Improvement of Compatibility of Passenger Vehicles – Next feasible steps

Robert Zobel

Thomas Schwarz

Volkswagen AG

Germany

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GOAL

Compatibility has been a research issue for more than three decades now. To improve vehicle safety two viewpoints have to be considered:

- **Self-protection**, the ability of a vehicle to protect its own occupants, both in vehicle-to-vehicle accidents and against other objects in the traffic environment.
- **Partner-protection**, the ability of a vehicle to protect the occupants of the opponent vehicle in vehicle-to-vehicle crashes.

Compatibility aims to ensure a compromise between self-protection and partner-protection. Partner-protection is often referred to as low aggressiveness towards other traffic participants. It has gained more importance recently due to significant improvements in primary and secondary safety.

The first goal remains to prevent accidents by measures of primary safety. Significant improvements have already been achieved in the last few years. Electronic Stability Program (ESP), for example, has a significant influence, particularly in the reduction of single vehicle accidents. It will be much more difficult to prevent vehicle-to-vehicle collisions by primary safety measures.

The **Compatibility** of a vehicle is understood as a combination of self- and partner protection in such a way that optimum overall safety is achieved. This means: Compatibility tries to minimize the number of fatalities and / or injuries, regardless of the vehicle in which the injuries or fatalities occur. Additionally, customers expect further improvements in the self-protection level. It will not be acceptable to compromise today's self-protection level.

To investigate compatibility in a single case, it is possible to crash two vehicles against each other and evaluate the injury values and deformations in both vehicles. In the real accident world, infinite vehicle combinations are possible. It is not possible to test all these combinations. This shows that it is difficult to gain compatibility evaluations by vehicle-to-vehicle crashes. Rather it is necessary to define a meaningful vehicle-to-barrier test.

PASSENGER COMPARTMENT

As already shown in previous publications, the first priority is to ensure sufficient survival space for the occupants.[1] There has been a big improvement in the past due to test procedures for regulation and consumer rating. Newer cars have a much higher compartment resistance (often referred to as compartment stiffness).[2]

In a car-to-car crash the deformation resistance of each car determines the deformation of both cars and therefore also the energy absorption. In a real world crash, VW New Beetle (Figure 1) vs. old car (Figure 2), the compartment of the old car showed significant deformation. The New Beetle, which performed well in offset crash tests, absorbed a significant proportion of the total energy in the front-end. The high compartment resistance, that is proof of a high self-protection level, lead to only minor intrusions into the passenger compartment of the newer vehicle. The higher deformation of the older car due to its softer front-end was to be expected. The deep intrusion into the compartment of the older vehicle was the main risk for the occupant.

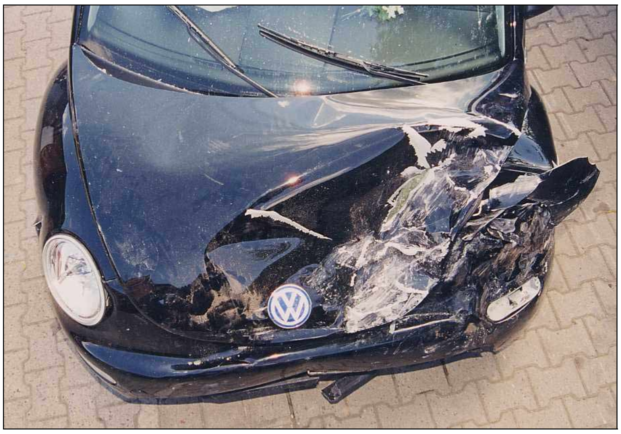

Figure 1: Real world accident new car vs. old car, compartment of new car intact

Figure 2: Real world accident new car vs. old car, high intrusions into compartment of old car

The current frontal offset test requirements use a deformable barrier face. The energy absorption capability of such a face is limited. The deformation travel of cars is limited, too. That means that heavier vehicles have to react by higher front-end deformation forces. The force level depends on the barrier impact speed. If the requirements are increased even further by a raise of the test speed, then these vehicles will have to absorb more energy within their front-end. Due to the limited energy absorption capability of the barrier face, this increase is higher for heavier vehicles than for lighter vehicles. As the deformation travel remains the same due to design restrictions, the front-end must deform at higher force levels, which will result in a higher deceleration of the opponent vehicle (Figure 3). This would be an additional disadvantage for the partner protection toward lighter opponents.

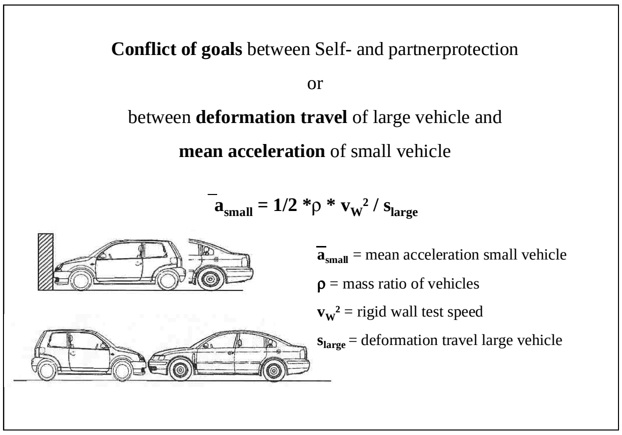

Figure 3: Conflict of goals in compatibility

COMPATIBILITY LIMITATIONS

As described in previous publications, the bulkhead principle shows the principle possibilities for compatible car-to-car collisions (Figure 4).

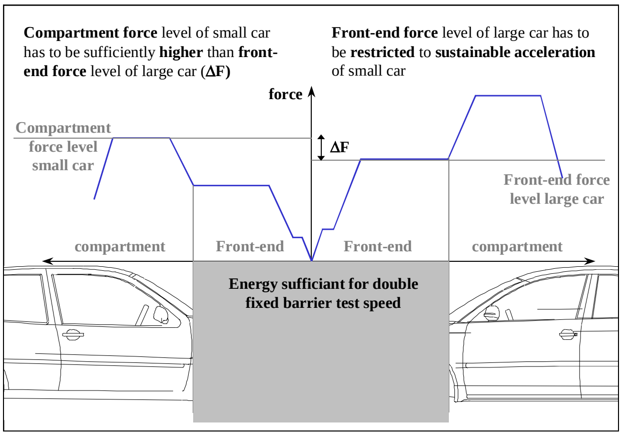

Figure 4: Bulkhead concept

It is a fundamental relationship between the design speed of two vehicles and the deformation energy that is needed when 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.

Under the prerequisite that both vehicles use the same amount of deformation energy as in the fixed barrier crash, both vehicles will experience the same or less deformation. This connection is obviously influenced by the deformation resistance of both vehicles. Usually the softer vehicle will deform first. At lower closing speeds the amount of deformation can be different. It is not necessary to have the same EES for both vehicles at all collision speeds. It is not a problem as long as the compartments of both vehicles remain intact. To avoid higher intrusions than in the barrier crash, it is necessary to have a compartment force sufficiently higher than the front-end force level of the opponent car. Usually this is more challenging for the lighter car than for the heavier car.

The maximum front-end resistance of the large car determines the maximum deceleration of the small car. The higher the mass ratio between the colliding vehicles, the higher the deceleration in the lighter vehicle will be. As described in [3], a mass-ratio of 1.6 seems to be a reasonable limit for compatible car-to-car collisions. Such a mass-ratio covers about 85% of the frontal car-to-car collisions in Europe.

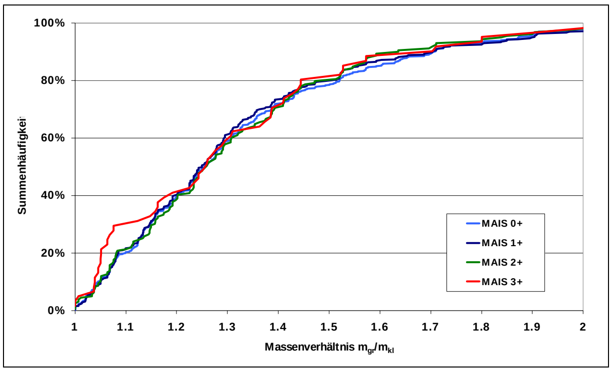

Figure 5: Mass ration in frontal car-to-car collisions for different severities (source VW/GIDAS accident data base)

As a first step it seems reasonable to address the most likely car-to-car collisions. Therefore a lower and upper mass limit can be defined which includes volume models and excludes niche vehicles. As an example these mass limits can be set to 800 kg and 2000 kg (Figure 6). If we now follow the basic rules of the bulkhead principle it is possible to calculate the necessary front-end forces and compartment forces for such vehicles.

To keep the maximum deceleration in the opponent vehicle below 40g, the 1.6 times heavier vehicle than the lightest one has to address that vehicle weight. Therefore the maximum front-end force from 800kg to 1280kg can be 320 kN (40g times 800kg). From there the force increases with the vehicle mass to 2000kg. At this point the computation results in a maximum force of approximately 500 kN (2000kg/1.6*40g). This means the actual deceleration in the small vehicle will be always below or equal 40 g. As shown in [1], this still leads to acceptable occupant loads, if modern restraint systems are used. Softer front-end designs are not prohibited, because these limits are upper limits: softer front-ends could also be acceptable.

While the front-end force of the heavy opponent must consider the deceleration of the lighter vehicle, the compartment resistance of the lighter opponent has to deal with the forces of the front-end of the heavier vehicle. This means the same principal calculations apply for the minimum compartment force. For the heaviest vehicle it is the same as the maximum front-end force plus a safety level. It remains the same till the 1.6 lighter vehicle. From there the necessary minimum compartment force decreases to the lightest vehicle.

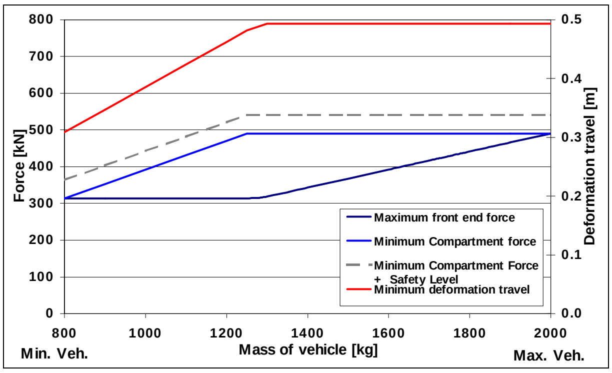

Figure 6: Calculated forces for maximum deceleration of 40 g in small vehicle (theoretical calculations)

Assuming a rectangular force deflection characteristic, the minimum deformation travel of the front-end is calculated and shown in Figure 6. It should be noted that these values are highly theoretical. Real world vehicles have an increasing force-deflection characteristic, which would result in much longer deformation travels. Due to this, the maximum deceleration of the small vehicle will be 40g for a very limited time. The mean deceleration will be much lower and lower levels can be accepted.

STRUCTURAL INTERACTION

Structural interaction is a prerequisite for compatible collisions and therefore also for all the above-mentioned theoretical calculations. Structural interaction means, that the structural components of the front-end deform on the same force level as in the barrier crash. That means that a similar amount of energy is absorbed without higher intrusions than in a barrier crash.

This is only necessary for crashes with high severity. In low severity crashes it might be even of advantage if there is poor structural interaction because this will result in a softer deceleration pulse. That is the reason why the influence of structural interaction is very difficult to detect in real world accident data. Unfortunately it is not known when designing a car which type of accident severity it will experience in its lifetime.

Structural heights today

The main load path of today's vehicles is carried by the longitudinals, which support the crossbeam. Because of the existing bumper tests these structures lie at similar heights above the ground. Figure 7 shows the projection of crossbeam of several vehicles from different sizes on a load cell wall.

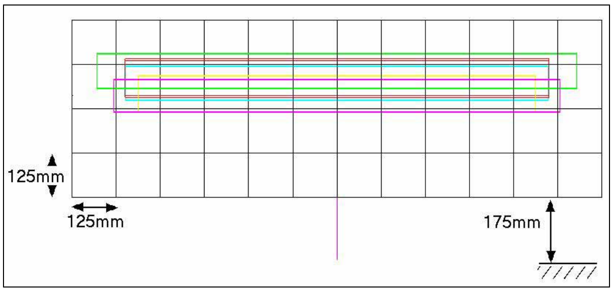

Figure 7: Projection of crossbeams of several vehicle classes on load cell wall

It is a challenge for the future to find a design of a vehicle front-end that enforces the coherence of main structures to enable deformation similar to that in a barrier crash.

Opportunities for Structural interaction

If the heights of structural parts of colliding vehicles do not match, over-/under-riding may result. During deformation, the height difference would increase. The over-riding car would mainly deform in the lower load paths; the under-riding car would deform in the upper load paths. This may lead to higher intrusions in some regions of deformation whereas other energy absorption capabilities remain unused. It might be desirable to create a front-end structure that locks with an opponent vehicle and prevents slipping movement in the vertical direction. If that is the case, a possible compatibility evaluation test procedure should be able to detect this.

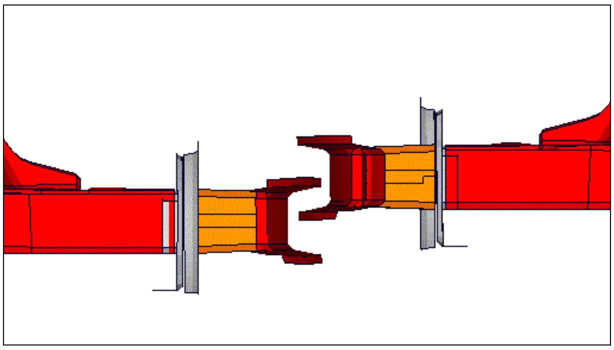

Figure 8: Theoretical construction of a modified crossbeam to improve longitudinal deformation in a vehicle-to-vehicle crash with height difference

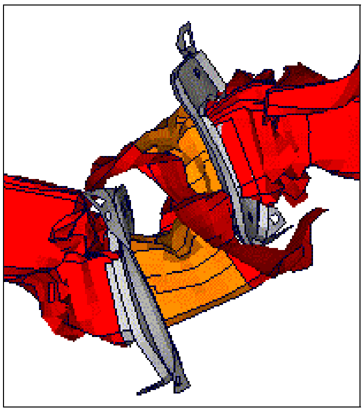

Figure 9: Deformed longitudinals after vehicle-to-vehicle crash simulation with modified crossbeam to improve structural interaction

It is very unlikely that the longitudinals of two colliding vehicles match in the horizontal direction. Therefore a strong connection between these (crossbeam) is desirable to improve compatibility. It could transfer loads from the higher loaded side to the other and would help to prevent local intrusions into the front-end between the longitudinals. In case of collisions with a very small overlap it might be of advantage to induce glancing-off of the vehicles before the compartment of either one of the vehicles starts to deform. This is also a consideration when introducing a compatibility evaluation test procedure.

A very crucial point for test procedures proposed for vehicle compatibility evaluation is whether they detect and evaluate the crossbeam in an adequate manner. A crossbeam is a non-aggressive, self- and partner-protection tool that has to be rated positively, irrespective of the test procedure applied.

Relevance of longitudinal load paths

Although the longitudinal load path is very important for the total energy absorption in the vehicle front-end, it should not be overestimated. In vehicle crash simulations it is possible to distinguish the energy absorption of every part of the car during the crash. Figure 10 shows the distribution of energy absorption in the longitudinal, including the crash box and the crossbeam of the vehicle, in relation to the total deformation energy of the vehicle, in such a crash.

The total share of these parts is between 25% and 40%.

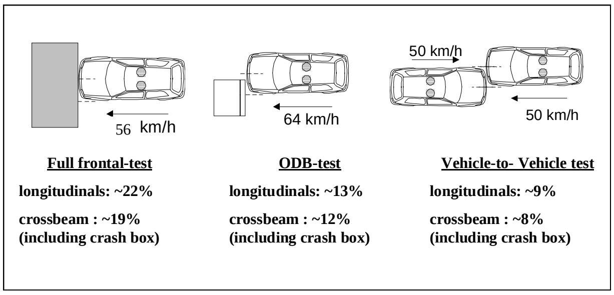

Figure 10: longitudinal load path deformation energy share

POSSIBLE TEST PROCEDURES

There are several test procedures with potential to further investigate the compatibility issue, each having advantages and disadvantages:

Full width rigid wall test including load cell wall (US NCAP)

The possibility of an additional assessment of load cell wall forces is currently being investigated by NHTSA. Since this test is a full overlap test, it is of lower severity for the front-end structure than an offset test, and results in less front-end deformation. The main disadvantage seems to be the unrealistically high loading of single load cells by impacting mechanical parts (e.g. engine, transmission). These parts create very high peaks when impacting the infinitely stiff wall that would not occur in vehicle-to-vehicle crashes [2, 4].

The currently used resolution of the NHTSA load cell wall (246*234 mm²) seems to be too coarse to be able to distinguish different vehicle types. It is likely that a crossbeam will not be detected by a stiff rigid barrier, only its supporting longitudinals will provide significant load at the load cells.

Full width deformable wall test including load cell wall (suggested by TRL with double honeycomb layer)

The full width test suggested by TRL adds a deformable layer in front of the load cell wall, to filter the peak forces created by mechanical parts when impacting the wall, without changing the deceleration pulse significantly. Whether this test is able to detect a crossbeam and evaluate its stiffness adequately has to be further investigated. Due to the low deformation of the front-end, it is questionable if such a test is able to detect supporting load paths behind the cross member plane. Although it uses a deformable face, it still provides sufficiant deceleration of the compartment to evaluate the restraint system performance.

Offset deformable barrier test including load cell wall

The additional load cell wall in the current offset deformable barrier test is of low benefit. There is a strong bridging effect, due to the deep deformable face, with the same stiffness over the full deformation depth. Most current cars fully deform the barrier and produce unrealistic force peaks due to impacting mechanical parts. It appears very difficult to gain additional information for a compatibility evaluation with this test. As it uses only the impact side longitudinal it does provide higher loading of the impacted side and detects soft compartments. It has to be studied, whether the compartment resistance derived from this test can be used for compatibility evaluation.[4]

Progressive deformable barrier (PDB) including load cell wall

This type of barrier, incorporating increasing force deflection characteristic, better reflects a real world opponent than the currently used barrier. Any barrier type with an increasing force-deflection characteristic produces higher sheer forces than the currently used barrier.

The deep barrier leads also to bridging effects; therefore a load cell force resolution is of lower relevance. One major problem seems to be the vehicle rotation after the crash due to the offset test configuration. If a vehicle has a desirably stiff cross member, the vehicle rotation results in a lateral loading of the honeycomb with a much lower resistance than in longitudinal direction. The currently proposed test procedure tries to address this problem by evaluating only a certain area of the deformable face, which cannot solve this problem completely. An impacting vehicle will intrude into the barrier and create a footprint of the vehicle front-end structure. Unfortunately the footprint is being changed during the rebound phase and also due to the rotation of the vehicle.

The problem of mass dependent force limits is so far neglected by this test proposal.

Progressive deformable barrier with a mass dependant impact speed

One-way of addressing this problem could be a mass dependent impact speed. Lower impact speeds for heavier vehicles would leave the possibility to develop a softer front-end without compromising the self-protection level. For lighter vehicles the increased test severity would enforce high compartment forces that are beneficial in car-to-car collisions. Although, from a scientific point of view, this approach might be reasonable, it seems to be not communicable to the customers. It will be very difficult to explain, especially to customers of larger and often more expensive vehicles, why their vehicles are tested with a lower impact speed.

The problem of the changing barrier deformation due to the vehicle rotation and rebound also remains for this test configuration.

Offset progressive deformable moving barrier

Another way to address the above mentioned problems might be a Moving Deformable Barrier (MDB) with a deformable barrier face incorporating an increasing force deflection characteristic.

That way the impact speed could be kept the same for all vehicle masses. The heavier vehicles are tested with lower severity and this allows them to remain a reasonable soft front-end. The lighter vehicles are tested with a higher severity, which will enforce these vehicles to create a sufficient compartment resistance. That is especially important for lighter vehicles in vehicle-to-vehicle collisions.

The vehicle rotation during the rebound might be of less relevance because the MDB also starts to rotate.

Although it has to be noted that such a test configuration creates much higher requirements toward repeatability and reproducibility than fixed barrier tests. Before moving in such research directions, it has to be further investigated how fixed barrier tests address these questions. In test series with this test configuration practically no vehicle was hit with the exact planned overlap.[5]

NEXT FEASIBLE STEPS

Since there is no full width test up to date in Europe, consumer or regulatory, it seems to be more useful to move in such a direction rather than adding another offset test. It has to be investigated if such a test will be able to ensure sufficient structural interaction and can detect design measures that prevent over-/underriding due to catching of the opponent front-end structure.

Any test with a mass dependent test speed seems to be incommunicable to the customers. For non-experts it will not be acceptable that a larger and in most cases more expensive car, has at least at a first glance, a lower self-protection level than a small car.

For the offset test using the ECE-barrier, the main disadvantage seems to be the early bottoming out of the barrier. There is a possibility that a deeper barrier with an increasing force deflection characteristic could have an advantage for prediction of the behavior in vehicle-to-vehicle collisions, because its behavior is closer to an opponent vehicle. This item has to be discussed as an optimization of frontal impact test procedure and is a long-term question with a couple of imponderables at this stage.

The remaining possibility of a Moving Deformable Barrier needs to be further investigated. Although such a test requires higher efforts towards reproducibility it might have significant advantages compared with fixed barrier tests. With such a test, the rotation of the tested vehicle in offset collision configuration, which blurs the deformation picture of any deformable barrier, might be at least partially compensated. This might be of further interest as a long-term research approach. For this test configuration a lot of open questions make an option only feasible in long-term and not available for mid term application.

Taking all these pros and cons into account, it is not surprising that there is no “industry”-position on compatibility available at this phase of research. There is a relevant part of industry that supports the attempt to enhance the full frontal impact by using layers that provide information about the front-end force distribution during a crash. Worldwide operating manufacturers, of course, appreciate the harmonization potential this test provides because it is close to FMVSS 208. NHTSA expressed its goal to implement a first step of compatibility via an average height of force or a similar approach within the short term. A full width barrier with a small layer could support this goal because this barrier has the potential also to be used for future compatibility evaluations. On the other hand it seems to be rather clear for all manufacturers that a rigid barrier, even with load cells, is not able to measure, for example, the capabilities of the cross beam. A rigid barrier already provides an infinitely stiff crossbeam, even if the car only has two longitudinals without any connection.

A harmonization under the umbrella of compatibility seems to be possible, as shown in the official IHRA report. But it needs a motion of all sides, including the U.S., at least to accept a full width frontal impact with a small layer as equivalent to the rigid barrier. With regard to self-protection, the two tests are so similar that it makes no sense, to conduct them both.

Although there is no common industry position for a test procedure, there are general guidelines, which at least the ACEA members share as a basis for their next steps. These guidelines are provided in the summary of the paper.

SUMMARY

- Longitudinals and cross member contribution to deformation energy in a crash should not be overestimated. Due to measures to improve structural interaction, this share may decrease in the future.
- Longitudinal and cross member height is already, in the current fleet, in a range which is derived from the pendulum test.
- This offers an opportunity to encourage a convergence of longitudinal heights of passenger vehicles. Larger vehicles might respond by supporting this range by cross members that prevent opposing cars from under-riding.
- Supporting load paths behind the cross member plane should be credited as well.
- Test procedures have to take into account the geometrical measurers that provide load paths between cars.
- Structural interaction should be encouraged by matching the (heights of) structures regardless of vehicle mass/size. Force homogeneity is not necessary to ensure it. Positive engagement of structure has to be also taken into account.
- As compatibility is not achievable for all mass ratios, a mass ratio of 1.6 and a curb weight of max. 2000 kg, which covers 80%..90% of all car-to-car-accidents, should be taken into account. It should be used to allow mass dependent front-end forces. This should also be reflected by compatibility evaluation.

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