PASSIVE SAFETY POTENTIAL OF LOW MASS VEHICLES

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ABSTRACT

In frontal collisions between cars of different mass, the lower mass car will experience a higher velocity change (delta-v) than its opponent, corresponding to the mass ratio. An experimental low mass vehicle (LMV) conceived by the working group on accident mechanics has been modified to withstand an impact of 71 km/h against a deformable obstacle (two stacked FMVSS 214 barriers mounted on a rigid wall) simulating the opposing (high mass) car. In order to fulfil the occupant safety requirements, the restraint systems, e.g. belts, airbag, kneebolster, deformable steering wheel, as well as parts of the interior geometry - have been adapted using mathematical modelling prior to the test. Significant conclusions for the design of future low mass vehicles can be drawn.

USE OF LOW MASS VEHICLES (LMV) could be a means of reducing energy consumption in traffic. Such vehicles should offer an acceptable level of safety in collisions especially with conventional vehicles of about twice the weight. The largest handicap of lower mass is the larger velocity change, delta-v, in collisions with heavier cars: In frontal collisions between a low mass car and a car of twice the mass, both running at the same (opposite) velocity, the resulting velocity for both cars will be one third of the initial velocity of the higher mass car. The velocity changes are therefore 2/3 of the initial speed for the high mass car and 4/3 of the initial speed for the low mass car (twice as much as for the heavier car!). At an initial collision velocity of 50 (56) km/h, a change of velocity of 66.7 (74.7) km/h results for the low mass car. This is the range of velocity change, delta-v, which is the base of the studies on collision safety of low mass vehicles performed by the accident mechanics group at the Universities of Zürich.

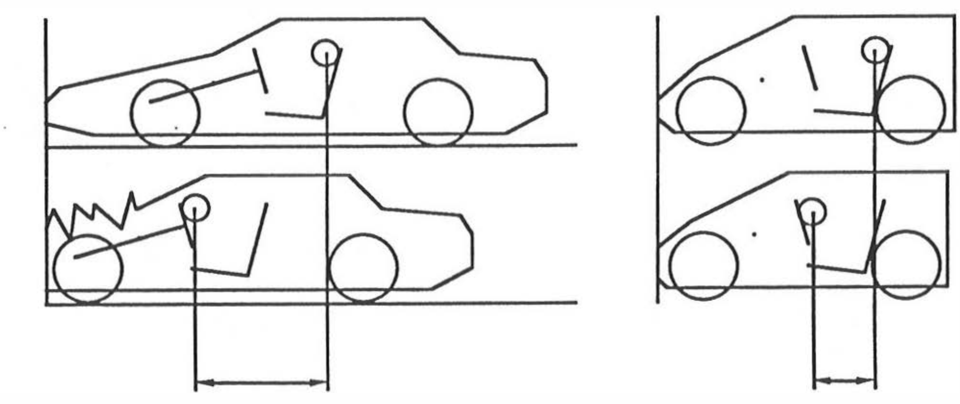
CRASH BEHAVIOUR OF THE CAR STRUCTURE

Structural integrity of the car interior is absolutely necessary for a reliable collision safety. Results from frontal crash tests with currently produced cars show that intrusion into the passenger compartment set the limits for safety. The steering column together with the steering wheel intrude in some cases into the passenger compartment. The footroom may be considerably reduced. These aspects of the collision behaviour of the car structure must be improved if collision safety is to be achieved at higher velocity changes in collisions.

In some currently produced cars of little height passengers occupy a footroom, which is to a large extent in front of the A-pillar and which has to be protected against intrusions in collisions. In this situation it is not easy to design a stiff structure as it may be very difficult to provide a stiff structural connection between the A-pillar, the longeron and the traverse beam in front of the footroom. Due to the large area required for the footroom there is little room left for the load bearing structure. Introducing a traverse in front of the footroom will increase the car length (or width) considerably. Among other reasons (unaggressive, upright driving position), the advantageous structural concept was a strong argument for the design of a high car in this safety study. At a cruising speed of up to 80 km/h, aerodynamics are of only secondary importance.

In earlier front constructions of the test vehicles, the force level under which the car deformed in the plastic range had been chosen at about 250 kN (Kaeser, 1992). This corresponds with the minimum resistance force of 25 tons proposed by Tarrière (1994) for smaller cars which would be compatible with heavier cars. For an assumed car mass of 600 kg and a constant force level of 250 kN during deformation, a velocity change of 20 m/sec (72 km/h) would result in a deformation of 0.48 m. With short cars this may be too much. The same mass and a force level of 300kN would result in a deceleration of 51 g and a deformation of

Fig. 1 Ride down distance of the head in conventional and in stiff short vehicle



0.4 m. Substantially smaller deformations will require much higher decelerations levels, which in general are hardly practicable. In earlier publications (Kaeser, 1992), it has been pointed out that the force level under which the low mass car will deform should be higher than the force under which the heavier car will deform. This is the reason for the high decelerations of the low car in collisions. On the other hand there is no interest for higher decelerations than necessary for car collision compatibility, as the strength of the car structure and of the fittings of all car parts must correspond to them. Furthermore the high deceleration rate reduces somewhat the total ride down distance in a collision compared with a conventional heavy car, see Fig. 1.

POTENTIAL AND LIMITS OF RESTRAINT SYSTEMS

Other parameters which will be very important in collisions at higher delta-v are hardly considered in the design of current cars. On one hand this concerns in the car interior the impact zone of the knees and the lower legs. On the other hand this concerns the required space for the head movement during collision with and without airbags. In very low cars the position of the passenger is more a reclining than a sitting position. In many cases the space above and in front of the head is insufficient when the head moves together with the upper part of the body, which rotates around the hip joint (combined with a forward movement).

Modifying the dangerous intruding behaviour of the steering column with the steering wheel into an impact behaviour which is adapted to the injury tolerances of the impacting body parts may show that eventually a dangerous behaviour of a structural part can be modified such that the formerly dangerous part tums to be an effective part of the restraint system. (The same applies to the knee impact zone).

In order to design a car which offers better safety for passengers in collisions with velocity changes of more than 70 km/h the above mentioned weak points of car interior design must be improved.

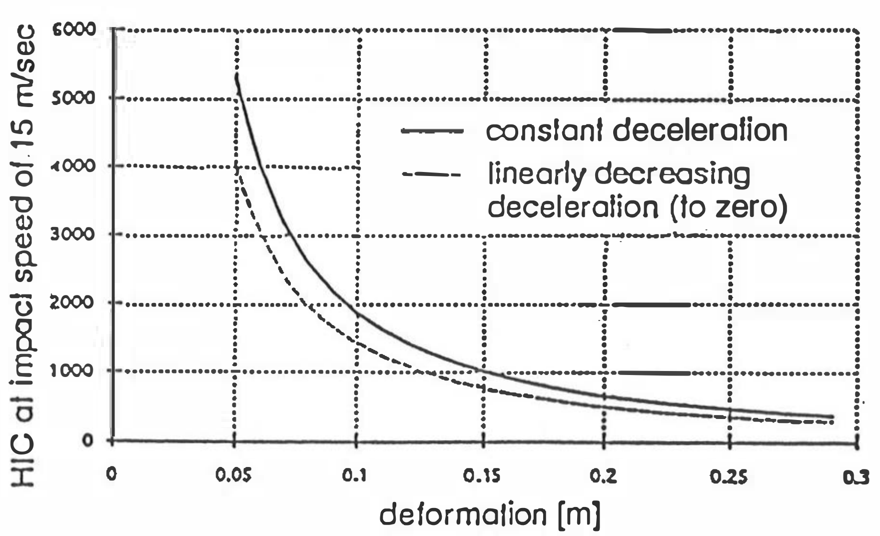
Stopping a passenger during a collision is a procedure which can be characterized by the application of forces on different parts of his body by means of the restraint system. The applied forces correspond to the decelerations of the involved masses. It is obvious that decelerations (velocity changes as well as the resulting covered distance) on connected body parts must be of the same order of magnitude. If not, connected body parts might be separated without violating current injury criteria which are based on decelerations or local deformations!

The restraint potential of vehicle safety systems can be increased by making greater use of load bearing capabilities of knee and femur. About 10 kN axial femur load seems widely tolerable (FMVSS 208). This improves the restraint potential for the lower part of the body which until today is mainly restrained by the pelvis belt and the slight backward inclination of the seat pan.

Seat belt geometry and seat pan stiffness has to be chosen such that submarining may not occur. For upright sitting passengers with a knee restraining device there is no risk of submarining. An efficient, comfortable knee restraint device which does not make entry and exit from a vehicle more difficult and which easily adapts automatically to the proper distance to the knees for best collision behaviour and which offers large deformations at the corresponding load levels should be considered.

For the head there is today only one directly applied restraint measure in use - the airbag. Making the best use of the distance between head and potential impact locations on the steering wheel, impact velocities of 50 km/h and more are today under control with the use of airbags as far as only head decelerations are considered. At higher velocity changes, the head might not come to a rest before the airbag is deflated. A head intrusion of 30 cm into the airbag at a mean deceleration of 50 g corresponds to an initial head velocity of 62 km/h. A significantly higher deceleration of 60 g would eventually allow a higher initial velocity of 68 km/h. However, the limits of the restraint potential of the airbag are in this range. Therefore a higher head impact velocity will require a structure behind the airbag which deforms under forces which correspond to tolerable decelerations of the head.

Fig. 2 Impact zone deformability and head injury criterion, impact velocity is 15 m/sec.



It has been shown, that the head of a PART 572 dummy may hit a specially designed structural wall with a metallic surface at velocities of more than 50 km/h fulfilling the Head Injury Criterion HIC = 1000 (Kaeser, 1994). This partition wall is in use today in some large passenger aircraft. It could be shown in this development that high decelerations at the beginning of an impact reduce the damage corresponding the HIC-criterion, see Fig. 2. This is not astonishing, as a reduction of velocity at the beginning of an impact leads to a larger reduction of the stopping distance than the same reduction of velocity at the end of the collision.

The mentioned effect - better a high deceleration at the beginning than at the end of an impact - causes problems for the designer of restraint systems. It leads to a restraint concept which even in noncritical impacts at low velocity changes will first apply the largest tolerable restraint force. This is valid as long as smart restraint systems capable to judge the severity of a beginning collision are not available.

FRONTAL CRASH WITH A LOW MASS VEHICLE AT 71 KM/H

In order to simulate an impact of the modified low mass vehicle ("Crashy") against a heavier car, two stacked FMVSS 214 barriers were used as an obstacle into which the LMV would crash with an initial velocity of 72 km/h. The reason to use such a stack of barriers was the assumption that the deformation of the heavy vehicle in a real world crash would be larger than the thickness of one barrier alone (19" = 483 mm).

We used almost the same vehicle for a crash test at 71 km/h as in previous crashes at lower impact velocities (Niederer, 1993). The load bearing structure was modified especially in the front part of the vehicle for the following two reasons:

1) A higher force level during deformation than in previous tests was required to run an impact test against FMVSS barriers which would contribute substantially to the total deformation at load levels above 350 kN.

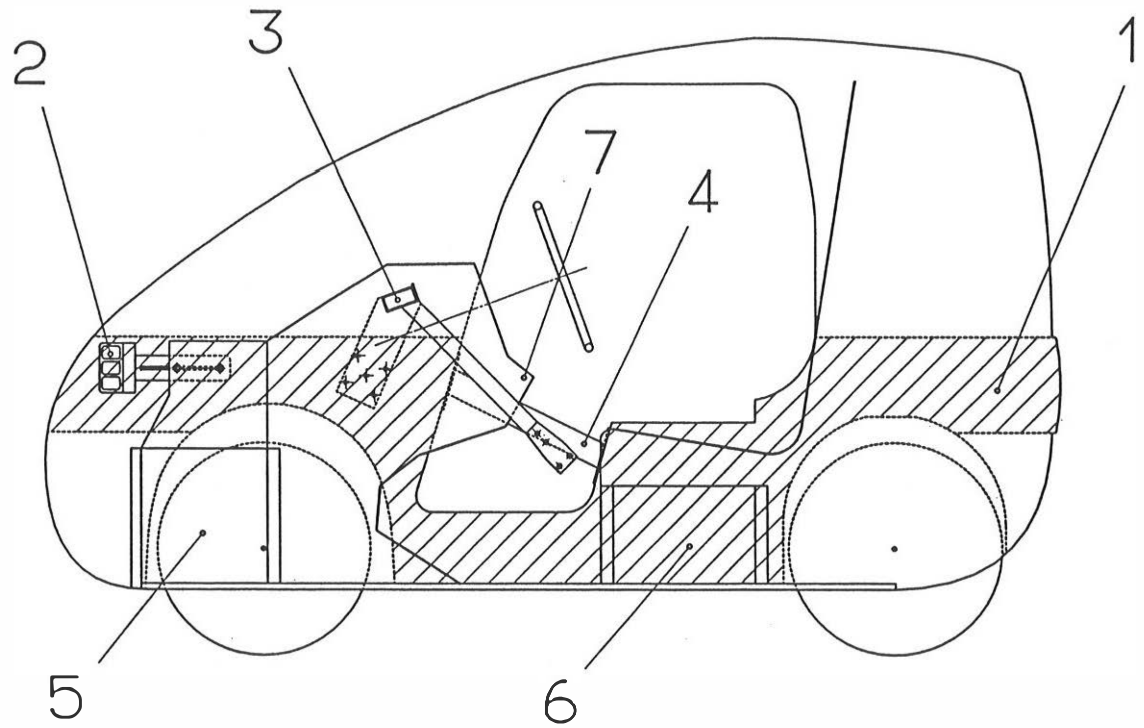
2) The amount of deformation of car structure had to be much larger. The original structure was made of glass fiber composite. In order to obtain large deformability at a nearly constant load level, a reinforcement was made with hollow aluminium beams featuring high plastic bending moments. The maximum load level was chosen at 420 kN in order to be significantly higher than the load level of the impacted barrier.

BASIC LAYOUT OF THE RESTRAINT SYSTEM

Since the cabin interior in its original configuration did not offer enough ride-down for the driver's thorax and head even when equipped with an airbag, it was decided to implement a deformable steering column. On the passenger side, a second driver position was built in. This second driver position was equipped with a relatively stiff steering column in a retracted position (80 mm, Option 2), e.g. modelling an active retracting steering column in its already retracted position, whereas the original driver side featured a steering column in the normal position that would deform passively (100 mm, Option 1) under the occupant's impact.

The shell type seats used were made of glass fiber composite. The seat pan exhibited a high stiffness. For geometrical reasons only 2 cm of foam covering the seat pan were allowed.

Fig. 3 Low mass vehicle used for crash test



1 Stiff hollow composite beam around the vehicle
2 Hollow aluminium beam (traverse) on deformable supports
3 Traverse for dashboard attachment
4 Steel bar replacing the door structure
5 and 6 Battery compartments

In addition to the restraint systems used in the earlier crash tests, a knee bolster (crushable foam) was also built in. The distance to the occupant's knee was approximately 50 mm. The feet of the dummy rested on crushable foam, too, to prevent excessive loads during the first moments of the impact. The doors of the vehicle were removed to allow for a better view of the occupant kinematics. Since the doors transfer the loads of the "rigid belt" towards the structures in the rear, they were replaced by two steel members. Fig. 3 shows the complete set-up of the vehicle prior to the test.

Table I: Summary of the key elements of the restraint system

Airbags & Generators	Petri production models, alterations only at the exhaust orifices
Belts	Different elongation characteristics (6% - 25%), anchor points defined, force limiters selectable
Steering system	Angle and position of steering wheel defined. Two options, simulated actively retracting column and passively deformable column, (force/deformation characteristics selectable)
Knee bolster	Characteristics and geometry selectable within limits given by cabin interior
Seat	Practically undeformable under nominal loads, 2 cm foam cushion

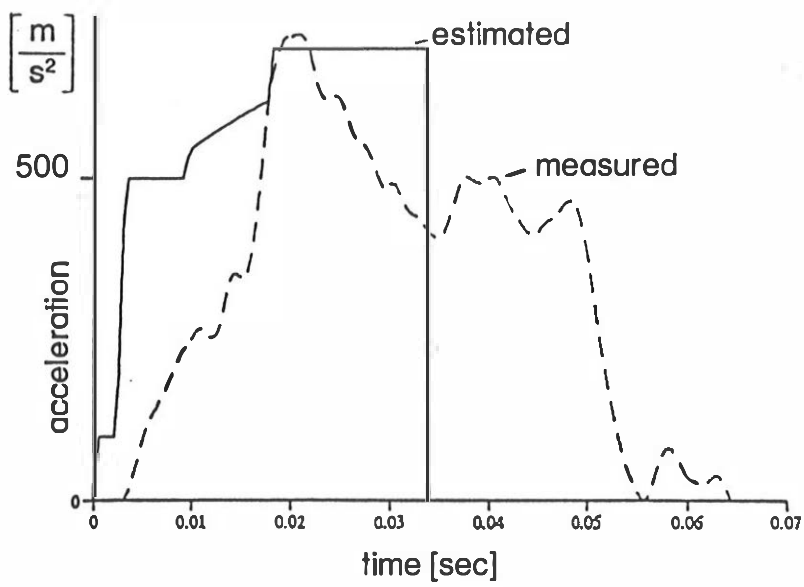
MATHEMATICAL MODELLING

The occupant protection criteria in an impact of such a high severity can only be met if the restraint systems are highly optimised. Mathematical modelling can allow for such optimisations prior to the actual test. The design of a mathematical model, using the rigid body method (MADYMO) for the dummy and most of the cabin interior parts and the explicit Finite Element method (PAM-CRASH) for the airbag, and the subsequent optimisation of the various parameters of the restraint sytem was the subject of a diploma thesis at the TU Berlin (Spiess, 1994).

Estimation of the crash pulse

Normally, the crash pulse of a vehicle in a given impact situation is known before mathematical models are used to optimise the restraint systems. In our case, however, only one test could be run. The crash pulse had to be estimated using the known deformation characteristics of the FMVSS 214 barrier plus the (estimated) deformation characteristics of the LMV. A simple Finite Element model (using the material for modelling the FMVSS 214 barrier provided by the PAM CRASH package) served this purpose. The resulting estimate is shown in Fig. 4. The crash pulse actually measured in the test exhibited a somewhat different characteristic (longer build-up slope, more elasticity), illustrating the problems associated with such estimates.

Fig. 4 Crash pulse estimated and measured below the seats.



Model characteristics

One of the reasons for the widespread usage of the rigid-body simulation program MADYMO (Version 5.0 was used) is that it provides well validated databases (1994), e.g. of the Hybrid III dummy. This database was used unaltered to model the two occupants (50% male Hybrid III dummies).

The various contacts between the occupant and the cabin interior were also modelled using the contact interaction mechanisms provided by MADYMO. These mechanisms use much less CPU time in comparison to their FE counterparts. However, care must be taken when modelling complex interactions such as the intrusion of the knee (and parts of the tibia) into the knee bolster, where the active contact surface is rapidly changing (as a function of the intrusion depth), and the direction of the intrusion is neither constant nor exactly known beforehand. In MADYMO, only force-deflection characteristics of a contact surface can be defined. This calls for a conversion of the known pressure-compression characteristics of the crushable foam taking into account the active contact surface, the direction of intrusion, the friction, and eventually a correction for energy absorbed while the knee moves in a direction tangential to the surface, but has already dived into the foam. Such corrections being difficult to estimate without a priori knowledge (e.g. impactor tests), a rather simple model using the mean knee cross-sectional area as a conversion parameter, was used.

The standard belt system provided by the software package was implemented. Belt retractors were simulated by pretensioning the belts. Belt force limiters were also included, since at least the forces introduced into the pelvis by the lap belt were assumed to be far too high.

The airbags were modelled using PAM-CRASH Version 12.1. Airbag models coded for this program were readily available at the Petri Ingenieurzentrum, where all the computer simulations have been performed. The PAM-CRASH program was coupled to MADYMO using the "common blocks" method, e.g. by creating a coupled executable.

For the pre-test part of the modelling study, two model data sets were set up, corresponding to the two different steering column options. Both data sets were optimised in an almost independent way, e.g. there were little constraints that the various parts of the restraint system would have to be identical for both options. Exceptions were the steering wheels and the seats.

Optimisation

The resulting model exhibits a relatively high complexity, making it impossible to optimise its various parameters in an automatic way, e.g. by systematically varying the model parameters and searching for a global minimum of a biomechanical quality function in the parameter space. Therefore, in order to minimise the number of simulation runs needed to find an acceptable solution, the interdepence of the various model parameters was determined in a number of simulation runs prior to the optimisation. Table II summarises the influence of the most important model parameters on the human tolerance criteria (as stated in the FMVSS 208 and other standards).

A side view of the model (option 1) is shown in Fig. 5.

Table II shows that the restraint system components responsible for the deceleration ot the lower body parts, have only little influence on the protection criteria of the upper body parts, and vice versa. This simple conclusion allows for an almost separated optimisation of the airbag, steering column, and shoulder belt system on one hand and foot cushion, knee bolster, and lap belt on the other hand.

Fig. 5 MADYMO model of the driver

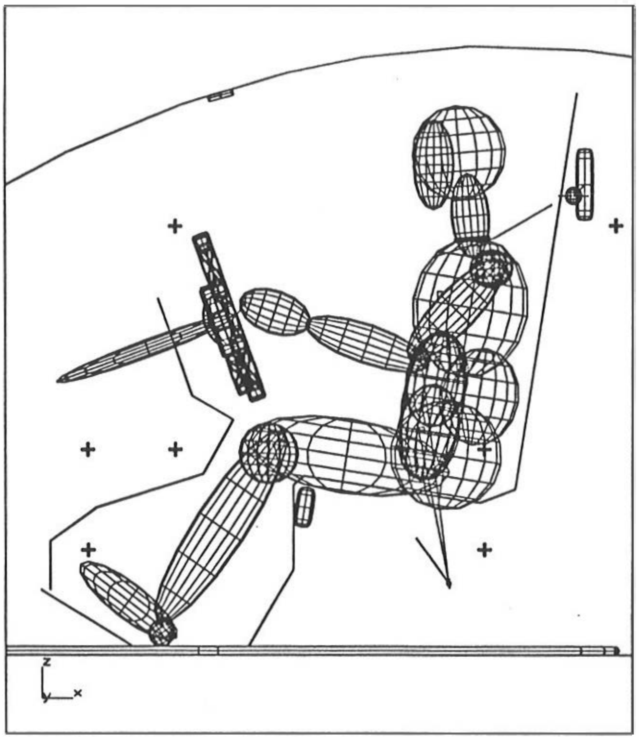


Table II: Interdependence between model parameters and human protection criteria

(++ = high influence; - = negligible influence)

	Feet	Femur	Pelvis	Thorax	Head Neck
Knee bolster characteristics and distance	0	++	++	0	-
Foot cushion	++	+	0	--	--
Lap belt elongation charact. and geometry	--	+	+	0	--
Lap belt force limiter	--	+	++	0	-
Seat pan geometry and deform. charact.	-	+	++	+	+
Shoulder belt elongation charact. + geometry	--	-	0	+	+
Shoulder belt force limiter	--	-	-	++	+
Airbag & Generator	--	--	-	++	++
Steering column deformation	--	--	--	++	++

Table III illustrates the allowable range for each parameter that was varied in the optimisation process, plus the actual value used in the subsequent test, for both options 1 and 2.

Table III: Allowable parameter ranges and optima found for options 1 and 2

Parameter	Range	Option 1	Option 2
Knee bolster stiffness	3..8 kN plastic limit	5.4 kN	
Distance knee-bolster	0..100 mm	50 mm	
Foot cushion stiffness	1..3 kN plastic limit	1.2 kN	
Distance foot-cushion	0..100 mm	30 mm	
Belt elongation	6..25%	25% shoulder 25% lap	8% shoulder 25% lap
Belt system	different geometries etc.		
Belt force limiter	2..5 kN plastic limit, at D-ring, buckle or A-anchor	4.5 kN, D-ring	
Airbag volume	80..120 l	80 l	
Generator	FG-80, 100..160% mass flow	FG-80	
Exhaust orifices	1..3, Ø 50 mm each	1	
Fabric	coated or uncoated	uncoated	
Trigger time	1..16 ms	6 ms	
Steering column	3..10 kN axial force limit	7.4 kN	rigid
Steering wheel position	0..-100 mm	0 mm	-80 mm

Some of the tolerance criteria used for the evaluation of the simulation results and their values at the end of the optimisation process are summarized in table IV.

Not all legal tolerance criteria could be met after the optimisation process. It should be noted here that first, these tolerance criteria have originally been defined for an impact speed of 48 km/h into a rigid barrier, and secondly, for a first test with a cabin interior geometry and seat characteristics not specially optimised for such severe impact conditions, these results seem acceptable.

Fig. 6 Crash test with the Low Mass Vehicle, t = 20 msec.

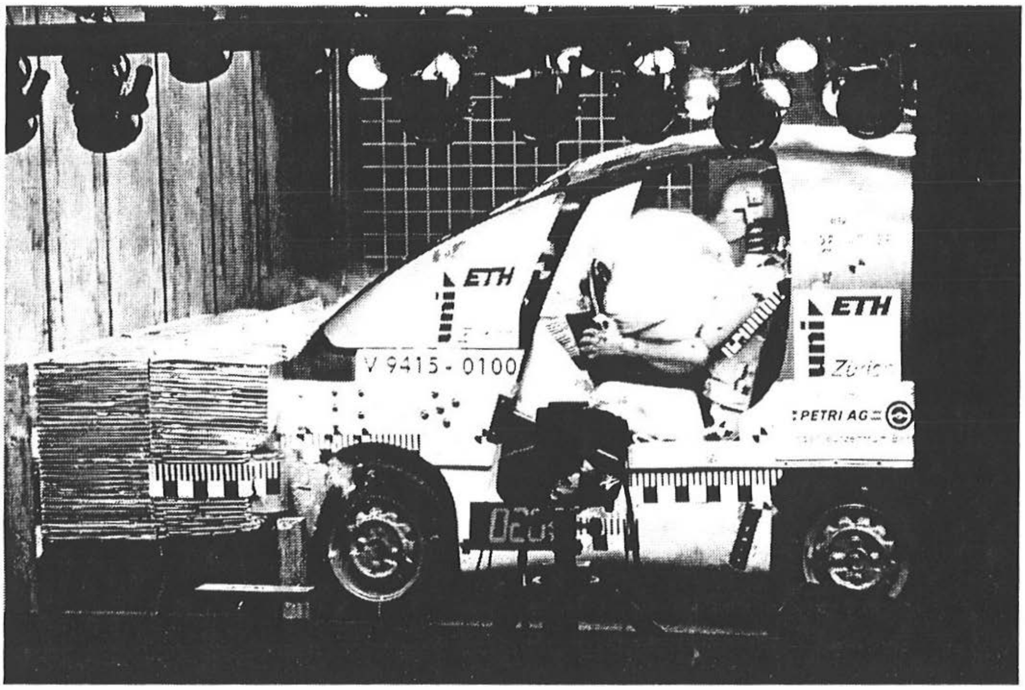


Fig. 7 Damage of the car front after test at 71 km/h.

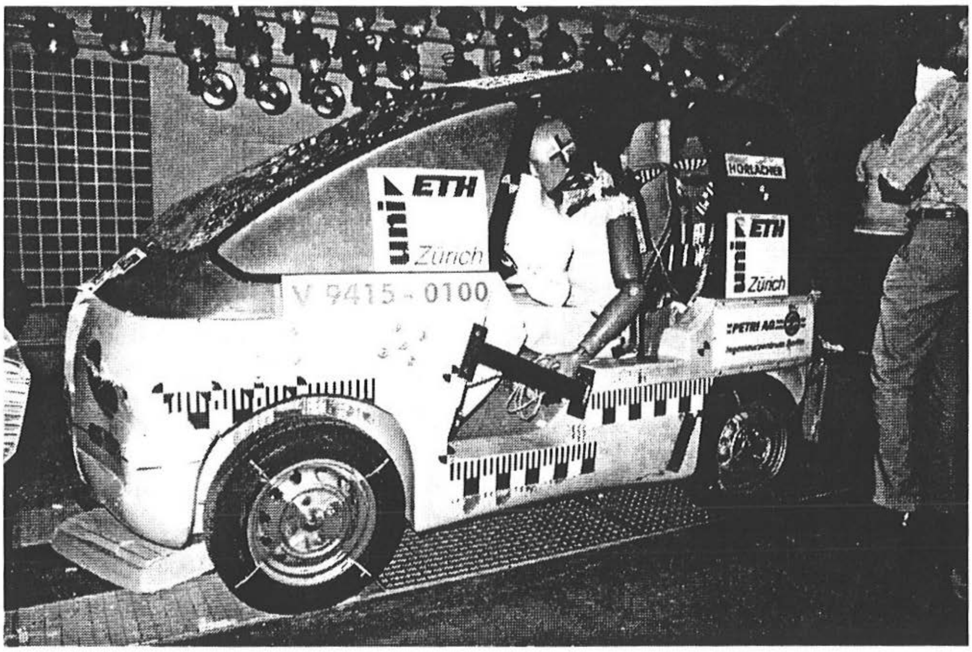
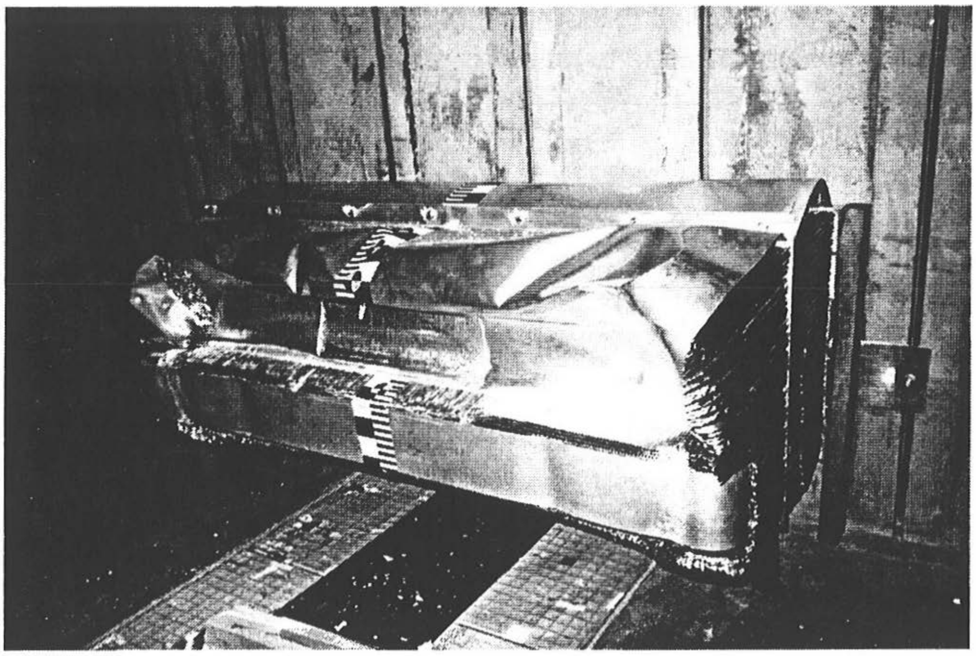


Fig. 8 Damage of the barrier after test with the low mass vehicle



TEST AND RESULTS

The restraint systems whose characteristics are summarised in table III, were built into the LMV. Vehicle accelerations at both occupant positions and in the centre tunnel were measured as well as belt and steering column resultant forces. Two fully instrumented Hybrid III 50% male dummies were placed into the car. Since the baggage compartment of the LMV was too small to hold the measuring equipment, an equipment carrier structure was added at the rear of the car. The corresponding weight was removed from the LMV, e.g. by removing some of the battery weight. The full scale test was performed at the crash test facility of the Petri Ingenieurzentrum, Berlin. Kinematics were documented using one high speed video system plus 3 high speed 16 mm movie cameras.

The impact speed was measured at 70.8 km/h. No intrusion into the passenger compartment was observed. The total deformation of the front structure was 280 mm, with an elastic component of 80 mm. The barrier showed a total deformation of 170 mm. During the impact, the equipment carrier structure separated from the car and its two longitudinal members collided with the seats, thereby lifting und pushing them forward. This influenced the occupant loads significantly, and eventually also led to the loss of some of the measurement channels. In Fig. 6 the Low Mass Vehicle is shown during the crash test at t = 20 msec. Damage of the vehicle and of the barrier is shown in Fig. 7 and Fig. 8.

Table IV: Resulting occupant loads for options 1 and 2

Loads exceeding legal tolerance critera are printed in boldface. Values marked with an asterisk are assumed to be influenced by the collision with the equipment carrier. Missing values are due to failure of some of the measurement channels.

		Model Option 1	Test Option 1	Model Option 2	Test Option 2
Head	HIC_{36}	810	**2210***	**1600**	-
Head	a_{3ms} [g]	64	**91**	90	-
Thorax	a_{3ms} [g]	**63**	**67**	**74**	-
Sternum compression	[mm]	41	54	45	-
Pelvis	a_{3ms} [g]	82	115	84	115
Femur	F_{axial} [kN]	4.6	**11.6/13.1**	4.6	**12.4/10.4**
Lap belt	F_{max} A [kn]	5.6	7.7	6	7.9
Shoulder belt	F_{max} C [kN]	8.0	4.5	7.9	4.3
Foot	a_{3ms} [g]	**266**	**280/244**	**266**	196

VALIDATION OF THE MODEL

As mentioned above, some of the components did not perform as anticipated, which can easily be explained by the fact that little experience existed for impact tests unter these severe conditions. Especially the impact of the measurement carrier into both seats resulted in an acceleration peak that propagated through almost all channels on the left (option 1) dummy's upper body parts. the belt force limiters, which are constructed using a steel ribbon deformed by bending through a slit in the D-ring, showed somewhat stiffer characteristic due to an additional torsion of the ribbon. The knee bolster also exhibited a stiffer behaviour than anticipated in the model. This clearly calls for a more exact modelling of the interaction between knee and lower leg and the crushable foam.

A large deviation between test and model was observed in the HIC value of dummy 1. The values which were uninfluenced by the contact with the equipment carrier tend to deviate in an acceptable range. By adapting the characteristics of the restraint system components and attempting to quantify the influence of the equipment carrier, a partly validated model was obtained. Using this model, the HIC for both options would be in the range of 1200.

CONCLUSIONS

An important result of the mathematical modelling process is the conclusion that a passively deforming steering column performs much better in terms of head deceleration than an acctively retracting one. This can be explained by the fact that, in the case of the retracting system, only additional ride-down distance is supplied, whereas in the case of a deforming column, this same distance is also used for the absorption of energy and thus deceleration of the occupant. The paradigm to be used in the design of such systems is therefore not only that sufficient ride-down distance must be supplied by an adequate cabin interior geometry and steering column construction, but also that all of this distance must be used for the deceleration of the occupant, e.g. by implementing belt retractors, airbags of sufficient volume and early triggering time, energy absorbing seat structure, and knee bolsters with a small distance to the knee at the time of the impact.

ACKNOWLEDGEMENTS

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