DEVELOPMENT OF A NEW CRASH CUSHION FOR THE PROTECTION OF PEOPLE IN WHEELCHAIRS IN A ROAD ACCIDENT

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ABSTRACT

All vehicles produced today are, as a matter of course, equipped with systems designed to protect the occupants should the vehicle be involved in an accident. Three point seat belts and airbags are fitted as standard in all modern vehicles.

Developments in the field of transport for disabled persons have not yet reached the same level. The demands placed on a wheelchair restraint system are considerably less than those which are standard for a restraint system in a passenger car. In Commercial Vehicle Development at Volkswagen AG in Wolfsburg a crash cushion has been developed improving safety in the transport of disabled persons to meet the higher, passenger car standards of safety and also take into account the special requirements of people in wheelchairs and staff accompanying them.

The first measure to improve levels of safety in the transport of disabled persons - a new development - is a cushion which is secured with a lap belt and which rests on the thighs of the person seated in the wheelchair. The cushion improves the kinematics of the occupant in an accident to such an extent that good biomechanical load results are achieved under stringent testing requirements.

INTRODUCTION

According to the VdK in Bavaria (Association for disabled ex-servicemen, surviving dependants and social insurance pensioners) there are approximately 800,000 people in wheelchairs in Germany. The necessity to be mobile is important for this group, as it is for those who are not disabled, in order to play an active role in daily life. The journey to work, to an event, to the doctor etc. is made by most people in wheelchairs in a disabled transport vehicle, with the exception of the group who are in a position to drive themselves. That means that over 5000 such trips are made every day in a city the size of Cologne (approx. 1 million inhabitants). In most cases the person in the wheelchair is not transported in seats fitted in the vehicle, but rather in their own wheelchair. The tasks of the accompanying staff are thus reduced as well as the time needed to get in and out of the vehicle. The person and the wheelchair are secured using a special wheelchair restraint system in the vehicle. This system is designed not only to prevent the wheelchair from moving or even from falling over in the vehicle, but also to offer safety in the most common accident situations.

DESCRIPTION OF THE TEST REQUIREMENTS

Elaborate passive safety systems have been introduced in the passenger car sector over the course of the past few years. The securing systems for the transport of people in wheelchairs have also been improved. These systems are tested according to DIN 75 078. In addition to a static test, a dynamic test must be carried out using an accelerating sledge with 12 g load over 20 ms to test the safety of the restraint system in a front-end collision.

According to the results of the crash tests against a solid wall carried out at Volkswagen AG with passenger cars and minibuses, however, the average vehicle deceleration during a full frontal collision is considerably higher than the values stipulated in the DIN.

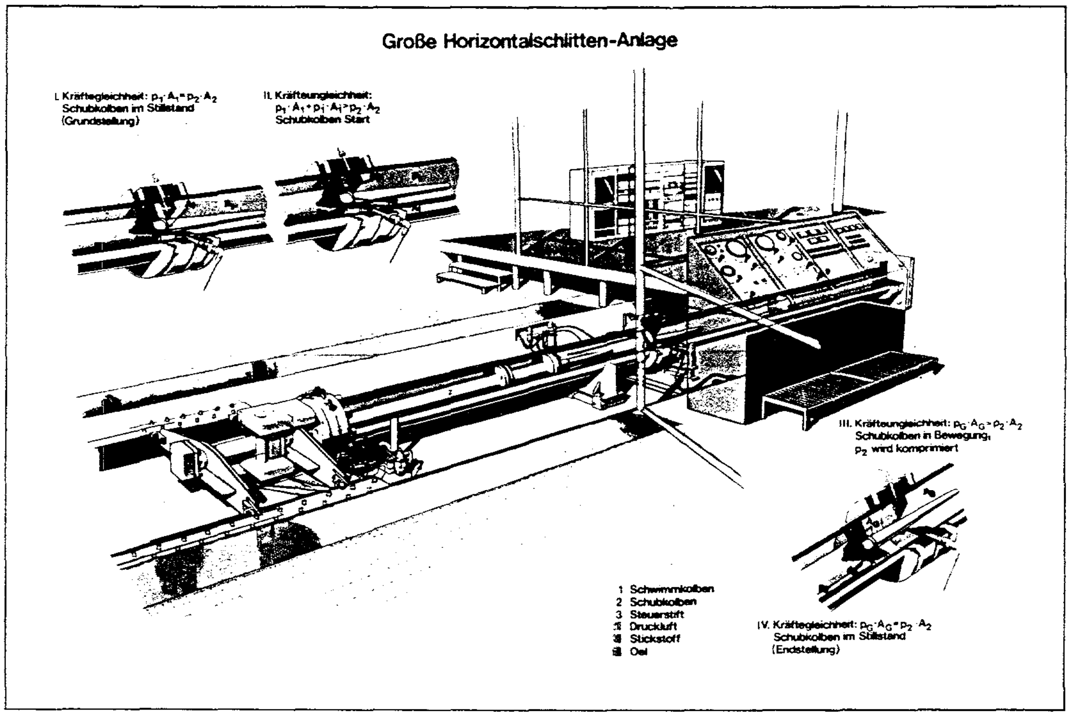

Figure 1. The large acceleration sled of the VW-AG.

In an accident with a passenger car, minibuses, such as are normally used for the transport of disabled persons, have a lower vehicle deceleration than the passenger car due to their heavier weight and greater stiffness. But even in this case, deceleration rates of the minibus exceeding 12 g are measured.

On the basis of the above test results, more stringent test requirements than in DIN 75 078 are used for the development of the restraint systems for people in wheelchairs as described below. For this reason, a test is used based on ECE-R17, which applies to passenger car seats and restraint systems. This requires an acceleration test at 20 g over 30 ms. The aim is to give people in wheelchairs a similarly high degree of safety at this increased load as is standard in today's passenger cars.

TEST SET-UP AND PROCEDURE

The tests presented here were carried out on the large horizontal sledge at Volkswagen AG in Wolfsburg (fig. 1). The sledge is propelled by a compressed gas thrust piston and is designed as a deceleration sledge, i.e. it is accelerated in the vehicle's reverse direction. The sledge body acceleration curve is set by a control pin and by adjustment of the load pressure. For the requirements of ECE Directive 17 [2] (20g over 30 ms) a half-sine sledge pulse of 70 ms duration is used. The maximum acceleration of the sledge is around 26 g (fig. 2).

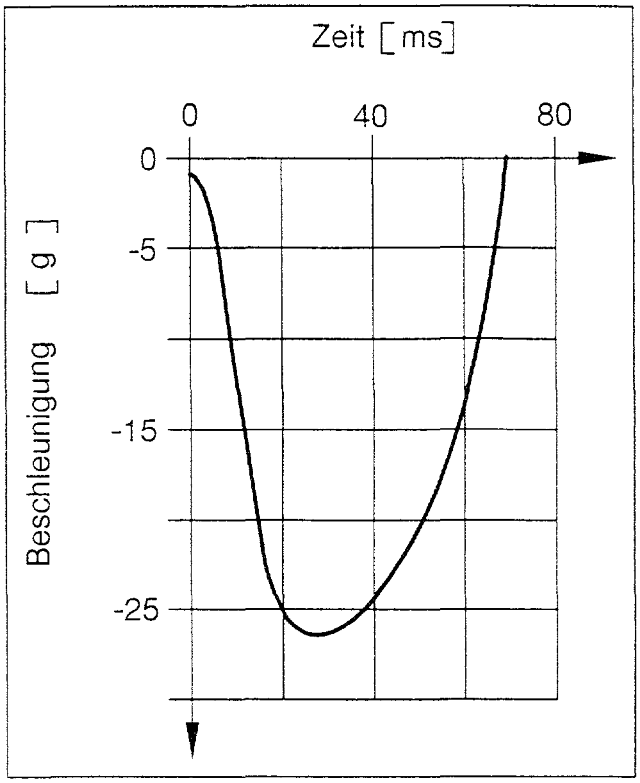

Figure 2. Used half-sine impulse for the tests.

INITIAL TEST AND DERIVED REQUIREMENTS

A comparison test was carried out with the most commonly used restraint system for transport of people in wheelchairs (fig. 3) at 12 g and 20 g acceleration pulse over 30 ms.

With this restraint system the wheelchair is stayed by four belts which are looped around the wheelchair frame with retractors on rails on the vehicle floor. The occupant is secured by an adjustable-length lap belt which is attached to the rails on the vehicle floor.

The test at 12 g acceleration resulted in a low to medium risk of injury for the occupant. The wheelchair sustained almost no deformation or damage at all. In the second test at a load of 20 g the sequence of movement of the dummy was similar to that in the first test. This sequence of movement is illustrated in figure 4 and described in table 1.

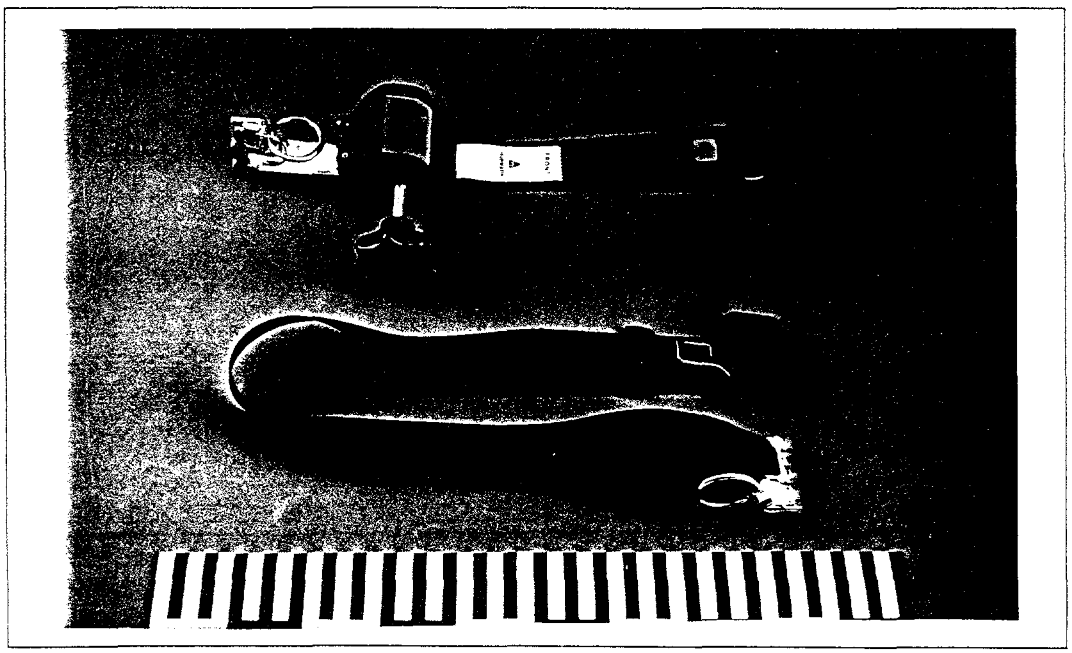

Figure 3. Pelvis- and wheel-chair belt with fittings.

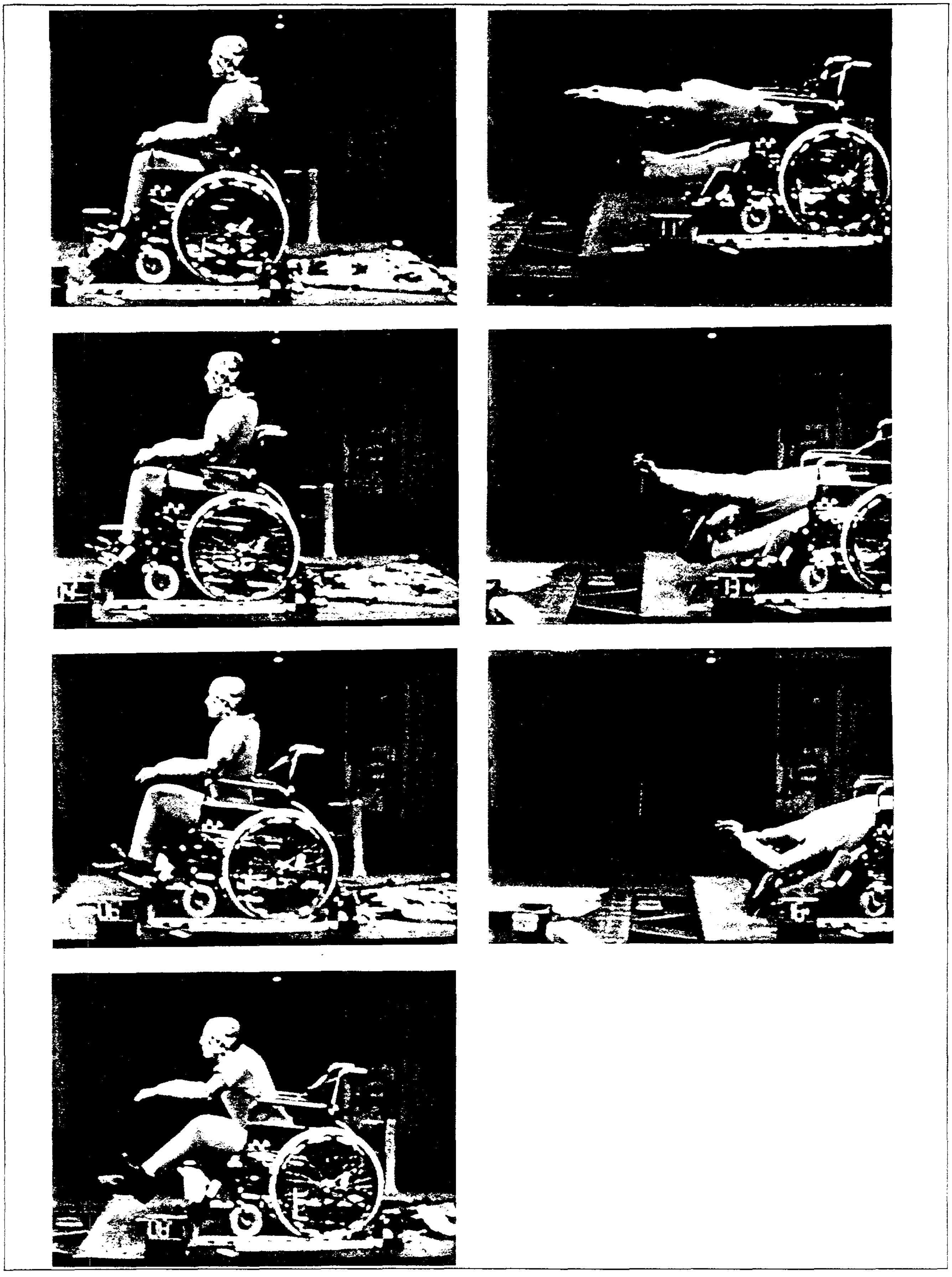

Figure 4. Movement of the dummy in the wheel-chair test with 20 g without impact cushion

Table 1. Sequence of movements at a load of 20 g

Phase	Time	Sequence
one	0 ms	Test start
	40 ms	Translatory forwards motion of the dummy on the seat base begins
	60 ms	The belt slack has been taken up. the max. belt forces at the pelvis and the max. pelvis acceleration are reached: the translational movement of the dummy is completed
two	80 ms	The jack-knifing effect causes the upper body and the legs to rotate around the H point and lap belt
	110 ms	The upper body and legs are horizontal: in this position the head acceleration peaks at a marked maximum of up to 90 g The head and upper body begin to overswing: the chest makes contact with the thighs and is supported by them: due to the belt sliding out of position a sequence of load peaks in the acceleration of the chest and pelvis occur
	135 ms	As a result of the severe overswinging of the upper body. the head impacts with the right foot and lower leg at a peak acceleration of 185 g The chest and pelvis acceleration drop down to insignificant levels
three	162 ms	The head strikes the right footrest of the wheelchair. two further head acceleration peaks occur
	200 ms	The process has ended: no upper body rebound occurs: the wheel chair has not tipped over. the dummy has not slipped off the seat base

The consequences in this test would be severe to fatal head injuries with possible fracture of the pelvis. Injuries to the cervical vertebrae caused by the impact of the head on the thighs cannot be ruled out. The wheelchair withstood the stresses of the test without breaking. The seat base was slightly torn and the wheels were severely buckled. In a real accident it would still be possible to rescue the disabled people from the vehicle.

Table 2. Test results of the wheel chair test.

	Wheelchair test without cushion	Limits
HIC value	1250	1000
Maximum head acceleration/3 ms figure [g]	185 / 88	/ 80
Maximum chest acceleration [g]	37	60
Maximum pelvis acceleration [g]	61	60
Maximum lap belt force [kN]	9.6	
Maximum wheel chair belt force [kN]	4.8	

Taking the existing system of a lap belt and belts fastening the wheelchair as a starting basis. the findings of the first test at 20 g load were used to develop the following catalogue of requirements.

The main objective of this process is to improve the safety of people in wheelchairs in a front-end collision. as this is statistically the most common type of collision. At the same time. consideration is also to be given to the loads placed on the wheelchair and the user-friendliness of the system.

Safety requirements:

- low risk of injury at an acceleration pulse of 20 g
- protection for persons with different types of disability. e.g. with hemiplegia which causes a slanting body position
- optimum belt position. prevention of submarining effect and risk of injury from the belt slipping out of position.
- reduction of the jack-knifing effect
- prevention of risk of injury from the belt buckle
- protection in other types of collision

Comfort requirements:

- quick and easy to use
- must function effectively with various types of wheelchair
- variability which allows use in different disabled persons transport vehicles
- must not severely restrict user's movement
- low weight
- cushion must be easy to fit between the armrests
- pleasant cloth covering
- high user acceptance

Requirements regarding load on wheelchair:

- no breakage of supporting structures of the wheelchair frame and wheels
- deformation of the wheelchair frame and wheels must not affect the occupant's sequence of movement
- forces acting on the seat base of the wheelchair must be low. The seat base material must be sufficiently prevented from tearing at its points of attachment or coming away from them, so as not to represent any additional risk of injury for the occupant.
- the wheelchair must remain stable throughout the course of the accident
- the wheelchair must not be locked in place by its wheels

CUSHION

In order to fulfil the safety requirements set out in the foregoing chapter, the primary need is to reduce the critical effect on the wheelchair occupant's head, i.e. the jack-knifing effect and the rotation of the occupant's upper body around the H-point must be restricted.

The basic idea is a wedge similar to those used in familiar child restraint systems. When positioned between the upper body and the thighs it prevents the critical upper body overswing of the. The intention is for the upper body to fold over the wedge in a controlled sequence of movement. The restriction of the movement prevents contact between the head and the lower leg or the wheelchair. At the same time, deformation of wedge should convert some of the occupant's kinetic energy into deformation work. This reduces the forces acting on the occupant.

The wedge should rest on the occupant's thighs and shall be referred to below as a cushion.

Other safety requirements may be fulfilled by having a belt which passes through the cushion. The belt buckle is relocated away from the abdominal region. This means that there is no longer any risk of injury from the belt buckle. The position of the belt inside the cushion is secure, preventing any risk of injury due to the belt slipping out of position. The cushion is still effective for an occupant with a bent or slanting upper body position.

The deformation of the cushion between the belt and the occupant's pelvis lowers the acting belt forces. As the cushion has a larger surface, the force acts over a greater area of the abdomen, leading to a more even distribution of the forces.

Another difference to the standard system as described in the foregoing chapter, is that the belt fastening points are relocated to the wheelchair frame (similar to the configuration in DIN 75 078, Part 2), in order to optimise the forwards movement of the occupant caused by slack and stretching of the belt, and to reduce the belt forces by improving the floor attachment angle and attachment height.

It is to be expected that the cushion also provides a protective effect in other forms of collision.

The cushion simultaneously fulfils a number of major demands set out in the foregoing chapter concerning comfort and ease of use. It is easy to fasten making almost no extra work for helpers. The cushion presents no problems for use in various types of vehicle and with the most common wheelchair types. It causes no major restriction of movement for the user. The weight of the cushion may be restricted to a reasonable level by selection of suitable materials. The cushion may by all means be used while travelling as a resting surface for objects or as a base to write on.

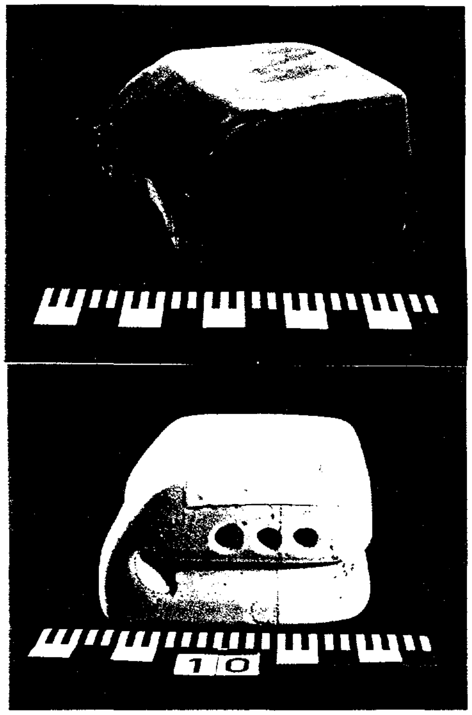

Figure 5. Crash cushion.

The cushion fulfils the demands concerning loads acting on the wheelchair. A greater load on the seat base is. however. to be expected as the forces of the upper body folding over the cushion are transferred via the thighs to the seat base. However. no breakage or dangerous deformation of the wheelchair was observed in the tests described below.

Description of the crash cushion

In the cushion (fig. 5) the belt is located in a belt rail between the flanks of the cushion. The cushion has a flat shape. Its dimensions are L=33cm. W=36cm. H=22cm. Holes were drilled in the blank to save weight. The top side of the blank is made of a very soft. comfortable foam in order to protect the head should it strike the cushion.

The tests show that with this cushion the occupant of a wheelchair is well protected in an accident. The detailed test results for this cushion are presented in the next chapter.

Material selection

The main materials that may be used for the cushion are polypropylene (PP) and polyurethane (PUR) foams. They effectively fulfil the demands of sufficient durability and moisture resistance with low weight. low production costs and sufficient suitability for recycling. Polystyrene was not selected due to its unsuitable damping characteristics.

Volkswagen AG has extensive findings on the energy absorption and deformation behaviour of PP and PUR foam with regard to their use as a damping element for passive safety [10].

In a series of tests a body block representing the chest and pelvis area of a dummy with a mass of 33.45 kg was accelerated to impact with a material sample of size 200 x 300 mm. Acceleration pickups in the model were used to determine the energy absorption and the maximum deceleration forces of the material at a speed of approx. 30 km/h. The tests were carried out on PP and PUR foam samples of varying density and height.

The model test shows that when a material of lower density is used the maximum deceleration force decreases (fig. 6). When the height of the material sample is reduced below a certain level the entire available deformation distance is used up by the impact. The remaining energy is passed on to the base plate via the material. which has reached full compression. This is accompanied by a serious increase in the maximum deceleration force.

Use of a greater material density results in a rise in the maximum deceleration forces with lower depth of deformation (fig. 6). Due to the lower depth of indentation. the surface area of material taking load from the body model is reduced. This is a geometrical effect which leads to a lower efficiency of the energy absorption system h.

The implications for the design of the cushion are that at a given cushion height xp the material density must not be below a certain level in order to prevent the cushion reaching full compression when the body impacts against it. At the same time, the material density should be sufficiently low as to achieve an optimum depth of indentation and, thus, transmit the load to as large an area of cushion as possible. This has the aim of maximising the efficiency of the energy absorption system. The maximum deformation force acting on the occupant at impact F_{max} must not exceed a certain level in order to prevent critical biomechanical load levels.

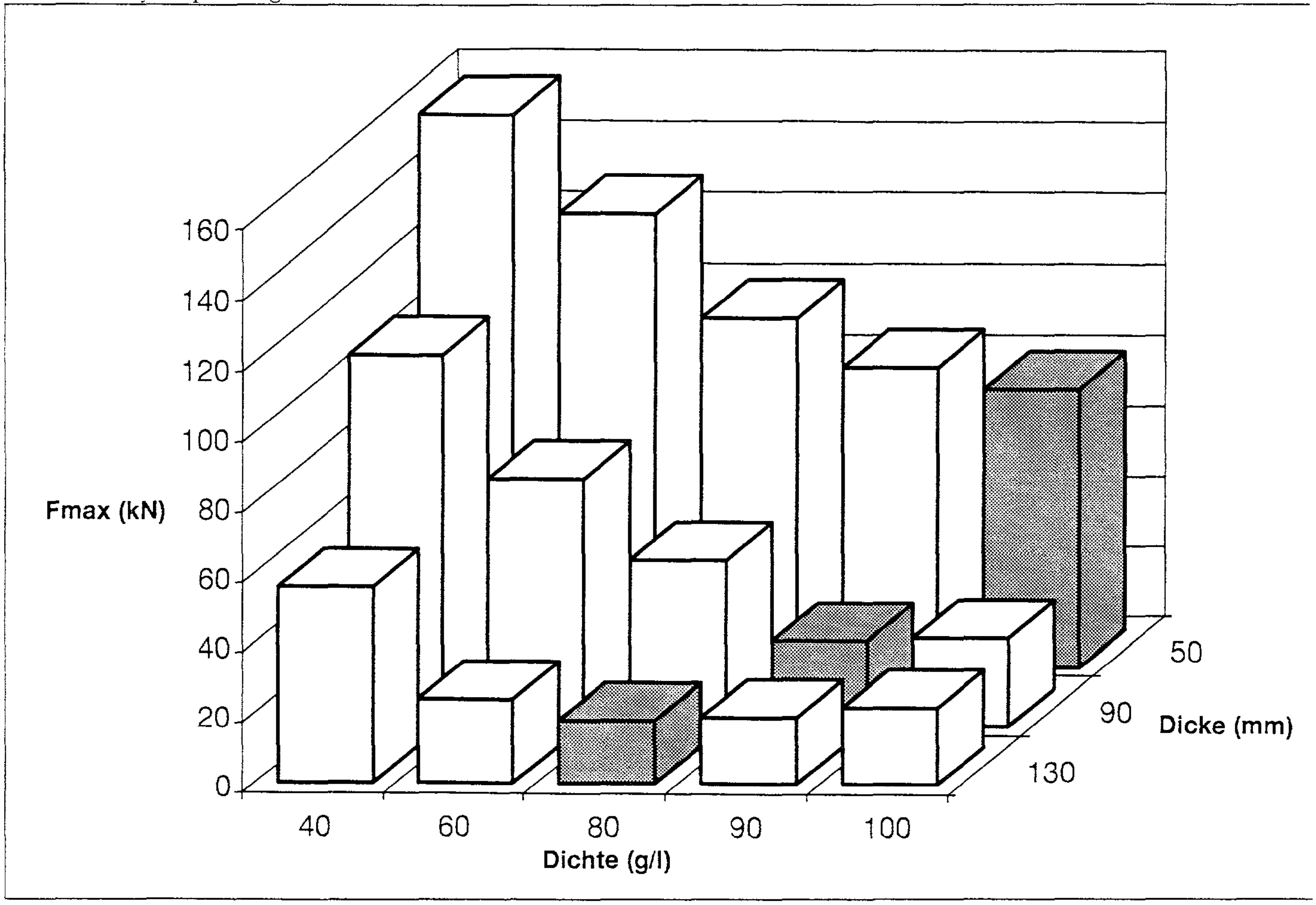

Figure 6. Maximal deformation force Fmax depending on material density and thickness for PUR.

The boundary conditions determine the material density at which the best efficiency of the absorption system h is achieved.

$$h = \int F\, ds / (F_{max}\, xp) < 1 \qquad (1.)$$

Using a cushion height of approx. 200 mm the best efficiency for PP foam is achieved at a density of approx. 30 g/l. With the same design PUR foam requires the twice this density, i.e. approx. 60 g/l. This weight disadvantage is compensated for by its efficiency at high indentation depths, which is approx. 10% greater than that of PP foam.

At these material densities PUR and PP foam have almost the same energy take-up capability. They differ greatly, however, in their reverse deformation (fig. 7). The PP foam releases again in reverse deformation a large proportion of the energy transferred to it. In the case of a body impact on the cushion this can lead to a severe rebound effect. The risk of injury is seriously increased by the high change in the velocity of the chest and unfavourable kinematics of the rebound with strong forces affecting the cervical vertebrae. PUR, on the other hand, absorbs the greater proportion of the energy, thus largely preventing any hazardous rebound.

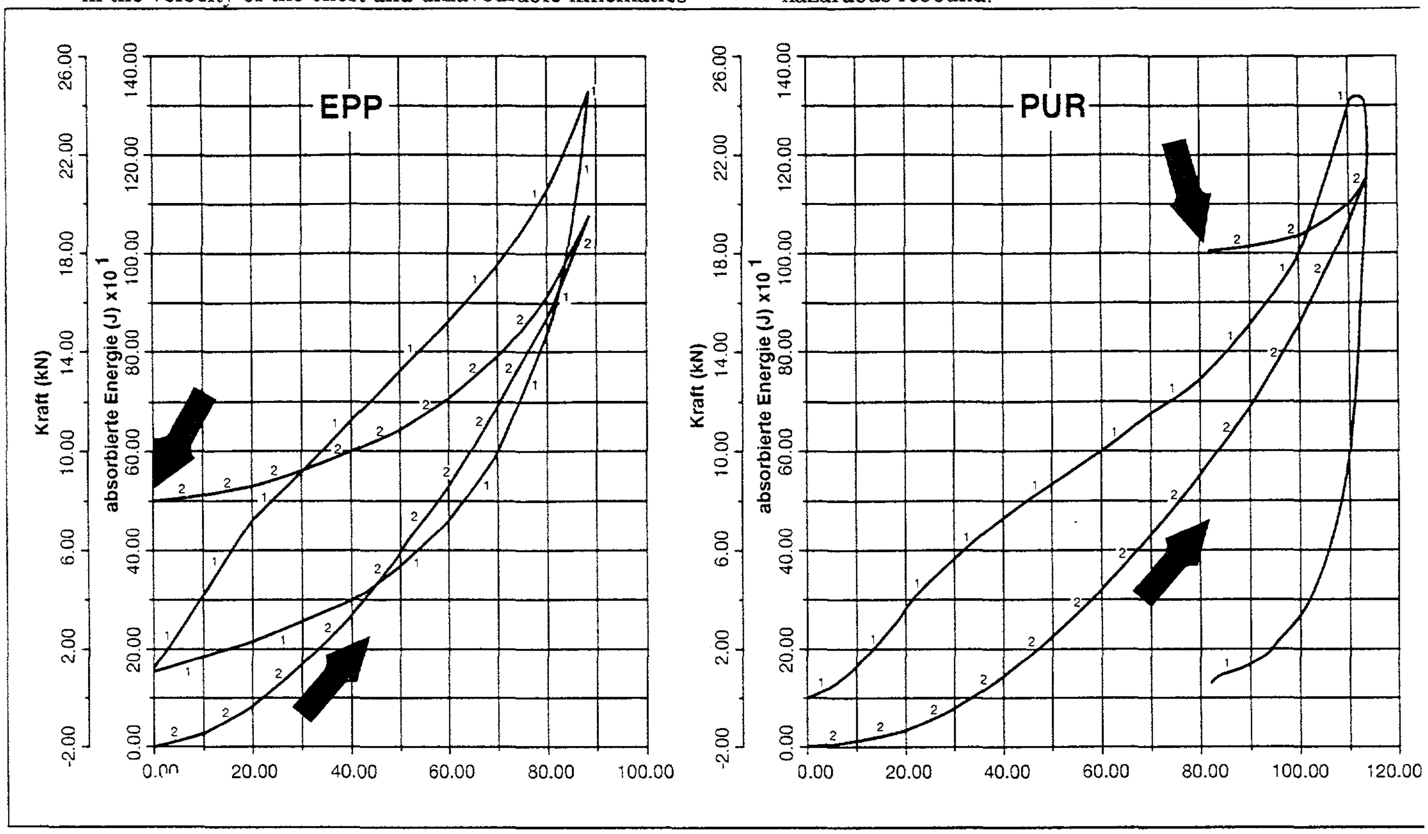

Figure 7. Energyabsorption and deformation force of PUR and EPP derived from drop tests with a thorax-pelvis-model

Table 3. Test results with PUR and EPP cushions

	PUR Cushion	EPP Cushion	Limits
HIC value	443	245	1000
Maximum head acceleration/3 ms figure [g]	60 / 48	50 / 41	/ 80
Maximum chest acceleration [g]	24	34	60
Maximum pelvis acceleration [g]	50	66	60
Maximum belt force [kN]	13	12	

Acceleration tests (20g over 30ms) were conducted with the test frame using cushions made of PP foam with a density of 30 g/l and PUR foam with a density of 60 g/l. The results are shown in Table 3.

The load on the chest from the PUR 60g/l cushion is 30% below that exerted with the PP 30g/l cushion. The reason for this is the better energy conversion as the upper body folds around the cushion. This is confirmed by the more severe deformation or breakage of the PUR cushion

The load on the pelvis from the PUR 60 g/l cushion is approx. 25% lower than that of the PP cushion. In the case of the PP cushion the measurements show a critical acceleration of the pelvis of 65g.

Due to contact between the head and the cushion occurring with the PUR cushion, the load affecting the head is around 55% higher with this cushion than with the PP cushion with which this head contact did not occur. However, the head injury risk - the HIC value of the PUR cushion is well below the limit of 1000 at 443. The higher deformation of the PUR cushion in the pelvis area is the reason for the greater forwards motion of the head leading to contact.

The maximum belt force is virtually the same with both cushions.

The PUR foam will be used for the further development of the cushion due to its better energy absorption behaviour and better load figures.

COMPARISON OF THE TEST RESULTS FOR A WHEELCHAIR OCCUPANT WITH AND WITHOUT CUSHION

The section describing the INITIAL TEST AND DERIVED REQUIREMENTS shows a wheelchair test at 20 g without a cushion. In this chapter, this test is compared with a wheelchair test with cushion. In figure 8 the sequence of motion of the dummy for the test with the cushion is shown at 1, 43, 61, 81, 112, 136 and 164 ms. Figures 9, 10 and 11 show the sequences of head, chest and pelvis acceleration. In each case the blue curve (1) represents the rates of acceleration in the test without a cushion and the red curve (4) represents the acceleration in the test with the cushion.

The sequence of motion may be divided into three phases.

In the **first phase** of the sequence the dummy moves forward in an upright posture. The upper body does not rotate! This horizontal forwards motion of the dummy is made possible by the stretching of the belt, compression of the cushion and compression of the dummy in the pelvis area. At 60 ms the belt guide area of the cushion absorbs energy and is considerably deformed.

The first phase ends for the dummy with the crash cushion at 78 ms. At this point in time all three acceleration values reach their maximum levels. At this moment the acceleration rates for the chest (26 g) and pelvis (43 g) reach their highest values for the whole sequence of movement in the test with the cushion. The figures for the head and pelvis acceleration show that in the test without a cushion the maximum acceleration is reached roughly 10 ms earlier than in the test with the cushion. This is caused by the longer path of movement of the dummy in the test with the cushion. During these 10 ms the cushion is deformed in the pelvis area.

At this point the feet have already slid off the footrests.

In the **second phase** of the sequence of motion the upper body begins to fold forwards. At 80 ms the head begins to rotate.

In figure 8 it may be seen that the flanks of the cushion have been forced apart at 90 ms.

From 100 ms the cushion seriously impedes the rotation of the upper body. This also considerably restricts the rotation of the head. The upper body of the dummy is considerably further away from its legs in the test with the cushion than in the test with no cushion. It may also be clearly observed that in the test without the cushion the chest acceleration reaches its maximum value (45 g) between 110 and 130 ms; the upper body strikes the legs (jack-knifing effect). In contrast to this, no increase in chest acceleration is observed in the test with a cushion.

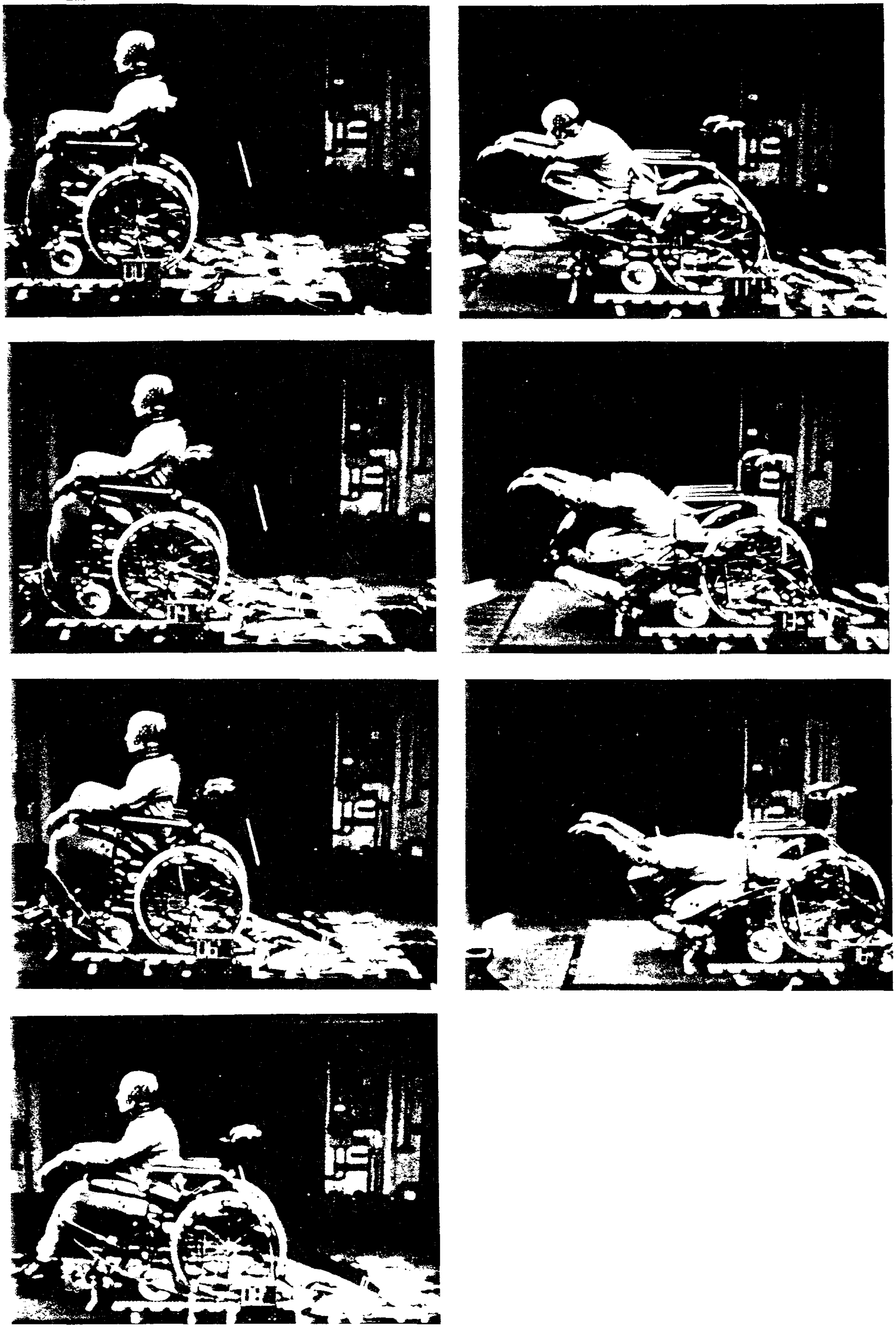

Figure 8. Movement of the dummy in the wheel-chair test with 20 g with impact cushion

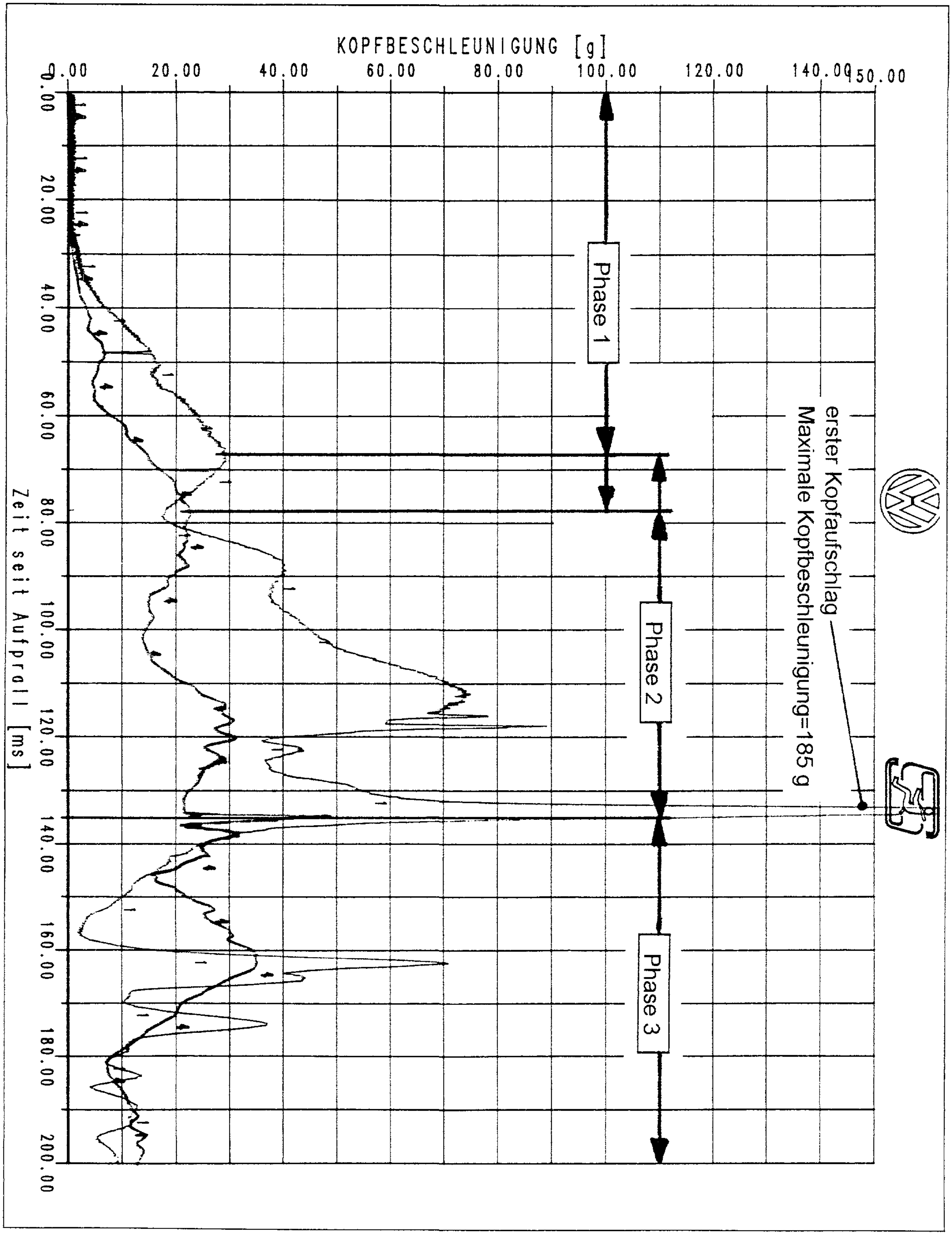

Figure 9. Head acceleration curve for the wheel-chair test with 20 g (curve1=without cushion, curve4=with cushion)

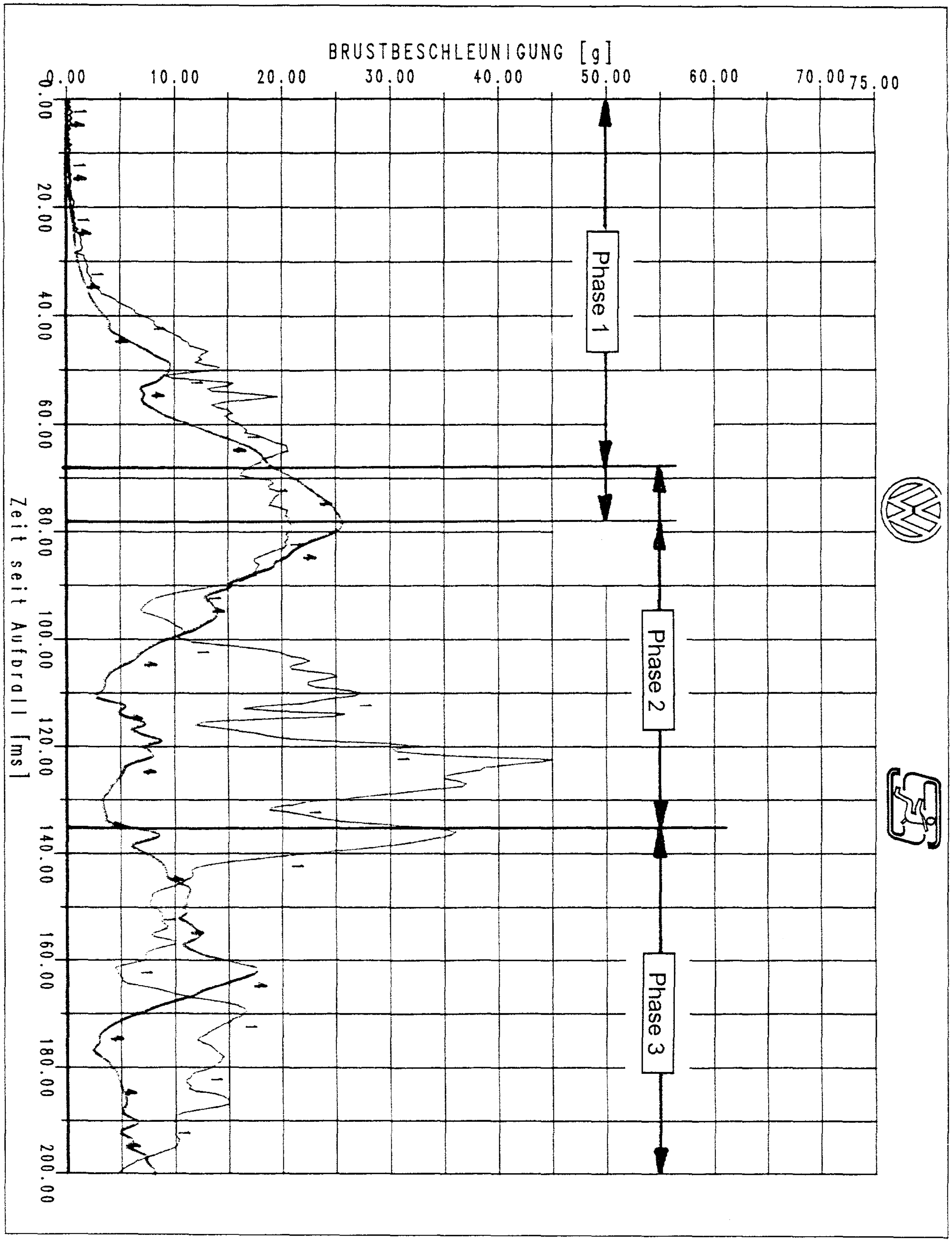

Figure 10. Thorax acceleration curve for the wheel-chair test with 20 g (curve1=without cushion; curve4=with cushion)

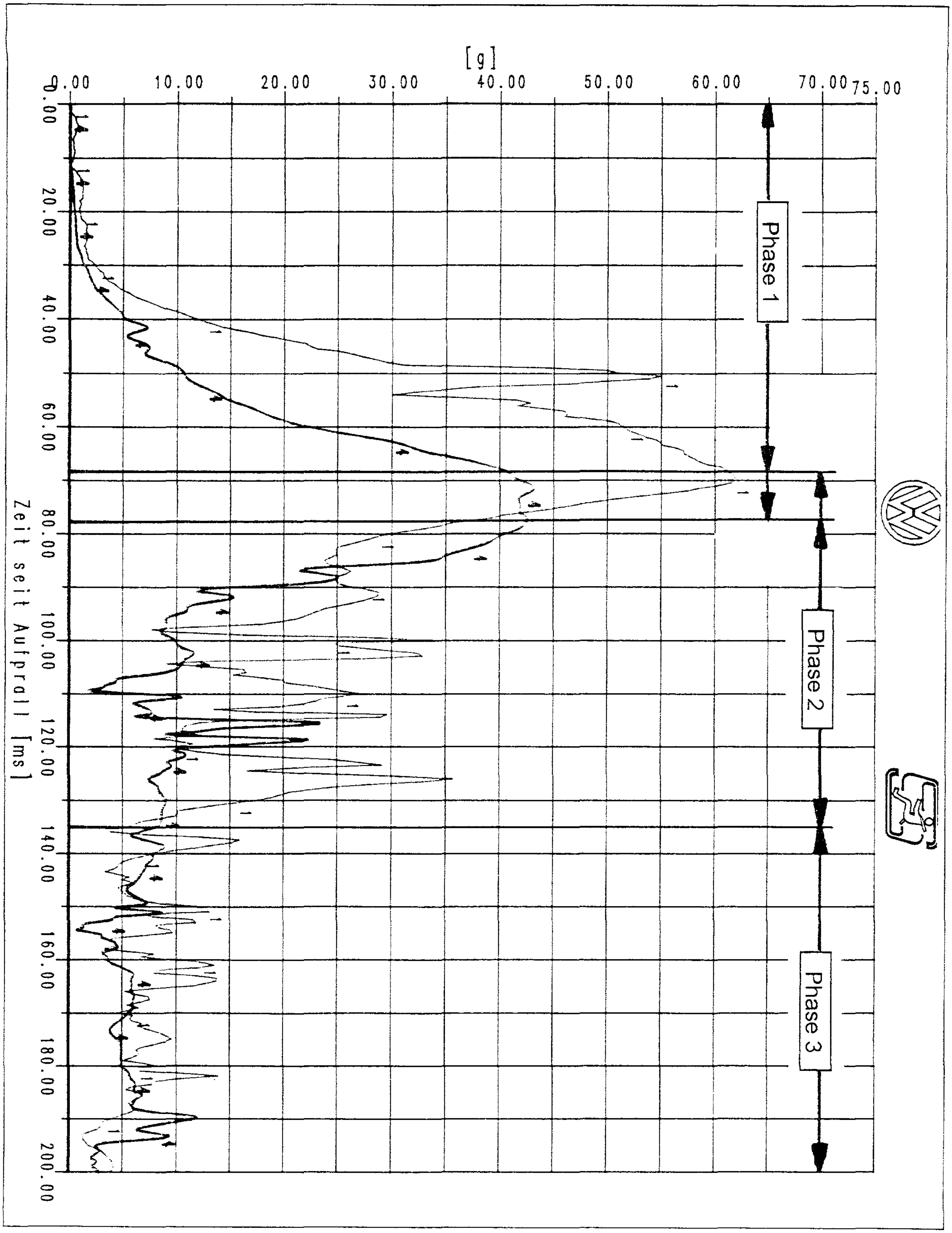

Figure 11. Pelvis acceleration curve for the wheel-chair test with 20 g (curve1=without cushion; curve 4=with cushion)

The second phase ends at 135 ms. At this point the head makes its first contact. In the test without a cushion the head strikes the lower leg hard. The resulting head acceleration is 185 g, which is well above the limit (see table 4). The cushion prevents any contact between the head and the lower legs. The head merely brushes against one of the feet. The head acceleration is 49 g. The contact of the head with the shoe is the result of the knee joint of the dummy bending upwards. In figure 8 the very unnatural position of the dummy's lower leg in the test with the cushion may be clearly seen. It is the authors' view that the lower leg of a human being cannot move into such a position as the entire knee joint is held and supported by the ligaments. The situation on a dummy is quite different. Here the knee joint is only prevented from snapping upwards by a thin pin. This model-type fastening system does not work as required in the test.

The **third phase** from 135 ms describes the end of the motion as the dummy comes to rest in its final position. A second head impact occurs during this stage at 162 ms. In the test with the cushion this is caused by the extreme overbending of the lower leg. The head acceleration of 35 g is only half as high as in the test without a cushion.

Table 4 . Test results on a wheel chair with and without cushion.

	Wheelchair test without cushion	Wheelchair test with cushion	Limits
HIC value	1250	274	1000
Maximum head acceleration/3 ms figure [g]	185 / 88	49 / 35	/ 80
Maximum chest acceleration [g]	45	26	60
Maximum pelvis acceleration [g]	62	43	60
Maximum belt force [kN]	7.3	10.4	

Table 4 compares the maximum acceleration rates with statutory limits. The table clearly shows that without the cushion the head acceleration considerable exceeds the limit and the pelvis acceleration is slightly over the limit. Under these circumstances a disabled person in a wheelchair would suffer considerable injuries in the accident.These extreme loads are prevented by the use of the cushion. The reductions in load achieved by use of the cushion amounted to 73% for the head 42% for the chest and 30% for the pelvis. The cushion prevents the serious exceeding of the statutory limits. This effectively eliminates the danger of severe injuries from the accident.

CONCLUSION AND FUTURE PROSPECTS

Disabled persons who are transported sitting in wheelchairs in minibuses are not yet protected by the same safety measures which are available to a passenger in a vehicle seat. Three point seat belts are fitted in minibuses, but cannot be used for ergonomic reasons. Solutions involving equipment which can be retrofitted have been developed, but have up to now failed to achieve success on the market, due to their relatively high costs and cumbersome handling.

The crash cushion developed by VW AG, however, may be used immediately in any model of vehicle without the need for modifications and may contribute considerably to improving the safety of persons in wheelchairs in a collision. It can only be hoped that this type of cushion is accepted by the operators of vehicles for the transport of disabled persons and by the people in wheelchairs themselves.

The potential for the further development of these crash cushions lies in the use of new materials and combinations of composite materials which distribute and absorb energy within the cushion even better.

REFERENCES

[1] ECE-R14

[2] ECE-R17

[3] Bundesanstalt für Straßenwesen (Federal Roads Authority): DIN Draft: Restraint Systems for Persons in Wheelchairs

[4] German Patent Office: Patent Application DE 43 40 937 A1, 1.12.93

[5] German Patent Office: Patent Application DE 195 14 837 A1, 21.4.95

[6] German Patent Office: Patent Application DE, 96

[7] Austermann, J.: Measures to increase the passive safety of persons in wheelchairs being carried in motor vehicles. VW Development Study, 1992

[8] Baumeyer, B.: Further development of a cushion to increase the passive safety of persons in wheelchairs while travelling in disabled transport vehicles. VW Development Study, 1995

[9] Steiner: Test bed description - large horizontal sledge for non-destructive vehicle collision simulation

[10] Köppen, W.: Use of synthetic materials to fulfil safety requirements in a side crash. VDI Berichte 1995