}^3$  corresponds to a velocity change of  $\Delta v = 44 \text{ km/h}$  at a mean passenger cell deceleration of  $\overline{a} = 15 \text{ g}$ , and SPUL =  $2600 \text{ m}^2/\text{s}^3$  (see also the next page) to a velocity change of  $\Delta v = 64 \text{ km/h}$ .



Figure 2: Probability distribution of the severity of pelvic Injuries.

The 50 % probability of this type of injury is to be found at a relatively high accident severity of around SPUL =  $2600 \text{ m}^2/\text{s}^3$ . If we compare this to the probability transition range for injuries in the abdominal region, it can be seen that the protection offered by the bones of the pelvic girdle is effective up to a very high accident severity, whereas submarining injuries occur considerably earlier, i.e. at lower accident severities.

The most common cause of injuries can be traced back to contact with the belt strap and belt buckle (80 %), pelvic fractures resulting from an impact on the steering wheel rim only occurred in two cases. The most severe injuries were incurred by male drivers of 60 years of age. An effect of the age of the injured person on the severity of the injury cannot be clearly deduced due the small number of relevant cases.

# PRESENT-DAY PROTECTION CRITERIA AND TEST LIMIT VALUES

Although, as a rule, the pelvic acceleration is measured in all safety tests carried out with dummies, no legally prescribed test limit value exists at present - neither for the abdominal region nor for the pelvic region. Only visual checks are prescribed and instructions are given to the effect that the lap belt must remain on the pelvis and the contact of the belt must not be displaced into the abdominal region (cf. FMVSS 209).

The traumatization of the abdominal region and of the pelvis is essentially due to two causes: lap belt syndromes are caused by the so-called submarining effect and injuries in the pelvis/hip region are caused by high forces applied directly to the pelvis or transmitted via the thighs [8]. The osseous pelvic girdle can withstand very high forces without losing stability. The condition on which this depends is, however, that the force is applied over a larger area (as is usually the case with a lap belt) and also that the force is applied to a fixed area below the iliac crest during the crash phase. When the pelvis is subjected to loads due to a knee impact and injuries are incurred in the hip region, it is difficult to distinguish pelvic injuries from injuries to the lower extremities. In [10], PATRICK et al. already concluded that it is impossible to predict where an injury will occur in the series of possible members: kneecap - knee - femur - neck of the femur - hip region, when a force is applied to the knee. Occasionally, in frontal collisions, with a combination of soft upholstery, unfavourable belt geometry or wrong belt usage, the pelvis slides under the lap belt loop or the lap belt slips up over the iliac crests. The ensuing forces act on the surface of the abdomen and lead to ruptures and lacerations of organs, i.e. intra-abdominal injuries in the pelvic region, as well as - but only in very severe accidents - to fractures of the lumbar spine [8].

The forces which cause abdominal injuries are generally in a lower range than the forces which may lead to injuries of the osseous pelvis. Protection criteria being discussed at present essentially relate to the lap belt forces [7], their change as a function of time [3] and to the angle of rotation of the pelvis [2]. These quantities do not really characterize a permissible load on the lower abdomen, but much more the occurrence or avoidance of the submarining effect and the resulting injuries. There are two opposing methods which utilize direct measurement of forces acting on the pelvis as an indicator for upward slippage of the lap belt; these are shown schematically in Figure 3. As opposed to these methods, ADOMEIT, in [2], suggests using kinematic quantities for evaluating the submarining effect in the sense of a yes/no criterion. Another method is proposed in [11] and [12]: an abdomen insert with high bio-fidelity for belt loading, known as a frangible abdomen, is used to judge the submarining has in fact occurred, as well as - more important - the risk of injury to abdominal organs as a measurable quantity.



Measuring technique with the Submarining Indicator Pelvis (SIP) Measuring technique with the APR pelvis (APR: Association PEUGEOT- RENAULT)

# Figure 3: Method used for measuring the submarining effect

All the criteria proposed here are either extremely difficult to simulate in an experimental test, or they alter the geometry of the abdominal/pelvic region, so that interference with the motion patterns cannot be ruled out. For this reason, a new criterion is to be proposed and put forward for discussion.

# SIMULATION OF REAL LOADING OF THE ABDOMINAL AND PELVIC REGION

The injury severity as obtained by analyzing accidents and the respective degrees of severity are based on the equivalent accident characteristic [5]. The loadings exerted on individual parts of the body of a mathematically described occupant model, as determined with the aid of computer simulation, are also known as a function of the same accident characteristic. These provide characteristic values for the loading intensities leading to certain injuries to the victim of the accident. The simulation program used here, which is described summarily in [5], ICMF (Occupants Crash Mechanics Computer Program for Frontal Collisions) is a two-dimensional (2D-) model. The results which can be achieved with this model have proved to correlate well with test measurement, 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 the head and the neck.





Another special feature is that the model is able to simulate submarining effects due to the exact description of the pelvic/abdominal region (Figure 4). 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) and, in the latest version an airbag system for the driver as well as the passenger. 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 [4] as shown in Figure 5.



with penetration and intrusion

without penetration and intrusion

Figure 5: Occupant crash mechanics computer program for frontal collisions (ICMF) Simulation of penetration of the steering system and intrusion of the interior surfaces

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  $v_1 = 40 \text{ km/h}$  and  $v_2 = 64 \text{ km/h}$ . 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 difficulty of obtaining an exact, realistic system description, this always being a problem of mathematical simulation [5].

The most common cause of injuries in the abdominal region and to the pelvis of strapped-in occupants can be traced back to belt-strap forces. Whereas the accident data studied also contained injuries caused by steering-wheel contact, the computer simulation over entire range of accident severity showed no evidence of any contact between the steering system and the lower part of the torso or the pelvis of a mathematically described occupant model. Thus a forward displacement of the pelvis and the associated steering wheel contact can, to a large extent, be eliminated by avoiding faulty belt operation and wrong belt usage by the occupant - as was the case in the model used in the computer program. Severe abdominal injuries are caused by the pelvis slipping under the lap belt strap (submarining) [1, 6]. These may be avoided to a large extent by fixing the pelvis in place in order to prevent the belt strap from slipping upwards. This fact must be taken into account when appropriate protection criteria for the abdominal region are to be defined.

Neither the maximum values of the pelvis acceleration nor those of the abdominal acceleration, which are calculated for the centre of gravity of the respective model elements, are suitable for describing the submarining effect since they do not enable any conclusions to be made concerning the upward slippage of the lap belt. In Figure 6, the abdominal acceleration is plotted as a function of the resulting pelvis acceleration; the pairs of values for which submarining was observed are indicated by squares. Here, it is conspicuous that the submarining effect already occurs at relatively low accelerations (approx. 66 g). The hypothesis expounded during a statistical test - that the difference in acceleration might be an indicator for abdominal injuries - had to be dismissed.

In the computer simulation model, knee contact with the dashboard only occurred as a result of the submarining effect in most cases. A knee impact without submarining was only detected in two of the sixteen cases where knee impacts occurred. This obvious disagreement between the results of computer simulation and the results of accident analysis, which show much more frequent knee and thigh injuries even in cases where submarining did not occur, may be traced back to the ideal seating dummy. This also indicates that the elimination of submarining by appropriate structural design measures, for example, would enable both knee and thigh injuries to be avoided to an equal extent, or at least to be reduced in severity.



Figure 6: Relationship between abdominal and pelvic acceleration

The angle of rotation of the pelvis has already been introduced as an indicator for abdominal injuries by ADOMEIT in [2]. This deduction, which is undoubtedly correct, is to be expanded upon here in the sense that the acceleration determined (by simulation or measurement) at the pelvis may attain a high, yet-to-be-determined level, as long as the pelvis rotation angle remains below a certain limit. If the critical pelvis rotation angle, at which the lap belt strap slips over the iliac crest, is exceeded, then the resulting pelvic acceleration must be reduced to a loading value which corresponds to an acceptable abdominal loading. The acceleration values to be defined for each injury severity level are determined by correlating the results of accident analysis with those of computer simulation. To do this, the calculated accelerations and angles of rotation are first plotted as a function of the specific accident power.

In Figure 7, the maximum values of the resulting acceleration at the centre of gravity of the pelvis are shown as a function of the accident severity. In this, each pair of values represents the results of one computer simulation. The cases where submarining occurred (indicated by squares) are not taken into account in the regression analysis, since the loading values are only supposed to represent the pelvis injuries. The regression curve, shown in Figure 7, starts with a steep, degressive increase and attains a maximum of max  $a_{res} = 85.6$  g at a relatively high accident severity (SPUL =  $3060 \text{ m}^2/\text{s}^3$ ). It was not possible to detect a further increase of the pelvis acceleration in the course of computer simulation for higher accident severity ranges. In this region, the pelvis sinks further into the seat upholstery if any considerable kinetic energy is present, and is subjected to a backward orientated moment of rotation due to the increased belt forces and the flat angle at which these act: thus increasing accident severities are accompanied by an increase of submarining occurrences (cf. Figure 7).



Figure 7: Pelvis acceleration as a function of the specific accident power.

The question from which accident severity onwards an instability of the pelvis/belt/seat combination is to be expected can be most surely answered with the aid of the maximum pelvis rotation angle as a function of the specific accident power. For this purpose, pairs of values for which the position of the pelvis remained stable and the lap belt strap contact remained in the iliac region are indicated by circles in Figure 8.



Figure 8: Pelvis rotation angles in relation to the specific accident power

For those cases where submarining occurred (indicated by squares), the angles at which the lap belt had already slipped up to the iliac crest are given, as well as the maximum values of the pelvis rotation angle. In order to indicate the relationship, an arrow is drawn between this critical pelvis rotation angle and the corresponding maximum value of the angle. In the correlation calculations used for determining the regression curve, the maximum pelvis rotation angle for stable pelvis positions and the critical pelvis rotation angle for submarining cases are used, since the higher maximum value for these cases does not provide any information relevant to the degree of injury. Submarining cases occurred from accident severities of approximately SPUL =  $3000 \text{ m}^2/\text{s}^3$  onwards, the minimum critical pelvis rotation angle is 26.4 degrees.



Figure 9: Resulting lap belt force as a function of the specific accident power

Once the critical pelvis rotation angle is exceeded, the belt strap, which has then slipped over the iliac crest, causes abdominal injuries of severities which depend on the belt strap forces. Figure 9 shows the maximum resulting belt strap force acting on the abdominal/pelvic region as a function of the specific accident power SPUL. As the absolute maximum of the lap belt force is exceeded when the lap belt slips over the iliac crest, the relative maximum resulting lap belt force which occurred during submarining was determined. This maximum is reached in the course of a further increase of the forces following the discontinuity in the force curve at the time at which submarining starts. In Figure 9, the relative force maxima acting on the abdomen are also shown as a function of the accident severity and are connected to the corresponding absolute maxima by arrows. The regression line for the abdominal forces rises with increasing accident severity and lies clearly below the regression curve of the absolute lap belt force maxima. Due to the close relationship between the pelvis acceleration and the resulting lap belt force (the correlation coefficient is r = 0.961), acceleration values can be deduced from these forces. The adjusted loading values for pelvic and abdominal injuries obtained by this method are made up of three different physical quantities:

- the maximum resulting pelvic acceleration, responsible for pelvic injuries,
- the critical pelvis rotation angle, above which submarining is to be expected, and finally, after the critical pelvis rotation angle is exceeded,
- the pelvis acceleration, however at a considerably lower level, which causes abdominal injuries.

# RISK FUNCTION AND NEW PROTECTION CRITERIA FOR PREVENTING ABDOMINAL AND PELVIC INJURIES

The relationship between the risk of abdominal and pelvic injuries, on the one hand, and the maximum resulting pelvic acceleration on the other hand is determined by utilizing the probability distribution of the respective types of injury (Figures 1 and 2) and by eliminating the specific accident power. The protection criteria to be applied for the pelvis and for the abdomen, in the form of different resulting pelvic accelerations, are separated by the critical pelvis rotation angle. It is assumed that the exceeding of this critical angle is a necessary condition for the occurrence of abdominal injuries. In this way, the model for pelvic and abdominal accelerations as shown in Figure 10 is obtained, in which the limits for the maximum resulting pelvic acceleration are plotted as a function of the pelvis rotation angle; the higher acceleration range is valid for pelvic injuries, the lower range for abdominal injuries.



<u>Figure 10:</u> Model for pelvic and abdominal injuries for a probability of 50 %, correlated to the pelvis rotation angle

For both types of loading, the acceleration ranges corresponding to the tolerance level (between AIS 3 and AIS 4 [13]) for a probability of 50 % are shown. The two dotted straight lines which represent the threshold value and the limiting value of the critical pelvis rotation angle were derived by correlating the results of accident analysis with those of the computer simulation. However, as the pelvis rotation angle is not suitable for use as an indicator for evaluating the severity of injuries, but only as a criterion for distinguishing between the two types of injury, the smallest angle at which abdominal injuries were observed is defined to be the "critical" pelvis rotation angle with a value of 20 degrees (20.66 degrees, to be precise). The transition between the range of validity for pelvic and abdominal injuries is characterized by the downward sloping straight line which intersects the tolerance level for abdominal injuries at a value of 25 degrees.

The joint plotting of the risk functions of pelvic and abdominal injuries (Figure 11) represents an exceptional case, since both types of loading are shown as a function of a common protection criterion, the maximum resulting pelvis acceleration, separated from one another, however, by the critical pelvis rotation angle  $\alpha_{crit} = 20^\circ$ . This is used to express the fact that, at least for loadings in the vicinity of the tolerance level, either pelvic injuries (at a pelvis rotation angle of  $\alpha_{pelvis} \leq 20^\circ$ ) or abdominal injuries ( $\alpha_{pelvis} > 20^\circ$ ) may be incurred.

If a 50 % probability for irreversible pelvic and abdominal injuries is tolerated (i.e. AIS > 3), the protection criteria deduced from both risk functions (Figure 11) are 13.0 g for abdominal injuries and 80.0 g for pelvic injuries (rounded down from 13.4 g and 83.6 g, respectively).



Figure 11: Risk function for pelvic and abdominal injuries as a function of the pelvis acceleration, taking into account the critical pelvis rotation angle

# SUMMARY AND FUTURE PROSPECTS

The relationship between the risk of injury and the representative physical loading quantities has been established for abdominal and pelvic injuries by drawing up the risk function. Biomechanical modelling, cross-checked with the aid of statistical analysis methods, has provided an adjusted model loading which is representative of the mechanics of injury processes and which corresponds to the quantitative characteristics of these processes for a certain probability of irreversible injuries. The adjusted model loading presented here is a protection criterion in relationship to which it is possible to represent both the risk of injuries and the severity of injuries. In order to determine a protection criteria level for distinguishing between tolerable injuries and non-tolerable injuries, a tolerance level was defined, grouping the injury severities for specific parts of the body together into reversible and irreversible injuries. The definition of protection criteria levels was made possible by specifying a 50 % probability.

The ability to measure the mechanical loading values must be seen as an essential condition for the introduction and acceptance of new protection criteria. This gives rise to a discussion on the effort required in order to determine, by experiment and measurement, the loading values on which the protection criteria are based, and the accuracy which can be achieved.

The protection criterion for abdominal and pelvic injuries is derived from two physical loading values - the resulting acceleration at the centre of gravity and, as a distinguishing factor between the permissible abdominal loading and the permissible pelvic loading, the pelvis rotation angle. Whereas pelvic acceleration measurements pose no problems, it is far more difficult to determine the pelvis rotation angle. Direct measurement of the absolute pelvis angle by evaluating high-speed film recordings is relatively complicated and is only reliable enough for clothed dummies if measuring marks are applied. A higher degree of accuracy can be achieved by measuring the relative angle between the pelvis and the thigh using a resistive angle transducer and by calculating the absolute angle of the thigh with the aid of the computer or by the evaluation of photographs. The absolute pelvis rotation angle is calculated by adding the coinciding values. This method was used in the validation tests for the ICMF simulation model [4], but can only be transferred to vehicle tests with great difficulty because the vehicle doors block the view of the thighs. A standardized solution may be to measure the speed of rotation, which is then integrated once to calculate the angle of rotation during the crash. A measuring transducer of this kind has been available on the market for about three years now. If the protection criterion proposed here is consistently adhered to, submarining injuries can be prevented to a large extent in the future by further development of suitable (already introduced, in some cases) seat designs. Furthermore, the introduction of this criterion would prevent the acceptance of an increased risk of submarining as a measure for the prevention of head impacts on parts of the passenger compartment.

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