Collision Safety of a hard shell low mass vehicle

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Abstract

Low mass vehicles and in particular low mass electric vehicles as produced today in very small quantities are in general not designed for crashworthiness in collisions.
Particular problems of compact low mass cars are: reduced length of the car front, low mass compared to the other vehicles and heavy batteries in the case of an electric car.
With the intention of studying design improvements, three frontal crash tests have been run last year: the first one with a commercial light weight electric car, the second with a reinforced version of the same car and the last one with a car based on a different structural design with a "hard shell" car body. Crash tests showed that the latter solution made better use of the small available zone for continuous energy absorption.

The paper discusses further the problem of frontal collisions between vehicles of different weight and in particular the side collision. A side collision test was run with the "hard shell" vehicle following the ECE lateral impact test procedure at 50 km/h and lead to results for the EuroSID 1 - dummy well bellow current injury tolerance criteria.

Introduction

Collision safety in frontal collisions depends on the quality of the restraint system together with an appropriate structural behaviour of the car structure- especially the passenger compartment- during collision.

Starting this project on collision safety of small low mass cars, a first step was to find out what level of collision safety a commercially available low mass car offered and to study small structural design modifications which would increase the safety level. Furthermore a different approach should be tried which is called "hard shell" or "impact belt" approach. A general discussion of the safety of low mass vehicles and first results of the tests performed were published earlier by the same authors (Walz et al 1991; Kaeser, Walz 1992; Kaeser 1992). Other authors have focussed on the topic of general traffic safety and possible safety improvements (Tarr 1991, Rio 1991).

These considerations are the base of three tests described in the following.

Fig 1 Small low mass vehicle after frontal crash at 33.5 km/h. Hard shell concept with a stiff "impact belt" encircling the whole car.

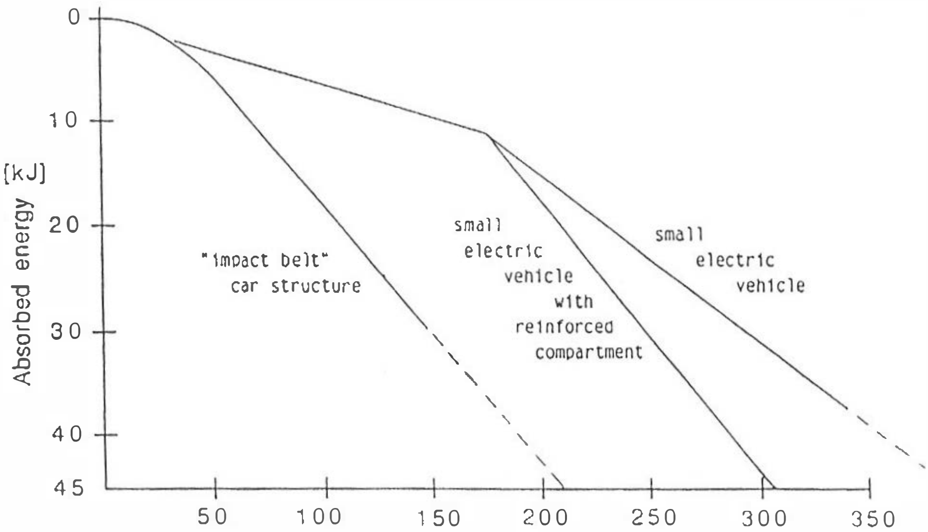


Fig 2 Structural stiffness and energy absorption of three different light weight electric vehicles in a frontal collision against a wall.

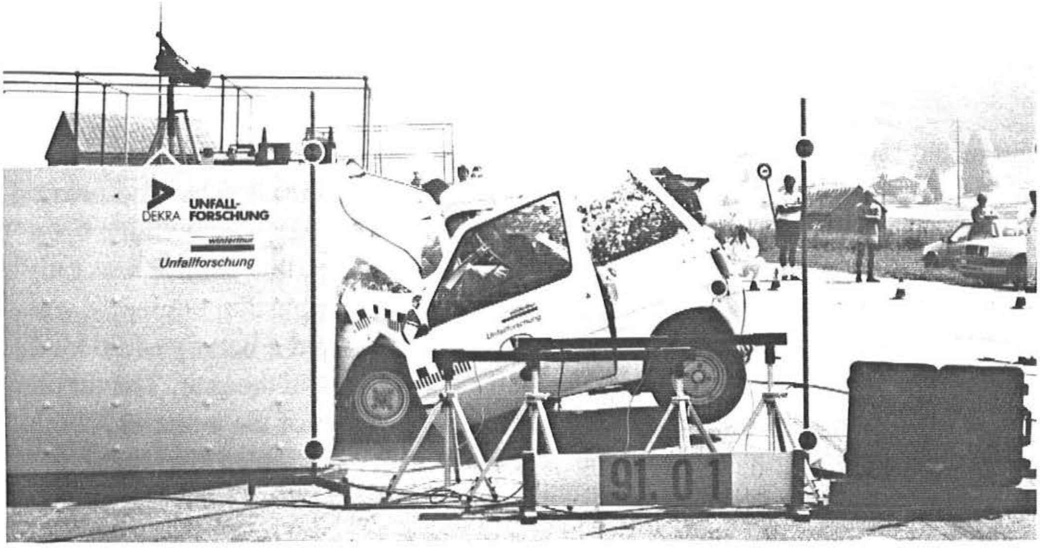
Frontal collisions against a wall: Results of tests with three different low mass cars

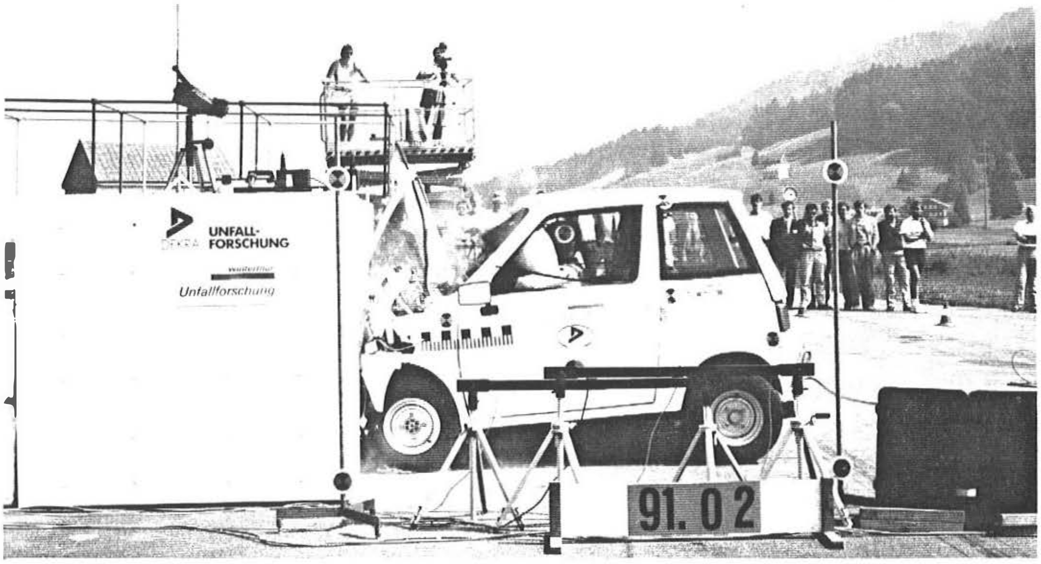
The first tested low mass electric vehicle (m=620 kg, l=2.49 m) had been designed -apart from the installed safety belts - without considering crashworthiness. The load bearing structure consisted essentially of a light frame of tubes with rectangular cross sections upon which a body made of fiberglass and polyester was mounted. Initially, this vehicle was only produced for use at low velocities (40km/h) with a small internal combustion engine. It was modified for use as an electric vehicle installing an electric traction and a battery of 50 kg in the car front and putting more batteries (200 kg) behind the two seats in the rear. The tubular frame under the floor is mainly responsible for the structural stiffness of the vehicle. As this frame is far below the center of gravity of the car, a slight rotatory motion around the transverse axis took place during collision resulting in a pronounced raise of the rear of the vehicle. A frontal impact of this car against a wall at an impact velocity of 40 km/h showed the expected results: collapse of the frame and the body under relatively low loads, therefore large deformations and collapse of the car interior, large forward movement of the rear batteries intruding strongly into the compartment and hitting the back of the seats. There would have been no chance for occupants to survive without severe injuries.

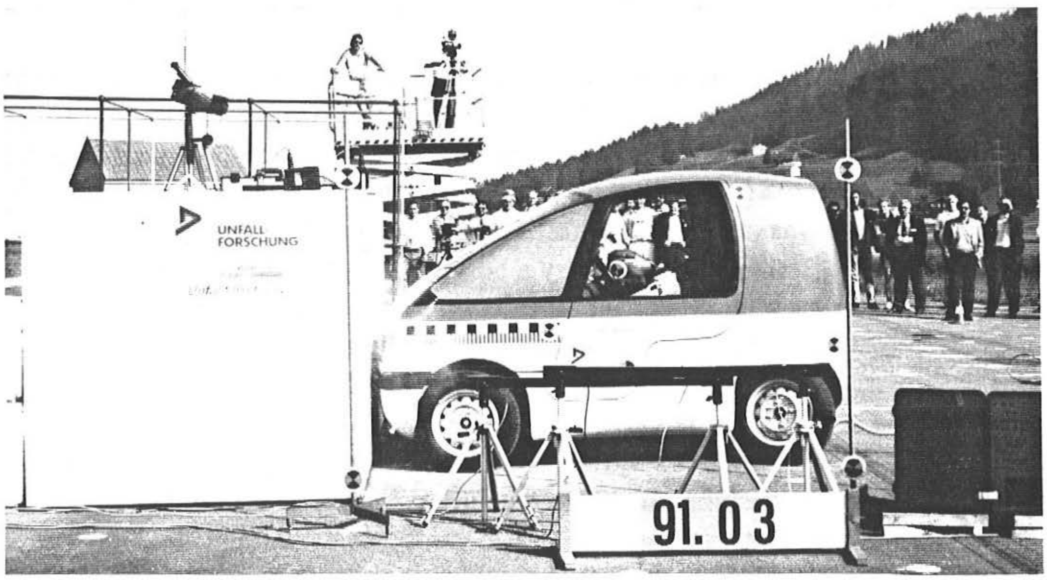
A second sample of this light electric car was tested after a reinforcement of the frame. To prevent intrusion from the traction unit into the passenger compartment a steel beam was placed behind the traction unit and supported by bars on both ends transmitting forces to the strongly reinforced longitudinal beams on both sides of the frame. Attachment of the safety belts as well as the batteries were adapted to sustain the forces under decelerations of more than 30 g. With these reinforcements and the installation of a small "Eurobag" in the steering wheel a vehicle mass of 680 kg resulted. The weight difference of 60 kg could be reduced to less than 20 kg if the structural modifications were introduced into the basic structure. The reinforced vehicle behaved in a satisfactory manner during impact. The car interior was not affected by intrusion. Partly also due to the Eurobag the head acceleration of the dummy in the reinforced version was reduced from 128 g to 51 g (level for 3msec) and the HIC level from 2230 to 421, see table 1.)

The design of the third car was based on the concept of a low mass vehicle with a hard shell which shall protect nearly the whole car interior from large intrusions of exterior impacting objects. The hard shell deforms under relatively high loads leading to high deceleration of the vehicle to which the whole load bearing structure must correspond (inertia loads of the batteries, of the occupants and of other large masses). Stiffness of the "hard shell" is chosen such that compatibility in collisions with heavier cars should be provided to a certain extent. This means that the forces under which the car front will undergo large plastic deformation should be at least just a little larger for the light car than for the heavy one. The required stiffness of the shell is provided mainly by a hollow fiberglass composite beam of approximately rectangular cross section which is integrated to the shell in a height above floor corresponding to the height of the bumper of an impacting car. Due to the chosen stiffness of the car front the deformation during frontal collisions is so small that the required survival space for the safety of the occupants is not affected.

The curves in Fig 2 characterize the different impact behaviour of the tested cars. The main difference in the force deformation characteristic during impact of the hard shell " impact belt" car compared with conventionally designed car fronts is, that plastic deformation takes place under a high force level from the very beginning, thus making best use of the small zone







Solec 90 Original, Solec 90 reinforced after the crash, Horlacher "impact Bell" after the crash

	Solec 90 Original	Solec 90 reinforced	Horlacher "impact Belt"
impact velocity	11 m/s (39.6 km/h)	11.2 m/s (40.3 km/h)	9.3 m/s (33.5 km/h)
mass of vehicle	621 kg	684 kg	552 kg
Head acceleration (3 msec)	128 g	51 g	45 g
HIC	2230	421	292
max floor acceleration	351 g	86 g	84 g
max impact deformation	340 mm	298 mm	138 mm
remaining deformation	310 mm	230 mm	20 mm
mean force during high energy absorption	250 kN	160 kN	260 kN

Table 1 Frontal crash tests with three different low mass vehicles

for energy absorption. The first and the second tested car show nearly identical energy absorption curves during a first phase of the impact. This is not surprising as the fronts of both cars are identical from the bumper to the traction unit. With the action of the beam preventing intrusion of the traction unit the gradient of absorbed energy increased much more with the reinforced car structure. However, with the first two tested vehicles, along a distance of more than 170 mm deformation took place under a very low load level wasting a great portion of the small front usable for energy absorption.

In Table 1 some characteristic data and results of the three crash tests are put together. Damage on the "impact belt" vehicle after the frontal crash test was relatively small. It can be assumed that the vehicle will resist a frontal crash against a wall at 50 km/h (with 2.2 times the collision energy compared to 33.5 km/h). The "impact belt" vehicle has been repaired after the frontal crash and has been used in a side crash test at 50 km/h (describe later). After the side crash test the vehicle has been repaired again and is prepared now for a 50 km/h frontal crash against an AUDI 100 cruising at 25 km/h, resulting in a delta-v of 50 km/h for the "impact belt" vehicle.

Towards frontal collision safety of small low mass cars

The crash test with the " impact belt" vehicle indicated how small low mass cars could be designed to obtain safety for the occupants in collisions with fixed objects like a wall. Now, what about safety in collisions between low mass cars and heavy cars? The handicap of the low mass car is that it undergoes a larger delta-v than the heavy car. As the front of the low mass vehicle is short, it is necessary for the heavier car with its larger deformable front to absorb to a large extend the kinetic energy. This means that the front of the larger heavier car must deform under a lower load level than the front of the low mass car. Deceleration peaks of the car body of 20 g during deformation of the crush zone in an impact are in the order of magnitude of current vehicles with a mass of about 1200 kg. In an impact with this vehicle of 1200 kg, a vehicle of 500 kg will experience a deceleration of 48 g. In a collision with a delta-v of 50 km/h, a deceleration level of 50 g results in a deformation of about 20 cm and this is even feasible with a very short car front.

The mean deceleration of the "impact belt" car in the phase of deformation under large forces was in the order of 48 g in the crash test at 33.5 km/h. It can be assumed that this vehicle fulfils or nearly fulfils the condition of impact force compatibility in collisions with heavier cars. Therefore it can be concluded that low mass vehicles can be designed whose load bearing structures withstand to a certain extent impacts with current cars with weights between 1000 and 1500 kg. This seems feasible even at a delta-v of 50 km/h. With an impact resistant "hard shell" car front the frontal collision safety problem of the low mass car can be reduced to the development of appropriate car interiors with sufficient free space in front of the occupants and corresponding restraint systems for large ride down distances.

A frontal collision between the impact belt against a current 1200 kg car will be run in august. First results will be presented at the conference.

Side collision

With current cars the critical event in a side impact is the blow on the occupant impacted by the door intruding the car interior at high velocity. This is the main cause for the severe injuries occupants suffer during side impacts. Encroaching could be prevented to a large extent if the door and the surrounding structure were designed such that they behave together like a continuous load bearing unit. They would be accelerated and deformed as a whole during the side impact on a vehicle. This can be realized to a large extent by designing the door as well as the side bars (sills) under the door as beams with high stiffness which is preserved during large deformations. This requires much larger beam cross-sections as they are in use today in car side structures. Again the mentioned "impact belt" seems a good attempt to solve this problem. Interlocking of the door with the surrounding structure by appropriate joints would help further to improve structural integrity during side impacts. Structural integrity is achieved easier in a short two door car.

If the door is pushed into the passenger compartment without being held by the car side structure, the delta-v, to which the occupant is exposed, corresponds to the velocity of the striking car; in the case of a car impacting the door at 50 km/h, delta-v would also be 50 km/h. On the other hand, with a side structure resistant to impacts delta-v would be the same for the struck car as for the occupant. In this case, an impact, following the European side impact test procedure with a mobile barrier of 950 kg impacting at 50 km/h. The side of our vehicle of 500 kg, would sustain to a delta-v of 33 km/h. This is an impact velocity which can be survived without severe injuries by an occupant if appropriate padding is applied to the impact region.

If encroaching of the door can be prevented it makes sense to apply padding on the door as a protection for the occupant who will hit the door when the whole car is accelerated by the impacting car. Corresponding to these considerations the Horlacher (see acknowledgments) "impact belt" vehicle has been padded in the interior on the door and the B pillar with two foam layers. The layer getting into contact with the occupant is a flexible foam with a nearly constant force deformation characteristic. The second layer between the first layer and the car structure is a hard foam deforming under approximately constant force. Foam properties and layer thickness must be chosen such that the forces and the deformations which the body of the occupant undergoes when are below human tolerance limits. The chosen force deformation characteristic for a first test is shown in Fig. 3. Total thickness of the door padding was 8 cm consisting of a 3 cm layer of flexible foam (DOW 82-35-1) on a 5 cm hard foam (DOW Polyol Specflex ND 730 Isocyamate). Compared to side crash test of padded cars run by other authors [J. Rio et al (ESV 91-55-0-10)] much stiffer padding was chosen here.

To be sure that in this test the door will not be pushed into the passenger compartment without being hold by the car side structure, the door has been fixed to the pillars in an appropriate manner.

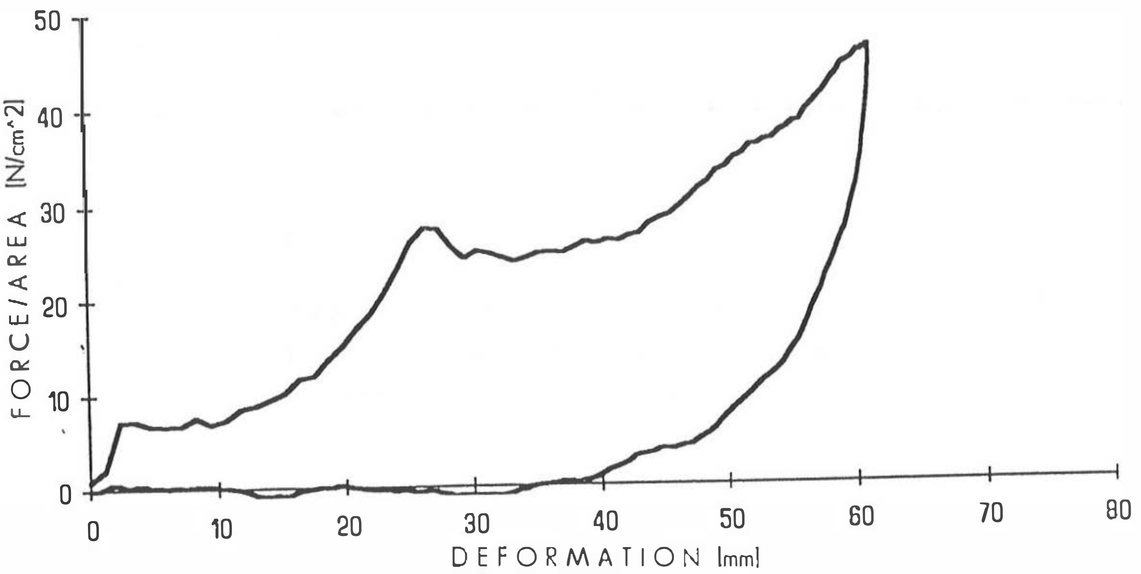


fig 3 Dynamic force-deformation characteristic of the foam combination as used for padding of the door interior (impact pendulum at 6 m/sec)

euroSID:		Maximum value	Time [msec]	3 msec value	Injury tolerance criteria
Head acceleration		75.9 g	42.0	73.1 g	80 g
HIC		340	37.3 -49.7		1000
Chest acceleration		69.1 g	51.7	66.4 g	
Spine acceleration		55.5 g	42.9	52.3 g	
Pelvis		56.8 g	41.1	55.4 g	
Abdomen force		1.9 kN	40.4		2.5 kN
Pubis force		3.1 kN	47.6		10 kN
Vehicle:					
	floor left	29.2 g	21.7	27.8 g	
Side acc.	door left	125.1 g	22.1	97.2 g	
	floor right	31.6 g	22.5	28.8 g	

Table 2. Side crash test with a stiff "impact belt" vehicle. Measurements on EuroSID and on the car structure.

The side crash test was run following the ECE lateral impact test procedure at BASt (Bundesanstalt für Strassenwesen) in Cologne. Impacting speed of the 950 kg barrier was 50 km/h, the corresponding delta-v of the "impact belt" vehicle with a mass of 552 kg at 31.6 km/h. Dummy type used was the EuroSID 1. Results of the side crash test are presented in table 2 and table 3. Accelerations, forces and deformations on the dummy are mostly well bellow injury tolerance criteria. It can therefore be concluded that another car structure of similar crash behaviour with similar padding in the interior as the tested vehicle would pass the ECE side crash test. However high speed film shows that the lower edge of the window opening of the door should be placed higher to prevent partial ejection of the shoulder of the dummy, as this - together with the impact of the head on the interior roof border- led to a large lateral flexion of the neck.

Accelerations measured on the struck and the non struck side of the car floor are practically identical (see Table 2). This indicates that during side impact of a barrier with defined force deformation behaviour, tbe tested car body - with exception of the door- is accelerated as a whole. Acceleration of the door is much higher in the first moment of impact. 40 to 50 msec after crash begin, however, when most values of acceleration, force and deformation on the dummy reach their maximum (see tables 2 and 3), the velocities of the floor and of the door show relative small differences: 30.6 km/h for the floor and 33.1 km/h for the left door (mean velocity in the time interval 40 to 50 msec).

The damage on the car side (see Fig. 5) indicates too that no significant intrusion of the door took place. Padding on the car interior worked as expected.

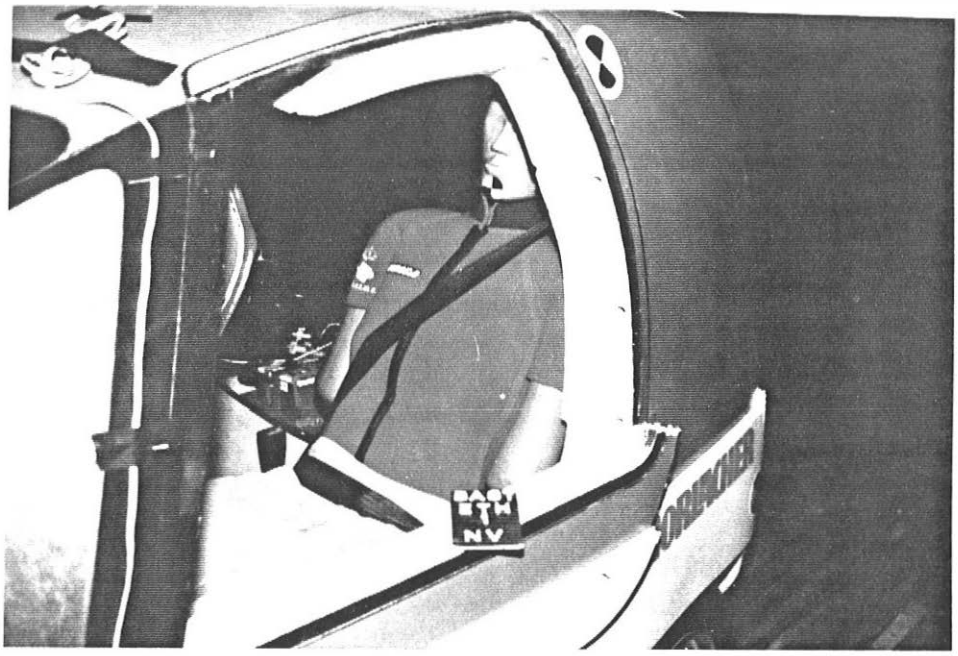


fig 4 Padding of the interior of the impact belt vehicle

Conclusions

From a technical point of view, it seems feasible to design low mass vehicles which fulfil high safety standards in frontal collisions with fixed obstacles and with heavier cars.

Compatibility in collisions between light and heavy cars require compensation of higher mass by lower stiffness of the heavy car and higher stiffness of the light car ("impact belt").

In side collisions the situation is similar to that of conventional passenger cars. A much stiffer side structure than currently in use are required to allow for efficient use of padding for the protection of the occupants.

euroSID 1:		Maximum value	Time [msec]	Injury Tolerance criteria	Cutting frequency
	upper rib	74.7 g	40.5		100 Hz FIR
Rib acc.	middle rib	64.7 g	64.7		100 Hz FIR
	lower rib	73.1 g	73.1		100 Hz FIR
Spine acceleration		55.3 g	43.0		100 Hz FIR
Thoracic	upper rib	65.0 g		< 85 g	
Trauma	middle rib	60.0 g		< 85 g	
Index	lower rib	64.2 g		< 85 g	
Rib	upper rib	17.9 mm	50.8	< 42 mm	
deflection	middle rib	18.9 mm	48.7	< 42 mm	
	lower rib	26.9 mm	46.1	< 42 mm	
Viscous	upper rib	0.172	45.5	< 1	
Injury	middle rib	0.199	44.3	< 1	
Criteria	lower rib	0.323	34.8	< 1	

Table 3. Side crash test with a stiff "impact belt" vehicle. Measurements on EuroSID 1 having reference to thoracic injuries.

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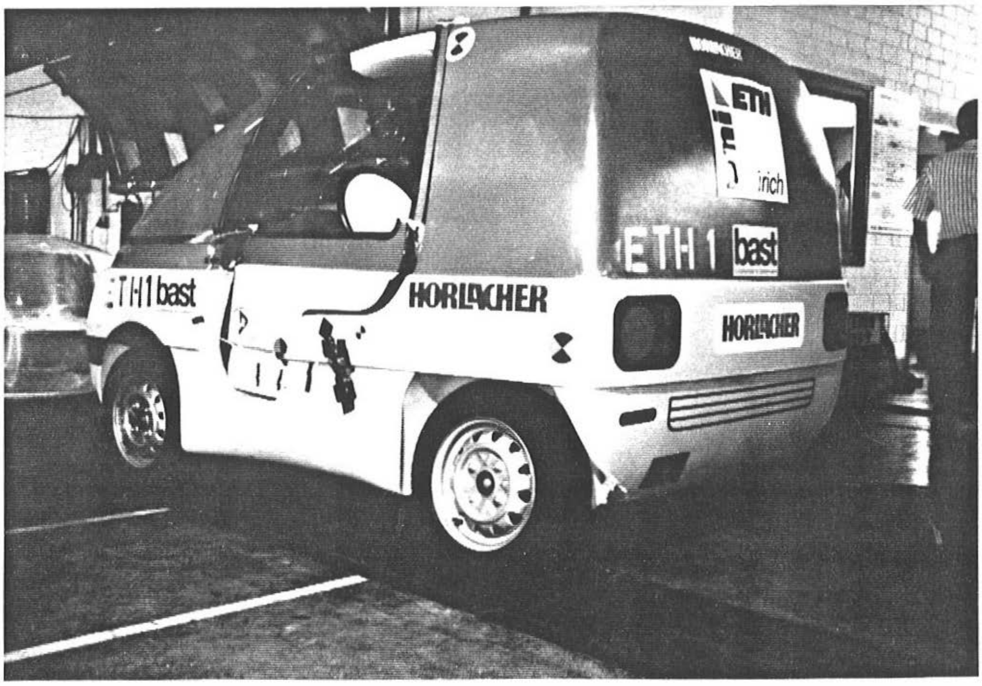

fig 5 Damage of the "impact belt" vehicle after side impact with the European barrier at 50 km/h

Company, the BASt at Cologne and DEKRA in Stuttgart. The "impact belt" hard shell car was built by M. Horlacher, Fiberglass constructions, Möhlin, Switzerland.

Literature

Walz F.H., Kaeser R., Niederer P. "Occupant and Exterior Safety of Low Mass Cars". IRCOBI Conference, Berlin, 1991.

Kaeser R., Walz F.H. "New Safety Concepts of Low Mass Electric/Hybrid Cars". ISATA Conference, Florence, 1992.

Kaeser R. "Safety potential of Urban Electric Vehicles". Urban Electric Vehicle Conference, Stockholm, 1992.

Rio J. ESV 91-S5-O-10
13th ESV Conference, Paris, 1991

Tarrière C., Thomas C., Troseille X. "Frontal impact protection requires a whole safety system integration".
13th ESV Conference, Paris, 1991