RESULTS OF FULL-SCALE CRASH TESTS, STATIONARY TESTS AND SLED TESTS TO ANALYSE THE EFFECTS OF AIR BAGS ON PASSENGERS WITH OR WITHOUT SEAT BELTS IN THE STANDARD SITTING POSITION AND IN OUT-OF-POSITION SITUATIONS

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Paper Number 98-S5-O-10

ABSTRACT

It can be expected that equipping new vehicles of all categories with air bags will lead to an increase of accidents in which injuries are assumed to be caused by an air bag. Answers to related questions call for comprehensive experimental findings. In this context possible injury-inducing effects of air bags in standard and non-standard sitting positions (out-of-position situations) of passengers are of particular interest.

DEKRA Automobil AG carried out several tests to analyse the effects of air bags on belted drivers in the standard sitting position and unbelted front passengers bent forward (out of position). In six full-scale crash tests the vehicle impacts a rigid barrier with 40 % frontal overlap. In four of the tests the collision speed was 55 km/h, in two tests 34 km/h the other 29 km/h. A belted dummy was placed on the driver's seat in the standard position. On the front passenger seat an identical dummy was placed unbelted and leaning forward. Two further tests were carried out with a stationary vehicle and triggered the front passenger air bag. On the front passenger's seat was an unbelted dummy bent forward. In one case its position was extreme, with the face close to the cover of the air bag. In the other case the distance between the dummy's nose and the dashboard - as in the full-scale tests - was 175 mm. Vehicle deceleration and vehicle damage measured during the tests, together with the loads on the dummies and their kinematics are described.

At the Institute of Forensic Medicine in Heidelberg seven sled tests were carried out to simulate frontal collisions at speeds around 50 km/h involving unbelted human cadavers in a standard sitting position. The restraint system used in each case was a full-size air bag in conjunction with knee pads. In addition to the dummy tests the measured accelerations of the cadavers and their injuries are described.

To summarize there follows an inter-disciplinary discussion and evaluation of all test results with regard to protective effects and possible injuries caused by air bags.

INTRODUCTION

Air bags as supplements to seat belts clearly enhance the internal safety of vehicles. To provide protection, an air bag needs to be inflated. Depending on collision parameters (angle of collision, delta-v, etc.) the time period between the begin of the collision and the end of the air bag inflation could be 40 to 80 ms. This needs a corresponding amount of energy. In this context, the possible loadings of occupants who are impacted by the air bag during its inflation are of special interest.

To study such effects, DEKRA Automobil AG carried out full-scale crash tests with a belted dummy on the driver side and an unbelted dummy bent forward on the passenger side in cars equipped with air bags. Further tests were conducted with a stationary car triggering the air bag on the front passenger side. In these tests, an unbelted dummy was sitting bent forward on the passenger seat. In addition, the Institute of Forensic Medicine in Heidelberg had carried out sled tests with unbelted human cadavers in a standard sitting position, protected by an air bag supplemented with knee bolsters. The test results, especially the mechanical loadings of the dummies and of the human cadavers and as well the injuries of the cadavers shall give more information to discuss the protective effect of the air bag and possible overcritical loadings induced by a contact with the inflating air bag..

FULL-SCALE CRASH TESTS

Test Base

Six full-scale crash tests were carried out with a 40 % frontal overlap impact of a car against a rigid barrier. In the first four tests the impact velocity was 55 km/h (**Figure 1**), in the fifth test 34 km/h and in the sixth test 29 km/h.

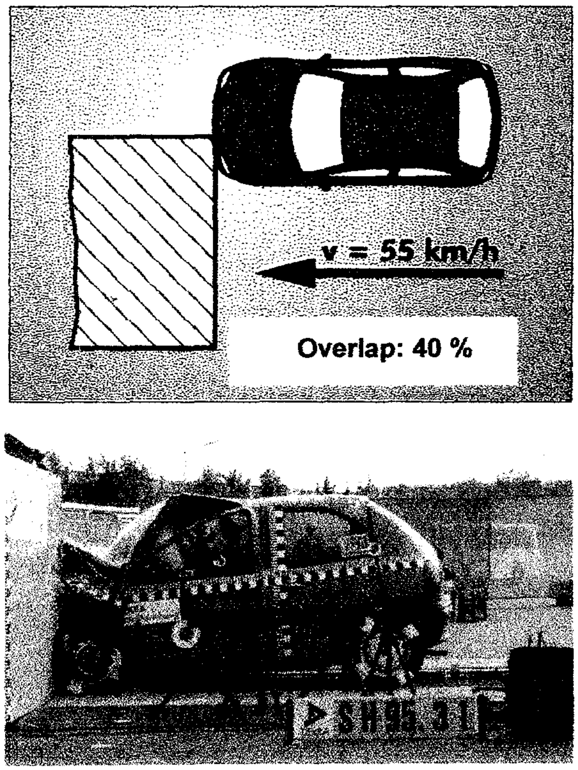


Figure 1. Example of a full-scale crash test

In each test, a belted Hybrid III dummy (50th percentile male) was located in the driver's seat in a normal seating position ("in position"). In the passenger seat an unbelted dummy of the same type was seated leaning forward ("out of position"), **Figure 2**.

The seating posture of the passenger dummy was selected to represent a position which is not normal but also not less realistic. Such a posture for example can occur when the passenger is looking for something in the glove box. Other, in some cases more extreme seating positions were proposed by the automotive industry for evaluating out-of-position vehicle occupant's interactions with inflating air bags (WEZEL, 1992).

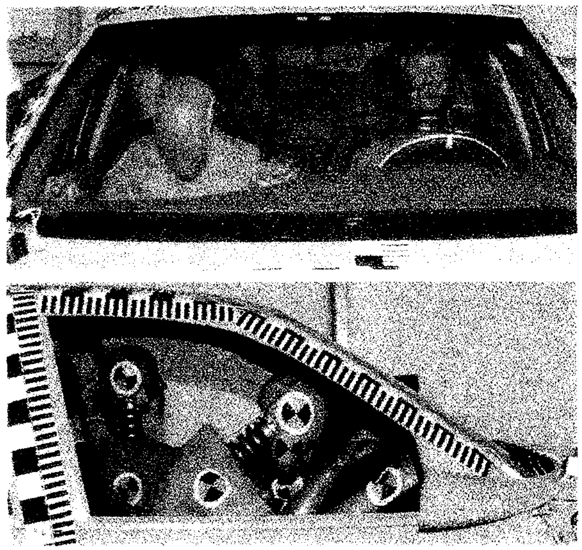


Figure 2. Seating position of the dummies in the full-scale crash tests

Test Vehicles

Table 1. gives an overview of the test speeds and the test vehicles with features of their air bags. The test weights given include both dummies and the installed data acquisition equipment (sensors, transient recorders and cables). The Ford Fiesta was equipped with smaller Eurobags and in the Opel cars were full-size bags. The gas generators in the Ford Fiesta and in the Opel Corsa employ the conventional technology with the propellant sodium azide or nitrocellulose. Hybrid gas generators are installed in the Opel Vectra. Test SH 96.01 serves to compare the loads acting on a passenger who is sitting bent forward without any restraint. The Vectra in test SH 96.02 is the same model as in test SH 96.01 but it is not the same car. In the tests SH 97.03 and SH 97.04 the same Opel Corsa was used. Between both tests, this car was repaired in a body shop with a complete interchange of all parts previously damaged in test SH 97.03.

Kinematics of and Damage to the Test Vehicles

The resulting velocities and the yaw velocities of the four vehicles with 55 km/h collision speed are shown in **Figure 3**. The curves given are results from overhead film analyses, corresponding to targets on the roof of the cars above their gravity centres. The rotational velocities rise to maximum between 2/s and 3/s within approx. 0.15 s. The reason for this is the eccentric impact force which is acting against the car front. The point of maximum rotational velocity gives an indication to the end of the bodyshell compression resulting from the (semi plastic) impact. In

Table 1. Test vehicles and their test speeds

Test No. Test Speed	Test Vehicle Test Weight	Passenger Air bag
SH 94.35 55 km/h	Ford Fiesta Fiesta 1 093 kg	Euro bags Driver: 30 litres Passenger: 60 litres Coated fabric with vent holes Conventional gas generator Propellant: Nitrocellulose
SH 95.31 55 km/h	Opel Corsa 1.2 i 1 136 kg	Full-size bag Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid
SH 96.01 55 km/h	Opel Vectra 1.6 16 V 1 434 kg	Not activated
SH 96.02 55 km/h	Opel Vectra 1.6 16 V 1 450 kg	Full-size bag (120 litres) Driver: 60 litres Passenger: 120 litres Uncoated permeable fabric Hybrid gas generator Argon (98 %), Helium (2 %)
SH 97.03 29 km/h	Opel Corsa 1.4 i 1 049 kg	Full-size bags Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid
SH 97.04 34 km/h	Opel Corsa 1.4 i 1 049 kg	Full-size bags Driver: 67 litres Passenger: 100 litres Uncoated fabric with vent holes Conventional gas generator Propellant: Sodium acid

this phase, the resulting velocities decrease from the original value 55 km/h to approx. 10 km/h. Neglecting the here minimal lateral motion, this gives an average velocity change of delta-v = (55-10) km/h = 45 km/h (12.5 m/s) and a mean deceleration of a = delta-v/delta-t = 8.5 g). Subsequently, the lateral motion of the centre of gravity superimposes its longitudinal motion increasingly. Therefore the resulting velocity does not pass through zero, but rather slightly increases at first and then dies down, until the car comes to a standstill in its final position.

An example of a curve of the longitudinal acceleration

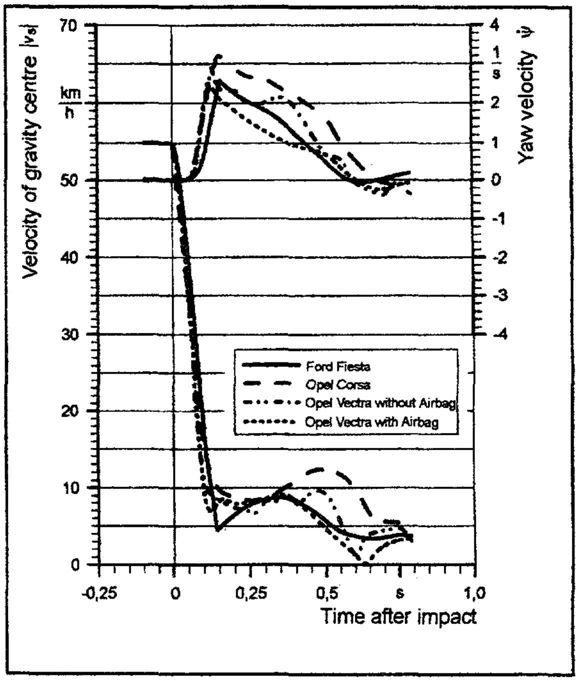


Figure 3. Resulting velocities and yaw velocities of the four cars with 55 km/h collision speed as determined by analysing the overhead films corresponding to targets on the roof of the car

(x-direction) measured at the vehicle is shown in **Figure 4**. The point of measurement is the right sill of the Opel Vectra in the region of the B-pillar base. The minimum of the CFC-60 (SAE J 211 a) filtered acceleration signal is -39,8 g. The corresponding velocity curve is determined by integrating of the CFC-1000 filtered acceleration signal.

Figure 5. gives an overview of the front damage of the four cars with the collision speed 55 km/h. The characteristics are typically for car to car offset crashes in opposing traffic with a severity clearly over the trigger threshold of the air bags. In contrast to the severely damaged driver side with deep intrusions, the passenger side is only of minor damage with less intrusions.

Figure 6. shows for the two tests with 34 km/h and 29 km/h collision speed the resulting velocites and yaw velocities of the Opel Corsa determined by film analysis as well as in Fig. 4. Here the characteristics of the velocities indicate that the crush phase ended near t = 0.12 s in both tests. During this time interval, as shown also in Fig. 6, the vector of the collision induced change of velocity once was delta-v = 29 km/h, in the other case 34 km/h. With delta-v = 29 km/h the air bags in the Opel Corsa did not trigger. Delta-v = 34 km/h triggered them.

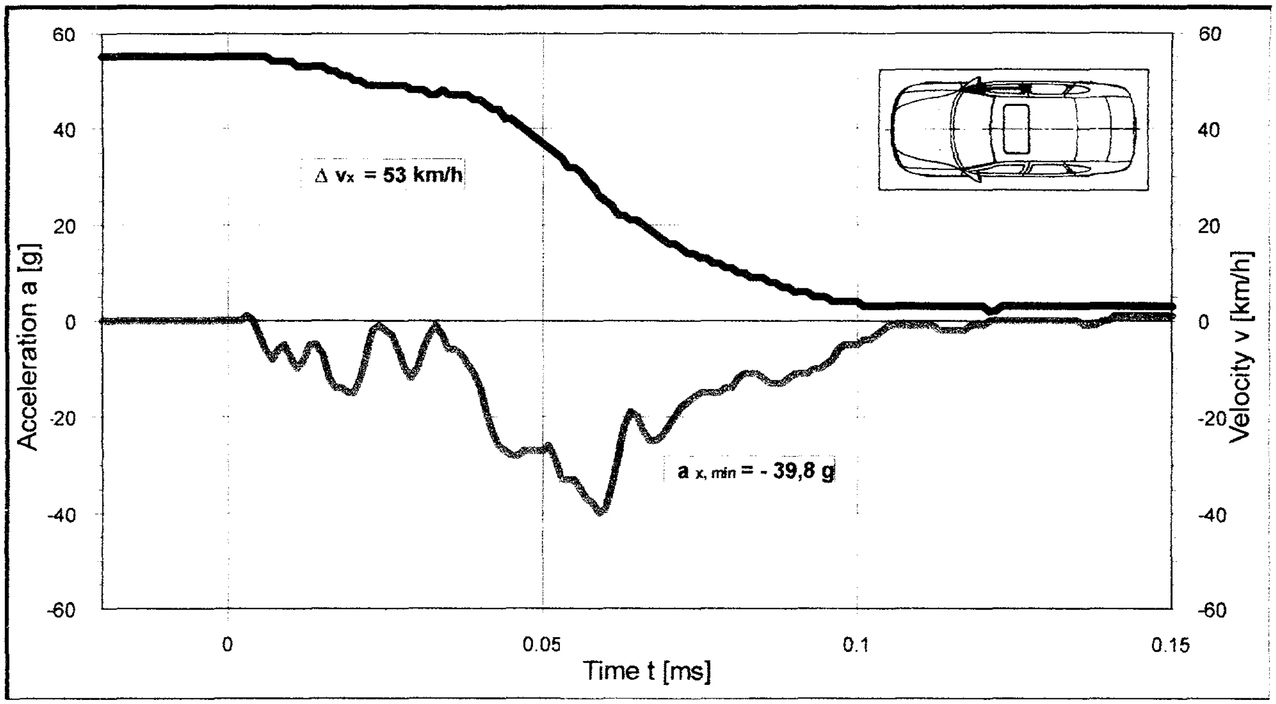


Figure 4. Acceleration measured in x-direction near the roof of the right B-pillar of the Opel Vectra and corresponding velocity (test SH 96.02)

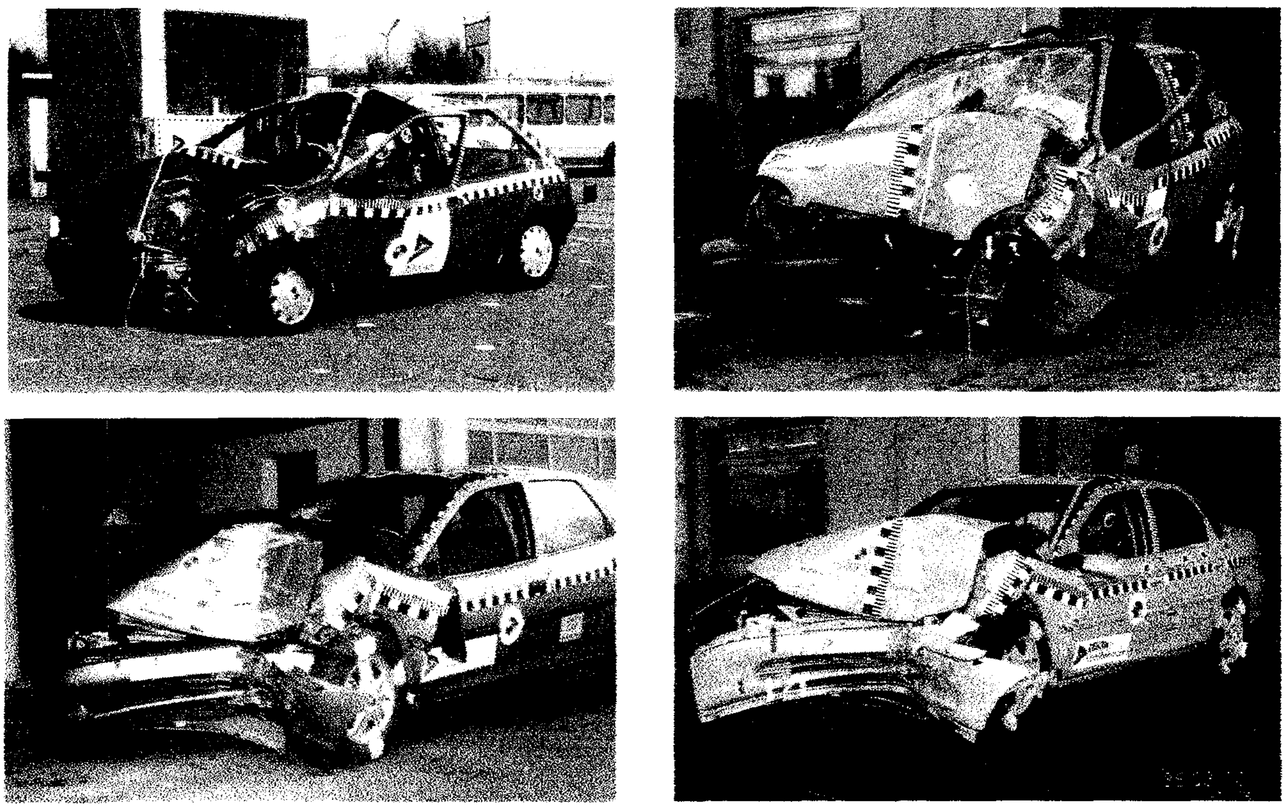


Figure 5. Damage to the frontside of the four test vehicles with 55 km/h collision speed

34 km/h. With delta-v = 29 km/h the air bags in the Opel Corsa did not trigger. Delta-v = 34 km/h triggered them.

Figure 7. shows the longitudinal decelerations (x-direction) measured on the floor of the passenger compartment of the Opel Corsa in the tests with 29 km/h and 34 km/h collision speed. Measurement point was in the centre between the B-pillars. The CFC-60 filtered deceleration signal has a maximum of 27.0 g at t = 59 ms after the start of the crash in the case without air bag activation. In the case when the air bags triggered the maximum of the deceleration signal was 39.6 g at t = 49 ms.

The corresponding velocities were determined by integrating the CFC-1000 filtered deceleration signals. They indicate a path through zero at approx. t = 80 ms. At approx. t = 100 ms the remaining velocity is close to -5 km/h. In the test without air bag ignition, the longitudinal change of velocity at the measurement point was delta-v = 33.7 km/h, in the case when the air bag triggered, it was delta-v = 38.8 km/h.

It should be mentioned that the air bag sensors of the test vehicles have not been installed in the centre of gravity or in the centre between the B-pillar roofs on the floor of the compartment. Therefore the air bag control unit in the tests carried out had not exactly the same acceleration information and velocity change as shown in Figure 3., 4., 6. and 7. But this information must be similar, so that the in Figure 6. and 7. shown kinematics give an idea of the air bag trigger threshold generated by actual designed algorithms in European cars.

An overview of the damage to the front of the car in both tests is given in **Figure 8**. The characteristic of this damage is typical in front to front collisions of two cars in opposing traffic with a medium severity close to the actual

Figure 6. Resulting velocities and yaw velocities in the two tests with 29 and 34 km/h collision speed as determined by analysing the overhead films corresponding to targets on the roof of the cars showed in conjunction with the vectors of the velocities before and after crash and the collision induced change of velocity delta-v

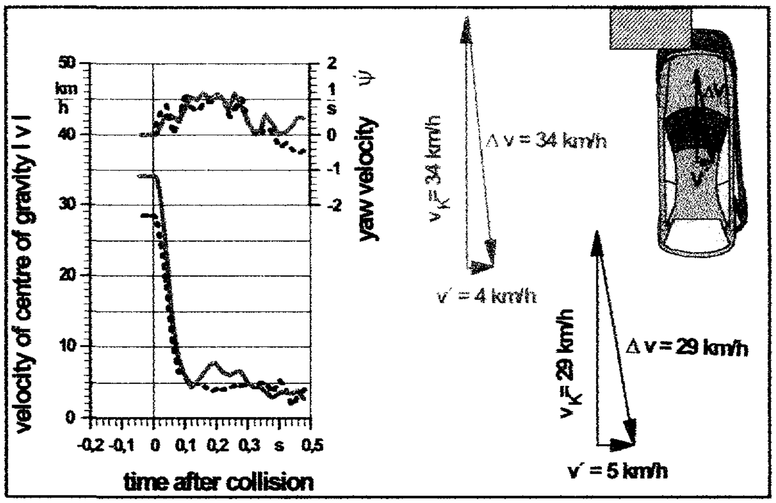
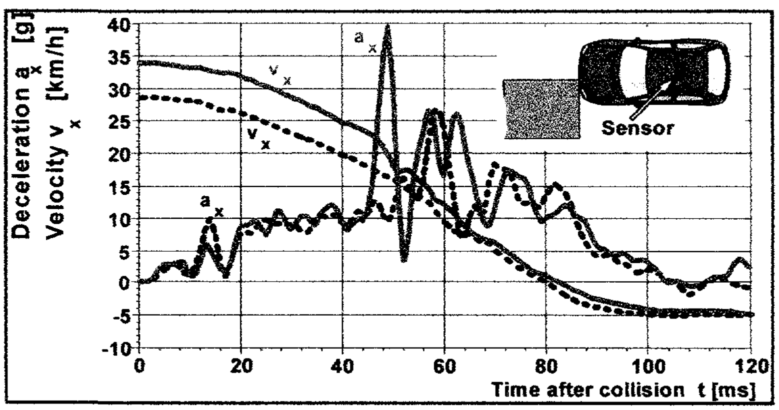


Figure 7. Longitudinal decelerations measured on the floor of the passenger compartment and corresponding velocities in the two tests with 29 and 34 km/h collision speed



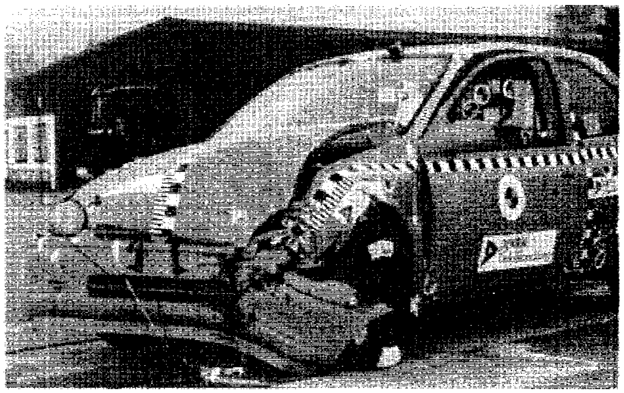


Figure 8. Damage to the front side of the test vehicle with 29 km/h (left) and 34 km/h collision speed (right)

SLED TESTS

Figure 9. shows an example of the sled tests. An overview of the test data is given in **Table 2**.

The simulated collision speeds were in the range of 47 km/h to 50 km/h. The sled retardation in these tests was in the range of 10.0 g to 17.4 g.

The occupants in the compartment on the sled were human cadavers*). The test loadings of the driver were simulated in six tests and of the loadings of the front passenger in one test. The age of the cadavers ranged between 26 and 55 years. In one case the gender was female (driver position, 37 years, weight 55 kg, height 167 cm). In the other cases the gender was male, the height between 170 and 189 cm and the weight in the range 70 to 96 kg. All cadavers were unbelted and at the start of the tests in a normal sitting position. The restraint system was a full-size air bag supplemented by knee bolsters.

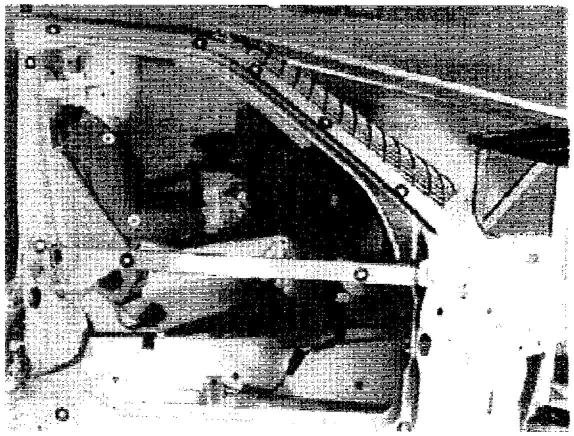


Figure 8. Example of a sled test

*) The ethic and legal precondition to use cadavers in sled tests was an agreement with their relatives who were informed about the test objectives and methods. The presumed or known attitude of the deceased was taken into consideration in the agreement. We are very grateful to all relatives whose agreement supported the improvement of injury prevention through the optimization of safety systems in the name of progress.

Table 2: Overview of the sled tests

Test	Collision Speed [km/h]	Sled Retard. [g]	Position	Height [cm]	Weight [kg]	Age [years]	Gender
L1	50	10,0	Driver	174	75	55	male
L2	50	10,8	Driver	167	55	37	female
L3	48	17,4	Driver	183	90	41	male
L4	47	16,0	Driver	170	70	31	male
L5	49	17,0	Driver	184	74	26	male
L6	47	17,0	Driver	174	79	38	male
L7	50	11,0	Pass.	189	96	29	male

RESULTS

Dummy Loadings in the Four Full-scale Tests with 55 km/h Collision Speed

The loadings measured on the belted driver dummy and the unbelted out-of-position front passenger dummy in the four full-scale tests with 55 km/h collision speed are shown in **Table 3**. In addition Table 3 contains the corresponding protection criteria (according to FMVSS- and ECE-regulations).

No neck loads were measured on the driver dummy in test SH 94.35. No femur loads and no chest loads were measured on the driver dummy in test SH 96.02.

Close to its limit HIC = 1 000 is the Head Injury Criterion HIC = 1 088 of the front passenger dummy in the Ford Fiesta (SH 94.35). Above its limit M_y = -57 Nm lies the extension moment M_y = -136 Nm measured in the neck of the out-of-position front passenger dummy in the Opel Vectra without air bag activation (SH 96.01). Also above its limit a_{3ms} = 60 g lies the deceleration a_{3ms} = 75 g measured in the chest of this unrestrained dummy. All other measured dummy loadings shown in table 3. lie clearly below their respective limits.

Table 3. Dummy loadings measured in the four full-scale tests with a collision speed of 55 km/h

Part of body	Test vehicle (Test number)							Protection criteria
	Front passenger dummy (OOP)				Driver dummy			
	Ford Fiesta (SH 94.35)	Opel Corsa (SH 95.31)	Opel Vectra* (SH96.01)	Opel Vectra (SH 96.02)	Ford Fiesta (SH 94.35)	Opel Corsa (SH 95.31)	Opel Vectra (SH 96.02)	
Head								
HIC	***1 088***	465	556	206	438	245	601	1 000
a_{3ms}	71 g	62 g	64 g	38 g	60 g	50 g	64 g	80 g
Neck								
$F_{x,45ms}$	528 N	45 N	724 N	20 N	-	146 N	66 N	1 100 N
$F_{z,45 ms}$	270 N	552 N	562 N	992 N	-	417 N	323 N	1 100 N
M_y (+) Flexion	133 Nm	26 Nm	0 Nm	68 Nm	-	26 Nm	19 Nm	190 Nm
M_y (-) Extension	-48 Nm	-55 Nm	***-136 Nm***	-29 Nm	-	-36 Nm	-17 Nm	- 57 Nm
Chest								
SI	308	211	704	235	346	332	-	1 000
a_{3ms}	38 g	34 g	***75 g***	37 g	46 g	39 g	-	60 g
Deflection	13 mm	28 mm	11 mm	20 mm	34 mm	35 mm	32 mm	76 mm / 51 mm
Pelvis								
a_{3ms}	35 g	37 g	38 g	35 g	43 g	45 g	57 g	60 g
Femur								
F_{left}	6.3 kN	5.2 kN	6.0 kN	6.2 kN	3.2 kN	3.4 kN	-	10 kN
F_{right}	3.6 kN	2.5 kN	9.6 kN	4.1 kN	9.4 kN	4.3 kN	-	10 kN

* Air bags not activated - not measured OOP: Out of position

Dummy Loadings in the Two Full-scale Tests with 29 km/h and 34 km/h Collision Speed and in the Two Stationary Tests

Table 4. shows the loadings of the belted driver dummy and the unbelted out-of-position front passenger dummy measured in the two full-scale tests (SH 97.03 and SH 97.04) with the Opel Corsa colliding at 29 km/h and 34 km/h collision speed against the rigid barrier. Also included in this table are the measured loadings for the unbelted out-of-position passenger dummy in the two tests with air bag ignition in the stationary Opel Corsa (SH 97.01 and SH 97.02).

Above its respective limit of 190 Nm is the flexion momentum of the neck M_y= 243 Nm of the out-of-position passenger dummy in the dynamic test with 29 km/h collision speed (SH 97.01). Also above the limit is the head acceleration a_{3ms} = 115 g of the out-of-position passenger dummy with the nose close to the dashboard in the test SH 97.01.

All other measured dummy loadings shown in table 4. are clearly under their tolerable limits. It should be mentioned, that in the dynamic tests the head of the unrestrained passenger dummy is not loaded clearly higher than the head of the restrained driver dummy.

Table 4. Dummy loadings measured in the full-scale test with collision speed of 29 km/h and 34 km/h and in the stationary tests

Part of body	Test (Test number)						Protection criteria
	Full-Scale Crashtests				Stationary tests		
	29 km/h Driver (SH 97.03)	29 km/h Pass. (OOP)* (SH 97.03)	34 km/h Driver (SH 97.04)	34 km/h Pass. (OOP)* (SH 97.04)	0 km/h Pass. (OOP)** (SH 97.01)	0 km/h Pass. (OOP)* (SH 97.02)	
Head							
HIC	120	156	484	402	801	49	1 000
a_{3ms}	29 g	37 g	67 g	60 g	***115 g***	35 g	80 g
Neck							
$F_{x,45ms}$	636 N	169 N	180 N	161 N	200 N	192 N	1 100 N
$F_{z,45\,ms}$	288 N	247 N	389 N	143 N	27 N	4 N	1 100 N
M_y (+) Flexion	56 Nm	***243 Nm***	7 Nm	17 Nm	42 Nm	12 Nm	190 Nm
M_y (-) Extension	-10 Nm	-11 Nm	-35 Nm	***-86 Nm***	-34 Nm	-42 Nm	- 57 Nm
Chest							
SI	84	128	151	172	13	3	1 000
a_{3ms}	24 g	34 g	31 g	40 g	12 g	7 g	60 g
Deflection	14 mm	5 mm	11 mm	9 mm	4 mm	2 mm	76 mm / 51 mm
Pelvis							
a_{3ms}	26 g	29 g	33 g	32 g	5 g	2 g	60 g
Femur							
F_{left}	1 kN	-	1 kN	6 kN	1 kN	0 kN	10 kN
F_{right}	1 kN	5 kN	-2 kN	5 kN	1 kN	1 kN	10 kN

* Distance between dummy nose and dashboard: 175 mm
** Dummy nose close to the dashboard (air bag cover) - not measured OOP: Out of position

The restraint system, consisting of belt and bag, relieved the strain on the driver dummy's neck (especially in test SH 97.03) and of its femurs. The chest of the restrained dummy is more deflected but less decelerated.

Loadings of the Cadavers

Table 5. gives an overview of the loadings of the cadaver's head, chest and pelvis measured in the sled tests. The values of chest deflection were measured at the level of the 8th rib. To tests L4, L5 and L6 two 3-ms-values of the chest deceleration are given. The first value was measured at the first thoracic vertebrae, the second value at the twelfth thoracic vertebrae. In the other test only one 3-ms-value is measured at the sixth thoracic vertebrae. Not measured are the forces and moments in the neck of the cadavers as well as their femur forces.

All the measured head loadings of the cadavers clearly lie under their protection criteria. With exception of a_{3ms} = 63 g in test L4 all the other chests were loaded under the limit a_{3ms} = 60 g. In test L6 the measured chest deflection of 72 mm is above the limit of 51 mm valid for tests without an air bag restraint but below 76 mm. This greater limit is valid if an air bag acts on the chest.

All measured pelvis decelerations clearly lie under the respective limit a_{3ms} = 60 g.

Injuries on the Cadavers

To determine the injuries in detail autopsies on the cadavers were carried out. **Table 6.** gives an overview of all the injuries coded according to the Abbreviated Injury Scale (AIS 90). Injuries of AIS 6 (maximum), AIS 5 (critical) and AIS 4 (severe) did not occur.

The maximum injury severity AIS 3 (serious) occured in test L3. Six rib fractures were observed. Furthermore in this test the cadaver was injured with AIS 2 (moderate) at the spinal column (laceration of the ligamentum flavum C6/C7) and with AIS 1 (minor) on the head (abrasion on the left forehead).

AIS 2 was also given in test L1. It was an injury to the spinal column (fracture of the sixth cervical vertebrae, degenerative predefected). In this test, with AIS 1 the thorax (rib fracture) and the headsurface (head rind laceration) were also injured.

In the three tests L2, L6 and L7 the maximum AIS was AIS 1. In two of these cases the spinal column was injured (haemorrhage) and in one case the body surface (skin abrasions at the left upper arm).

In tests L4 and L5 the cadavers remained uninjured.

Table 5. Loadings of the cadavers measured in the sled tests

Part of body	Gender and height (test number)							Protection criteria
	Driver						Passenger	
	male 174 cm (L1)	femal 167 cm (L2)	male 183 cm (L3)	male 170 cm (L4)	male 184 cm (L5)	male 174 cm (L6)	male 189 cm (L7)	
Head								
HIC	86	162	520	426	229	195	224	1 000
a_{3ms}	29 g	34 g	73 g	69 g	51 g	39 g	42 g	80 g
Chest								
a_{3ms}	26 g	33 g	*63 g*	36 g / 49 g	51 g / 46 g	46 g / 50 g	42 g	80 g (60 g)
Deflection	-	-	-	32 mm	38 mm	*72 mm*	-	76 mm / 51 mm
Pelvis								
a_{3ms}	26 g	34 g	41 g	45 g	38 g	44 g	25 g	60 g

Table 6. Severity of injuries determined in authopsies after the sled tests

Test	MAIS	HEAIS	TOAIS	ABAIS	SURAIS	SPAIS	EXAIS
L1	2	0	1	0	1	2	0
L2	1	0	0	0	0	1	0
L3	3	0	3	0	1	2	0
L4	0	0	0	0	0	0	0
L5	0	0	0	0	0	0	0
L6	1	0	0	0	1	0	0
L7	1	0	0	0	0	1	0

AIS: Classification according to the Abbreviated Injury Scale AIS 90
MAIS : Maximum AIS HEAIS: AIS Head TOAIS: AIS Thorax ABAIS: AIS Abdomen
SURAIS: AIS Surface SPAIS: AIS Spinal Column EXAIS: AIS Extremities

It is evident that in the sled tests no head injuries, abdomen injuries or injuries of the extremities occured. The maximum AIS of the body surface was AIS 1 and of the spinal column it was AIS 2. Only the thorax had an AIS 3 injury (six rib fractures) in one case.

Dummy Kinematics

The analysis of the high speed films gives an impression of the movements during the tests and the characteristics of the dummy kinematics in relation to the air bag interaction in those cases with activated bags.

Of special interest are the movements of the unbelted OOP-passenger dummies. Two examples of this are given for the 55-km/h tests SH 96.01 (Opel Vectra with unactivated air bag) in **Figure 9.** and SH 96.02 (Opel Vectra with activated air bag) in **Figure 10.**

The totally unrestrained dummy (Figure 9.) follows its inertia and impacts the front windscreen with the top of the head at t = 70 ms after the start of the collision. As a result of this impact and the superimposed forward motion of the dummy´s torso, the neck becomes extended to the rear. At t = 84 ms the head penetrates the glass of the windscreen which shatters. Furthermore at t = 88 ms the dummy impacts the instrument panel with his left shoulder, followed by an impact of the right shoulder at t = 96 ms. The foremost position of the head is reached at t = 100 ms. Subsequently the dummy moves back. During the rearward motion the dummy head has chin contact with the instrument panel between t = 120 ms and t = 130 ms. Afterwards the head moves back near to his starting position.

In the test with activated air bag (figure 10.) the bag begins unfolding at t = 32 ms after the start of the collision. At t = 36 ms the OOP-dummy touches the unfolding air bag, first with the lower half of the face and shortly afterwards with the upper torso. The mean contact

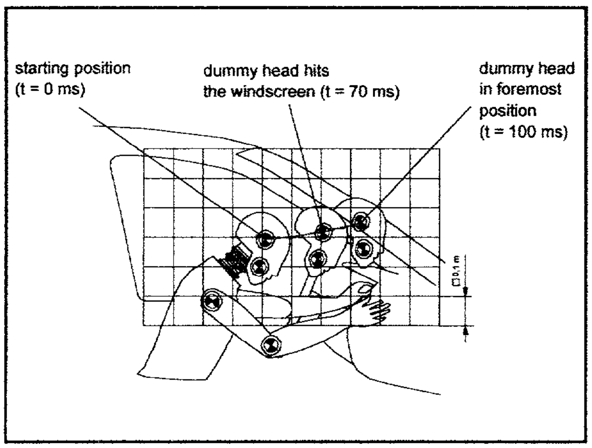


Figure 9. Movement of the unbelted front passenger dummy in test SH 96.01 (55 km/h, Opel Vectra, Air bags not activated)

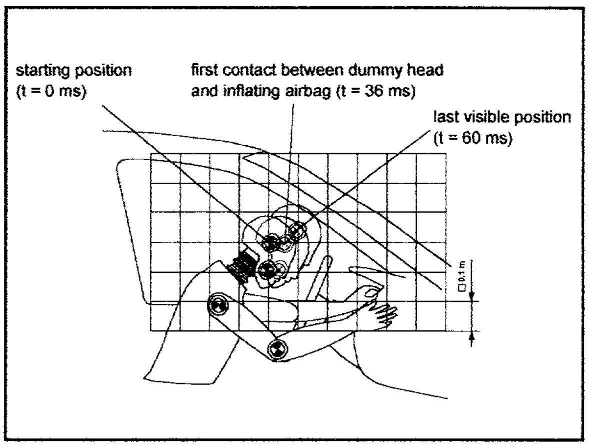


Figure 10. Movement of the unbelted front passenger dummy in test SH 96.02 (55 km/h, Opel Vectra, Air bags activated)

area between the unfolding air bag and the dummy is in the area of the dummy's upper torso. As a result of this, the air bag displaces the forward movement of the dummy in an upward direction. The air bag then forces the dummy, which is still moving forward due to its inertia, into an upward motion. The air bag is thereby compressed more on the left half than on the right. Due to this the dummy experiences a rotation to the right away from the driver. The air bag seam tears open at t = 68 ms. During the upward motion, the dummy impacts the front of the windscreen with the top of its head at t = 70 ms, then penetrates the screen. The front windscreen bows severely as a result of this impact, but remains securely anchored in its frame. Due to the penetration of the windscreen glass the dummy neck is compressed. The forward displacement of the head reaches its maximum at approx. 90 ms. At this moment the dummy has turned through approx. 17° to the right. Subsequently the rearward motion of the dummy commences.

Looking back to table 3. it can be seen that in both described tests SH 96.01 and SH 96.02 the totally unrestrained out-of-position passenger dummy has higher loading at his head than the dummy which has a remaining restrained effect of the air bag. In both cases the head impact to the windscreen is not severe so the head deceleration remains in a mid size region clearly under the tolerable limits of HIC = 1000 and a_{3ms} = 80 g. With a dummy the risk of cut injuries to the the face during the windscreen penetration cannot be measured.

The chest of the totally unrestrained dummy clearly has a higher acceleration loading than the chest of the dummy with remaining restraint effect of the acting air bag but the dummy's chest deflection in the test without air bag activation is smaller.

Not visible in the high speed films is the significant higher loading of the right femur of the totally unrestrained dummy in test SH 96.01.

In conjunction with the monitored movements it is evident that the measured extension moment of the neck M_y = -136 Nm of the totally unrestrained dummy is more than twice as high as the corresponding tolerable limit of -57 Nm. As a main result of the tests SH 96.01 and SH 96.02 should be mentioned that the neck seems to be the most endangered body part of the out-of-position passenger who has no remaining effect of an acting air bag.

The movement of the unrestrained out-of-position passenger dummy in test SH 97.03 with 29 km/h collision speed and not triggered air bag is shown in **Figure 11.** Corresponding to this in **Figure 12.** the movement of the same dummy in test SH 97.04 with triggered air bag is shown.

In test SH 97.03 the inertia of the totally unrestrained passenger dummy leaning forward out-of-position causes a pronounced forward movement relative to the vehicle beginning at t = 26 ms after the start of the collision. At t = 77 ms the dummy's head strikes the dashboard first with the nose and then with the mouth. This leads to a forward movement of the head with a forward bending (flexion) of the neck. The forehead then contacts the dashboard at t = 90 ms. This is the point at which the flexion of the neck reaches its maximum. At t = 105 ms the dummy is at its most forward position. As the movement continues the dummy's body falls back into the seat.

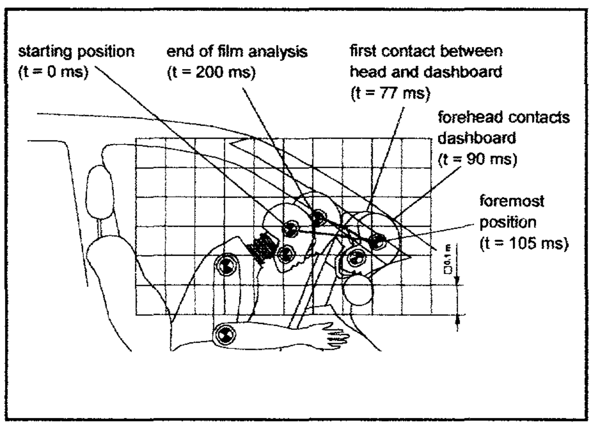


Figure 11. Movement of the unbelted front passenger dummy in test SH 97.03 (29 km/h, Opel Corsa, Air bags not triggered)

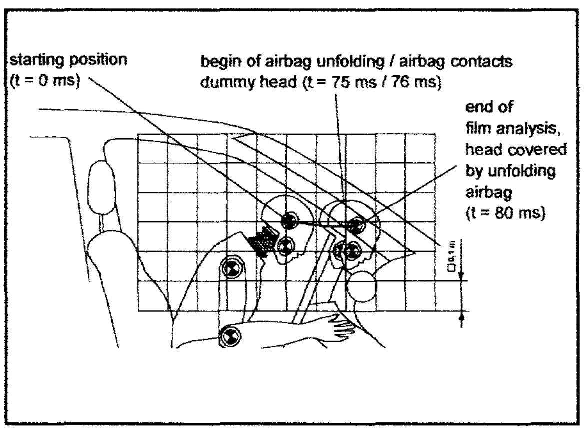


Figure 12. Movement of the unbelted front passenger dummy in test SH 97.04 (34 km/h, Opel Corsa, Air bags triggered)

In test SH 97.04 the inertia induced forward movement of the out-of-position passenger dummy begins at t = 29 ms after the start of the collision. At t = 75 ms the emergence of the air bag from the dashboard and its subsequent unfolding begins. At t = 79 ms the air bag touches the dummy's face on the right hand side. At this stage the dummy head is above the air bag, which is inflating beneath it. The further deployment of the air bag under the dummy's torso is displaced to the right. As the forward movement proceeds, the crown of the dummy's head strikes the windscreen at t = 84 ms. This results in some areas shattering and deformation of the glass. The air bag is fully deployed at t = 104 ms. The forward displacement of the dummy relative to the vehicle is completed by t = 102 ms when the head has its maximum penetration into the windscreen. A maximum deformation depth of approx. 23 mm was later determined in this region. As the sequence continues the dummy falls back into its seat.

Looking back to table 4. it can be seen that the head of the out-of-position passenger dummy in test SH 97.03 with 29 km/h collision speed (without air bag trigger) is less severely loaded than the head of this dummy in test SH 97.04 with 34 km/h collision speed (triggered air bag). In both tests the tolerable protection criteria of the head were not reached.

In the test without air bag triggering the chest of the passenger dummy is on a lower deceleration level than the chest of the dummy in the test with a 5 km/h higher collision speed (triggered air bag). The chest deflects more when acting with the air bag than in the case without air bag triggering. Chest retardations and deflections are clearly below their tolerable protection criteria.

With a flexion moment of 243 Nm clearly above the limit of 190 Nm and in conjunction with the monitored kinematics should be mentioned that the neck of the totally unrestrained out-of-position passenger dummy in test SH 97.03 is the most endangered part of his body.

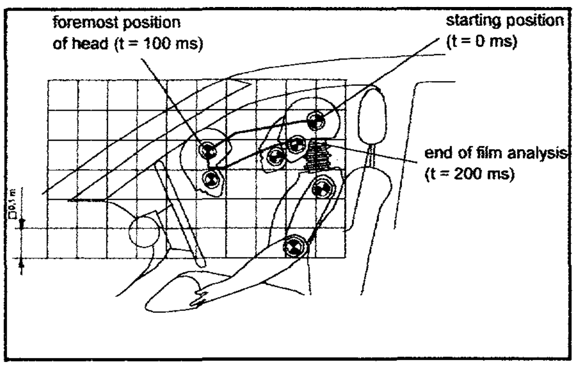


Figure 13. Movement of the belted driver dummy in test SH 97.03 (29 km/h, Opel Corsa, Air bags not triggered)

To complete the description of dummy movements, **Figure 13.** contains the results drawn from the film evaluations for the driver dummy, restrained only by his safety belt in test SH 97.03 (without air bag triggering). The forward displacement of the head ends at t = 100 ms after the start of the collision before a contact with the steering wheel is possible. In conjunction with the measured loadings of this dummy as shown before in table 4 it is evident, that there is no potential for severe or life treatening injuries. Therefore it is consequent that the air bag did not trigger in this test because it was clearly not necessary.

Figure 14. shows the drawn results of film evaluation for the belted driver dummy in test SH 97.04 (with triggered air bag). In this test the air bag is completely unfolded at t = 86 ms after the start of the collision. 20 ms later the air bag has restrained the head completely and no contact of the head with the steering wheel occurs. As shown in table 4. before all measured loadings of this dummy lie clearly under their protection criteria. To summarize the seat belt and the air bag which was also triggered effectively protected the driver dummy.

Cadaver Kinematics

The sled tests also were filmed by high speed cameras from the side in order to analyse the movements of the cadavers and their interactions with the air bag. In all tests the driver has full passive protection from an air bag (volume 70 litres) supplemented by knee bolsters. The begin of the air bag unfolding was visible 8 ms after the begin of the collision.

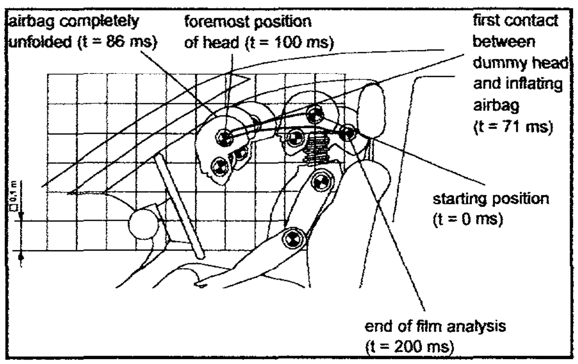


Figure 14. Movement of the belted driver dummy in test SH 97.04 (34 km/h, Opel Corsa, Air bags triggered)

The time interval to complete the unfolding of the air bag was ascertained to 30 ms.

The drivers remained in forward movement caused by inertia after the beginning of the simulated collisions. Between t = 45 ms and t = 50 ms after the start of the collision the knees make contact with the knee bolsters. At the same time the air bag touches the central region of the cadaver's chest and chin. Between t = 70 ms and 80 ms an extensive energy absorbing and restraining interaction to the head and torso was given by the air bag.

The movement of the head occurs in forward and upward direction (x-z-plane). It was stopped at t = 80 ms to t = 90 ms after the start of the collision by a head impact to the upper region of the windscreen or to the roof area. The neck bending backwards (extension) reaches its maximum between t = 110 ms and 120 ms. In this phase the forward movement of the torso was not totally completed. This results in a bending of the neck induced by a superimposed thorax movement and a retroflexion of the head and neck caused by the impact of the head.

During the torso movement in forward direction could not be observed in all tests a symmetrically restraining effect of the air bag. In some cases this leads to a rotation of the head and torso around their vertical axis.

The volume of the air bag on the passenger side was 150 litres. In this test the kinematics of the cadaver on the passenger seat was similar to described above movements of the drivers. It should be mentioned that clear forward displacements of torso and abdomen could be observed in this test. Followed by a head impact to the windscreen a backwards bending of the neck occurs with an extension angle of more than 90°.

DISCUSSION AND CONCLUSIONS

The life saving benefit of air bags as a supplement of safety belts has been proven in real life accidents many times over.

OTTE (1994) analysed a sample of 13 cases with air bag activation in cars with a collision induced change of velocity in the range delta-v = 12 to 55 km/h. The maximum injury severity of all belted drivers was MAIS 2. It was a result of this accident analysis that the main protective effect was given by the safety belt.

An evaluation of driver injuries in 400 Mercedes-Benz cars involved in accidents with air bag activation concluded that the air bag substantially reduced the maximum injury severity in severe accidents (ZEIDLER, 1994). With an Energy Equivalent Speed up to EES = 60 km/h in 137 Mercedes cars of the newer series with triggered air bags no occupant injuries to the head and neck occurred with a severity more than AIS 3. In 292 cases involving cars of the same series but without an air bag, head and neck injuries with a severity AIS 4 to AIS 6 were given in some cases with an EES of more than 51 km/h.

Accident analysis of the BMW accident research agree with these results. In accidents with frontal collisions and severe or fatal injuries (MAIS 4 to MAIS 6) of belted drivers occurred in single cases with an EES of more than 40 km/h. In frontal collisions with a triggered air bag acting as a supplement to the safety belt up to an EES = 60 km/h the maximum of the injury severity was MAIS 3. This means that no occupants were severely injured or killed in cars equipped with air bags in this accident sample (MESSNER and HÜBNER, 1996).

Similar results are given by a study of 47 German accident hospitals to ascertain the injury patterns of car occupants saved by air bags. The analysis of 119 accidents of the year 1993 led to the result that their injuries in the region of head, neck and thorax were mostly of minor severity (SCHLICKEWEI et al., 1995). Partially air bag induced contusions and abraisons could be observed in the region of thorax and face.

The American National Highway Traffic Safety Administration NHTSA published in 1995/96, that in the USA since 1987 the air bag has saved 1 500 drivers from fatal injuries, 570 of them only in the year 1995. Furthermore NHTSA estimated that at least in 164 crashes air bags avoided fatal injuries of front passengers in cars (BIGI, 1995; VDA-Mitteilungen No. 2., February 18, 1997). Although in the USA 19 fatalities on the driver side and 32 deaths of children on the front passenger side were registered in accidents with air bag triggering in low speed crashes. The majority of these people did not use safety belts or child restraints. Some of the fatalities were children in rearward facing child restraints placed in the front passenger seat with activation of the corresponding air bag.

There is a greater probability that unbelted occupants are "out of position" in the moment of the air bag ignition. Therefore it is possible that they came into contact with the air bag during its inflation. Even an unbelted occupant who is sitting in a normal position can come into such an out-of-position situation as a result of the inertia acting in the phase of pre-crash braking.

The fast upcoming of air bag equipped cars of all categories could lead to an increase in the number of reported accidents with air bag-induced injuries of occupants. Corresponding cases are published by ZUPPICHINI et al. (1994) and LÖHLE (1996). To judge the injuries it is necessary - as in cases with acting of a safety belt only - to indicate and separate injuries which are of minor severity and therefore in severe accidents tolerable. On the other hand it is necessary to indicate and describe severe and fatal injuries which are induced by an air bag. This is the input needed for the further development of smart restraint systems which are acting in function of the accident severity.

Some test results published earlier (BERG et al., 1995, BERG et al., 1996) and repeated in this article have shown that even an unbelted forward leaning out-of-position front passenger in crashes with 55 km/h collision speed and 55 % frontal overlap against a rigid barrier could obtain a residual protection from an air bag. Therefore it is to be expected that life threatening contacts with the air bag in its unfolding phase could be a result of more extreme forward bent postures.

SCHMITZ (1997) published results from nine sled tests (collision speed 50 km/h) with two different dummies (50th percentile male, 5th percetile female) and a variety of sitting positions. Increased stresses were indeed measured both on an unbelted dummy and on a dummy sitting in a forward leaning posture, but these nevertheless lay below the appropriate protection criteria. Dummy loadings which would predict serious or fatal injuries were established in a case of extreme sitting posture, a sleeping position with the seatback reclined. However the immediate effect of the air bag was not significant in respect of the high forces but rather the unfavourable sequence of dummy movement.

The overview of the results of the dummy tests with 55 km/h collision speed and of the cadaver sled tests with 47 to 50 km/h collision speed shown in this article do not lead to an identification of body parts which are at high risk of injury. Neither the comparison of the measured loadings in the tests nor their distance to appropriate protection criteria or the AIS ranking of the injuries of the cadavers show systematically features. Most frequent were injuries to the cervical spine. However, the most severe injury occured to the thorax. It should be mentioned in this context, that there is an influence of the age and anthropometric characteristics to the response of mechanical loadings and to the injury risk of human cadavers. YOGANONDAN et al. (1993) *published results* from similar sled tests with cadavers (age between 70 and 75 years) suffered up to 10 rib fractures. In contrast to the autopsy results described in this article, these rib fractures often were in the lower region of the frontal thorax.

A residual protective effect of air bags for unbelted occupants in non-extreme out-of-position situations could not be established with equal clarification from the two full-scale tests with 29 km/h respectively 34 km/h described in this article. The neck of the dummy in the tests without air bag triggering (29 km/h) was stressed with a flexion moment well above the appropriate limit. In the test with air bag triggering (34 km/h) the permitted limit for the extension moment of the neck was clearly exceeded. However the neck loading was not caused so much by the air bag as by the contact with the windscreen. The deployment of the air bag, and with it the restraining effect, was hindered by the torso and head of the dummy to such a degree that a severe impact of the head against the windscreen could not be avoided.

The risk of injuries induced by the air bag increases in cases of extreme out-of-position situations. In this article two tests are described where the air bag was activated in the stationary vehicle. When the dummy sits bent forward in a non-extreme posture with a distance of 175 mm between its nose and the dashboard all the measured loadings are lying below their appropriate protection criteria. In an extreme posture with the nose close to the dashboard (air bag cover) however, the acceleration value of the resulting head movement enforced by the cover opening and air bag unfolding, are lying clearly above its limits.

Tests with cadavers also indicate an increased injury risk if there is immediate contact between parts of the body and the air bag cover at the beginning of the air bag release (SCHROEDER et al. 1997). Thus, for example, acceleration loadings of the head were measured above the appropriate protection criteria. In one case an open fracture of the nose occurred which was related to the impact of the air bag cover. Serious injuries of the neck vertebrae also were found.

Only a few cases are known from the history of real world accidents in Germany which give reason to suppose that effects of an air bag could lead to fatal injuries. Among these is the case of a belted female passenger (age 57 years, height 157 cm, weight 67 kg) in a taxi which collided head on at a speed of approx. 30 km/h with a tram at an angle between 80° and 85° (MAXEINER and HAHN, 1996). Both full-size front air bags in the taxi triggered. The driver suffered slight injuries, but the front passenger received very severe injuries to the neck vertebrae from which she died 13 days after the accident. Skin abrasions to her face provided evidence of an aggressive air bag contact. It was established that the front passenger seat was almost in the foremost position. An active forward bending movement of the torso immediately before the crash was suspected. The woman was wearing thick, bulky winter clothing and her safety belt was correspondingly loose. As the air bag released an extreme out-of-position situation caused by a further increase in the forward movement of the torso resulting from pre-crash braking and the impact deceleration can therefore be assumed.

Other published reports on air bag induced fatalities of out-of-position front passengers in cars also points to the neck vertebrae as the most endangered body part (HUELKE, 1996). In particular the loading of the neck vertebrae in its z-direction while the superimposed dynamic extension of the neck could lead to overcritical stresses in this region.

Furthermore an asymmetric contact between the unfolding air bag and the face of an out-of-position passenger could lead to a rotational loading of the neck vertebrae. This was observed on both dummies in the 55 km/h-test with the Ford Fiesta. Under such circumstances the tolerance limits of the neck loadings could be lower than under symmetrical stresses. To define adequate protection criteria, more reliable traumatomechanical studies are necessary. In particular this is relevant for the "soft tissues" like arteries, veins, nerves and muscles as for the human pain- and loading-sensors in the muscles, ligaments and condyles of the neck vertebrae.

The fact that mechanical dummy loadings did not reach their useful corresponding protection criteria (forces in x- and z-direction, bending moments in y-direction described as extension and flexion) do not guarantee that in real life accidents under similar conditions no injury to the involved occupants is possible. This is verified in particular in the results of cadaver sled tests. In this context it should be mentioned that in traumatomechanical tests with human cadavers the loading of the neck vertebrae often is underestimated (MATTERN, 1994; MATTERN et al., 1995).

Out-of-position situations of vehicle occupants are - in contrast to situations with a normal belted seating position - fundamentally undefined and numerous. The effect of an air bag acting to an occupant concerned in an abnormal position is therefore very dependent on the individual circumstances. These difficulties are being taken into account in the further technical development of smart air bags through graduated gas generators output, adjusted to the severity of the accident and to occupant parameters (BIGI et al., 1996).

To follow the philosophy predominant in Europe the air bag is not an autarchical restraint system. That means that the air bag has to supplement the safety belt. Therefore it is consequent not to design the air bag trigger threshold too low. As shown in the offset tests with 29 km/h and 34 km/h impact speed it was sufficient that the air bags did not trigger in the test with 29 km/h. In such crashes the safety belt alone delivers an adequate protection - if the occupants are using their belts.

Against this background there is a considerable need for objective public clarification of the mutual effects of air bags and safety belts, as well as of possible dangers in out-of-position situations and cases of misuse. The air bag has opened up possibilities for further reducing the number of vehicle occupants killed in accidents. A prerequisite for the realisation of these possibilities is the widespread fitting of air bags to all cars as far as possible. Tragic exceptions and the danger of injury in extreme circumstances are reasons for further development. However, the protective potential and the benefit of air bags today has been proven not only through tests, but repeatedly by the history of real world accidents.

ACKNOWLEDGEMENT

It is our pleasure to thank the Adam Opel AG, Technical Development Centre Europe, Rüsselsheim, for the surrender of two Opel Vectra and one Opel Corsa in the framework of the carried out full-scale crash tests.

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