DESIGN OF A PEDESTRIAN COMPATIBLE CAR FRONT

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ABSTRACT

The paper deals with the development and the design of a car front which corresponds to human tolerance levels in car/pedestrian collisions up to an impact velocity of 40km/h. At higher velocities less severe injuries are to be expected than with current car fronts. Starting from specified load limits of various body parts of a pedestrian, the course of development is described:

- 2-dimensional mathematical simulation, preliminary design and testing of the main components of the car front (bumper, leading edge and head impact area)
- design and construction of the entire car front and the verification in several full scale crash tests

The presented pedestrian-activated displaceable hood seems to be a suitable solution to reduce significantly the severity of injuries in car/pedestrian collisions. There is no severe change of current styling and little additional space is needed for energy absorbing components.

1. GENERAL ASPECTS

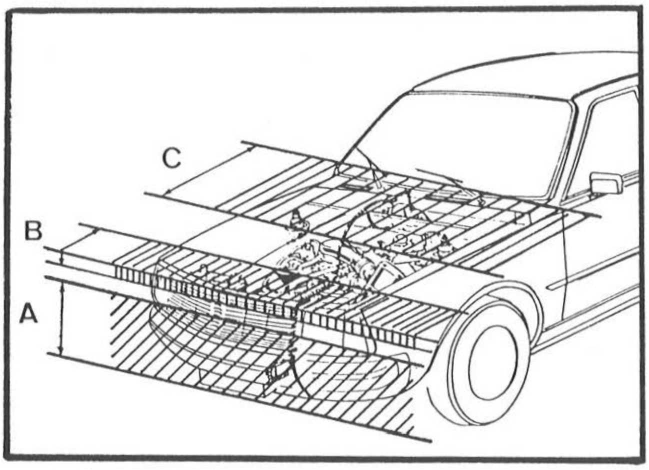
The main aspects of collisions of cars with pedestrians are quite well known today. The size of the problem is documented by numerous statistics. The number of pedestrians involved, injuries, fatalities and further consequences of the accidents makes it necessary to take it into consideration in the design of cars. Statistics show that head and lower limbs are the most frequently injured body parts and the head is mostly involved in severe injuries. Better automobile design for pedestrian injury prevention means, therefore, first of all, that the head impact should be mitigated. Some important parameters of the collisions are well documented such as size and age of pedestrians. Others, like velocity of impact, for example, are not well known because of the lack of accurate methods to determine them. Nevertheless, it has been concluded in different studies that improvements in the design of vehicles could bring a large reduction of injuries for collision speeds up to 40 km/h. On one hand most collisions between cars and pedestrians occur at impact speeds below 40 km/h, on the other hand necessary deformation and energy absorption grows as the square of impact velocity. At higher impact speeds than 40 km/h this may lead to requirements which cannot be fulfilled in a practical manner. The kinematics of impact, especially the impact speed of the head depend strongly on the shape of the car front. The energy absorption depends on the stiffness of the impacted locations.

The knowledge on pedestrian accidents has reached an extent which allows us to define the requirements of pedestrian safety on car design in an appropriate form for design and performance evaluation. The resulting specifications must be compatible with other requirements for normal use, production, maintenance and reliability. In what concerns the shape, styling aspects are an important parameter. Aerodynamics for example got a high priority. The resulting reduction of sharp edges on the car was good for the pedestrian. In what concerns the shape of the car front a good compromise must be found.

The main design problem seems to be how to integrate all the different requirements in a construction which fulfils all important conditions without generating new problems. Even more important is how to do this at low costs. Not everything which seems necessary or desirable can be done in one step of evolution. It is important to start and continue this evolution making steps in the right direction. After studying general questions of pedestrian impact with purely experimental fronts in our research group the question arose how to realize a car front with conventional technologies - such as metal sheet components - in a way, which seems with some modifications, acceptable for mass produced cars.

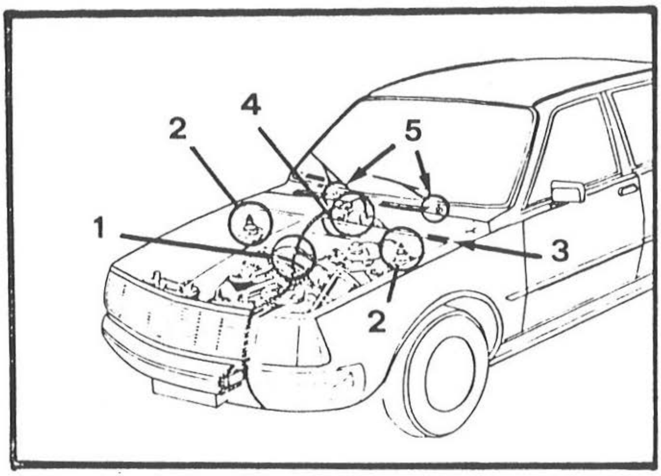
2. CAR FRONT DESIGN AND PEDESTRIAN INJURY PREVENTION

Present automobiles are in general not designed to allow for large deformations under defined forces at the typical locations of impact in pedestrian collisions. Large areas of the vehicle front are too rigid and/or allow only minor deformation. This holds especially for the fenders, stiffeners and bedding of the hood, for the area of the windscreen with its frame, the windshield wiper supports, window edge bedding and the window pillar (see following figures). If a reduction of the danger to pedestrians is to be achieved, i.e., if up to a certain collision speed, no or only minor injuries resulting from an impact are tolerated, the parts mentioned above must on the one hand deform under forces lower than the injury tolerance limits of the impacting body parts of the pedestrian. On the other hand the available deformation space must be such that the speed difference between the impacting part of the body and the impacted location of the vehicle can be reduced.



A: Tibia impact region
B: Femur/pelvis impact region
C: Head impact region

Figure 1
Typical location of impact
in pedestrian collision for adults



1 air filter (20 mm)
2 shock absorber support (12 mm)
3 cowl (5 mm)
4 heater fan (5 mm)
5 wiper support
(in parenthesis: distance to hood structure)

Figure 2
Critical part below the hood at the possible head impact location (Renault R18)

3. INTEGRATED METHOD OF CAR FRONT DEVELOPMENT

An integrated car front design methodology includes real accident analysis and simulation methods to outline both the relevant collision configurations and the essential parameters in car pedestrian impacts. Furthermore, in a phase of modifying or re-designing a car front, efficient design tools, e.g., component test facilities and easy to use 2-D-simulation programs, guarantee an optimal design procedure. The interplay of all these tools is shown in the following flow chart.

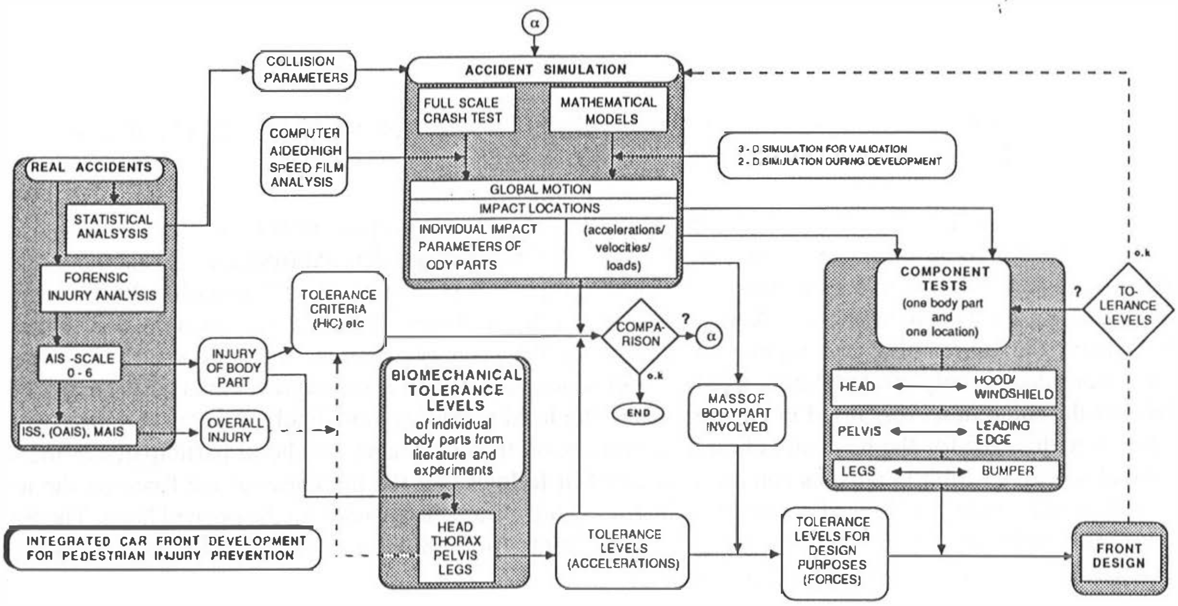


Figure 3 The elements of an integrated car front development for pedestrian injury prevention

The different tools were described in earlier studies:

- Real accident analysis (Gaegauf et al. 1981; Walz et al. 1983)
- 3-D-simulation with CALSPAN EVS-program and motion analysis (Mesqui 1982)
- 2-D-simulation, energy absorption and design procedure (Kaeser et al., 1983, 1984)
- Reliability of surrogates, influence of vehicle geometry (Niederer et al., 1983, 1984)

The following table shows an example of the results of this method suitable for engineering purposes.

	Tolerance Criteria		Effective Mass Involved	Contact Area on Car	Example for Front Geometry	Contact Zone Must Deform at	Example: V_{coll} : 35 km/h	
	For Test Purposes (Accelerations)	For Design Purposes (Forces)					Corresponding Local Impact Velocity	Deflection at Impact Locations
Head	HIC < 1000 80g (> 3 msec)	4'000 N	5 kg	150 cm^2	-	27 N/cm^2	11 m/sec *)	8 cm
Thorax	60g (> 3 msec)	10'000 N	17 kg	-	-	-	-	-
Pelvis/ Thigh	60g (> 3 msec)	6'500 N	11 kg	17 cm x H_{LE}	H_{LE} = 10 cm H_{LE} = 15 cm	40 N/cm^2 25 N/cm^2	10 m/sec	9cm
Lower Leg	60g (> 3 msec)	4'000 N	7 kg	10 cm x H_B	H_B = 10 cm H_B = 16 cm	40 N/cm^2 25 N/cm^2	10 m/sec	9 cm

Table 4 Tolerance criteria and required deformability

H_{LE} = height of contact area at the leading edge of the hood / pelvic impact

H_B = height of bumper

*) head impact velocity corresponding to a height of leading edge of about 70 cm

The deformability of impact points - defined as force per area under which the structure deforms - is only a function of the assumed tolerance levels. On the other hand the required thickness of energy absorbing material or structure is a function of the local impact velocity which is for its part proportional to impact speed and a function of car shape, essentially of the height of leading edge of the hood.

4. DEVELOPMENT OF A PEDESTRIAN - COMPATIBLE CAR FRONT WITH A DISPLACEABLE HOOD

The car front, designed in view of the protection of pedestrians, presented in this section is based on a principle suggested by Appel (1978). The idea of a displaceable hood was derived from the consideration that it is difficult to create a permanent deformation space for the purpose of pedestrian protection within the dimensions of the compact car fronts common today. A foam covering of the necessary thickness, for example, would seriously detract from the functioning and styling of a front. In the principle chosen here, therefore, the necessary deformation space is only created during a collision in which the hood is displaced rearwards by the impact of the pelvis. At the same time, it is lifted in the area where the head impact is most likely to occur. On one hand this creates enough space for the head and chest acceleration, on the other hand, the hood participates in the initial energy absorption during the displacement, from which it follows that the thickness of the foam on the leading edge can be reduced by 50 %. Furthermore, the rigid windshield frame is covered by the opened hood. The Renault R18 was chosen because of the suitable geometry of its front. The R18 has a hood which covers the entire front. Consequently the fenders did not have tobe modified.

4.1 Requirements

The tolerance limits (see TABLE 4) of humans (adults and children) should not be exceeded up to a collision speed of 40 km/h. Criteria for the judgement of the resulting specifications are:

- The absorbed energy resulting from front collision should suffice for activating the hood down to speeds of 20 km/h for an adult.
- The time between pelvis and head impact (about 100 msec) should suffice for complete opening.
- If the pedestrian is falling down to the ground after impact with the car front this should happen in a way secondary head impact is not likely to occur.
- The modifications must not jeopardize car passenger safety (e.g. in head-on collisions).
- The experimental front should allow a repeated use of as many components as possible in the test program.
- The development should not impair the suitability for daily usage and its further development for mass production; the entire hood may not be heavier than the traditional ones (20 kg).

The last two requirements are not easy to comply with at the same time. Therefore, in a first stage, re-usability was emphasized so that the program could be conducted with an acceptable amount of time and financial efforts. In a second stage, this requirement could be abandoned in favor of easy maintenance and mass production.

4.2 Design of the Modified Car Front

4.2.1 Opening Mechanism

An opening mechanism whose operation can be divided into four functional phases was chosen and designed from a large number of possibilities.

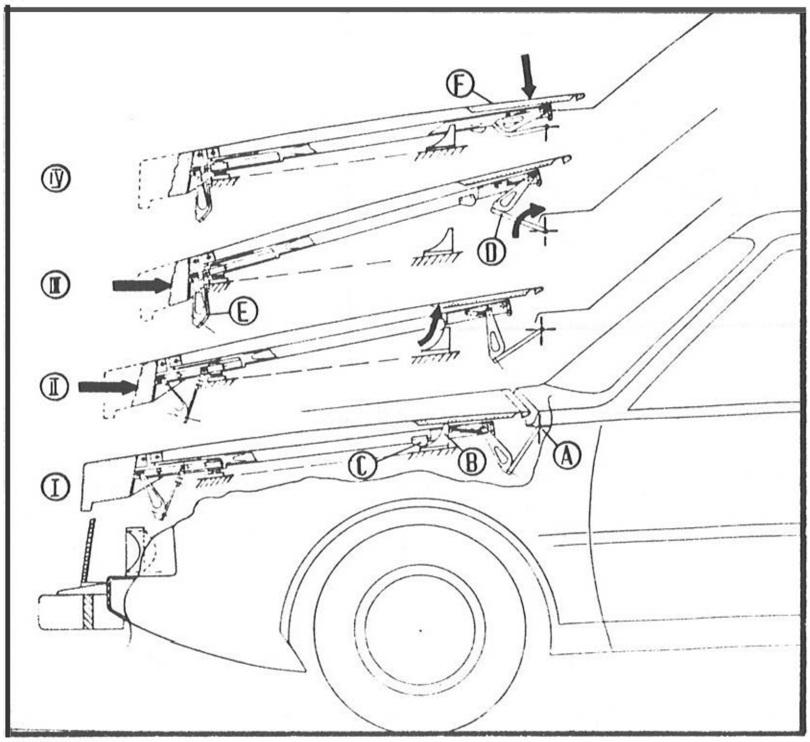


Figure 5 Section of the front with displaceable hood

Phase I: Hood in initial position. The hood can be opened normally (rotation around point A).

Phase II: During the pelvis/thigh impact, the foam on the leading edge is compressed and the hood accelerated backwards. As the guide shoe (C) slides up the ramp (B), the back part of the hood is lifted.

Phase III: When the guide shoe reaches the end of the ramp, the bearing yoke (D) takes over the guiding of the hood. At the same time, the retarding yoke (E) starts to decelerate the hood relative to the car undergoing plastic bending.

Phase IV: Shortly after the hood has stopped relative to the car (after about 0.1 sec at an impact speed of 35 km/h), the head impact occurs. The head impact area (F), designed correspondingly, reduces the maximum accelerations after the first impact and decelerates the head movement without exceeding the admissible tolerances. If the head impact occurs on or near the bearing yoke, the yoke undergoes plastic deformation under a tolerable force level for the head.

4.2.2 Determination of the Effective Pelvis Mass

For the opening process, the acting pelvis mass plays a central part. Estimates were made possible by a series of tests with an experimental front (see following figure). On the basis of assumptions on the masses involved, a study on the dynamics of the pelvis impact gives indications concerning forces involved, necessary displacements and time intervals during displacement of the hood.

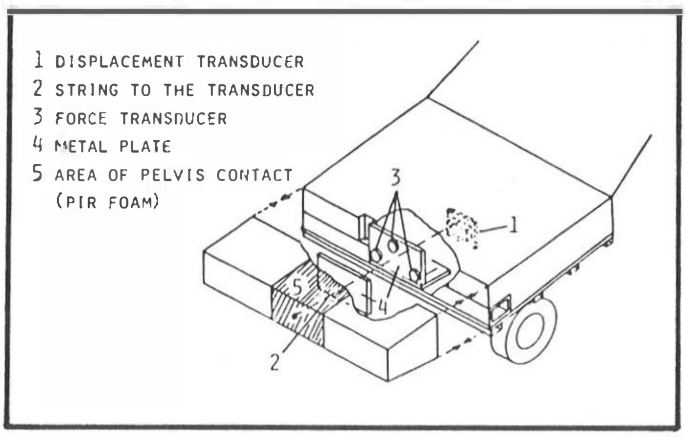


Figure 6 Experimental front with force-sensing device

The force-sensing device presented above was calibrated with the impact pendulum equipment, see Kaeser et al., 1983. The force-deformation characteristics registered in the conducted collision tests with Humanoid Part 572 dummy showed that the effective pelvic mass varies from 13 to 27 kg as a function of impacting conditions and height of leading edge.

4.2.3 Mathematical Simulation of the Mechanism of the Displaceable Hood

The mathematical modeling of the motions was carried out in a carthesian coordinate system with the vehicle as system of reference and is divided into two phases:

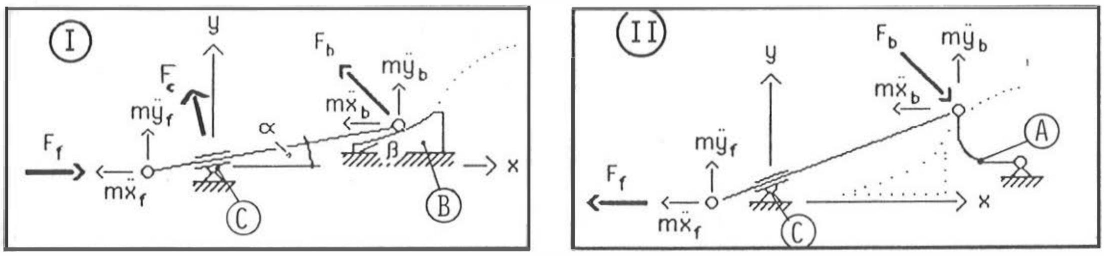


Figure 7 Mathematical models of the opening mechanism, 1st and 2nd phase
A: bearing yoke
B: lifting ramp
C: guide rail

Phase I Acceleration of hood (relative to the vehicle):

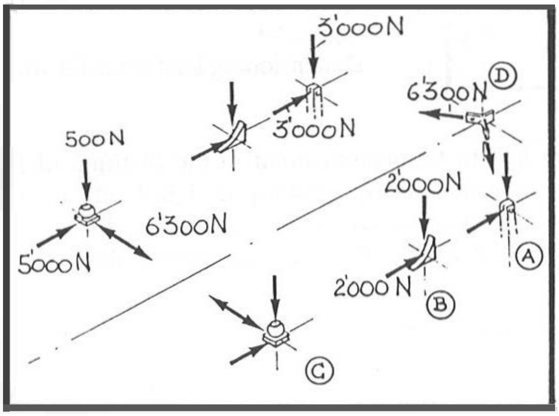
The mass of the hood (according to specification less than 20 kg) is concentrated in 2 points which are rigidly connected by a mass-free rod. One mass slides along the ramp; the force F is introduced without friction in the other mass. In the point A the rod is guided by a single axis bearing. The resulting differential equation of deformation time history was numerically solved using step by step integration.

Phase 2 Deceleration until hood has stopped (relative to the vehicle):

At the upper end of the ramp, the acceleration phase is completed; the pelvis of the pedestrian and the hood have the same velocity. A deceleration force acting at the front end now stops the hood together with the pelvis relative to the vehicle. The back end of the hood is guided by the bearing yoke during this phase. The bearing yoke A also stops the rotation of the hood around point C.

On the basis of the state of movement at the end of the acceleration phase and the admissible total displacements at the front and back hood, the necessary deceleration forces, assumed constant, are determined by observing energy principles.

Furthermore, lateral guiding forces occurring as a result of excentric impact has been taken into account. The results of the mathematical simulation of the mechanism are the reaction forces shown in the following figure, which has been used for dimensioning of the hood and bearing points.

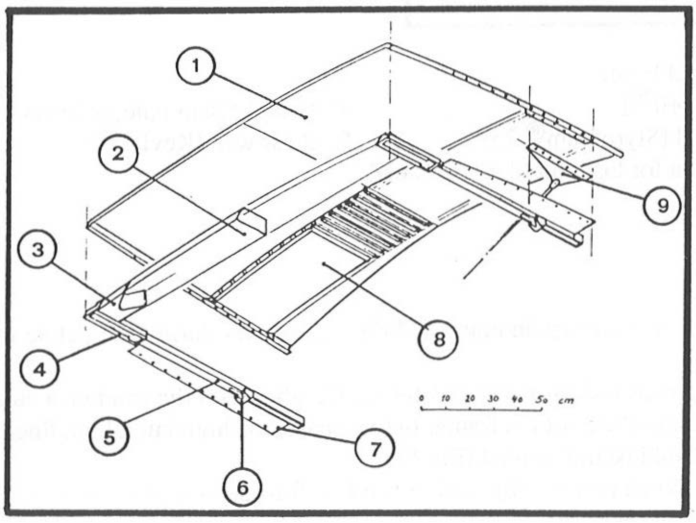


A : spindle of bearing yoke
B : lifting ramp
C : hinged bearing
D : contact point of back side guiding

Figure 8
Bearing forces from mathematical simulation

4.2.4 Design Details

The following figure shows the main parts of the displaceable hood and describes the function, shape and design of the head impact region and the frontal beam.

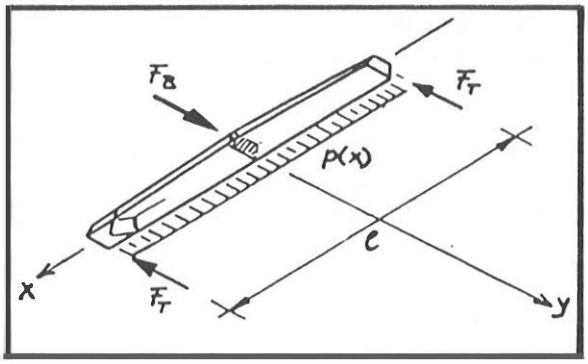


1: upper panel (aluminium)
2: frontal beam
3: reinforcement for load introduction
4: guide rail (aluminium)
5: square tube (aluminium)
6: guide shoe (steel)
7: shear panel (aluminium)
8: head impact region (sandwich type with foam core)
9: rear lateral guiding (steel cable with aluminium fitting)

Figure 9
Hood structure (view from below)

a) Frontal Beam made of Fibre Reinforced Composite Materials

Function and Loads: The frontal beam introduces the pelvic force F_B into the hood. The bending moment is due to the inertia forces.



F_B = 6´000 N
F_T = 1´500 N
p(x) = 2.2 N/mm
l = 1´350 mm

Figure 10
Dimensioning load cases for frontal beam

Design of the Frontal Beam: As the frontal beam had to be manufactured in the Institute of Lightweight Structures and had to be reused several times, a structure made of composites was designed with a factor of safety of 1.5 with respect to collapse. Another possibility for one-time use would be , e.g., a box of steel or aluminium sheet filled with foam. The design of the frontal beam with the materials used can be seen in the following figure.

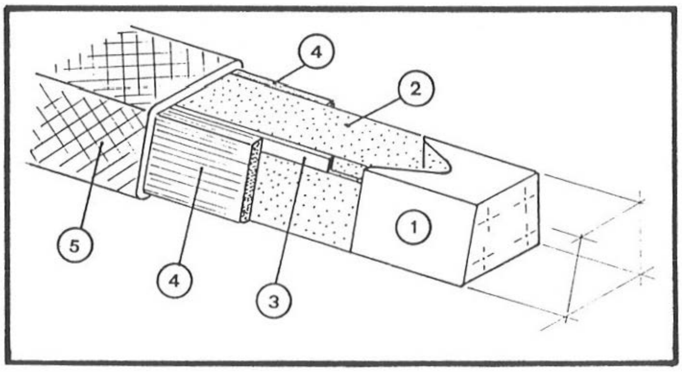
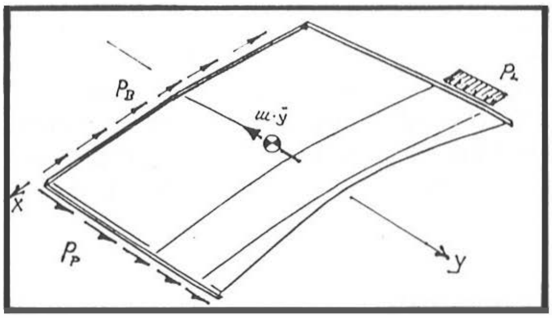


Figure 11 Design of frontal beam
1: fitting (Resofil®)
2: core material (Styrofoam® 25)
3: reinforcement for load introduction (steel)
4: stringer (laminate, 6 layers glass)
5: shear web (Kevlar®)

b) Hood Panel with Sandwich Region:

The slightly doubly curved hood panel must sustain entirely differing stresses during the pelvic impact and during head impact.

1) During the opening process, it acts as a shear panel and forms, together with the sandwich structure in the head impact region, the rear stiffener of the frame. In this phase, the high lateral guiding forces in case of an excentric impact should be transmitted (Fig 12a).
2) During the head impact, the sandwich part is subjected to bending forces vertical to the surface and should collapse under a defined load (Fig 12b).



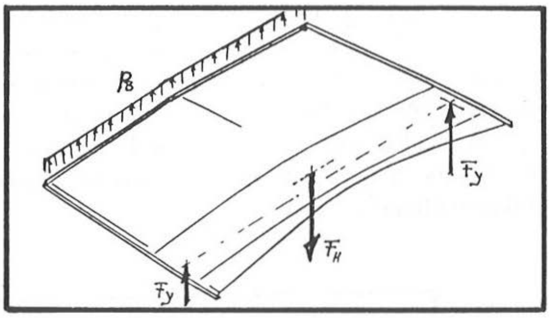
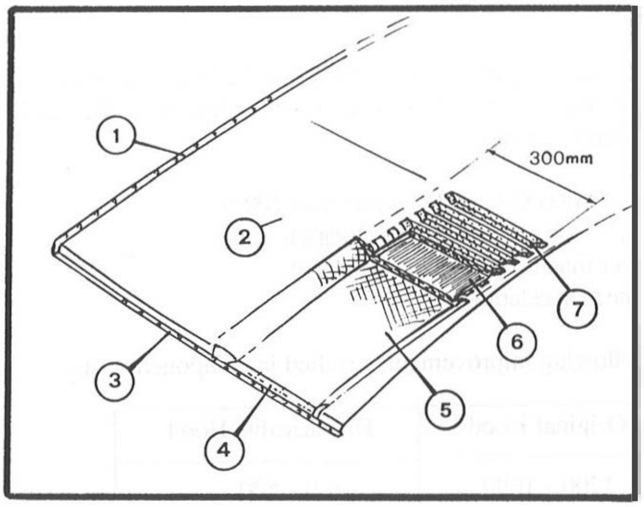


Figure 12a
Forces during opening in pelvis/corner impact
p_L = 31.5 N/mm
p_P = 9.2 N/mm
p_B = 4.7 N/mm

Figure 12b
Forces during head impact
F_H = 4'000 N
F_Y = 1'600 N
p_B = 0.6 N/mm

The original steel hood, initially used, was replaced by an aluminium sheet, because of the forces of inertia at the beginning of the head impact, although the requirement for an upper panel with a very small mass could possibly be better met with a synthetic material. The final successfully applied sandwich structure is equipped with an aluminium-made facing on the upper, impacted side, a facing made of glass and carbon fibre on the bottom side and a foam core, as illustrated in the following figure.



1 load introduction to frontal beam
2 aluminium sheet (1mm)
3 stiffener introducing force to shear panel
4 wood-made stiffener introducing side guiding forces
5 glass laminate
6 unidirectional carbon fibre
7 foam strip (10x10x300mm) (AIREX® C70.70)

Figure 13
Details of head impact region

Functioning in Head Impact: By using the same structural arrangement until close to the edge of the hood, the following collapse behavior is achieved over the entire width of the hood: The strip-wise support of the upper panel enables large local deformations under small forces, so that the forces of inertia remain small. In the further course of the impact, the covering layer buckles as a result of the compressive strain in a pattern corresponding to the distance between the strips and thus provides force/deformation characteristics which as a whole are favorable.

4.2.5 Component Tests

The component test setups described in Kaeser et al. (1983) has been used to verify function and efficiency of the different parts developed for the new car front.

a) Guiding and Opening Mechanism; Pelvis Impact

Defined test conditions with an impacting mass of 25 kg and an impact velocity of 6 m/sec allowed a testing of the opening mechanism in the range of the minimum velocity for which the hood should still open. At the same time, these tests had to prove the sturdiness of the components dimensioned on the basis of the calculated opening and reaction forces (frontal beam, guide rail, longitudinal profile, lateral guiding, shear panel). An accelerometer built into the impact mass registered the maximum force acting on the simulated pelvis (see following figure).

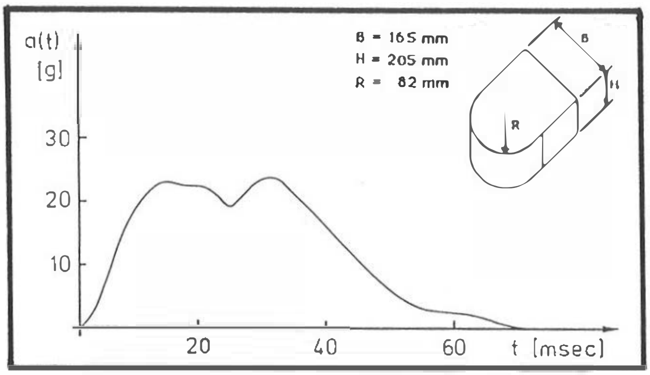


Figure 14
Accelerations on impactor during opening tests

The only change which became necessary on the basis of the tests was a redimensioning of the retarding forks.

b) Head Impact on Hood

The hood was tested with the head pendulum (Kaeser et al., 1984) in the lifted position. The points of impact were selected according to the tests already conducted on the original vehicles. Thus, the results could be compared. For the comparison three common criter a were used:

- HIC = Head Injury Criterion (should be less than 1000)
- dt(a> 80g) = time interval during which the acceleration of the head is larger than 80 g (less than 3 msec)
- a max = maximum head accelerat on

As compared to original design, the following improvements resulted in component tests:

		Original Hood	Displaceable Hood
HIC		1200 - 1600	300 - 500
dt (a>80g)	[msec]	8 - 10	3 - 4
a max	[g]	140 - 160	80 (alu) - 130 (steel)

Table 15 Improvement of head impact (component tests)

The consistent behavior is due to the deformability of the whole impact region on one hand, and to the collapsible bearing yoke (for head impact near yoke) on the other. The specific density of the top layer and the material directly beneath influences the maximum acceleration of the head. As a result, an aluminium design with the strip-wise foam support used reduced maximum accelerations below 100 g.

4.2.6 Full Scale Tests

A series of full scale tests were performed. The dummies "Part 572 Humanoid" and "Child 6 years Humanoid" with a modified neck were used for this purpose. The test conditions included collision speeds of 25 and 35 km/h and dummy positions resulting in head impact points in the middle of the hood and directly above the bearing yoke, at the corner of the hood. The acceleration time histories were measured on the pelvis, chest and head of the dummies. Since the component tests and the first full-scale tests had already led to uncritical values for the pelvis and the chest impact, the head impact was given particular attention. The figure below presents a typical time history of the resulting head acceleration.

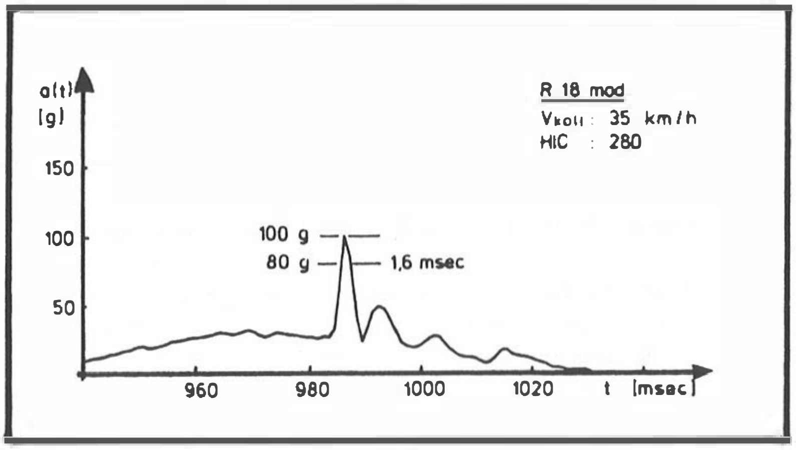


Figure 16 Resulting head acceleration in the impact on the modified front

As a whole, head impacts on the hood are associated with uniformly low accelerations across the entire width for both collision speeds. The accelerations were all lower than the required tolerances. The head accelerations and the Head Injury Criteria in a 35 km/h collision were measured as follows:

HIC	200 - 600	tolerance limit: 1000
dt (accel. > 80g)	0.5 - 2 msec	tolerance limit: 3 msec
a max	85 - 105 g	

4.2.7 Comparison of the Original and Modified Front

The comparison could be limited to one impact point for two reasons. On one hand, for the modified hood, the behavior under head impact does not depend on the place where the impact occurs. On the other hand, for the original front, one of the more unfavorable points in the inhomogeneous original front had to be taken (fan housing under the impact point).

A comparison is made between the maximum resulting head accelerations, the HIC values, the time intervals during which the head acceleration exceeds 80 g and the qualitative time histories of the head acceleration.

Exp No	Front	v_{coll} [km/h]	1) a_{max} [g]	2) dt [ms]	3) HIC	Average Values amax [g]	dt [ms] (a>80g)	HIC
123	R18	25	148	3.5	580			
124	orig.	25	127	2.5	510	138	3.0	545
128		35	156	12.0	1660			
180		35	142	9.5	1280			
181		35	146	9.5	1100	148	10.3	1347
183	R18	25	87	1.2	200			
186	mod.	25	86	0.5	180			
184		21	89	1.5	207	87	1.1	200
179		35	100	1.2	280			
182		35	89	3.0	620			
187		35	103	2.0	232	97	2.2	377

Table 17 Comparison of head accelerations and HIC of original versus modified front in full scale tests; 1), 2), 3) see following comment

1) a max: The maximum head acceleration is mainly caused by inertial forces and is found to depend much less on the collison speed than on the material and the design of the contact area: In relation to the original vehicle at a speed of 35 km/h, a 30 % reduction of the collision speed merely leads to a 7 % reduction of the maximum acceleration, whereas the modification of the front design leads to a 52 % reduction of the maximum acceleration. These results are not only based on the tests presented in the figure above, but were measured with all different variants of the modified hood.

2) dt (a < 80 g): The time interval during which the resulting head acceleration exceeds 80 g depends on various factors:

- During the first moment of the impact (1-5 msec), the inertial forces determine not only the peak of the acceleration, but also its duration. If it is possible to keep the accelerated part of the effective mass of the hood low by a corresponding design of the contact area, the acceleration peak will be low and short. This can be done in two ways: Using a surface material which has a low specific mass and designing in such a way that only a small area (or a small volume) participates in the impact phenomena in the beginning.
- Whether there is a second acceleration peak depends on the following criteria: The load bearing behavior of the hood, the available deformation space and the remaining kinetic energy of the head.

In the original configuration, the collision behavior of the hood itself, separated from the vehicle, is satisfactory, however, there is not enough deformation space. Consequently, the force/deformation-characteristics of the original vehicle are not given by the hood, but primarily by the underlying vehicle parts. In the modified front, the new hood design and the lifting of the back part of the hood enabled reducing the first acceleration peak and eliminating the second one. The time intervals of accelerations over 80 g achieved in this way are less than 3 msec for 25 and 35 km/h.

3) HIC: The HIC value, which reflects the combined effects of absolute value and time history of the head acceleration, emphasizes the aforementioned improvements: With the modified front, the HIC could be reduced to uncritical values (200-600) at both collision speeds.

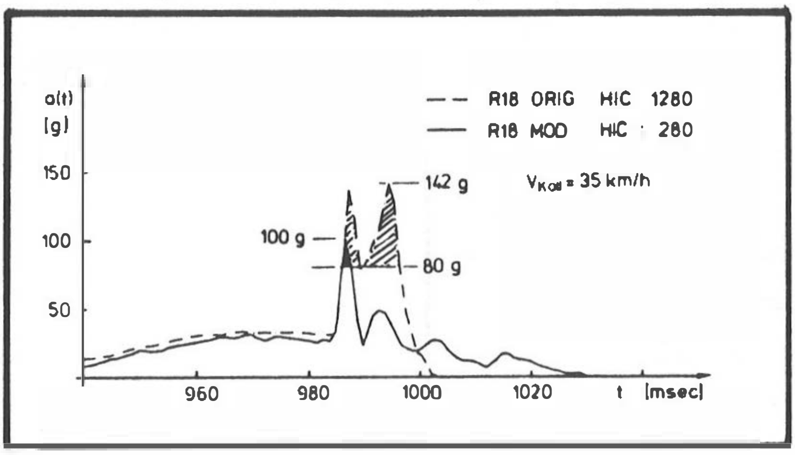


Figure 18
Head accelerations during collision with original and modified front

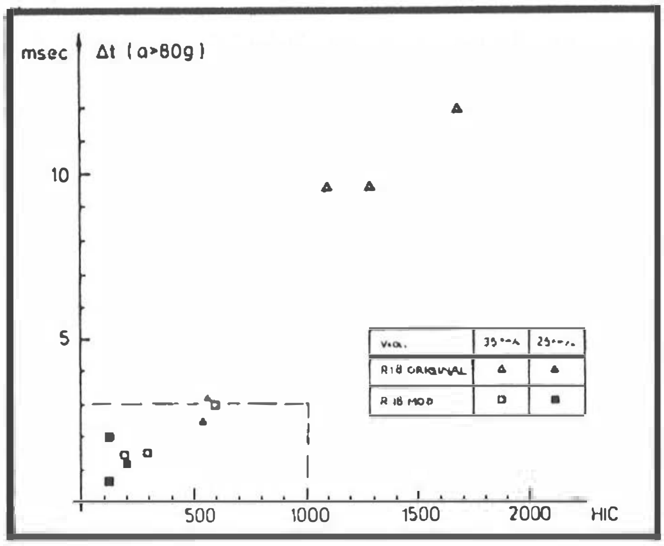


Figure 19
With the modified car front, HIC and time interval when acceleration exceeds 80g could be reduced to acceptable limits

4.2.8 Assessment of Hood in View of Requirements

I. Injury Tolerance Limits of Pedestrians

Head:	The tolerance requirements were met.
Pelvis:	Measurements during the examination of the opening mechanism and during full-scale tests yielded to accelerations less than 30 g.
Knee/lower leg:	Measurements in the component tests showed uncritical values (less than 40g).
Chest:	The original and the new design are far below tolerance limits (less than 30g).

II. Risks for Car Occupants

Two measures were taken to ascertain passengers safety:

- The rear edge of the hood was bent and covered with a rubber profile such that there is no danger of additional injuries for passengers who are not wearing seat belts and are projected through the windshield.
- In order to prevent the hood from penetrating into the passenger compartment, a predetermined

buckle point was built into the longitudinal stringers: The hood, while being displaced in the direction of the passenger compartment, is blocked from moving too far and is held down by the bearing yokes and lateral guiding cables. Under increasing deformation, the hood buckles upwards with the front with the back edge remaining down.

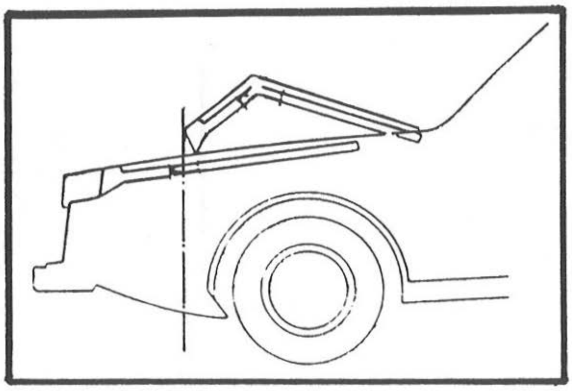


Figure 20
Predetermined buckle point of the new car front in head-on collision

III. Behavior of the Hood in Minor Accidents: In order to prevent an undesired displacement, a shear bolt was integrated in the hood locking. This device allows the opening mechanism to function only at forces above 800 N.

IV. Maintenance Work: The experimental front has a locking mechanism similar to that of the original and it is operated from the passenger compartment. The new hood can be opened in the same way and to the same extent as the original one.

V. Re-Usability as Experimental Front: Besides the deformation elements and the upper panel containing the sandwich structure, all the elements could be used again after each test.

VI. Mass Production: The requirement that the hood be easy and inexpensive to produce and that the lifting mechanism doesn´t need servicing under the condition of a one-time use (in case of a collision) was not taken into account for the experimental front because this would be part of an industrial development program. For the hood, low mass forces (first acceleration peak) combined with necessary rigidity (energy absorption) are to be aimed at. For the hood surface synthetic materials and composites, fibre reinforcements as well as aluminium should be taken into consideration.

VII. Children: The test with the child dummy showed that the modified hood is also of advantage for children. Even if the hood does not open because of the small mass of children, the soft nose provides for a reduced pelvis/upper leg and shoulder impact. As only low head acceleration occured both in the tests with the original R 18 hood and those with the displaceable hood (only mild head impacts at collision speeds up to 35 km/h), there was no significant difference in this respect, though the modified softer neck was used.

5. CONCLUSIONS

The presented displaceable hood reduces the accelerations during car-pedestrian impact far below the tolerable limits up to collision speeds of 40 km/h and seems therefore an efficient mean to prevent injuries.

The elements of the described design procedure (2-dimensional simulation for design purposes, component tests, full scale tests and 3-dimensional mathematical validation) are powerful tools in car development.

6. LITERATURE

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