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STUDY OF VEHICLE ADAPTIVE STRUCTURES FOR FRONTAL COLLISIONS

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Abstract: In order to reduce the occupants' risk of injury in a frontal impact, besides developing passenger protection systems (safety belt and airbag), it is necessary to improve the collision performances of the vehicle structure. For that, the behaviour of nowadays cars should be assessed in full impacts, and factors influencing this behaviour in various collision situations. Non-uniform crash of the frontal structure and uncontrolled deceleration pulses are the main negative effects of a car structure's behaviour in a frontal impact. Consequently, deformations and intrusions into passengers' cell and therefore risk of injury are high, especially with relative high speeds.The study of constructive concepts and solutions to ensure the integrity of the vital passengers' space and an optimum deceleration rate regardless of collision circumstances represents the main objective of this work. In addition, a constructive solution is proposed for a front structure including three different concepts, intended to fulfil these requirements.

1. FRONTAL CRASH PARAMETERS

In order to design vehicles that should be secure enough in any collision, one should be aware of the entire range of possible car crashes. To that extent, a series of statistics performed by vehicle manufacturers and research institutes (Justen 1993, Seiffert, NASS-National Automotive Sampling System and FARS-Fatality Analysis Reporting System, respectively) offer a wide database of collision parameters in car crashes. The main collision parameters are collision speed, the type of obstacle, impact location and direction. When frontal collisions are considered, from the analysis of such databases a few conclusions may be inferred, namely:

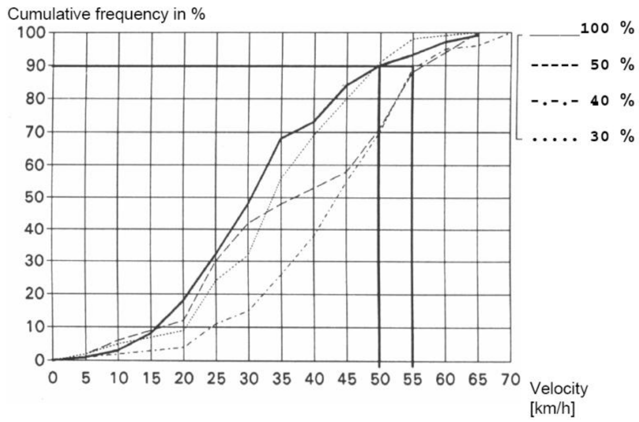


Figure 1. Cumulative frequency of velocities in frontal collisions (source: Justen 1993).

- We may talk about frontal collisions when the angle between the impact direction and the vehicle longitudinal axis varies between -30° and +30°;
- Over 90% of frontal collisions happen at speeds below 90 km/h (Figure 1.)
- Frontal collisions happen mostly with partial overlap (overlap of the frontal part of the vehicle over the obstacle) in a rate of 30% up to 100%;

- Practically the variety of obstacles against which vehicles collide is countless; however, they are mainly included in the following three types of obstacles: rigid barrier, deformable barrier and pole.

1.1. COLLISION SPEED

For optimal frontal crash behavior, all kinetic energy should be dissipated by the front structure. The lowest deceleration level of the passenger compartment is obtained, if the available deformation length in front of the car is as long as possible. For a specific crash velocity, the optimal situation is achieved if the entire available deformation length is used without deforming the passenger compartment. This implies, that in a given vehicle concept the structure must have a specific stiffness which is determined by the relation between the crash energy at this velocity and the available deformation length. Higher velocities result in a higher level of kinetic energy, which cannot be fully dissipated by this front structure. Hence, the passenger compartment has to deform, which means that the necessary survival space cannot be guaranteed. Lower velocities will not use the whole available front structure causing the forces acting upon the occupant to be higher than necessary. In case of a deformable barrier, the barrier also absorbs energy and increases the total deformation length. So for a similar level of energy absorption in the vehicle structure, the crash velocity of the car against a deformable barrier must be higher as in case of a crash against a rigid wall.

2.1. OBSTACLE TYPE

The obstacle stiffness has a great influence on the car behaviour upon the impact. The rigid elements of the frontal vehicle structure having the role to take over a great amount of energy during the impact are the two longitudinal members and the engine. For example, a typical axial regularly deforming longitudinal member may take over approximately 25% from the energy of impact. The behaviour of the frontal structure of the vehicle is significantly influenced by the type of obstacle:

- In case of rigid barrier-like obstacle (wall of a building, heavy vehicle), in the first half of the collision longitudinal members start to deform, and in the second half the engine ensemble is hauled backwards, first deforming the passenger firewall, then deformations of thresholds and rooftop and intrusions occur.
- In case of a deformable barrier-like obstacle (another motor vehicle) loading is generally not so heavy – less rigid elements in front of the vehicle deform first, whereas rigid elements of the structure (longitudinal members) would not start to deform from the beginning of the impact. Consequently, the frontal structure absorbs a less quantity of energy, which may determine the occurrence of intrusions and deformations in the passenger compartment. Despite the vehicle deceleration being more reduced in this case, the quantity of energy to be taken in is the same. The dynamic rigidity of the structure, that is, its resistance to quick transformation of kinetic energy into deformation energy diminishes, which determines greater frontal structure deformations in the passenger compartment area than in the front part of the car.

Figure 2. presents an estimation of the distribution of energy absorbed by the front structure of a car crashing against a fixed non-deformable barrier, at a speed of 56 km/h (De Santis 1996, Leeuwen 1997).

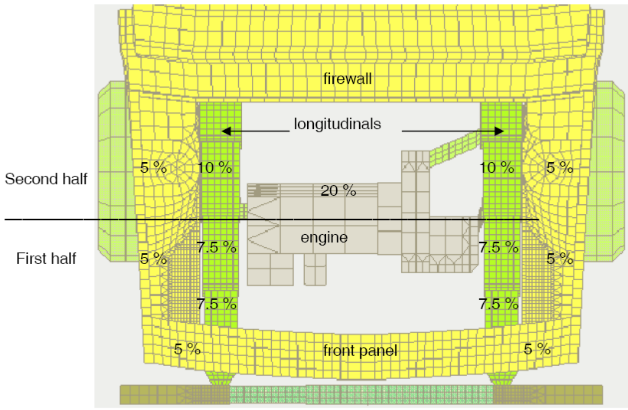


Figure 2. Estimated energy absorption percentages in the frontal structure.

3.1. COLLISION PLACE AND DIRECTION

The overlapping rate of the front of the car against the obstacle establishes which part of the vehicle frontal structure is hit and the way the energy absorption is distributed. In case of full frontal overlap against a rigid flat barrier, both longitudinal members and the engine will absorb the greatest energy amount. In the first half of the collision only longitudinal members will be strained and in the second half the engine ensemble will be strained as well. In case of frontal impact with the same type of barrier but with a partial overlapping of less than 70%, the entire frontal structure will not be involved in taking the energy in. An surrounding structure would mean the ensemble of frontal structure elements of more reduced rigidity as compared to the longitudinal members, namely: bumper reinforcement, front mask, semi-wings, wings, hoods, front bumper, rails, etc. Researches (Ragland 1991) showed that in vehicle-vehicle collisions the energy absorption rate is very high in the first half of the collision.

Table 1. Relative energy absorption for several frontal crash overlaps against a rigid wall

Frontal overlap percentage	Stiff parts in the structure	Part of total energy absorption first half of crash duration	Part of total energy absorption second half of crash duration
70 - 100%	-2 longitudinals -surrounding structure -engine / firewall	50 %	50 %
40 - 70%	-1 longitudinal -surrounding structure -engine / firewall	25 %	35 %
30 - 40%	-1 longitudinal -surrounding structure	25 %	15 %

The explanation is that the front structure rigidity is not evenly distributed, and in an impact with an overlap below 50%, it is only one longitudinal member absorbing energy, whereas the other longitudinal member and the engine block are not involved. Impact against a stiff pole may be regarded as a frontal impact with small overlapping to a rigid wall, where one longitudinal member or the engine only will be hit. Change of collision direction in case of collision against a flat rigid barrier (0° to 30°) leads to the so-called glance-off, where the vehicle brushes the barrier and changes direction, continuing is way.

2. THE BEHAVEYOUR OF VEHICLES STRUCTURES IN FRONTAL IMPACTS

One of the conditions imposed to car design and manufacture in order to achieve occupants' safety in frontal collisions is that the passenger cell should not deform and not allow objects from outside to enter by intrusion in the occupants' compartment. To that it is necessary that the front part of the car structure should take enough energy out of any real collision. Therefore, the deformation distance in front of the passenger cell, also called deformation area, should be used efficiently enough in order to ensure the wished deceleration to passenger cell.

With full overlap frontal collisions to an obstacle, the two front longitudinal members absorb the greatest amount of energy by progressive deformation of the tubular metallic structure of which they are made. Frontal loading and distribution rate to the resistance structure of nowadays cars is shown in Figure 3. The main problem of this kind of structure is that in real-life collisions the two front longitudinal members are not often simultaneously solicited, and therefore their load is not purely axial. Most frontal car crashes occur with partial frontal overlap, where there is only one longitudinal member bearing the stress, or the stress is not on an axial direction. Given such collision circumstances, the situation is extremely frequent where longitudinal members yield prematurely by bending before absorbing the energy through axial deformation.

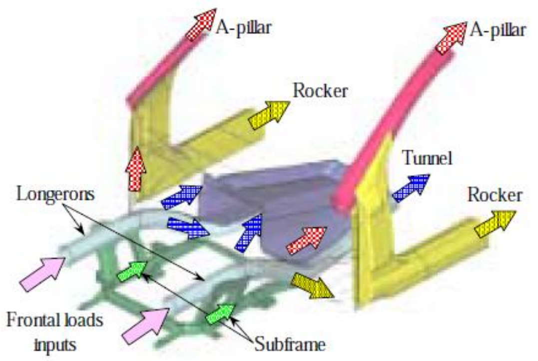


Figure 3. Load paths on car body elements during frontal impact

Therefore, the front part of the resistance structure in nowadays cars, having the role of taking in the impact load by deformation, is confronted to two major issues:

- The same amount of energy should be absorbed by one longitudinal member as well as both longitudinal members;
- The same amount of energy should be absorbed in case of a frontal impact on an axial direction, and with a frontal impact frontal on an oblique direction.

These issues cannot be solved by the increase of longitudinal members rigidity only, so that each longitudinal member would absorb the entire amount of energy in offset collisions, because in full overlap collisions the same longitudinal member should be a lot more softer, with a lower rigidity, so that it might take with the other longitudinal member the same amount of energy. Likewise, a highly rigid longitudinal member is necessary with frontal collisions in which loading is oblique, as it has a higher bending resistance, which helps with transforming the oblique load into an axial load and prevents crash by bending.

The same longitudinal member, much softer, is necessary in the event of axial load frontal collision in order to prevent the occurrence of too strong deceleration forces.

In order to absorb the entire amount of kinetic energy, proportional to the square of speed, the deformable structure should have specific rigidity. This rigidity is expressed by the average force that, multiplied with the deformation distance results in the energy absorbed. For an acceptable rate of occupant injury, total deceleration should be as low as possible, by using the maximum available deformation length without the deformation of the passenger cell.

3. THE NECESITY OF AN ADAPTIVE VEHICLE STRUCTURE

The improved frontal crashworthiness of cars necessitates totally new design concepts, which take into account that the majority of collisions occur with partial frontal overlap and under off-axis load directions. Realistic crash tests with partial overlap have shown that conventional longitudinal structures are not capable of absorbing all the energy in the car front without deforming the passenger compartment. It is clear to see that in case of a full overlap collision there is no intrusion of the passenger compartment, while in the offset test the passenger compartment of the same car collapses. The reason for this is that the structure of the longitudinal members is specifically designed for meeting the less severe requirements of the compulsory full overlap test, in which both longitudinals are loaded axially.

Increased protection for the entire collision spectrum can be obtained by structures consisting of longitudinal members with an advanced geometric form, giving higher bending resistance without increasing the axial stiffness, in conjunction with a rigid connection between the front ends of these members.

In order to obtain an amount of energy absorbed in an offset collision similar to the full overlap collision, the longitudinal member that is not directly solicited by the power of the impact should take in a part of the load by deformation in offset collision. Constructive solution by which load may be distributed on both longitudinal members in offset collision are briefly presented in the following section of our work. For an attempt to try a cable and rod adaptive system concept a series of numerical simulations have been made in full overlap and 40% offset overlap, and at 30% collision angles. The results of these simulations indicated close amplitude deceleration rates, which prove that re-allying front vehicle structures is possible in motor vehicles registering a deceleration pulse that is almost dependent on the overlapping of the vehicle to the obstacle and the collision direction. In such case the issue is to determine the optimum pulse rate of collision with different speeds, the aim being the minimum injury of the occupants.

The issue of making an adaptive structure that should be able to modify its own rigidity during the impact in order to ensure the optimum energy absorption in various collision circumstances requires the management of deceleration intensity, as it has been proved that deceleration rate is greatly influencing the injury risk of occupants. Therefore during full collisions the car structure should generate an optimum pulse over the passengers' cell, allowing for the kinetic energy to be fully absorbed.

The collision rate depends on the relative collision speed and should be independent from the other vehicle's position. The energy taken in should depend on the total car mass and the relative collision speed, which on its turn depends on the colliding speed of both vehicles and their compatibility in terms of mass.

From previous research (8), it is known that a traditional deceleration curve with an increasing deceleration level, from the beginning with a relatively soft structure to the end of the crash with a high force level, is far from optimal. For a low crash velocity a constant crash pulse is ideal while for higher crash velocities a high-low-high crash pulse is optimal. An active control of the structural response is necessary in order to minimize restraint system loads in low speed impacts and to create high-low-high pulses for higher crash velocities.

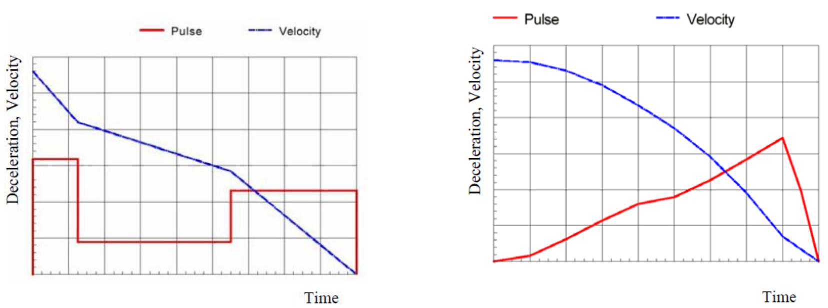
Researchers (Witteman , Motozawa and Kamei) studied the possibility of reducing occupant injury severity without increasing vehicle deformation by actively controlling the vehicle deceleration in a crash. The influence of the change in vehicle deceleration with time on occupant injuries in crashes has been studied by modifying the deceleration curve of an actual vehicle and optimizing it in order to reduce occupant injury by using the sensitivity analysis method applied to dummy simulations. Witteman, gave a method to calculate an overall severity index based on bio-mechanical injury criteria. An integrated numerical model of dummy and car interior was described with corresponding restraint parameters yielding the lowest overall severity index. The conclusions are that the pulse can be described by three phases, ensuring minimal risk for the occupants:

Initial collision phase. The impact is detected by the safety belt and the airbag sensors. For an optimal airbag release upon the collision, the front structure rigidity should to be higher in order to trigger a deceleration rate above the airbag release threshold. The occupants not being in contact to the retention systems yet, the deceleration rate of the passengers' cell may be very high, without any risk of injury. Car deformation length is reduced in this phase.

Airbag release phase. The relative movement of the occupant relative to the vehicle is restricted by the safety belt and the releasing airbag. As in real-life car crashes the occupants have suffered injuries caused by the impact to the vehicle's interior (dashboard, windshield or steering wheel) or by the relatively high speed impact against the inflated airbag, it is recommended that in this phase the relative occupant/vehicle speed should be low and therefore the passengers' compartment should be also low.

Occupant contact phase. In this phase the occupant comes in contact with the airbag and a rigid contact between the occupant and the vehicle results. Deceleration rate may be high, without any risk of injury, as the occupant is not submitted to great stress in contact to the interior of the vehicle.

The optimum deceleration rate for the numerical model of the car interior, used by Witemann, at 56 km/h speed in frontal full overlap to a rigid barrier is shown in Figure 3a. Figure 3b shows the real normal deceleration rate in the same collision circumstances. The conclusion of Witteman's study was that overall severity index was 35% lower in the optimum collision rate than in real time rate.



a. b.

Figure 4. a. Optimal deceleration pulse b. Deceleration pulse of actual cars.

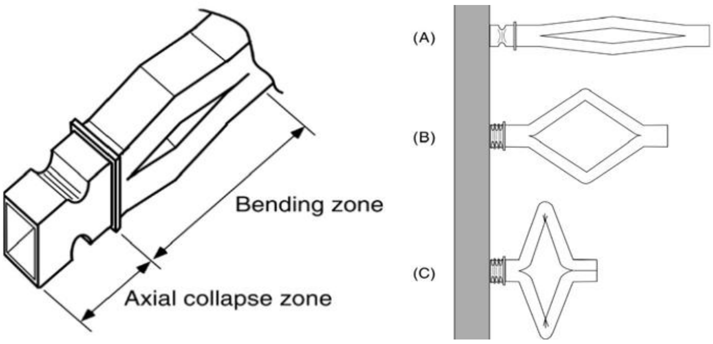
4. THE CONCEPT OF NEW ADAPTIVE STRUCTURE

The adaptive frontal structure proposed in this work includes three different concepts that follow:

A. Collision-aware rate control
B. Charge transfer between longitudinal members
C. Full impact transformation into glance-off

4.1. OPTIMAL DECELERATION PULSES

Feasibility of the “high-low-high” crash pulses, have one major difficulty that a vehicle structure will always start buckling or bending at its weakest point. This means that even if the front structure is stronger in its most forward parts, but weaker in parts closer to the firewall, the weaker part will always buckle first. Thus a pulse with an initial deceleration peak can almost only be created by inertial effects or by actively controlling the stiffness of the energy absorbing members during deformation. Motazawa and Kamei have designed a structural concept that is able to create a fixed high-low-high pulse. The fundamental model (see figure) is a hollow member designed to act as a longitudinal. It consists of a front zone for axial collapse, and a center zone for bending. The axial collapse zone incorporates a stress concentration in order to induce regular buckling deformation, while the bending zone has a mildly cranked shape to stabilize the bending deformation direction. Each of the cross-sections is set so that the deformation load of the axial collapse zone will be slightly less than the maximum load of the bending zone.



a. **b.**

Figure 5 a. Fundamental model of a crash load control structure (Motozawa, Kamei)
b. Deformation process in the fundamental model

Figure b shows the deformation process of the fundamental model. In the first phase of collision, soon after the first moments of impact, the axial crash area starts to deform because of load (A) concentration. Axial load remains constant until total deformation of this area. When the load reaches deformation by bending zone buckling, the second phase of the deformation process is practically starting, the structure being quickly deformed in this phase (B). After full bending deformation is complete, the third phase (C) starts, the increase of load rate on the longitudinal members determining their deformation.

4.2 TRANSFER LOAD BETWEEN LONGITUDINAL RAILS

It has been subsequently shown that with frontal collisions, a series of parameters such as: collision location and direction, collision speed and the type of obstacle significantly influence the deceleration rate of passengers’ cell and implicitly their risk of injury.

The kinetic energy of the car for a certain impact speed rate is the same regardless of the type of frontal collision (full overlap or partial overlap), the amount of energy that should be absorbed by the vehicle/obstacle system is the same. In this sense, it is important that the front structure of the vehicle should be conceived in such a way that the impact load should be distributed as evenly as possible to the elements destined to the absorption of energy (longitudinal members).

A concept of front adaptive structure resides in transferring the load from the solicited longitudinal member to the other longitudinal member, unloaded, for better energy absorption, and the optimization of passengers' compartment deceleration. From a constructive point of view, a solution for such an adaptive system is one that transfers the load by using two hydraulic cylinders attached to the two longitudinal members so that the axial deformation of the loaded longitudinal member would determine the compression movement of the piston attached to that cylinder transferring hydraulic fluid for the opposite cylinder, forcing the compression of its piston (see figure). Implementing the system would lead to vehicle mass and cost increase and would require a considerable space for assembly.

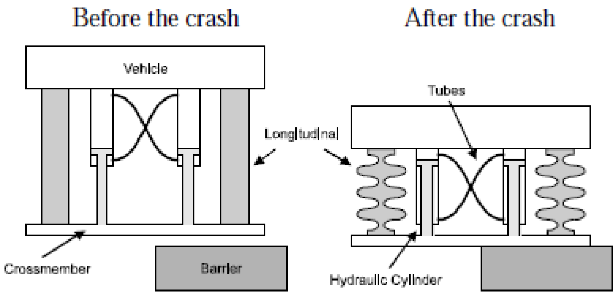


Figure 6. A hydraulically controlled frontal car

4.3. TRANSFORMING SMALL PARTIAL OVERLAP IMPACT INTO GLANCE-OFF IMPACT

Small lateral overlap frontal vehicle/vehicle collisions at high speeds have a greater risk of injury, first of all because of the relatively high closing speed recorded at the beginning of the collision, and secondly because of full hanging between vehicles during first vehicle contact. This phenomenon occurs even in small lateral overlapping, causing sudden change of gear and intrusions into passenger safety area.

The part of the car situated in front of the passenger cell, to the exterior of the resistance structure delimited by longitudinal members, namely the front wheel area, is less rigid than the central part of the structure, therefore having a more reduced energy absorption capacity, and a frontal impact may cause passenger cell deformation. In that sense a concept is submitted to analysis which is aimed at transforming small lateral overlap frontal collision into glance-off, by which is intended to substantially reduce deceleration of both vehicles and implicitly the increase of passengers' safety.

During the glance-off, the involved cars would never reach the same speed. The S force impulse is a temporary integral of the contact force rate between the colliding vehicles. Taking the influence of forces exterior to the collision (air resistance, driving resistance, etc.) as negligible, one can notice that the force impulse corresponds directly to speed changes.

$$S = \int F_{const}(t)dt = m \int a(t)dt = m\Delta v \quad (1)$$

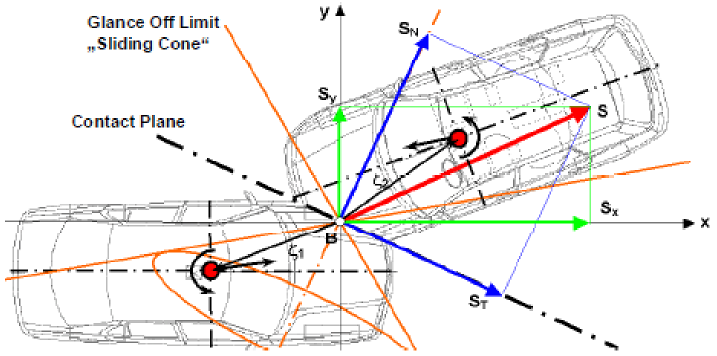


Figure 7. Frontal Offset Crash

Glance-off collision has two specific parameters:

- The angle of contact plan (φ) between the longitudinal axes of colliding cars. This angle is defined by the direction of the relative speed vector of the contact surface between the vehicles
- The value of glance-off resistance (μ), which is given by the ratio between the tangent component and the normal component of force impulse.

Generally speaking, glance-off resistance rate is an extremely sensitive factor for the crash car reconstruction and, theoretically, it could have values ranging from 0 to the infinite. According to researches performed by Winkler (7) in the event of 20% partial overlapping frontal impact between two vehicles of 2500 kg and 1000 kg, respectively, each having a colliding speed of 100km/h, for μ=0,5 and φ=160°, table 2 presents comparative results for full collisions and glance-off collisions, respectively.

Table 2. Reduction of Biomechanical Injury Values for an Exemplary Sliding collision

Collision type	E_{def} [MJ]	S [kNs]	Δv1 [km/h]	Δv2 [km/h]
Full overlap	1	40,6	58	146
Sliding colision	0,3	9,5	14	34

The fact that injury risk rate of occupants in glance-off is much lower than in full collision is obvious, proportionally to change of speed, Δv, as seen in figure 8.

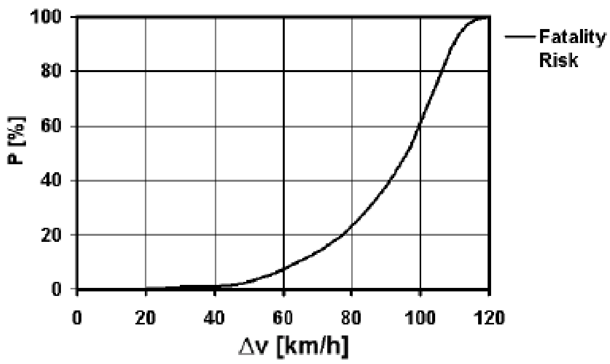


Figure 8. Probability of a lethal accident depending on the change of velocity (Evans 1994)

As a constructive solution, the frontal structure proposed is displayed in figure 9. The deformation area is attached to the longitudinal members by a detachable connection facilitating car repair after the accident by replacing this sub-structure.

The shape of the anterior deformation longitudinal member has been conceived after the fundamental model allowing the collision-aware rate control. At the beginning of the impact occurs axial deformation of the longitudinal member end, when deceleration should be high, then deformation by bending of the bent structure zone starts, deceleration being reduced. After the anterior deformation area crashes in strong collisions, the axial deformation of the actual longitudinal members and the involvement of the engine ensemble into the load taking-over rate start.

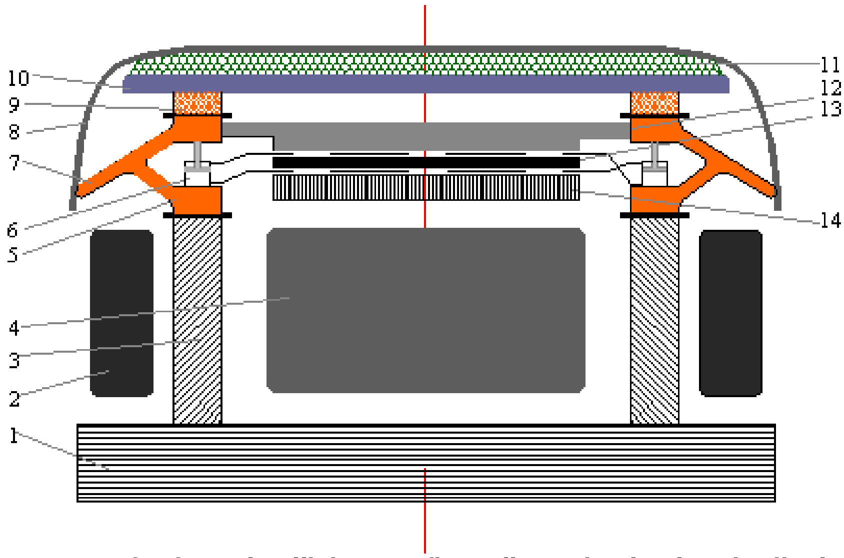


Figure 9. Adaptive structure for frontal collisions: 1-firewall, 2-wheel, 3-longitudinal member, 4-engine, 5-adaptive part, 6-hidraulic cylinder, 7-deflecting device, 8-bumper, 9-collapse member, 10-transversal member, 11-shock absorber, 12-tragger, 13-AC condenser, 14-cooler

Hydraulic pistons installed in the anterior longitudinal member arc have the role to ensure load transfer from the loaded longitudinal member to the other longitudinal member by means of hydraulic liquid, for better energy absorption and optimization of passenger cell deceleration. The installing place of hydraulic pistons solves the issue of the space necessary to the implementation of this concept.

The third concept is implemented in the new adaptive structure by the construction of the quarter-light situated in front of the wheel. It has the role to protect the front wheel area, is less rigid than the central car body, with a more reduced energy absorption capacity, presenting a high risk of passenger cell deformation. Another important role of this quarter-light is transforming the partial overlap frontal impact into a glance-off impact, by this substantially diminishing the risk of occupants' injury.

5. CONCLUSIONS

It is possible to achieve adaptive car frontal structures, which should ensure an optimum deceleration rate for the passenger cell, regardless of the collision circumstances, and which should ensure transformation, under certain circumstances, of full collision into glance-off collision.

The solution for the frontal structure proposed in this work includes three distinct concepts integrated into a technically feasible constructive form. A great advantage is the deformable structure zone that was so conceived as to be replaced. It is possible that from an economic point of view implementing this solution might increase a lot the costs of a car. One of the disadvantages of the structure would be a shorter deformable area, which would be partially compensated by the hydraulic system ensuring better energy absorption.

The proposed structure definitely requires a series of technical adaptations and an evaluation of its efficiency as compared to current frontal structures is necessary.

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