DEMANDS FOR COMPATIBILITY OF PASSENGER VEHICLES

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ABSTRACT:

Any discussion of vehicle compatibility represents an attempt to take an integrated approach pertaining to the numerous conflicts associated with goals related to passive vehicle safety. In order to keep the complexity of such a discussion within manageable limits, it would appear appropriate to concentrate on the most relevant collision modes. Compatibility characteristics are observed in vehicle crash testing. These must also be investigated in real-world accidents to verify their relevance to injury reduction. A list of relevant compatibility characteristics is given. Although, from a theoretical point of view, stiffness should be a dominating factor, it is difficult to find this in real-world accidents. A "bulkhead" concept is given as an attempt to avoid excessive crush of smaller vehicles by limiting the force level of the striking vehicle in frontal collisions. The demand for self-protection, as defined by the barrier impact speed for which the vehicle is designed, limits the range of mass ratios, for which the bulkhead concept can be established. An over-view of ongoing compatibility research by automotive industry is given. One of the goals of this research is to classify vehicles compatibility by computer simulation, to the extent possible, and by vehicle crash testing, to the extent necessary.

INTRODUCTION:

From a theoretical point of view, it is quite easy to talk about compatibility. Even in car-to-car crash tests there are observations such as override and under-ride of longitudinal frame members, different amounts of deformation of colliding vehicles etc. If compatibility were to be derived only from crash tests, the question of relevance for injury avoidance would still remain open. We would deal with compatibility as a certain kind of "crash-esthetics" that deals with deformation behavior merely from an academic perspective. For example, the purely axial collapse by pleating of longitudinal frame members is noteworthy. It is obviously the best way of absorbing energy. Other types of deformation, however, although not as effective from a theoretical point of view, should not be criticized, as long as it cannot be proven by real world accidents that this different behavior results in higher injury risk. Much effort has been expended to generate interesting accident data bases. They should be applied in research on passive safety as much as possible.

Vehicle types and collision modes.

Cars are subjected to many different collision modes:

A car may collide with an object such as a tree or a pole. It may experience a rollover. These are single vehicle accidents. No other party is involved that may be injured by the car in question. The issue in these cases was whether the vehicle was able to reasonably protect its occupants. Thus, in these cases, only self-protection is relevant.

When one car strikes another, the deformation of two vehicles can be compared - bearing in mind that the impact exposure for each vehicle is different unless the impact is head-on. The injuries in the two vehicles can also be compared. The accident may permit an evaluation as to which vehicle offers greater self-protection. There are, however, observations to the effect that some vehicles tend to produce higher injury levels in the opposing vehicle than others. Thus, a car-to-car accident may not only permit a comparison of the level of self-protection provided by the two vehicles, it may also permit identification of the hazard to which one car may be exposed in an impact with another. This potential hazard posed by a vehicle is called its aggressiveness. The inverse of aggressiveness is the ability of a vehicle, to protect the occupant of an opposing vehicle: partner protection. It is difficult to distinguish between good self-protection and good partner protection. This can only be done based on a larger body of accident data. When an accident tends to be more severe in terms of injuries for different vehicles, when struck by a particular vehicle or type of vehicle, then there is a probability that this opponent or class of opponents is more aggressive and provides less partner-protection than the average. Fig. 1 indicates the well-known fact that larger vehicles cause higher injury levels up to now, when they are involved in accidents with smaller vehicles.

When a car is hit by a truck, the lack of partner protection for most trucks is obvious. It is even obvious for most sports-utility-vehicles. The typical result of such accidents is a high injury level in the car and minor or no injuries in the truck or SUV. Typical measures for partner-protection by trucks are under-ride guards, etc. As long as they do not exist, individual self protection measures on a passenger car to protect against trucks are nearly inconceivable.

In accident involving cars and pedestrians, a car normally strikes an unprotected person. The measures that are adequate in such a case are currently being discussed in technical groups. A pedestrian, when hit by a vehicle, will deform the vehicle only few centimeters. Such deformation is virtually independent of the deformation that occurs in the other collision modes. This means that at least in a first phase of structural compatibility study, pedestrian accidents can be treated separately. There is no need to include them directly in a car-to-car compatibility study. This may change, when compatibility studies become more sophisticated and are able to influence the design of vehicle structures from the outset.

For two-wheeled vehicles, this is not generally true. Heavy motorcycles can pose a special hazard to a car, particularly in a significant side impact. Thus, they must also be taken into consideration with respect to passenger cars. When the occupant of a two-wheeled vehicle strikes another vehicle, the cyclist should be protected to a certain degree by special clothing and the helmet. At any case, for him a minimal amount of deformation is also needed as compared to car-to-car collisions, and in this context the situation is similar for pedestrians.

When dealing with compatibility of passenger-cars, two accident modes must be considered: single vehicle accidents and car-to-car collisions. Collisions with trucks generally demonstrate the need for under-

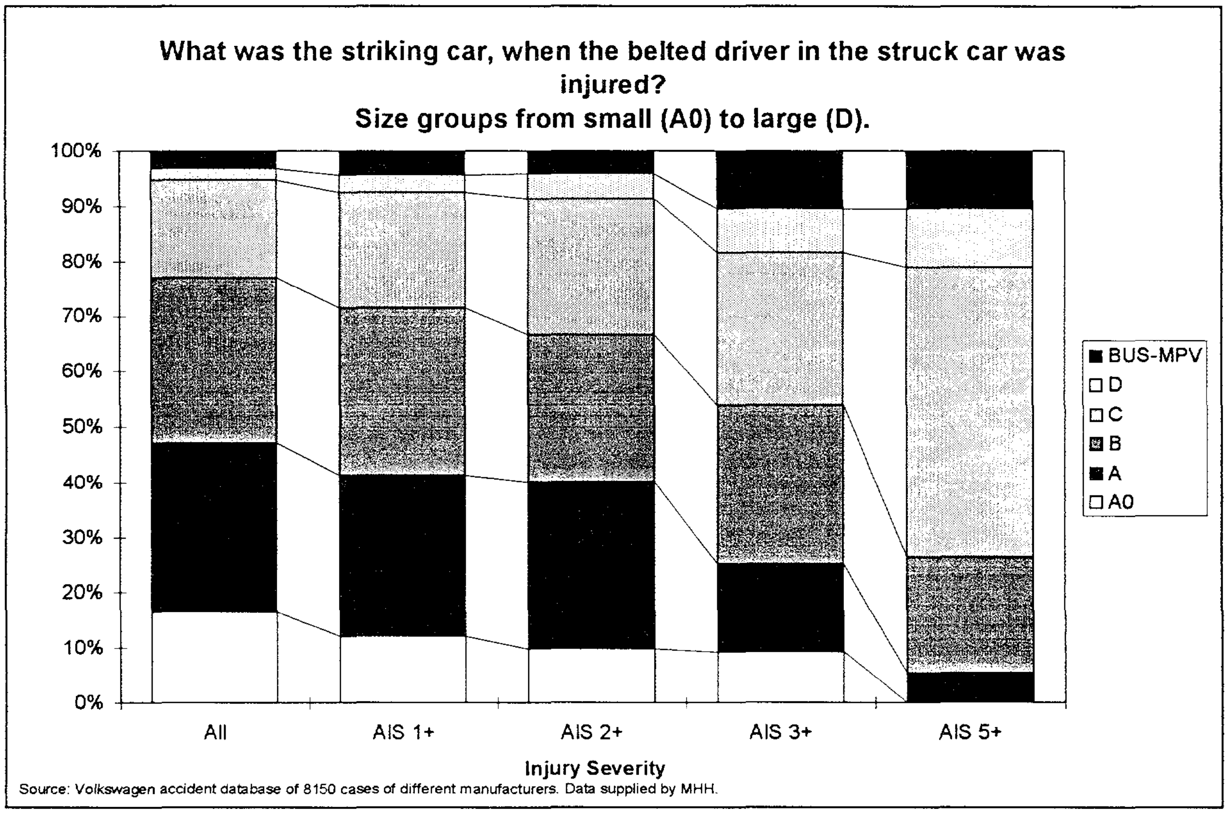

Fig. 1: Hazard of different size groups in passenger car to passenger car accidents.

ride protection by the truck. When generally accepted underride protection exists, then it makes sense to define a car structure that is compatible with the force deflection curve of the underride protection or which allows a glancing blow that prevents the car from actually impacting the truck when the collision angle is sufficiently acute. Impacts between pedestrians and two-wheeled vehicles can be understood as nearly independent of other collision modes, inasmuch as their structural demands are relevant only for the initial centimeters of the collision. These structural demands are not relevant for the behavior of a car in a single-vehicle or a car-to-car collision with a velocity change that has injury potential. On the other hand, the structural demands on the vehicle front-end to make it compatible, when striking a side of another vehicle might also be relevant for impacts with pedestrians and/or two-wheeled vehicles.

Fig. 2 depicts the accidents that are related to these collision modes with fatalities and injuries. This figure shows clearly that the single vehicle predominates as far as fatalities are concerned, and that car-to-car accidents predominate as far as injury producing accidents are concerned. Therefore, the strategy for compatibility cannot be to optimize partner protection by decreasing self protection. The strategy for compatibility should be to optimize both partner protection and self protection in such a way that the sum of all fatalities and the sum of all injuries is minimized.

When a harmonized approach to compatibility is considered, then the American SUV problem must be kept in mind. (Gabler, 1998, Hollowell, 1996) The geometrical problems that occur in a collision between an SUV and a car are documented unambiguously by two photographs from the Insurance Institute for Highway Safety (IIHS) (fig. 3). While in frontal impact an adequate path to direct impact loads into the lower section of the SUV's front end might prevent the small car from underriding, the situation in side impact is even worse, because here the chance of a head impact against the front of the striking SUV is very likely under corresponding collision angles. The mass ratio provides additional incompatibility between these vehicles. The SUV is a vehicle with structural behavior that is in some respects similar to a car, but in other aspects similar to a truck. Therefore some of the principal countermeasures must be implemented on the

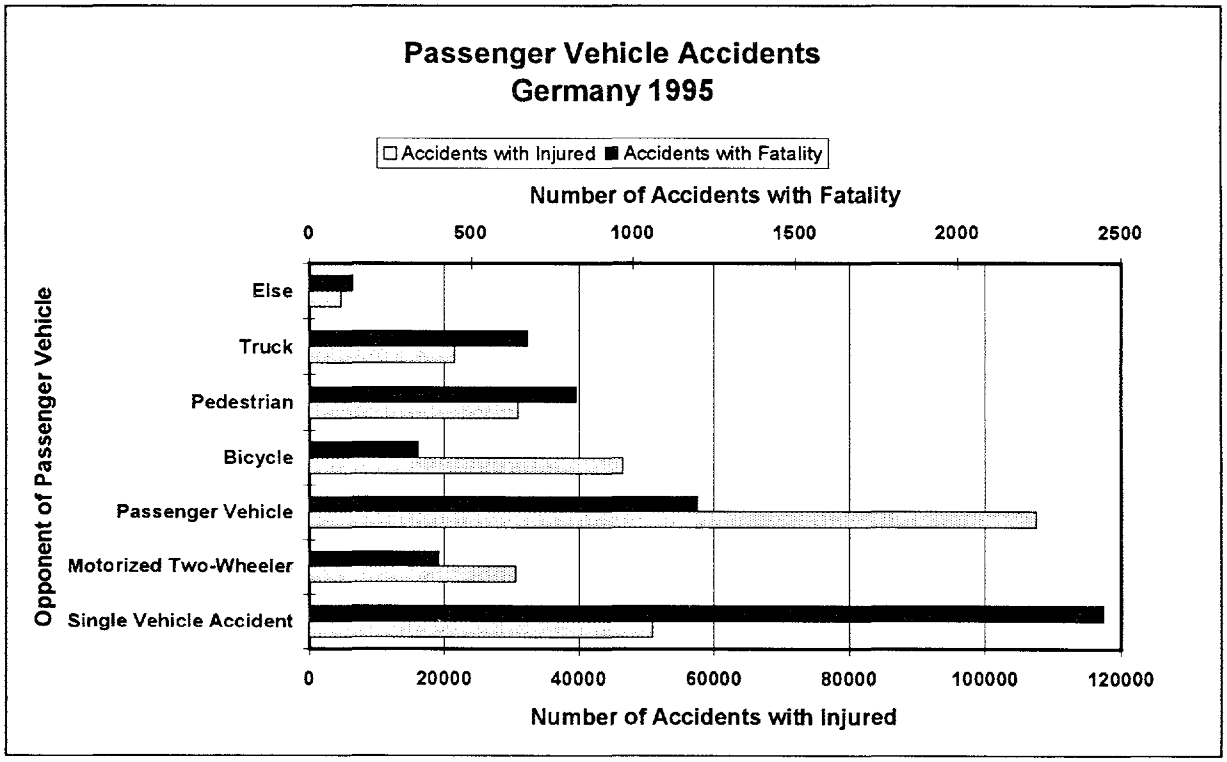

Fig. 2: Number of passenger vehicle accidents with at least one injured person involved (lower axis) compared with the number of passenger vehicle accidents with at least one fatally injured person involved (upper axis). Data are from official German statistics.

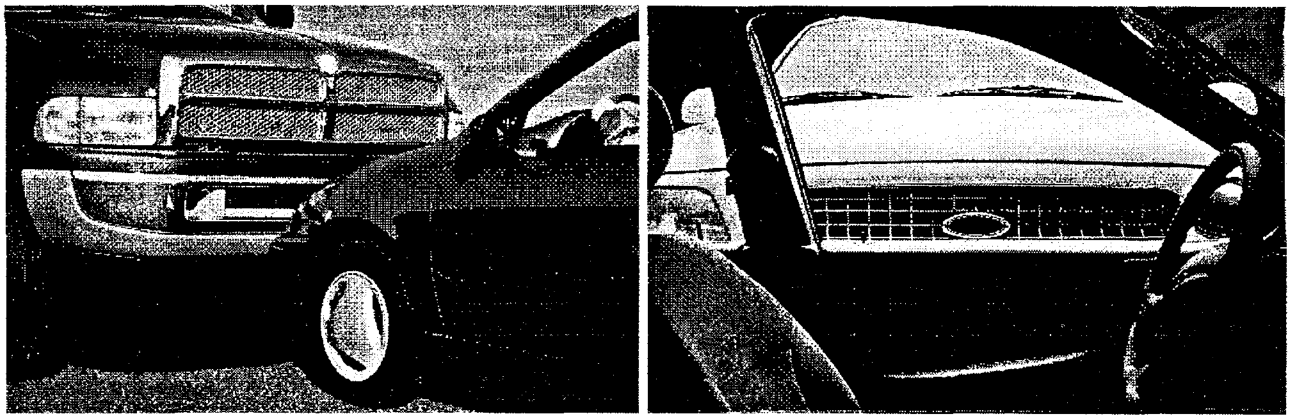

Fig. 3: Geometrical comparison between car and sports-utility vehicle. There are major discrepancies between the two front structures and between front and side. (Courtesy of IIHS (IIHS, 1998))

SUV as required on trucks. The mass ratio implications, however, must be resolved by the car and its restraint system. Viewed from the vantage point of larger vehicles, including SUVs etc., some authors assert that it is the small vehicle that brings about these problems. These authors tend to suggest lower limits for the mass of smaller vehicles be mandated. "Get rid of the small car" is the battle cry of this group of scientists. But, as so often with battle cries, they are not very helpful. In the future, considerations such as fuel consumption, emissions etc. will exert more pressure in the direction of smaller, technologically perfect vehicles. Thus, the existence of these two extremes of passenger vehicles must be kept in mind if compatibility is to be discussed productively. By bearing both in mind, we are also forced to deal with the different vehicle fleet existing in Europe and in Northern America. This may - we are still permitted to hope - prevent us from defining separate European and American compatibilities. By taking both aspects into account, there might be an opportunity to create a harmonized compatibility concept.

Compatibility characteristics

Compatibility offers the chance to define very interesting car-to-car impact test configurations. These crash tests will have to be observed very carefully. But who is able to decide how relevant a certain observation in a crash test is for real-world accidents? There are many observations that are of potential interest with regard to compatibility, but who defines priorities among all these items?

For most researchers dealing with this subject, it is clear that from the outset that great care is required in the analysis of accidents so that important decisions on relevance and priorities can be reached. Unfortunately, accident researchers include primarily conventional parameters about vehicles and occupants in their data bases. Accurate descriptions of structural behavior are very difficult to obtain. It is cost intensive to measure all the relevant deformation. Therefore, from the standpoint of accident analysis, priorities for compatibility features can be derived only in an indirect manner.

At ACEA (Association des Constructeurs Européens d'Automobiles), European manufacturers conducted an accident analysis to permit discussion of the relevance of compatibility features. This was accomplished by defining a list of possible compatibility features. The following items were taken into account:

- vehicle mass
- vehicle stiffness
- lateral fork effect
- vertical fork effect
- low/high vehicle front end regarding frontal impact
- high front end of the striking vehicle regarding side impact
- longitudinal engine
- transverse engine
- additionally for side impact: a well-balanced distribution of the force in the vehicle front

This list contains only the most obvious items which have been discussed in the literature thus far. The goal was and is to understand the priorities for these features for compatibility. To this end, a combined effort was made between the ACEA Crash Compatibility Task-Force and scientists of the Technical University of Berlin. Volkswagen provided information on car-to-car accidents. The car manufacturers and the staff of Technical University of Berlin provided geometrical data on the vehicles, which were added to the database to permit some of the compatibility features to be studied.

It is not the purpose of this paper, to present the results of this ongoing research. Some of the difficulties encountered, however, should at least be mentioned: When the influence of longitudinal and transverse engines was studied, it was easy to show that vehicles with longitudinal engines tend to induce higher injury risks for a struck vehicle than vehicles with a transverse engine. Therefore, a rash conclusion would be to blame longitudinal engines for being more aggressive than transverse engines. However, a more careful look at the data discloses that vehicles with longitudinal engines tend to be larger vehicles. Thus, an adjustment was made. The database was biased towards a similar mass distribution of vehicles with longitudinal engines and vehicles with transverse engines. With this biased data set, the influence of engine orientation could be studied once more. The result was that in the biased data set, no difference between vehicles with longitudinal engines and vehicles with transverse engines could be detected. So we have no indication that engine orientation is relevant with regard to compatibility.

This result must still be verified by other data sets. It has to be verified through case-by-case analysis. The work on the compatibility feature "engine orientation" has not been finalized. This observation, however, clearly shows that accident analysis on compatibility features must be conducted very carefully. There is the dominant effect of mass. Mass of an opposing vehicle influences the velocity change of the struck vehicle under consideration. It is therefore relevant in terms of injury risk in the struck car. From what we know to date, it will be the predominant factor. All other influencing factors appear to be of minor importance or priority. This means that all other studies have to be conducted on a basis of a mass adjusted data set. Otherwise they are likely to focus upon features as incompatible that are related to vehicles of higher mass.

Some principal results should be mentioned here, but it should be noted that they are still preliminary:

- vehicle mass
  - dominant influencing factor
- vehicle stiffness
  - stiffer vehicles demonstrate slight advantages regarding self protection
- lateral fork effect
  - no results to date
- vertical fork effect
  - different height of longitudinal frame members in the colliding cars shows no disadvantages
- low/high front end of the vehicle regarding frontal impact
  - higher longitudinal frame members tend to provide lower degree of self protection
- high front end of the striking vehicle regarding side impact
  - higher sill height provides higher protection in side impact
  - higher longitudinal height provides lower partner protection in side impact
- longitudinal engine
  - no significant influence
- transversal engine
  - no significant influence
- additionally for side impact: a well-balanced distribution of the force in the vehicle front
  - no results to date

The results mentioned briefly here are the result of an accident analysis that was performed with Volkswagen data by the Technical University of Berlin (Prof. Appel and Mr. Deter). The work was initiated and funded by ACEA. It will be finalized in a compatibility project of European automotive industry and funded by the EU (BRITE-Euram).

An approach to detect stiffness influences from accident data

An attempt was made to identify differences in vehicle stiffness from accident analysis. Accident data provide the vehicle deformation index VDI. VDI6 provides an estimation of the depth of vehicle deformation (fig. 4).

In case of a car-to-car accident, two VDI6 are provided. These are compared to decide whether one vehicle excessively deformed the other. Then the VDI6 of the vehicle itself was summed for all car-to-car accidents with the particular vehicle involved. A mean value was computed. The same procedure was used for the other cars, i.e. for the opposing cars in the same

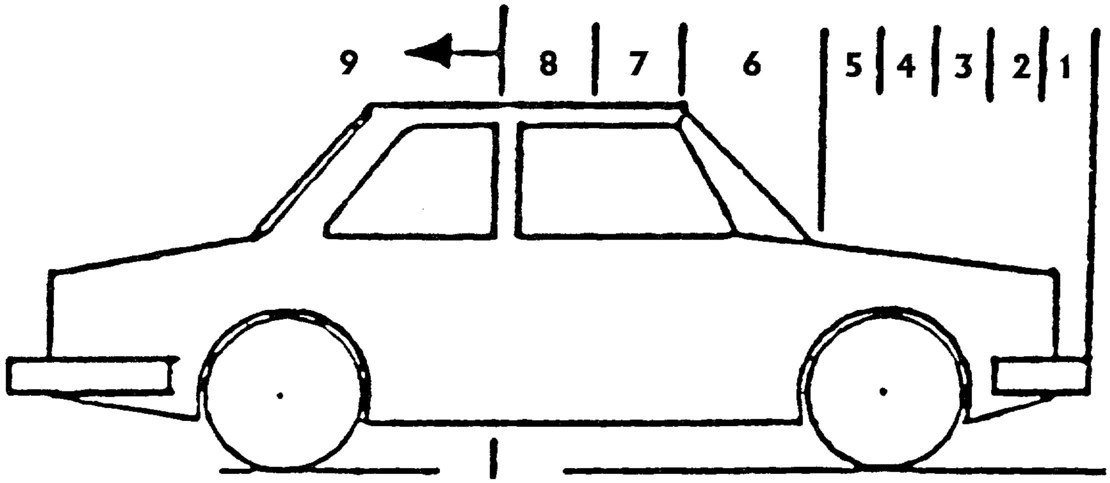

Fig. 4: Vehicle deformation index VDI for deformation extent guide (VDI6). (Source: Manual for Coding. Variables in the in-depth investigation work. Accident Research Unit, Hanover, 1990)

accident sample. Ultimately, two mean values exist, reflecting the average deformation of the car and of its opposing cars in one sample of car-to-car accidents. The difference of the two values was then computed. If it is positive, it indicates that the vehicle under consideration tends to have more deformation than its opponents - meaning that it tends to be deformed more by its opponents. If the number is negative, it indicates that the vehicle under consideration tends to have less deformation than its opponents - meaning that, it tends to deform its opponents more. This can be an indication of aggressiveness. However, before such a conclusion is drawn, this notion must be checked very carefully.

First of all, size classes are compared. A0 represents very small vehicle-models, A, B, C, D represent incrementally larger vehicle classes. There is no significant difference between A0 and A. But the other classes behave as expected (fig 5): Higher size groups tend to deform their opponents more.

The deformation comparison offers quite a different picture when model versions and different generations of models are compared. One would expect that these models should tend to become stiffer with each subsequent generation. This is true e.g. in fig. 6 for version A-A-1 to A-A-3. (Note that all names are artificial. The number refers to the model generation.) The same is true for model C-A. Its stiffness increased from generation C-A-3 to C-A-4. The other generations of this model are not relevant because of an insufficient number of accidents (1 and. 2).

For size group B (fig. 7), the finding diverges even more from that which would be expected: "Newer model versions are stiffer." Model A-B shows no significant change. Model B-B shows a trend towards decreasing stiffness. The same applies to D-B. When interpreting the bars, one has to check carefully the line, which indicates the number of cases.

These findings were compared to fatalities and injuries in those cars and in their opponents. This study is not finalized, so that no conclusive results can be presented at this time. A trend is clearly evident and must be verified by carefully comparing the models involved. Neither self protection, nor partner protection appears to be strictly related to these findings. When this is true, it shows that we must exercise great care when interpreting crash test results. Higher deformation probably does not necessarily mean higher risk of injury and vice versa. This statement was checked against the maximum AIS of belted drivers, but it was also checked against injuries of body regions that are probably more sensitive to deformation, such as those of the leg and foot and those that are probably more sensitive to deceleration such as the head. Thoracic and pelvic AIS was also checked but in all cases no clear correlation was found. The same computation was made with the injuries of the belted driver of the opponent vehicle. Again no correlation was seen.

An in-depth study will be performed in order to check these preliminary results more thoroughly and, if necessary, on a case-by-case basis.

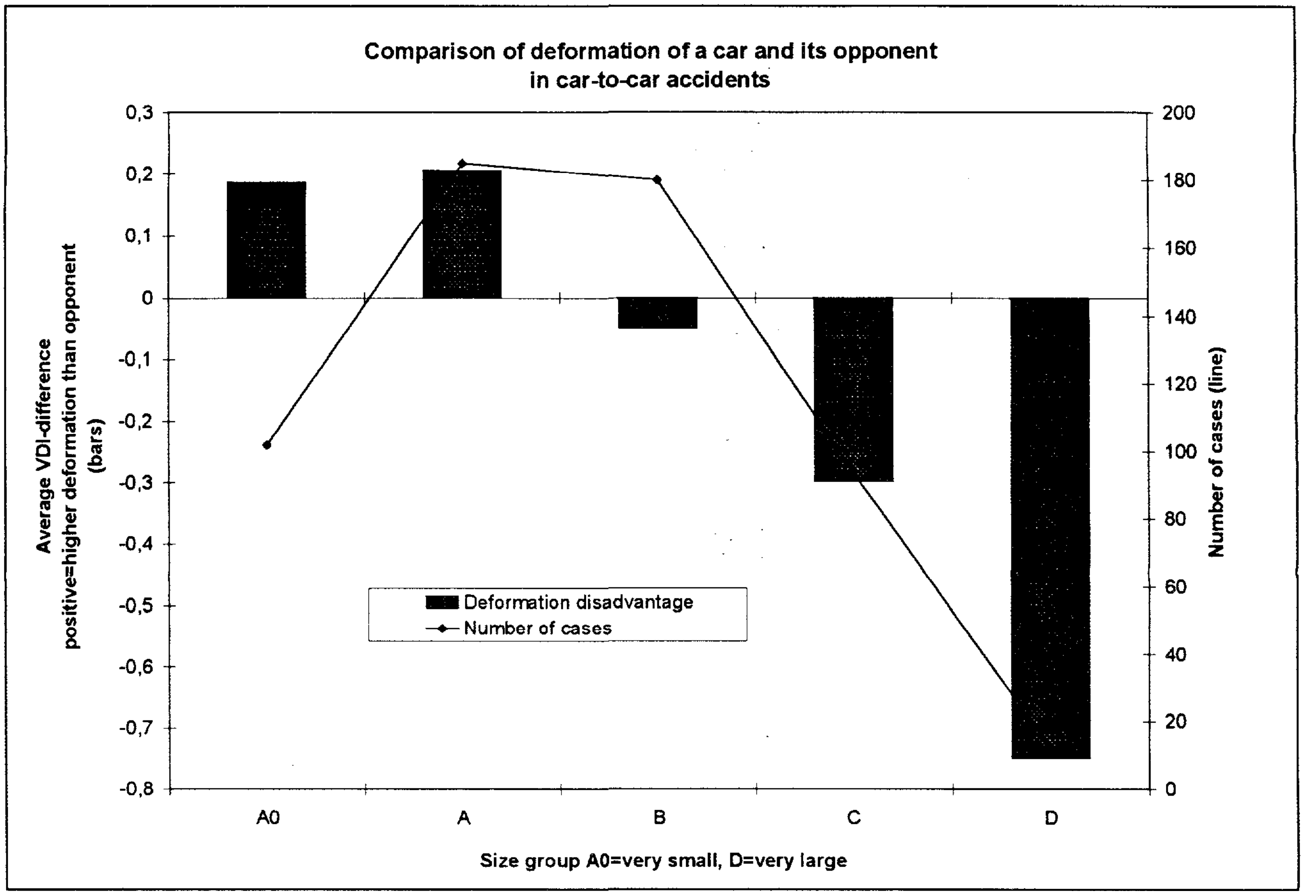

Fig. 5: The deformation behavior of different size groups, based on a comparison of VDI6 in car-to-car accidents.

The bulkhead concept

At first glance, it would be expected that partner protection must be examined on the basis of vehicle-to-vehicle crash tests. However, before additional new crash tests are generated to prolong the list of crash tests to be performed with respect to passive safety, it must be determined whether current tests already generate information that can be used to identify partner protection. Surprisingly, the long-established test with a rigid barrier provides such information, if properly interpreted.

The test against a fixed barrier compels manufacturer to make provisions for sufficient deformation energy. If the barrier impact must be conducted with an impact velocity v_B for a vehicle with mass m, then the required deformation energy is approximately equivalent to the kinetic energy of the barrier impact:

$$E = \frac{1}{2} * m * v_B^2$$

A frontal vehicle-to-vehicle collision can involve vehicle 1 and vehicle 2 with masses m_1 and m_2 and velocities v_1 and v_2. The kinetic energy before the crash is

$$E_{before} = \frac{1}{2} * m_1 * v_1^2 + \frac{1}{2} * m_2 * v_2^2$$

The velocity after the crash is assumed to be the same for both vehicles v_{After}. The rebound is neglected in this example. Thus, v_{After} is computed using conservation of momentum by

$$(m_1 + m_2) * v_{after} = m_1 * v_1 + m_2 * v_2$$

This results in a kinetic energy after the crash:

$$E_{after} = \frac{1}{2} * (m_1 + m_2) * v_{after}^2$$

The lost energy is the deformation energy D in this accident

$$D = E_{before} - E_{after}$$

$$= \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (v_1 - v_2)^2$$

Thus, this well-known computation shows that the deformation energy depends on the two masses and the closing velocity $v_c = v_1 - v_2$ of the two colliding vehicles.

The following inequation is remarkable and shows the opportunities for compatibility.

If there is a collision between two vehicles of different masses at a closing velocity of $v_c \le 2 * v_B$ and if each vehicle is designed for a barrier impact with v_B, then the deformation energy of both vehicles is sufficient to sustain the collision without intrusion into the occupant compartment.

This can be proven by the following calculations: The available deformation energy of the two vehicles is

$$E = \frac{1}{2} * m_1 * v_B^2 + \frac{1}{2} * m_2 * v_B^2 = \frac{1}{2} * (m_1 + m_2) * v_B^2$$

For this collision the energy absorption will be

$$D = \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (v_1 - v_2)^2$$

$$= \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * v_c^2 \le \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2$$

It has to be proven that D≤E. This can be derived from the following calculations:

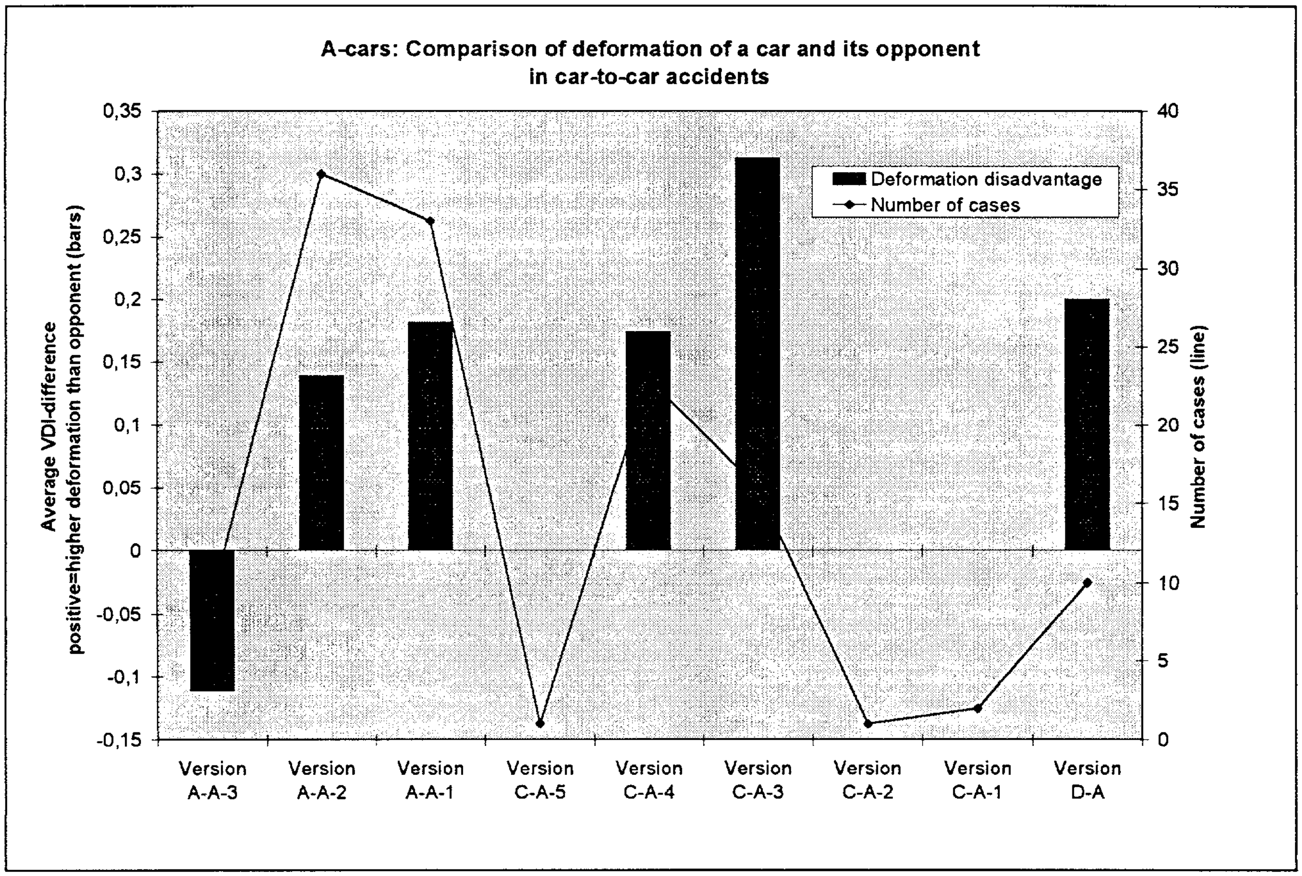

Fig. 6: The deformation behavior of size group A, due to a comparison of VDI6 in car-to-car accidents.

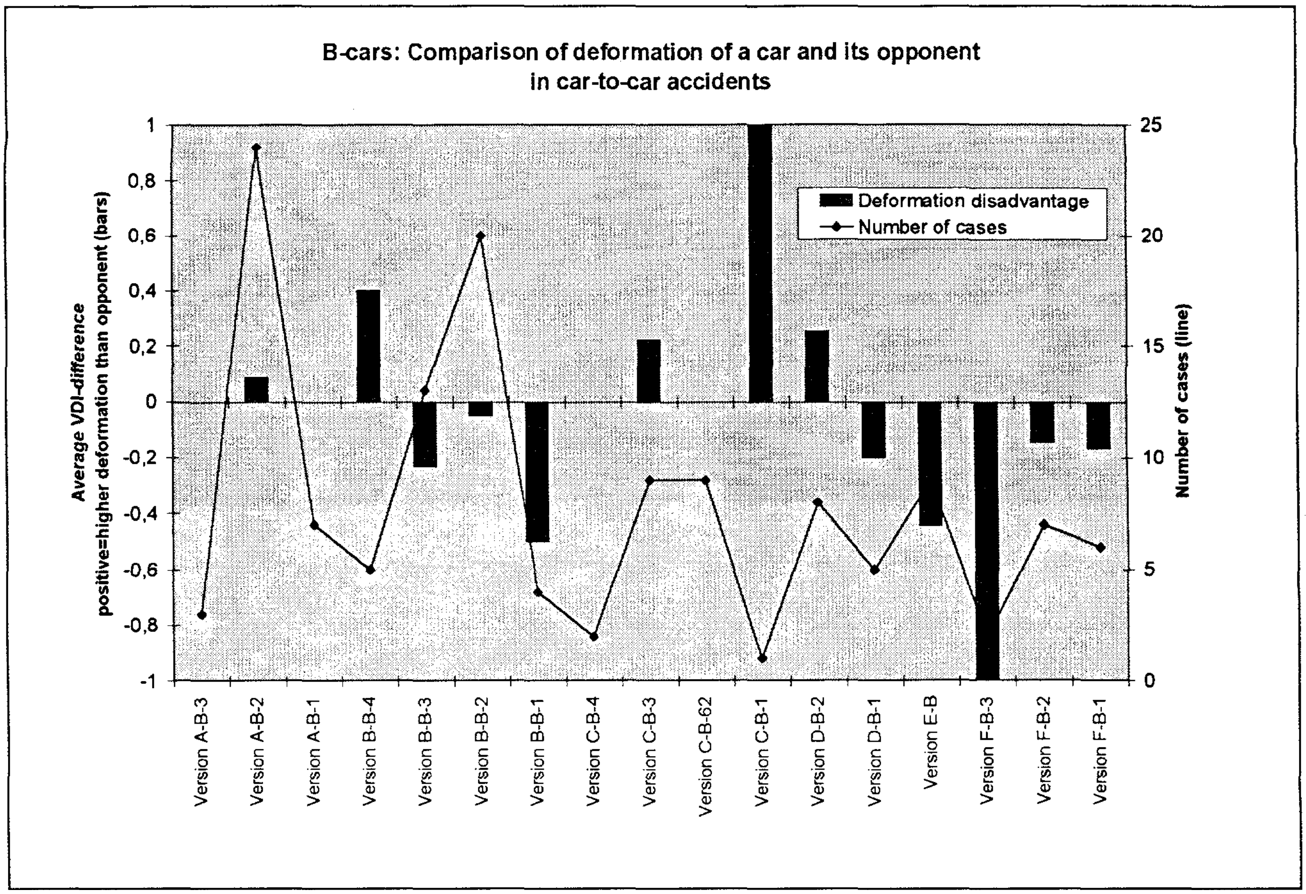

Fig. 7: The deformation behavior of size group B, based on a comparison of VDI6 in car-to-car accidents. (Carefully check the number of cases, when interpreting the results.)

Obviously a square is always positive:

$$(m_1 - m_2)^2 \geq 0$$

This means that

$$m_1^2 - 2 * m_1 * m_2 + m_2^2 \geq 0$$

holds. By adding 4*m1*m2 it can be seen that also

$$m_1^2 + 2 * m_1 * m_2 + m_2^2 \geq 4 * m_1 * m_2$$

holds. As a consequence of this

$$(m_1 + m_2)^2 \geq 4 * m_1 * m_2$$

or dividing by $(m_1 + m_2)$

$$m_1 + m_2 \geq \frac{4 * m_1 * m_2}{m_1 + m_2}$$

From this

$$\frac{1}{2} * (m_1 + m_2) * v_B^2 \geq \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2$$

The result of this is a basic finding on compatibility:

$$D = \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * v_c^2 \leq \frac{1}{2} * \frac{m_1 * m_2}{m_1 + m_2} * (2 * v_B)^2$$

$$\leq \frac{1}{2} * (m_1 + m_2) * v_B^2 = E$$

as long as $v_1 - v_2 = v_c \leq 2 * v_B$.

The computation looks rather theoretical, but the result has practical consequences. It is a fundamental relationship between the design speed of two vehicles and the deformation energy that is needed when the two vehicles collide:

When two vehicles collide, and if their closing velocity is less than their doubled design speed, then

there is sufficient deformation energy available for this particular crash. This holds regardless of the mass-ratio of the two vehicles.

This means for vehicles with 50 km/h design speed: When they collide with a closing velocity of not more than 100 km/h, then compartment collapse, even of the smaller vehicle, can be avoided, because sufficient energy absorption is possible, sufficient deforming material is available. This finding holds, regardless of the mass ratio. This restricts the problem of compatibility to the question: Are we able, to compel both vehicles to deform?

Looking at real world crashes, very different types of deformation can be seen: Sometimes both vehicles deform similarly, sometimes one of the vehicles looks very good, while the other vehicle is completely destroyed. The second case is typical for a crash between a very stiff vehicle and a very soft vehicle. The question arises, what is a stiff vehicle, and what is a soft vehicle? Was the undestroyed vehicle too stiff or was the destroyed vehicle too soft?

The bulkhead concept means that we define a force level that is the maximum force-level for front-end of a car to deform. A bulkhead has to be built which is able to sustain this maximum force level. This bulkhead would avoid a compartment collapse, as long as one of the vehicles is still deforming.

The bulkhead concept would force both vehicles to deform. It takes advantage of the fact that sufficient deformation energy is available. It will decide the question of too stiff and too soft. Forces up to the maximum force-level are acceptable. Everything else is too stiff. If we had already a bulkhead concept, all collisions up to a closing velocity of $2*v_B$ would occur without excessively deforming one of the collision partners, regardless of the mass ratio. This is possible, because the fundamental relationship of compatibility, derived above, holds.

But unfortunately, there are

Limitations to the bulkhead concept

A consequence for barrier impact speed will be shown here:

When a (small) car with mass m_s collides with another vehicle with deformation force F, then for the deceleration a_s, the following equation holds:

$$m_s * a_s = F$$

For the large vehicle with mass m_l, which is designed for a barrier impact speed v_B, we need deformation energy D, which is sufficient to compensate the kinetic energy at barrier impact test speed:

$$D = \frac{1}{2} * m_l * v_B^{\ 2}$$

On the other hand, deformation energy is computed by

$$D = \int F(s)ds = F * s_l$$

with deformation travel s_l of the large vehicle.

The equation only holds for the average force level F of the force deflection curve of the large vehicle's front structure.

$$\frac{1}{2} * m_l * v_B^{\ 2} = D = F * s_l$$

$$\left(\frac{1}{2} * m_l * v_B^{\ 2}\right) \Big/ s_l = F$$

When this large vehicle and the small vehicle mentioned above collide, then by the principle of action and reaction the forces are equal. This can be assumed by neglecting dynamic effects that more or less produce oscillation for which the static approach generates the average behavior. Thus, the static computation is more or less a lower limit of the dynamic computation. It leads to

$$\left(\frac{1}{2} * m_l * v_B^{\ 2}\right) \Big/ s_l = F = m_s * a$$

or

$$\frac{1}{2 * s_l} * \frac{m_l}{m_s} * v_B^{\ 2} = a$$

This shows a relationship between barrier impact speed, mass ratio, and the available deformation stroke of the large vehicle. It is clear that there exist limits of feasibility for the deformation stroke. The length of vehicles must be restricted for several reasons, including those of an environmental nature. The deceleration of the vehicles must be restricted, because the restraint system is able to load the occupant in an acceptable manner only in case of a vehicle deceleration within certain limits.

Therefore, there is a relationship between these principal vehicle parameters, as long as we want to keep the question of compatibility in mind. One question is, what average deceleration we can permit for a vehicle, especially for a small vehicle? We should keep in mind that we are speaking about the average deceleration of the compartment. Today, with a compartment deceleration of 20 - 25 g we already need good restraint systems to achieve acceptable occupant loadings. A compartment deceleration of 30 g is already an upper limit in terms of acceptable dummy loads. Furthermore, this level of 30 g is probably not acceptable with respect to older vehicle occupants.

Now, it is easy to compute, what v_B is acceptable, as long as compatibility is possible. If we use a mass ratio of up to $\mu = \frac{m_l}{m_s} = 1{,}6$, it does not describe all vehicle-to-vehicle mass combinations, but covers approximately 90% of all frontal collisions in real-world accidents (in Germany). A deformation distance of $s_l = 0{,}7\ m$ is higher than available deformation travel in the current fleet. If we accept a deceleration of 30 g that is higher than current restraint systems permit, then we find

$$30\ g = \frac{1}{2} \cdot 1{,}6 \cdot \frac{v_B^2}{0{,}7}$$

$$v_B = 16\ m/s = 57{,}8\ km/h$$

When we take into account that the 30 g level is an upper limit and that a mass ratio of 1,6 does not cover the whole fleet, than we must accept, that current barrier test speed is at the upper limit. 56 km/h, the NCAP test speed for FMVSS 208 is already equivalent to the EES which is achieved when 64 km/h test is performed against a deformable barrier. Therefore, an increased barrier impact speed represents an additional decrease of the possibilities for compatibility. If test speed would be increased to 60 km/h, then the mass ratio for which compatibility measures are possible will decrease by the formula

$$30\ g = \frac{1}{2}\,\mu \cdot \frac{(60\ km/h)^2}{0{,}7}$$

$$\mu = 1{,}48$$

If test speed were to be increased to 64 km/h, then the analogous computation leads to a mass ratio of $\mu = 1{,}30$. This means that compatibility is only possible in the range of 1000 kg to 1300 kg vehicles, e.g. that is not sufficient. When, by reason of environmental considerations, we can expect that small and fuel efficient vehicles will have an increasing market share, then we must allow for a larger compatibility range. For details compare Zobel 1997 and Zobel 1998.

The VDA-approach on compatibility

VDA, the Association of the German Car Manufacturers has developed an approach on compatibility testing that is based on the ADAC-approach. (ADAC is the General German Automobile Club) (Klanner, 1998). This proposes a deformable barrier to test the deformation of the barrier, when impacted by the vehicle. The barrier should provide sufficient deformation that no vehicle bottoms out. From the amount of barrier deformation, the deformation energy provided by the barrier can be estimated. The assumption is that at a fixed test speed, stiffer vehicles produce more deformation to the barrier. Thus, the deformation of the barrier is taken as an estimation of the aggressiveness of the vehicle's front structure. Furthermore, the force behind the deformable barrier is also measured.

This approach offers good information to evaluate the load distribution in the front of a vehicle. If the vehicle has only two stiff longitudinal frame members and nothing in-between, then the shape of the deformed barrier will show this. The shape observed is very sensitive to the force-deflection curve of the barrier.

This approach, however, leaves some open questions, which could probably be answered by rigid barrier testing. The force behind the barrier is a consequence of the interaction between barrier and car. If the vehicle shows only little deformation, then the question remains as to whether this happened because the vehicle was only slightly stiffer than the barrier or whether it indicates an absolutely stiff vehicle. The deformable barrier will indicate a higher stiffness. But if this high stiffness occurs, it provides no information about the undeformed part of the vehicle. This information is needed when we think about the ability of vehicles to force potential opposing vehicles to deform and about the ability to be forced by opposing vehicles to deform.

This approach answers some of the questions about compatibility, others remain. This is probably a short term approach which may be enhanced in the future. For this purpose, a major compatibility project has been established.

Basic ideas of the EUCAR-project on compatibility

This compatibility project is a pre-normative project with the objective of minimizing fatalities and injuries in the vehicle fleet by taking into account self protection and partner protection. Analysis of the interaction of the structures of colliding vehicles with regard to injuries in the striking and in the struck vehicle will be made through hardware testing and computer simulation. The goal is the development of common design rules to achieve an optimum structural interaction between vehicles. This goal will be achieved through requirements relating to implications of vehicle structure, such as restricted force levels, dummy loads, etc.; it is not to be understood as a restriction on design options. It is to be achieved to the extent possible through computer simulation with finite element models (FEM).

Accident analysis is performed, to identify vehicles or vehicle groups that are statistically remarkable, positively through a low injury level or negatively through a high injury level in the vehicle itself or in the struck vehicle. Hardware tests are performed to reproduce the findings from accident statistics, and to verify measurable differences between statistically positive and negative vehicles. Finite element modeling (FEM) is performed to reproduce test results, to replace hardware testing where possible by FEM, and to use FEM as an additional tool to identify findings from accident analysis. The knowledge of these steps is summarized in a suggestion for a procedure for an enhancement of compatibility of the vehicle fleet that could lead to a European standard.

Principal items of compatibility are vehicle mass, vehicle stiffness, lateral fork effect, vertical fork effect, low/high front end of vehicles in frontal impact, high front end of the striking vehicle in side impact, longitudinal engine, transverse engine, a well-balanced distribution of the force in the front end and other effects to be derived from accident analysis.

A consortium of a sufficient number of manufacturers representing different vehicle concepts, e.g. front-wheel or rear-wheel drive, longitudinal or transverse engine, large and small vehicles, offers good prerequisites for such an analysis. A European approach is necessary to influence the behavior of as many vehicles as possible. Compatibility is not so much a characteristic of a single vehicle, but rather that of a vehicle fleet. Previous theoretical approaches showed that an increase in compatibility in the vehicle fleet will lead to a significant decrease of fatalities and injuries in vehicle accidents. French estimations find 675 fatalities avoided and 12850 severe injuries avoided annually in the EU. Cooperation with other institutions interested in this research is therefore desirable and is being actively sought, because of the relevance of the project to European and probably worldwide regulation.

The project defines the steps to deal with compatibility. Regarding results, it remains open, because these should depend on the accident analysis, crash tests and crash computer simulations performed within the scope of this project. It is not easy, to preserve this degree of freedom for such a scientific project, because there is a great deal of political pressure for a quick solution.

For other compatibility projects compare Faerber, 1997, Hobbs, 1996, Klanner, 1998.

Activities of a car manufacturer to enhance fleet compatibility are described by Schoeneburg, 1996 and 1998.

Conclusion

Compatibility research must deal simultaneously with self protection as well as with partner protection. Otherwise, there is the danger that self protection will be reduced by the attempt to achieve higher levels of partner protection. Car-to-car accidents predominate as far as all injuries are concerned. Single vehicle accidents predominate as far as fatalities are concerned.

Not all compatibility features that are theoretically valid, are valid in terms of injury reduction. Dominating everything is the influence of mass. All other influencing factors are of minor importance. Nevertheless, there is a tendency that higher longitudinal frame members may even provide lower levels of self protection. They may even also provide lower partner protection in side impacts. Higher sill height may offer more self protection in side impacts, but all of these results were obtained from German accident data and must still be verified by other European data sets.

Stiffness and the amount of deformation of a vehicle in a crash is not a significant influencing factor. It is surprising that the influence of stiffness is so difficult to detect.

When two vehicles collide, and if their closing velocity is less than their doubled design speed, then there is sufficient deformation energy available for this particular crash. This holds, regardless of the mass-ratio between the two vehicles.

As a consequence, the small vehicle should be able to force the large vehicle to deform. This can be assured if the designer of the small vehicle knows the force level that is required to force the large vehicle to deform. A maximum force must be defined for this purpose. The bulkhead concept means that the compartment of the small vehicle is protected by a "bulkhead" in such a way that it cannot collapse as long as the other vehicle is still deforming, and as long as the maximum force level is not exceeded.

This bulkhead concept has certain limitations. The higher the level of self protection is defined, the higher this maximum force level must be. This means that deceleration in the small vehicle is high. Current restraint systems are able to protect the occupant up to a certain degree of compartment deceleration. If one takes into account this conflict of demands the context of a current barrier impact speed of 56 km/h only up to a mass ratio of 1.6, this bulkhead concept remains valid. However, this will already cover 90% of mass ratios occurring in Germany in car-to-car accidents.

A short-term compatibility test has been defined by VDA, the German Automobile Industry Association. A compatibility project, funded by the European Commission was commenced at the beginning of this year. Nearly all European manufacturers are participating. Its recommendations on compatibility evaluation is expected in 2000.

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