IMPLEMENTATION AND ASSESSMENT OF MEASURES FOR COMPATIBLE CRASH BEHAVIOR USING THE ALUMINUM VEHICLE AS AN EXAMPLE

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ABSTRACT

The compatibility of passenger cars is mainly attributable to the parameters of mass, the shape of the contact surfaces and the rigidity of the vehicle's front end. Due to its low density, aluminum offers excellent conditions for compatible behavior in road traffic.

Using the Audi A8 as an example, a presentation is made of the design measures which have a positive impact on the distribution of kinetic energy on both the vehicles involved in a crash. Great importance is placed on structural and passenger simulations using FE and MBS programs during the concept phase of vehicle development.

In the meantime the compatible design of the vehicle's front end has been confirmed by test series performed by independent test centers. Findings show that the aluminum body is subject to highly regular deformation in an offset crash both with a vehicle of identical mass and with vehicles of lower mass. The aluminum body is also capable of absorbing a high proportion of the total energy produced by the two vehicles.

Finally, further test results are forming the basis for discussing how well the 40% offset crash at 40 mph (IIHS crash test) against a deformable barrier can simulate a real crash.

INTRODUCTION

In addition to protection of the vehicle's own occupants, which has reached a high standard on account of the relevant legislation (e.g. FMVSS 208) and rating procedures (e.g. NCAP or IIHS), increasing significance is being attached to protection of the other party involved in an accident. In this respect the compatibility of the vehicles in head-on collisions as well as in side impact collisions must be considered.

The VW Group (Audi, SEAT, Skoda, Volkswagen) offers vehicles in a wide variety of mass and size categories for sale. There is accordingly much motivation to investigate the important topic of compatibility between different vehicles.

The difference in mass of the accident vehicles exerts a significant influence on compatibility in road traffic. For frontal impact, a simple consideration of momentum supports this as the velocity change of the heavier car will be less than that of the lighter car.

$$m_1 \bullet v_1 + m_2 \bullet v_2 = (m_1 + m_2) \bullet v_{after} .$$

The demands placed on the small light-weight vehicle by a heavier vehicle - especially in fully overlapped collisions - are superproportional. Even in the case of a lateral impact the high kinetic energy of colliding cars has a negative effect on the intrusions and thus directly on the potential for injury. A reduction of weight for large cars is therefore desirable for several reasons:

- Reduction of fuel consumption leading to greater environmentally friendliness.
- Improvement of the mass compatibility in road traffic.

As far back as the mid-eighties Audi began developing aluminum vehicles to reduce the effect of weight incompatibility of larger cars. Different studies showed that fatalities can increase for reduced weight cars when the reduction occurs through both mass and size reduction. But aluminum allows mass reduction to be achieved without changing size or reducing crashworthiness. The aluminum bodyshell was conceived anew and designed with the aid of extensive computer analysis, Figure 1.

By using FEA (Finite Element Analysis) and employing complex MBS models (Multi Body System) the vehicle structure and restraint systems were optimally coordinated. This paper sets out the advantages of the newly-developed Audi Aluminum Space Frame Concept (ASF) in real accident situations.

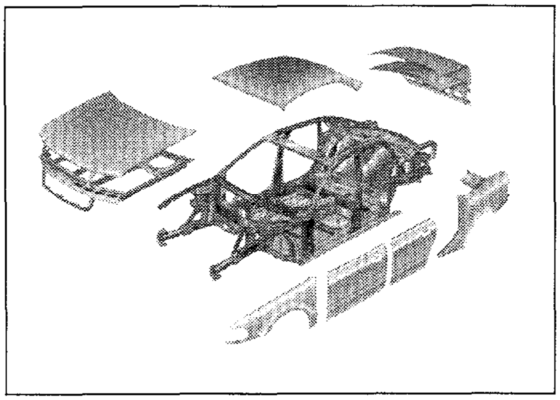

Figure 1. Audi A8 Aluminum Space Frame (ASF).

Definition of Compatibility

When a single-vehicle accident occurs, injuries of the occupants depend on the collision mode, on the impact velocity, on the personal condition of the occupant and on the inherent safety of the car. Inherent safety is the ability to avoid injuries to its occupants, when a collision mode at a specific velocity occurs. This ability is measured by vehicle behavior and interpretation of the dummy kinematics and loads. The inherent safety of a car can also be called self protection or occupant protection.

In a car-to-car accident, collision modes, impact velocities, and the personal condition of driver can be observed in the same manner. But injury to the occupants does not only depend on the inherent safety of the car, but also on the structural behavior and mass of the **other** car. It is obvious that an accident between a heavy and a light car may be different from an accident between two light cars. An accident between a rigid and a yielding car might be different to an accident between two yielding cars. The distribution of the stiffness at the front of a vehicle might influence the interaction between the structures of the two colliding vehicles. In car-to-car accidents we therefore also study partner protection, the ability of the car to avoid injuries to other participants in the collision. Lack of partner protection is referred to as aggressivity. Vehicle aggressivity can be defined to be the number of fatalities/injuries in the vehicles struck by the subject vehicle divided by the number of subject vehicle registrations or by the number of crashes of the subject vehicle (aggressivity metric) /1/.

The goal of compatibility is to bring these two issues together

- to enhance partner protection
- without decreasing occupant protection

or to optimize occupant protection in such a manner that the overall crashworthiness performance of the vehicle is maximized.

Of great importance here is that the problems are faced both by the large, heavy car as well as by the smaller, lighter vehicle. If the smaller vehicle does not possess a stable passenger compartment, designed to receive the front structure forces of the opposing car, then there can be no compatible crash behavior in road traffic /2/.

Data analysis

Figure 2 shows the situation as identified in the Volkswagen accident data base. This is a data base of 10160 passenger cars (53 % are not Volkswagen or Audi models). The accidents were collected in Germany.

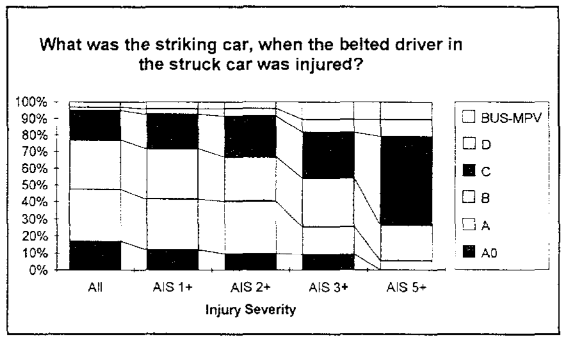

Figure 2. Distribution of the size-groups of the striking vehicles when a belted driver in a struck vehicle was injured.

The vehicles are divided in 6 groups: **A0** such as the VW Polo, Opel Corsa etc., **A** such as the VW Golf, Ford Escort, **B** such as the Audi A4, VW Passat, MB C-Class, **C** such as the Audi A6, BMW 5xx, MB E-Class, **D** such as the Audi A8, Volvo 7xx, MB S-Class and **Bus - MPV**, comprising minibuses like the VW Caravelle and similar products. Accidents between those types of vehicles were checked and it was registered what the striking car was when the belted driver of the struck car was injured. All collision modes are included. The data were checked for all belted drivers, injured and not injured, and for the different MAIS classes.

It can be observed that MAIS 5 and 6 occurs to a level of more than 90 % in crashes when a B-, C-, D-, or bus-type vehicle strikes another vehicle, although these groups are less than 55 % of the striking vehicles for all drivers.

In the United States the distribution is even more dramatic, as an analysis by the NHTSA working group on vehicle aggressivity and fleet compatibility shows /3/. Because of the high market share (approximately 50% of new registrations), the class of Light Trucks and Minivans are significantly represented in the number of fatal accidents. LTVs - which includes sport-utility vehicles, pickups and vans - are about twice as aggressive as passenger cars if the total number of fatalities in the opposing car is considered. A IIHS study /4/ even proves, that occupants of passenger cars are six time as likely to die when they collide with a large truck compared with another car.

This and other observations were the reason for Audi, Seat, Skoda and Volkswagen to form an internal expert group to study vehicle compatibility phenomena. Extensive analysis identified a number of parameters which significantly influence the compatibility behavior of a vehicle in a real accident situation.

BASIS DESIGN CRITERIA FOR A COMPATIBLE VEHICLE BEHAVIOUR

Crash incompatibility can be reduced. In order to achieve a coordinated crash behavior for two vehicles, three fundamental design guidelines - here described in outline - must be observed.

Vehicle mass

The difference in mass between the larger and the smaller vehicle must be minimized. With environmental friendliness in mind the target is to thus achieve a reduction of weight for large cars without changing size or reducing crashworthiness.

Crush zone stiffness

Structural factors include the frontal stiffness as determined from crash tests and engine location. The aim must be to make the stiffness of the vehicles compatible. This means that the passenger cell must be brought up to a sufficiently high impact level before it collapses and deforms the front below this impact level limit.

The stiffness should also be designed to produce a gradual impact level. This insures that the front structure absorbs at least a part of the kinetic energy in a side impact.

Geometry and structural interaction

The force of the front structure must be evenly distributed on the other vehicle. For this an extensive support for the longitudinal and engine forces - similar to a protective shield - is necessary. A deflection has a positive effect on the opposing car as it retains a part of the kinetic energy and must not be converted into deformation.

Geometrical factors also include the hood profile, sill and bumper height /5/.

NUMERICAL EVALUATION OF CRASH COMPATIBILITY

To evaluate the many parameters which must be considered in order to adhere to the above cited design guidelines a large number of costly crash tests are required. The ability of computer simulation to act as a substitute for actual car-to-car testing therefore has to be studied.

At the 15. ESV-Conference it was shown how computer simulation can be adopted in order to obtain a realistic analysis of these highly complex occurrences /6/. The great advantage of computer simulations is the possibility to conduct many optimizations with investigating only one parameter of the system. Calculation of variants and extensive optimization calculations can be conducted in this way, in order to determine the principal compatibility parameters and introduce improvements on vehicles.

Numerical evaluation of the complex occurrences in a car-to-car accident calls for the correct modeling of all relevant assemblies and part-systems /7/. By way of an example, an Audi A4/Seat Ibiza side-impact crash with regard to compatibility was analyzed with the finite element program PAMCRASH. The simulation model was built up as follows:

1) Modeling and validation of the Audi A4 side structure with the Euro-SID dummy, including the door trim and door padding, in a side crash according to EEVC conditions.
2) Checking the Seat Ibiza frontal crash model by means of a 55 kph „auto, motor und sport“ offset-test.

3) Combining the models and calculating structural behavior and EuroSID loadings in a car-to-car crash in which the Seat was driven at a right angle into the side of the Audi in accordance with EEVC experimental conditions.

Figure 3 shows one step of the crash analysis.

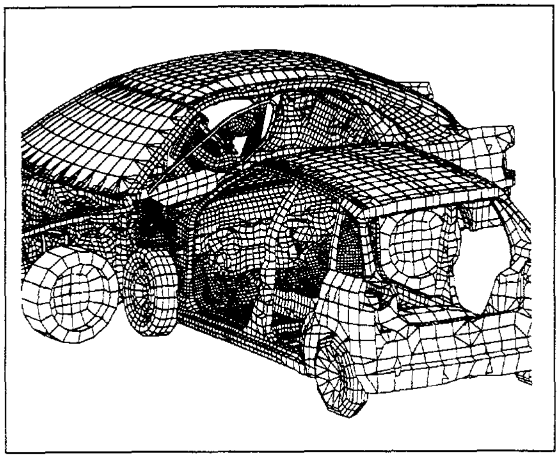

Figure 3. Complete FE Model for Analysis of the Car-to-Car Compatibility Crash.

In order to evaluate the loads on the occupants, a crash test was carried out with precisely the same peripheral conditions as in the numerical simulation. Because of the extensive validation already carried out, combining the various part-models presented no problems. Both the elapsed time and the maximum values in the calculation and the experiment coincided very well. The work showed that calculation of car-to-car accidents as a means of investigating compatibility is a tool capable of analyzing deformation behavior and the resulting loads on dummies in the preliminary development phase for various vehicle structures.

THE DESIGN CONCEPT OF THE AUDI A8

To really reduce the weight on an automobile dramatically you have to be consistent and start where the car is heaviest - on the bodyshell. The objective, after all, was to achieve a dramatic decrease in weight despite significant improvements in rigidity, the ability to absorb and take up impact energy, and driving characteristics under all conditions. Accordingly, particularly great significance was given to the crash simulation tests, the data obtained in this process being verified and confirmed in subsequent practical testing.

The technology which makes all this possible is the Audi Space Frame ASF. This development clearly demonstrates the potential of aluminum for weight reduction without size reduction.

Audi Space Frame ASF

ASF consists of extrusion-pressed aluminum profiles connected by vacuum-pressure-cast intersections and surrounding the entire passenger compartment, shown in Figure 4.

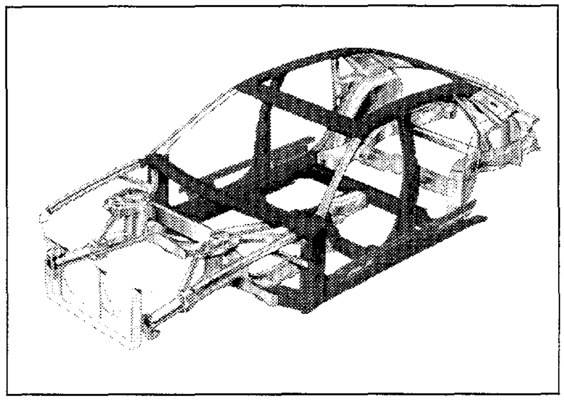

Figure 4. The Audi Space Frame ASF Structure Concept of the Audi A8.

The superior stability of the Space Frame results primarily from the intersected connections made of high-efficiency aluminum alloys and with the help of an optimized vacuum-casting procedure. In their thickness and shape, the intersections are tailored precisely to the specific loads varying from one part of the body to another. Figure 5 shows the fundamental advantage of aluminum used in the right design and configuration.

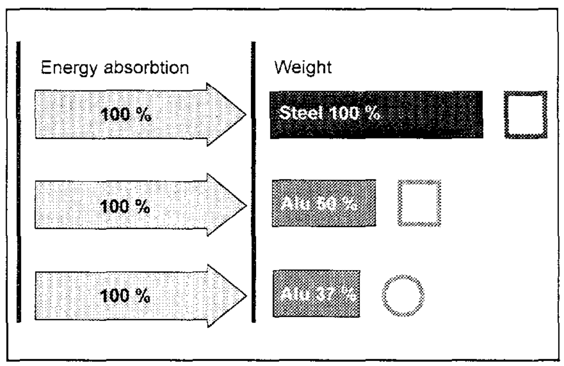

Figure 5. Weight Comparison: ASF / Steel structural members during a crash.

For comparing the weight and energy absorption of an unitary steel bodyshell with that of aluminum, you will see that the Audi Space Frame ASF is roughly 40% lighter despite its superior strength.

Frontal impact protection

At the front area of the body shell the ASF structure is designed as a defined deformable front end. It possesses a side member system composed of aluminum extrusions and die cast nodes which is especially effective at converting impact energies into deformation. The side members are linked under the floor and along with the passenger cell form a stable composite which offers an excellent survival area. During the development of the front end structure the most up-to-date crash calculation procedures were employed, Figure 6.

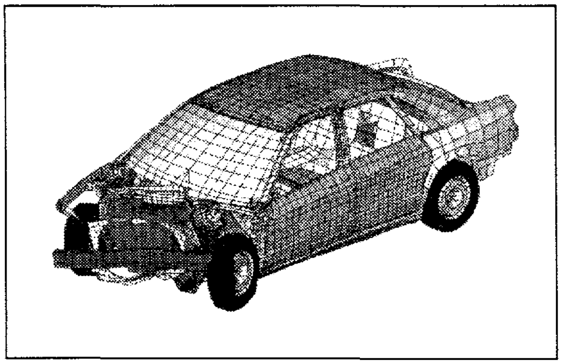

Figure 6. FE-Analysis Offset Crash.

The gradual deformation impact level of the side member system assures effective crash behavior at many different collision speeds. The front side member displays a high energy absorption capacity at an impact level of 80 kN. The aim was for an optimal realization of the following requirements in a design:

- high occupant protection,
- good compatibility for front and lateral collisions
- as well as a favorable insurance category rating.

A circular section achieves the favorable ratio of energy absorption to employed weight. The rear member section only undergoes deformation when the energy absorption of the front section has been concluded, Figure 7.

In a car-to-car accident the frontal structural impact is evenly distributed to the other vehicle by a solid bumper cross member and a stable front end (Figure 6).

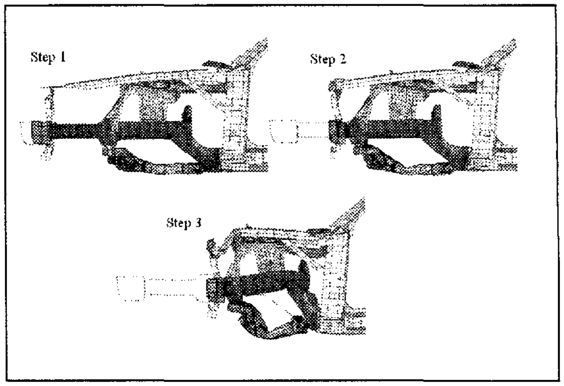

Figure 7. Gradual side member deformation.

Side impact protection

The Audi Space Frame also provides an excellent survival capsule for the occupants in the case of a side impact. The high side structure rigidity is an important pre-condition for low passenger loads. The whole concept encompasses a multitude of individual measures that have been carefully coordinated via computer simulation. A major contribution is made by an interlocking structural brace which consists of the high-strength B pillar with a sheet metal shell and interior extrusions with wide sill steps, doors with flexural impact members and extensive structural overlaps. The rigid sills form just as much a part of the whole system as the large cross members in the seat area.

In addition to the crash test required by law Audi conducts further crash tests based on real accident situations. Exemplary is the lateral collision with a tree or pole as depicted in Figure 7.

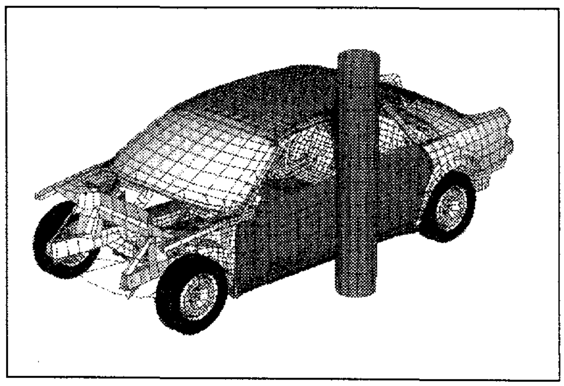

Figure 8. FE analysis of a pole impact

Because of the high local loads the pole impact places particular demands on the body shell structure. The ASF's ability to use the whole structure to dissipate the energy and thus to distribute the localized loads insures very good protection for the occupants even by a tree impact.

COMPATIBILITY TESTS

Side impact

The individual compatibility plays a important role for a car-to-car crash in the case of a side impact. The ASF safety cage is ideal for transferring high loads with low deformation.

Audi A8 - Audi A8 (self compatibility)

Impact velocity:	50 kph
Mass ratio	1.0
Test institute:	Audi

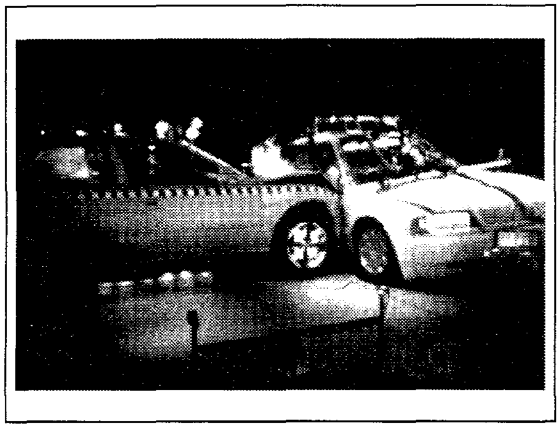

Figure 9. A8/A8 car-to-car lateral crash

The requirement for the self compatibility of vehicles heavier than 950 kg (mass of the deformable barrier) represents a tightening of requirements in comparison to the statutory side impact crash EG 96/27.

Comparison of occupant loads

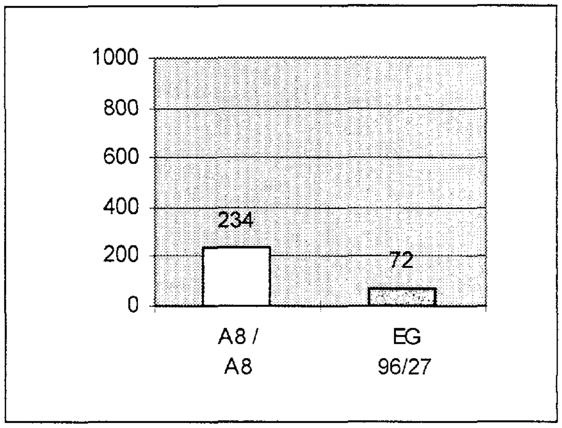

Figure 10. HIC self compatibility / EG 96/27.

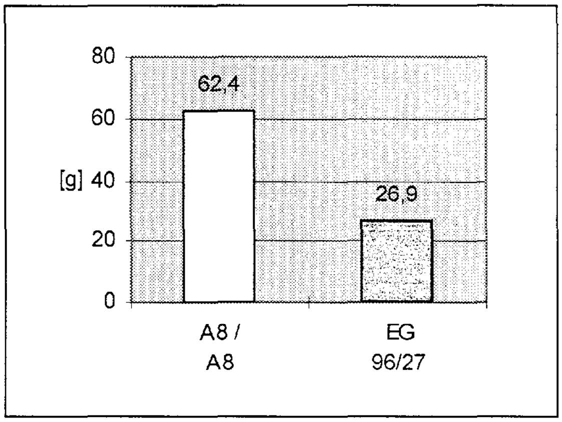

Figure 11. Head a(3ms) self compatibility/ EG96/27

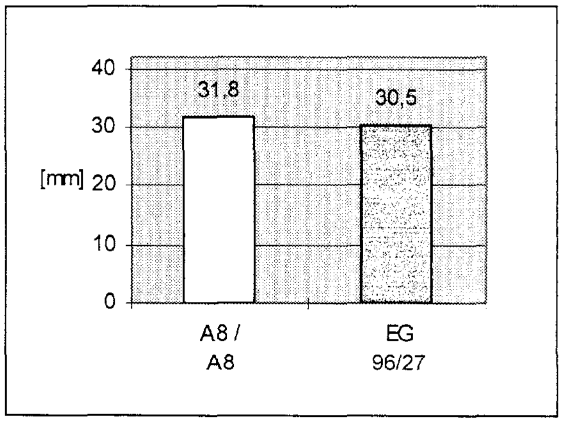

Figure 12. RDC self compatibility/ EG 96/27

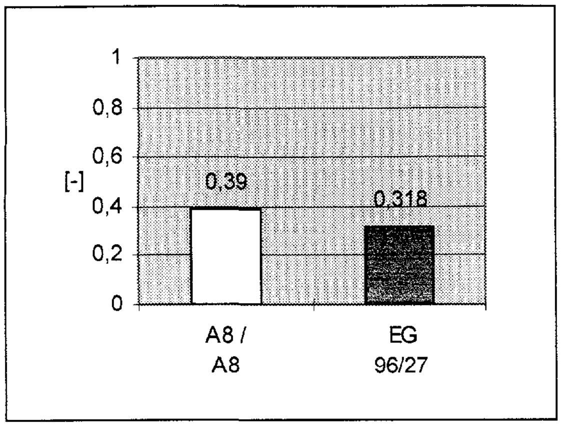

Figure 13. VC self compatibility/ EG 96/27

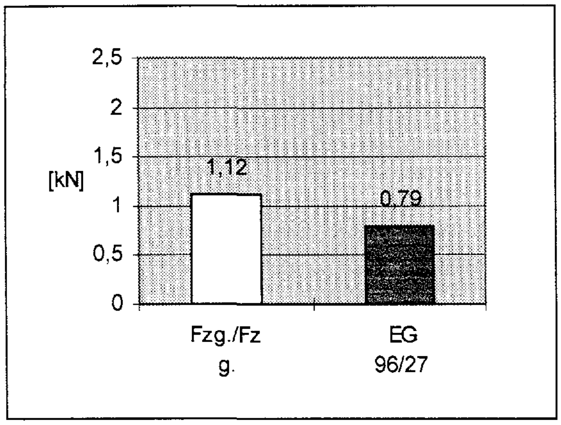

Figure 14. APF self compatibility/ EG 96/27

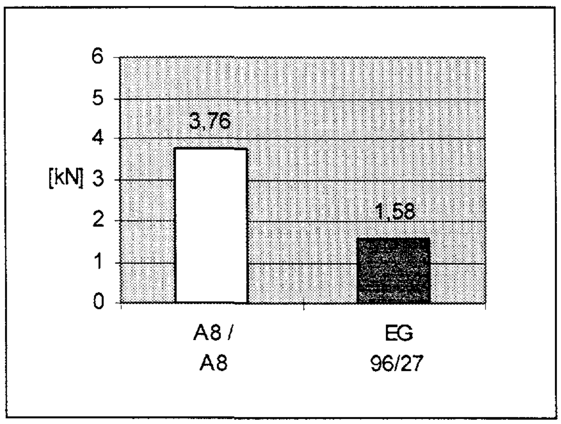

Figure 15. PSPF self compatibility/ EG 96/27

Evaluation the side impact crash test

The solid aluminum bumper cross member in the front end of the colliding Audi A8 distributes the load across a wide area into the side structure of the hit car and produces an even and homogenous deformation.

Despite this clearly higher demand made on the side structure of the ASF for individual compatibility in comparison to EG 96/27 the occupant protection values lie clearly below the statutory limits.

Frontal impact

In car-to-car frontal crash tests with 50% overlapping the compatibility behavior of the Audi A8 was tested against different heavy collision partners.

Audi A8 - VW Polo

Speed:	50.0 kph (v_s 100 kph)
Mass ratio:	1.48
Test institute:	TÜVautomotive commissioned by ams (Edition ams 18/95)

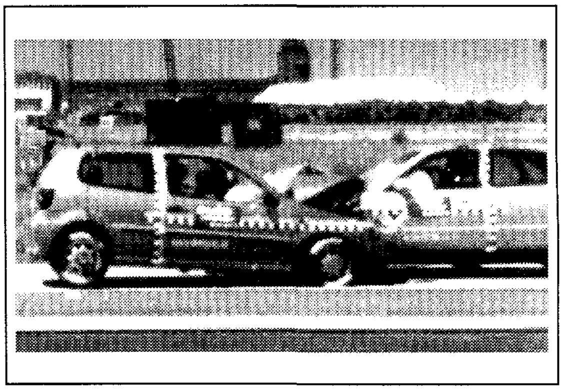

Figure 16. A8 / Polo car-to-car frontal crash

Audi A8 - Audi A3

Speed:	49.9 kph (v_s 99.8 kph)
Mass ratio:	1.26
Test institute:	TÜVautomotive commissioned by ams (Edition ams 6/97)

Figure 17. A8 / A3 car-to-car frontal crash

Audi A8 - Audi A8

Speed:	56.5 kph (v_s 113 kph)
Mass ratio:	1.0
Test institute:	VW-WOB

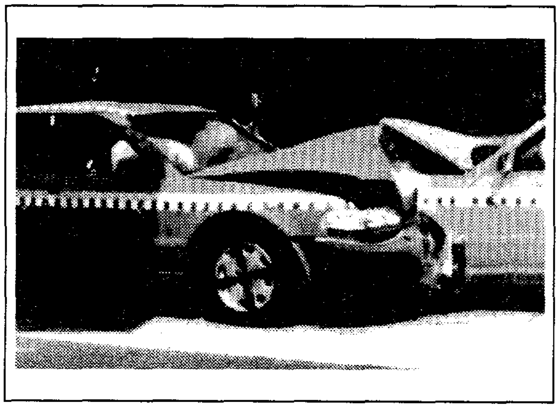

Figure 18. A8 / A8 car-to-car frontal crash

Audi A8 - same class (2157 kg)

Speed:	56.5 kph (v_s 113 kph)
Mass ratio:	0.92
Test institute:	VW-WOB

Audi A8 - same class (2560 kg)

speed:	54.7 kph (v_s 109.4 kph)
Mass ratio:	0.78
Test institute:	TÜVautomotive commissioned by AUDI

Comparison of occupant loads

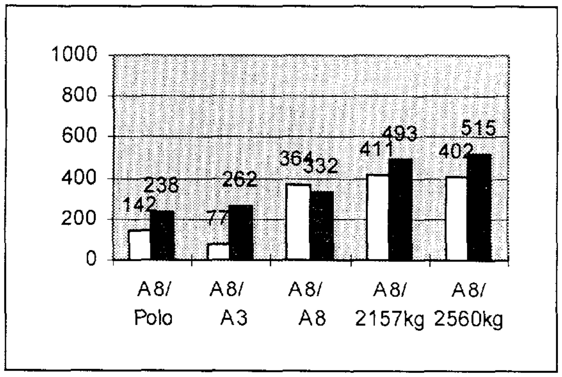

Figure 19. HIC: A8 / Partner frontal crash

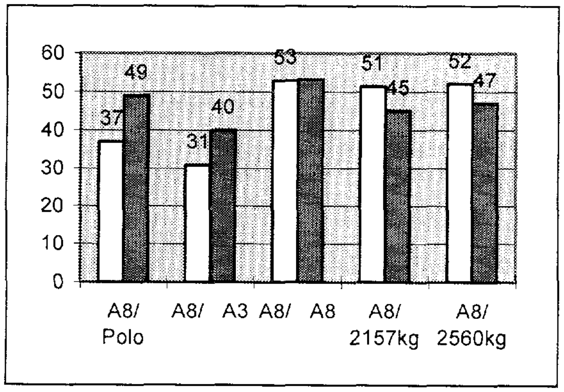

Figure 20. Chest [g]: A8 / Partner frontal crash

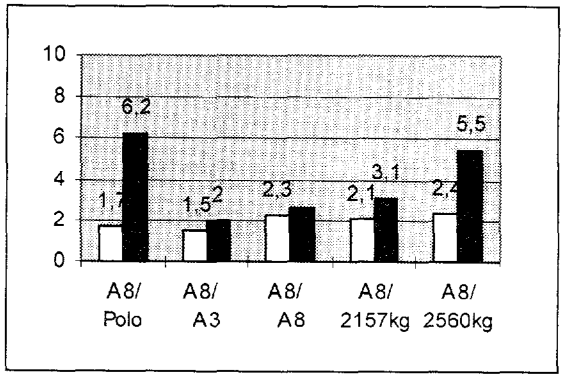

Figure 21. Femur [kN]: A8 / Partner frontal crash

Head and chest loads in both crash partners display similar load levels. Because of the vehicle kinematics caused by the difference in mass, the Audi A8 vehicle delays in collisions with lighter crash partners are lower. This is reflected in the lower occupant loads in the Audi A8. The relatively high knee loads in the Polo are caused by the higher vehicle intrusions; the hard local impinging of the instrument panel on the 2560 kg vehicle is the cause for the high value recorded for the right knee (left knee 2.5 kN).

The test results show that not only does the Audi A8 offer a very high level of protection for the Audi occupants but that relatively balanced occupant loads are recorded in the crash partner vehicles. The frontal impact protection measures introduced in the front end show quite impressively that the Audi A8 is effective in guaranteeing partner protection.

Comparison of the vehicle structure deformation

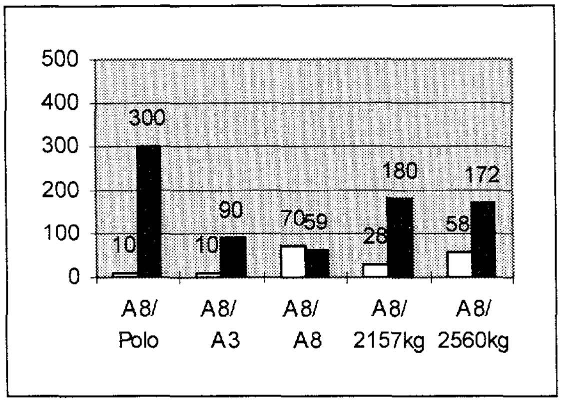

Figure 22. Footwell intrusion in [mm] A8 / partner frontal crash

The very low footwell intrusions in the Audi A8 show the effectiveness of the rigid 'security cage' of the ASF vehicle structure even in cases of serious accident collisions.

Evaluation of the frontal crash tests

On the basis of the low mass and the gradual deformation behavior in the front end the Audi A8 provides sufficient deformation path in the tests in order to convert the kinetic energy so that the occupant load in both vehicles can be predicted to reach a non-critical level.

Overall the tests show that the Audi A8 exhibits a distinct compatibility crash behavior.

How well simulate the 40% offset crash at 40 mph (IIHS/Euro-NCAP) against a deformable barrier a real crash?

The results of a IIHS study /8/ suggest that a 40 percent offset crash into a deformable barrier at 64 kph represents a real-world crash severity below which about 75 percent of all MAIS 3 or greater injuries and roughly half of all fatal injuries to passenger car occupants in frontal offset crashes occur in the United States. The frontal crash tests conducted above with 50% overlapping were compared to the offset crash IIHS in the following.

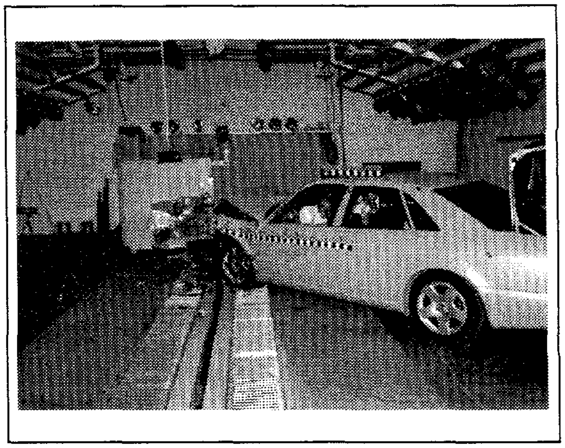

Figure 23. A8 Offset IIHS

Comparison of the occupant load

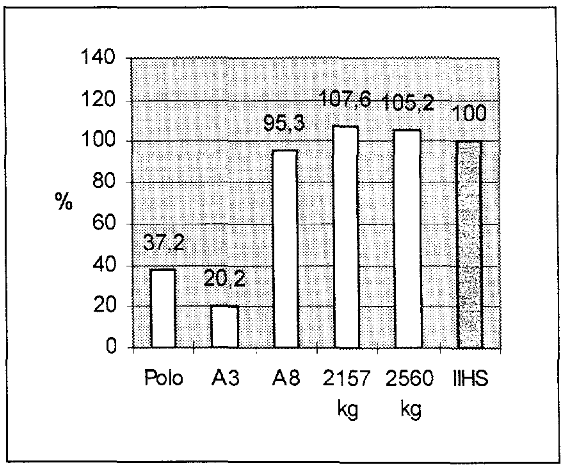

Figure 24. HIC: A8 against partner

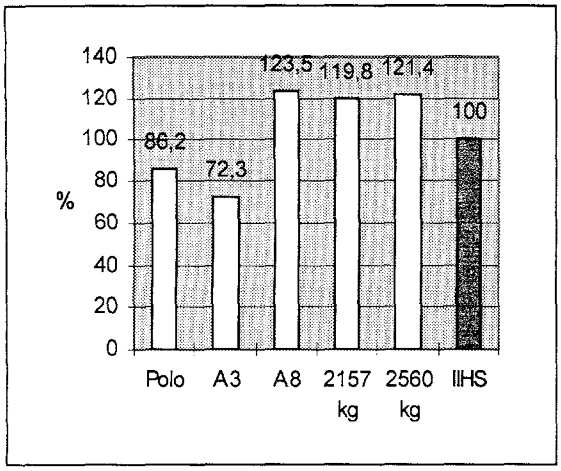

Figure 25. Chest acceleration: A8 against partner

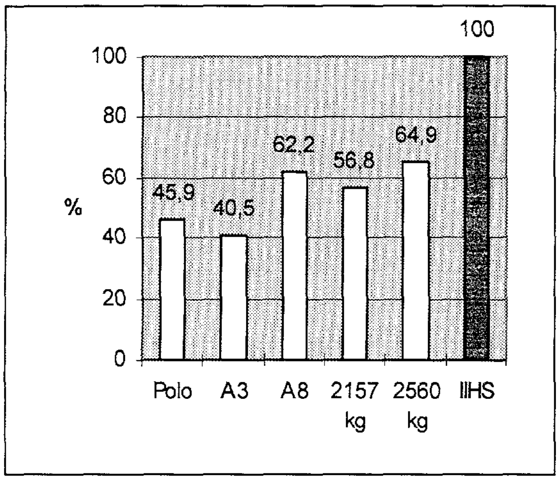

Figure 26. Femur load: A8 against partner

The HIC in the offset crash IIHS is of a similar level as the car-to-car crash tests. The chest loads are lower, the thigh forces tend to be higher.

Comparison of the vehicle structure deformations

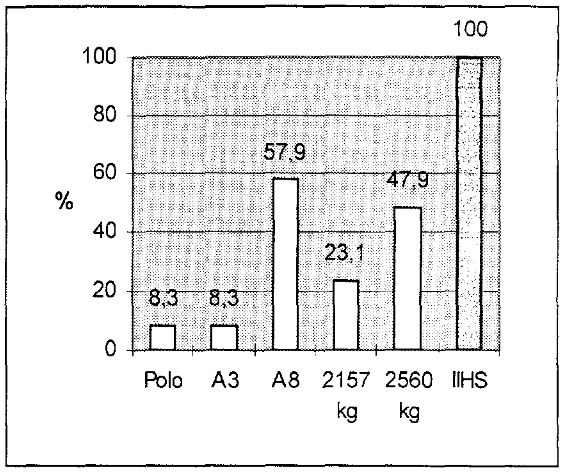

Figure 27. Footwell intrusions: A8 against partner

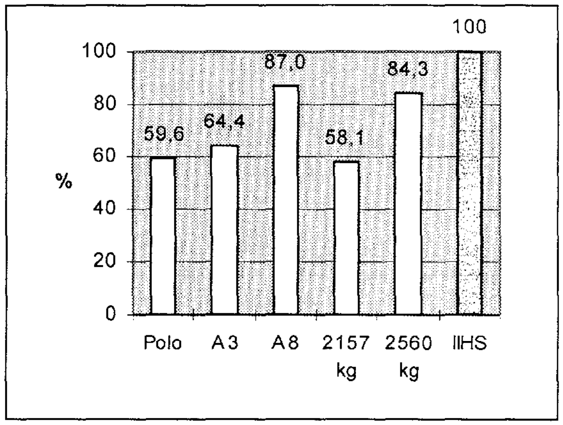

Figure 28. Front end deformation: A8 against partner

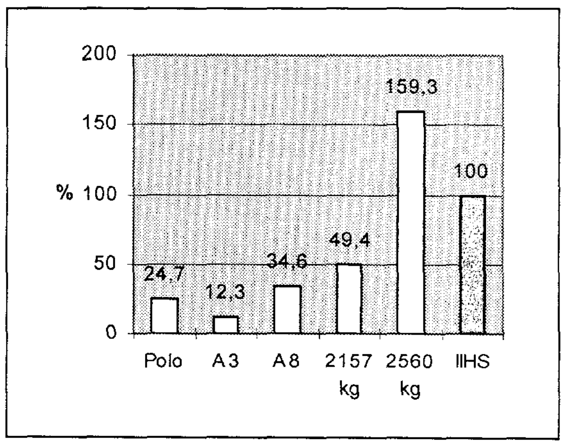

Figure 29. Side structure deformation; A8 against partner

Evaluation

Both the footwell intrusions of the vehicle cell as well as the front end deformations in the offset crash IIHS are higher than in the car-to-car crash tests.

The deflection effect in the car-to-car crash is not considered in the offset crash IIHS. At this impact speed the Audi A8 deforms the barrier completely and hits the bare wall.

Results

It is evident that the IIHS offset crash deforms the Audi Space Frame differently in comparison to the car-to-car crash tests. A higher occupant load was not ascertained in the offset crash IIHS.

The footwell intrusions, which occur at this level in the fully overlapped frontal crash as 35 mph against a bare wall, mean that an impact velocity of 64 kph for vehicles in the C class and above (luxury cars) and for LTV's should be discussed to achieve an additional development potential for compatible behavior in real accident situations.

CONCLUSION

The work presented here shows that aggressivity/ compatibility is not just a LTV vs. passenger car issue but also applicable between the various size and weight classes of passenger cars. An overall view must be equally taken incorporating the front as well as the side impact. In this respect computer simulations will take on an increasingly important role. The applicability of current methods has already been shown.

In addition to a mass reduction for larger cars, for example, by utilizing light-weight metals such as aluminum, detail solutions are those which ensure that vehicles behave in a compatible manner. For example, it is essential for a strong cross-structure to be retained at the front - like a protective shield - in order to prevent aggressive behavior and distribute the loads on the other car. Similarly, a coordinated deformation characteristic in the front structure is plausible, in order to ensure a high level of partner protection, but also good protection for vehicle occupants in a single-car accident. Precisely these in-depth investigations make computer simulation essential, since it permits each individual parameter to be investigated and optimized separately.

Tests conducted by independent institutes have shown that the Audi A8 with its newly developed aluminum ASF technology displays a compatible behavior in car-to-car accidents. The occupant load and the structural deformation of both vehicles lie within acceptable limits both against small, light-weight vehicles as well as against larger, heavier vehicles.

The IIHS or Euro-NCAP offset crash with 64 kph against a deformable barrier tends to be used to analysis real crashes; however, it cannot replace using car-to-car crashes. It has been shown that the load values for the vehicle occupants admittedly lie in the area of a crash with approximately a closing speed of 110 kph against a vehicle of identical mass, but that there is a different deformation picture with higher intrusions in the footwell areas for big cars like the Audi A8. A reason is the non-existing deflection of the vehicle from the deformation element. An increase in the impact velocity against the barrier of over 64 kph does not achieve the goal. A unrequired stiffening of the front end would be the result.

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