PRIORITIES FOR THE ASSESSMENT OF FRONTAL IMPACT COMPATIBILITY

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ABSTRACT

Vehicle-to-vehicle crash compatibility is a complex subject that has been extensively researched during the last 40 years. For the purposes of this paper, compatibility is defined as the optimisation of vehicle design to help minimise the number of injuries and fatalities that occur in collisions between passenger vehicles. For the evaluation of compatibility in these collisions, the criteria of self-protection and partner-protection are considered together in a measure of 'total safety'. It is also shown that separate evaluations of self-protection and partner-protection should not be used to guide regulatory policy on passenger vehicle to passenger vehicle compatibility because they are less effective at bringing about reductions in the total number of injuries and fatalities in passenger vehicle to passenger vehicle collisions.

Front-to-front passenger vehicle collisions from the German In-Depth Accident Survey (GIDAS) relational database are evaluated, and it is shown that, in a collision between two vehicles with unequal masses, the driver of the lighter vehicle typically experiences a higher risk of injury than the driver of the heavier vehicle. However, by analysing these accidents at the collision level, it is shown that the 'total safety' of front-to-front collisions between passenger vehicles in the German fleet is independent of the mass ratio of the involved vehicles. In other words, the 'total safety' of a collision between a heavier passenger vehicle and a lighter passenger vehicle is equivalent to the 'total safety' of a collision between two equally massive vehicles. It is therefore concluded that mass-dependent criteria cannot be justified as the principal evaluative measure in future regulations that aim to address compatibility in front-to-front collisions between passenger vehicles.

Structural homogeneity is analysed using collision simulations between a mid-sized passenger car and a larger Sports Utility Vehicle (SUV). Vertical and horizontal structural homogeneity are analysed separately by using homogeneous 'shields' as substitutes for the bumper crossbeam structure. The simulations show that the vertical alignment of primary structures and improved vertical homogeneity result in improved compatibility. If vertical homogeneity is achieved, horizontal homogeneity between the main load paths does not provide additional benefit and hence this should not be prioritised in a compatibility assessment. The assessment of horizontal homogeneity is only relevant for small overlap collisions outboard of the vehicles' longitudinals.

Finally, the ability of various barriers and test procedures to evaluate compatibility is discussed. It is concluded that vertical alignment may be evaluated by measuring load cell wall forces and that low speed tests may be used to improve homogeneity.

INTRODUCTION

Research on collisions between small and large passenger vehicles was well underway in the early 1970s [2], and, by 1973, it had been recognised that the compatibility of a vehicle is a product of its self-protection, which describes the functions of its design that protect its own occupants, and its partner-protection, which describes the functions of its design that protect other road users in the event of a collision [3]. By 1974, it had also been found that the outcome of a vehicle-to-vehicle collision is influenced by the vehicles' mass ratio, their force-deformation characteristics, and the architecture of the energy absorbing structures [4]. By the beginning of the 1980s, constructive measures to improve compatibility had already been proposed, including lateral connections between the longitudinals, changes to deformation force levels in the crumple zone, and increased structural support in the passenger compartment [5].

Compatibility research in Europe is currently being led by the Frontal Impact and Compatibility Assessment Research (FIMCAR) project. The FIMCAR project has the objective to "propose an assessment approach for frontal impact integrating self and partner protection" [6]. To this end, it has prioritised the evaluation of structural alignment, load spreading, energy absorption management, compartment integrity in single vehicle collisions, and restraint system capacity. The consortium has stated its intention to propose a combination of a full-width and an offset test, and it is also considering a mobile offset barrier as an alternative to the fixed mobile barrier [7].

The Japanese compatibility working group has focussed their research on mismatches in front rail height and determined that height mismatches greater than 100 mm can lead to override/underride and increase the risk of occupant injury. The working group has developed several metrics for

the evaluation of front rail height using the Full Width Rigid Barrier (FWRB) [8], which have also formed the basis of similar activities in the FIMCAR project [9].

In the USA, the Insurance Institute for Highway Safety (IIHS) is developing a test procedure to address small overlap collisions [10], and the National Highway Traffic Safety Administration (NHTSA) is investigating test procedures to address small overlap and oblique offset collisions [11]. However, neither organisation is directly addressing compatibility in these activities.

The objective of this paper is to build upon this broad base of research and identify priorities for the assessment of compatibility in the current and future vehicle fleets.

DEFINITION OF COMPATIBILITY

Many measures of passenger vehicle safety tend to focus on self-protection, and hence a particular passenger vehicle design may be considered "safe" for its own occupants even though it could theoretically pose a higher risk of injury to the occupants of a passenger vehicle that it collides with. The sole evaluation of self-protection is relevant for single vehicle collisions, but, in studies of vehicle-to-vehicle compatibility, the evaluation of partner-protection is also common. This results in the complexity of having two measures of vehicle safety, which are independent and applicable to different portions of accident environment, and hence this approach "may not be ideal from the perspective of trying to steer the vehicle fleet as a whole in the direction of optimum safety" [12, p3]. Therefore, similar to the approach taken in [12], the applicability of a 'total safety' measure of compatibility is discussed below.

The accident environment is complex, and collision characteristics such as speed, direction, and overlap all contribute to the risk of injury to a vehicle occupant. For a vehicle to be considered "safe", it does not have to provide the same level of self-protection in all collision configurations, but it should be designed to help minimise the risk of injury to its occupants across the range of likely collision events. Similarly, for a passenger vehicle to be considered compatible, it does not necessarily have to provide the same level of self-protection and partner-protection in collisions with all other passenger vehicles, but it should be designed to help minimise the risk of injury to all involved persons across the range of likely collision partners.

Based on this broad view of compatibility, the evaluation of a compatible collision or a compatible vehicle requires detailed knowledge of the entire accident environment. For example, reduced risk in an infrequent collision type could result in increased risk in another, more frequent collision configuration and hence an overall increase in the total number of injuries and fatalities. However, knowledge of the accident environment is retrospective and limited in scope. For the design of new vehicles that will operate in a future accident environment, it may therefore be impossible to accurately evaluate their compatibility using this approach.

Even without perfect knowledge of the entire accident environment, it is possible to select a frequently occurring collision configuration and use it to provide a partial evaluation of the compatibility of different vehicle designs. This approach is already used in regulations and consumer testing and is the state-of-the-art method for evaluating safety. In the discussion below, the effects of speed, overlap, etc. are hence ignored, and it is assumed that the vehicle designs are the only significant variable that affects a collision outcome. The discussion below refers to the risk of fatality, but it may also be interpreted in terms of injuries since, as described in the Abbreviated Injury Scale (AIS) in [13], the severity of an injury can be rated according to its survivability.

If, for any particular passenger vehicle, a "safe" frontal collision is considered to be one in which there is ρ risk of a fatality occurring then, for a front-to-front collision involving two identical passenger vehicles, the outcome can be considered compatible if the risk of a fatality occurring is ρ in each vehicle and hence $2\times\rho$ overall. However, for a vehicle-to-vehicle collision involving non-identical vehicles, the risks of fatality for each vehicle's occupants are likely to be different. In this case, there are two possible approaches: an evaluation at the vehicle level and an evaluation at the collision level.

If, under this premise, the evaluation is performed at the vehicle level, the outcome can only be considered equivalent to the example above if the occupants of the first vehicle and the occupants of the second vehicle each have a ρ risk of fatality. If all likely combinations of passenger vehicles are considered, the theoretical optimum for compatibility would only be achieved if all vehicles had equal self-protection and equal partner-protection In contrast, if the evaluation is performed at the collision level, the outcome can be considered equivalent to the example above if the risk of a fatality occurring is $2\times\rho$ overall. When considered across all likely combinations of passenger vehicles, this would be achieved if the combination of self-protection and partner-protection, i.e. the 'total safety', were equal.

Let us assume that one or more regulatory test procedures is defined so that all new passenger vehicles have collisions that are considered compatible when evaluated at either the vehicle level or the collision level. In either case, the risk of a fatality occurring in any front-to-front collision would be same: $2\times\rho$, and hence the total number of fatalities that would occur in the entire accident environment would also be the same. In contrast, the cost of the vehicles designed to satisfy the two possible sets of test procedures would be different, since equal 'total safety' provides for more freedom of design. Furthermore, the goal of equal self-protection and equal partner-protection may be unreasonable, since some vehicles would need to reduce their partner protection to satisfy the requirements whilst others would need to reduce their self-protection. The additional costs would also not bring about a reduction in the total number of injuries and fatalities, and hence this approach would be inappropriate for regulation. If resources are available, it would be more appropriate to apply a 'total safety' approach to passenger vehicle to passenger vehicle collisions and then use the additional resources to reduce the total risk of fatalities across all collisions to a value less than ρ.

PRIORITIES FOR COMPATIBILITY

In the previous section, it is shown that the compatibility of a vehicle design may be evaluated by measuring the 'total safety' for all occupants involved in a collision. In terms of injury risk, the important physical properties of any collision are the interface force and the structural interaction. The former dictates the deceleration and deformation of a vehicle whereas the latter dictates the efficiency with which it is deformed and hence the degree to which its structure can protect its occupants. Correspondingly, the critical physical properties of a vehicle's design are the relationship between force and deformation, which may also be referred to as its stiffness, as well as the structural geometry and mechanics of the vehicle's deformation. The mass of the vehicle also has an effect since, as described by Newton's second law of motion, for any given force, the deceleration of a vehicle is inversely proportional to its mass.

In this section, the effects of vehicle mass ratios and structural homogeneity are investigated in front-to-front collisions and evaluated according to the definition of compatibility from the previous section. Vehicle stiffness is not investigated as an independent variable in this paper, since previous studies have shown a strong relationship between vehicle stiffness and mass [14].

Vehicle mass

The effect of vehicle mass on occupant protection is a frequent topic of discussion in safety related publications. Depending on the perceptions of the author, the focus may be directed towards either the "aggressiveness" of larger, heavier passenger vehicles (for example, [15]) or the "inferior" safety of smaller, lighter passenger vehicles (for example, [16]). However, the evaluation of collisions based on risk ratios, which describe the relative risk of injury in two colliding vehicles, has also been criticised because it does not distinguish between positive and negative behaviour. For example, in [17] it is shown that the perceived 'inferior' safety of lighter vehicles may in fact be attributed to their high level of partner protection and the correspondingly low level of injuries and fatalities that occur in the vehicles with which they collide.

In Figure 1, the cumulative distribution of belted drivers is shown for front-to-front collisions between passenger vehicles. The independent variable in this figure is the mass ratio of the driver's vehicle compared to the collision partner's vehicle. For the hypothetical case of a collision between a 1500 kg vehicle and a 1200 kg vehicle, the driver of the first vehicle would be plotted with a vehicle mass ratio of 1:0.8, and the driver of the second vehicle would be plotted with a vehicle mass ratio of 1:1.25. The mass ratios are calculated from the estimated total vehicle mass, which includes the mass of the occupants and payload and hence reflects the true mass, momentum, and kinetic energy at the time of the collision.

The data are taken from the GIDAS relational database and only include matched pairs of drivers. The data are limited to cases where both vehicle masses are known, the MAIS of both drivers is known, both drivers were belted, both vehicles were manufactured between 1981 and 2005, the direction of force on both vehicles indicates a frontal impact (VDI1 = 11, 12 or 1), and the location of damage on both vehicles indicates a frontal impact (VDI2 = 1).

In Figure 1, it can be seen that 23% of all belted drivers experience front-to-front collisions where their vehicle has a mass ratio of less than 1:0.8 and, since the distribution is based on matching pairs, 23% experience a mass ratio of more than 1:1.25. However, it can also be seen that the mass ratios less than 1:0.8 account for only 13% of MAIS 2+ injuries and 7% of MAIS 3+ injuries whereas the mass ratios greater than 1:1.25 account for 33% of MAIS 2+ injuries and 42% of MAIS 3+ injuries.

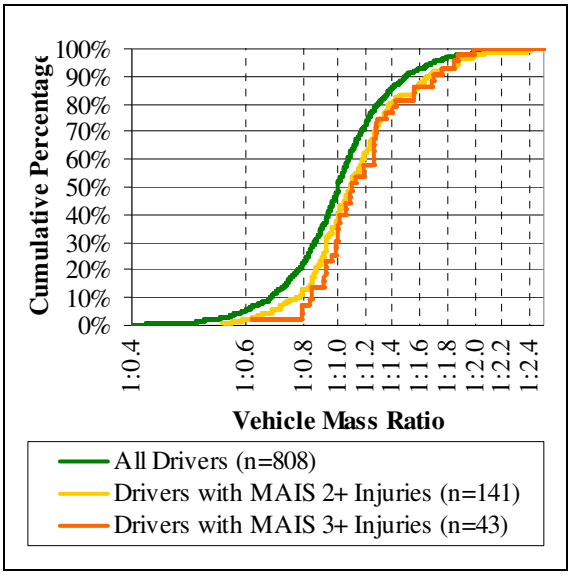

Figure 1. Vehicle mass ratio: cumulative distribution of belted passenger vehicle drivers involved in front-to-front collisions with other passenger vehicles.

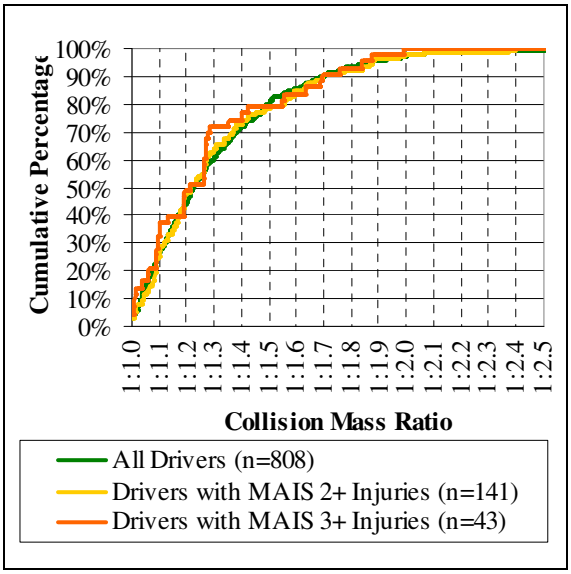

Figure 2. Collision mass ratio: cumulative distribution of belted passenger vehicle drivers involved in front-to-front collisions with other passenger vehicles.

Using a Kolmogorov-Smirnov test, it can be shown that the difference between the distribution of all drivers and the distribution of drivers with MAIS 2+ injuries is statistically significant ($p = 0.015$). This result reflects observations from numerous other accident analyses and indicates that the drivers of lighter vehicles are more frequently injured in front-to-front collisions than the drivers of heavier vehicles. However, as discussed at the beginning of this section, mass is not the only factor that influences injury risk. A higher MAIS is recorded for the driver of the heavier vehicle in 20% of the cases included in Figure 1.

The results derived from Figure 1 are interesting, but they represent a vehicle based approach to the evaluation of the collision outcomes. The definition of compatibility at the beginning of this paper promotes a collision based approach to ensure that actions are taken that maximise the benefit across the entire accident environment. By considering the data at the collision level, it is possible to determine whether collisions between vehicles with unequal masses are responsible for a disproportionately high number of injuries when compared to collisions between vehicles with equal masses. Under the null hypothesis, which is that collisions between vehicles with unequal masses are equivalent to collisions between vehicles with equal masses, it may be concluded that higher mass ratios do not represent a higher risk of injury to the community as a whole, even if, as shown in Figure 1, they represent an increased risk of injury to one of the involved individuals.

In Figure 2, the data from Figure 1 are distributed according to the collision mass ratio, which is the ratio of the lighter vehicle's mass compared to that of the heavier vehicle. Hence, for the hypothetical collision between the 1200 kg and 1500 kg vehicles discussed above, <u>both</u> of the drivers would be plotted with a collision mass ratio of 1:1.25. It is critical to note that both drivers are plotted in Figure 2 for each collision. The data could also be plotted according to the maximum MAIS for both drivers combined, but this would not reflect the fact that MAIS scale defines injuries according to their survivability and that the risk of a fatality occurring in a collision is greater when both of the drivers are injured.

The results in Figure 2 show a clear similarity between the distribution of all drivers and the distribution of drivers with MAIS 2+ injuries. However, due to the relatively small number of drivers with MAIS 3+ injuries, it is not clear whether higher collision mass ratios result in a higher, lower, or equivalent risk of injury.

The differences between the distribution of all drivers and the distribution of drivers with MAIS 2+ injuries are not significant (Kolmogorov-Smirnov test, $p = 0.801$). The lack of a significant difference cannot be taken as proof of the null hypothesis. However, the data in Figure 2 appears to support the conclusion that the total risk of injury to all occupants in a collision is independent of the relationship between the masses of the vehicles involved. Therefore, from a societal perspective, there is no justification for a mass-dependent assessment of compatibility in front-to-front collisions between passenger vehicles.

Structural homogeneity

Homogeneity can be defined by addressing the way a structure either applies forces or the way it reacts forces. A deformable honeycomb element is an example of a structure that applies forces homogeneously (i.e. it has a constant stiffness distribution), whereas a rigid wall is an example of a structure that reacts to forces homogeneously (i.e. its behaviour under loading is independent of the distribution of the forces that are applied to it). A vehicle structure that reacts homogeneously to different loading conditions is more robust, and hence this definition is used as the basis for the discussion in this section.

To investigate the effects of vertical structural homogeneity and horizontal structural homogeneity as independent variables, simulation models have been developed with homogeneous 'shields' as substitutes for the bumper crossbeam structure. The vertically homogeneous shield is designed to be rigid in the vertical direction but flexible in the horizontal direction. In contrast, the horizontally homogeneous shield is designed to be rigid in the horizontal direction and flexible in the vertical direction. Figure 3 shows the two types of shields and the way that they deform in a collision with a Full Width Deformable Barrier (FWDB).

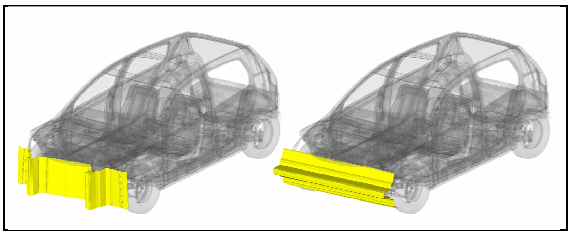

Figure 3. Typical deformation behaviour of the vertically homogeneous shield (left) and the horizontally homogeneous shield (right).

The shields are modelled using a thin mono-directional ply structure and are similar in mass to the bumper crossbeam structures that they replace. Translation and rotation of each shield is controlled within the vehicle's local coordinate system. Vertical and lateral translation is fixed, but movement in the collision direction is free. All rotations are fixed except for those about the axis parallel to the direction of homogeneity and, for the horizontally homogeneous shield, rotations about the vertical axis. The shields are 250 mm in height and are positioned to cover a zone between 330 mm and 580 mm of ground clearance.

To investigate the effects of the shields, a series of front-to-front collision simulations has been performed with models of a mid-sized passenger car and a large SUV. Severable variables have been investigated, including various overlap conditions, changes in vehicle ride height, and changes to the sizes of the homogeneous shields, and the most significant results are described below. The simulations have all been performed with a mass ratio of 1:1.9, collinear velocity vectors, and an approach speed of 112 km/h. In addition to the vertically homogeneous shields and the horizontally homogeneous shields, basis simulations have also been performed with 'inhomogeneous' models without bumper crossbeams.

The results of the simulations have been evaluated using a method described in [1], which uses measurements of compartment deformation to predict the 'total safety' for both vehicles' occupants. This method applies the collision based approach to the evaluation of compatibility that is recommended earlier in this paper. However, a weakness of this method is that it does not directly evaluate changes in the compartment deceleration, nor does it consider either vehicle's restraint system. A more detailed description of the evaluation method is not possible within the constraints of this paper, and hence the following discussion is restricted to a description of the vehicle deformations that have been most influential in the evaluation. In most cases, these differences have been measured in the passenger car, although the deformations of both vehicles have been evaluated equally.

The first significant conclusion from the simulations is that vertical homogeneity further improves the interaction between structures under dynamic loading even when initial, geometrical alignment of the structures is provided. At the nominal ride heights, the car longitudinal is lower than the SUV longitudinal, but the two structures overlap by more than 50% of their respective heights. In upper diagram in Figure 4, it can be seen that the geometrical alignment of the longitudinals results in the interaction and deformation of both structures. However, the car has a moderate degree of dive, which results in loading of the car upper longitudinal and deformation of its compartment at the upper A-pillar and instrument panel crossbeam. In the lower diagram in Figure 4, it can be seen that the addition of the vertically homogeneous shields reduces the dive of the car and the deformation of the upper longitudinal, which results in a 29% reduction in the compartment deformations in the car.

The second significant conclusion is that a horizontally homogeneous structure has limited effectiveness when the main load paths of the vehicles are not in vertical alignment. To investigate this, the SUV and its driving surface have been raised by 125 mm in the simulations. In

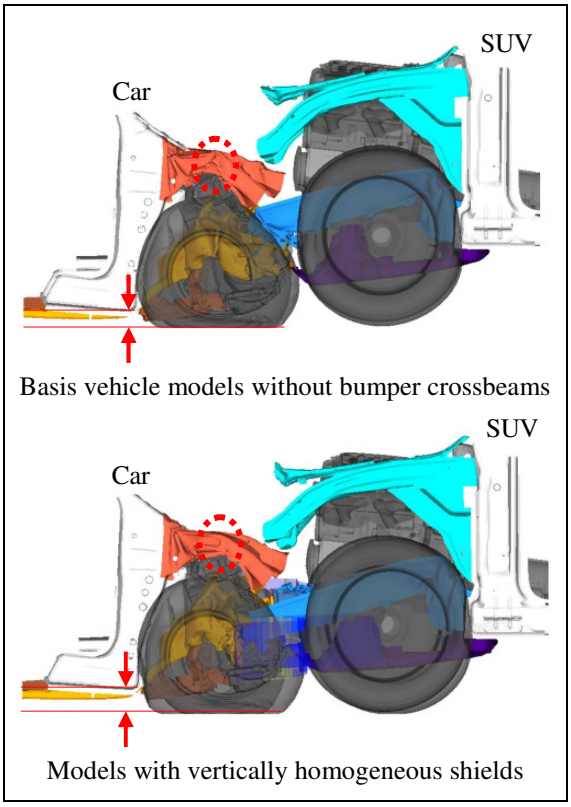

Figure 4. Front-to-front collision with 100% overlap. Side view after 70 ms.

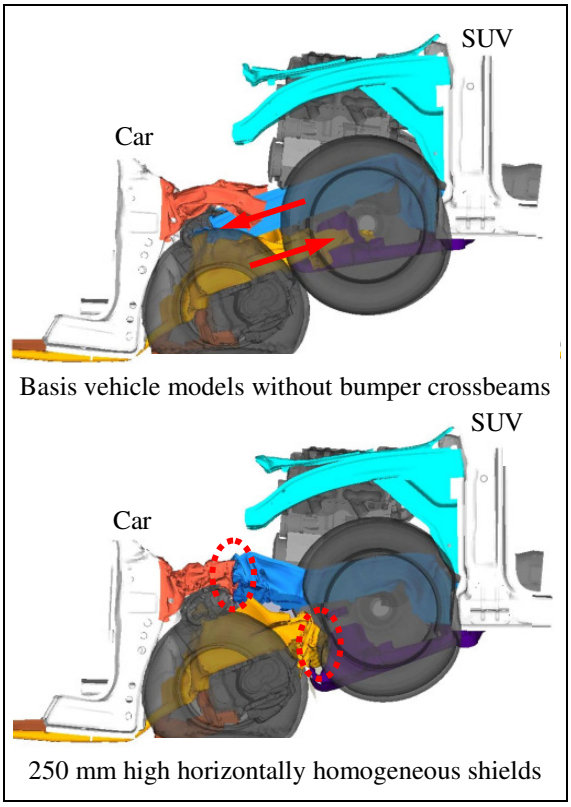

Figure 5. Front-to-front collision with 100% overlap and 125 mm raised SUV driving surface. Side view after 70 ms.

the upper diagram in Figure 5, it can be seen that the main load paths of the vehicles do not interact and they remain largely undeformed. In the lower diagram in Figure 5, it can be seen that the horizontally homogeneous shield improves the structural interaction and the primary load paths of each vehicle interact with the secondary load paths of the other vehicle. This results in a 20% reduction in the compartment deformations in the car, but override/underride still occurs, and the resulting deformations are still four times higher than those observed in the simulation with the SUV at its nominal ride height.

The third significant conclusion is that horizontal homogeneity is only marginally more effective than vertical homogeneity in partial overlap collisions. This result challenges conventional wisdom, since it is often argued that crossbeam structures are necessary to prevent the 'fork effect'. However, although the upper diagram in Figure 6 confirms that horizontal homogeneity indeed prevents the fork effect, the lower diagram in Figure 6 shows that vertical homogeneity is equally effective at achieving this goal. The vertically homogeneous shields do not increase the interaction between the primary load paths of the vehicles, which have a lateral offset, but they enable the left SUV longitudinal to interact with the engine and gearbox of the car and they also enable the left car longitudinal to interact more effectively with the engine subframe of the SUV. The compartment deformations in the car are slightly lower in the simulation with the horizontally homogeneous shields, but the effect on any occupants would be marginal.

Figure 5 and Figure 6 provide an interesting contrast, since the former shows that horizontal homogeneity is ineffective in cases of vertical offset, whereas the latter shows that vertical homogeneity is still effective in cases of lateral offset. In both cases, the loads from the primary load paths are supported by secondary load paths in the collision partner vehicle. The critical difference between these two cases is that the former still results in override/underride, which places additional loading on the passenger compartment and increases the risk of occupant injury.

The final conclusion from the collision simulations is that horizontal homogeneity is beneficial in low overlap collisions, but only if it extends beyond the width of the longitudinals. Low overlap collisions have been investigated with 33% overlap between the vehicles. In this configuration, there is no interaction between the longitudinals of the basis vehicle models. As shown in the upper diagram in Figure 7, the car longitudinal is supported by the left wheel of the SUV, which is able to support the forces necessary to deform it. In contrast, the SUV

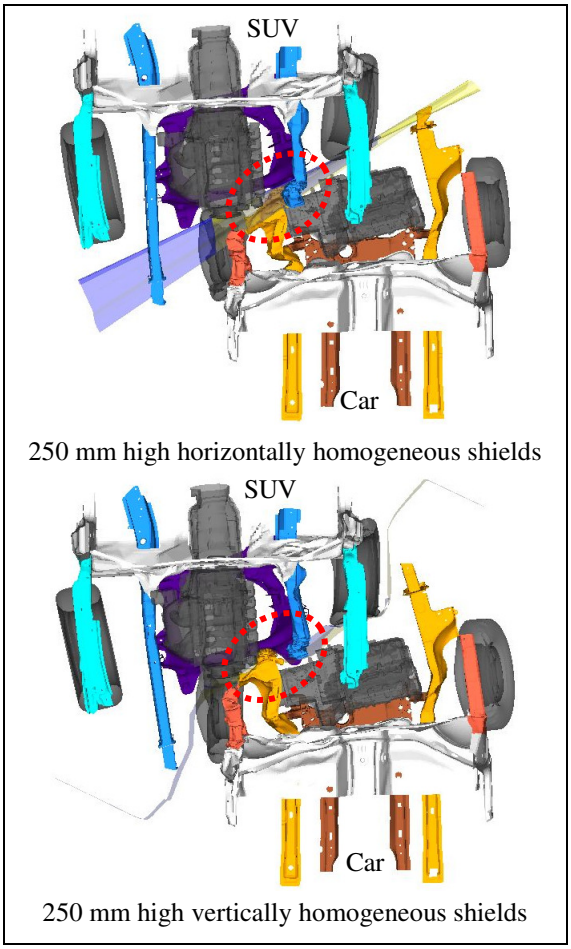

Figure 6. Front-to-front collision with 66% overlap. Modified vehicle models with. Top view after 75 ms.

longitudinal remains undeformed whilst directly loading the A-pillar of the car. With the addition of a wide, horizontally homogeneous shield, which is shown in the middle diagram in Figure 7, loads are transferred between the two vehicles' longitudinals, and they are both deformed to a greater degree. However, this is only possible because the horizontally homogeneous shields overlap. In the lower diagram in Figure 7, the shields only cover the region between each vehicle's longitudinals and hence they do not interact in a low overlap collision. The SUV longitudinal remains effectively undeformed, and although the horizontally homogeneous shield averts the direct interaction between the SUV longitudinal and the A-pillar of the car that occurred in the basis simulation, the load path including the car longitudinal and the wheel of the SUV is more heavily loaded. Due to a lack of deformation in the SUV longitudinal, the collision energy is dissipated by increased deformation in passenger compartment of the car and, to a lesser degree, the footwell of the SUV.

The first priorities for improved compatibility are hence the vertical alignment of primary structures

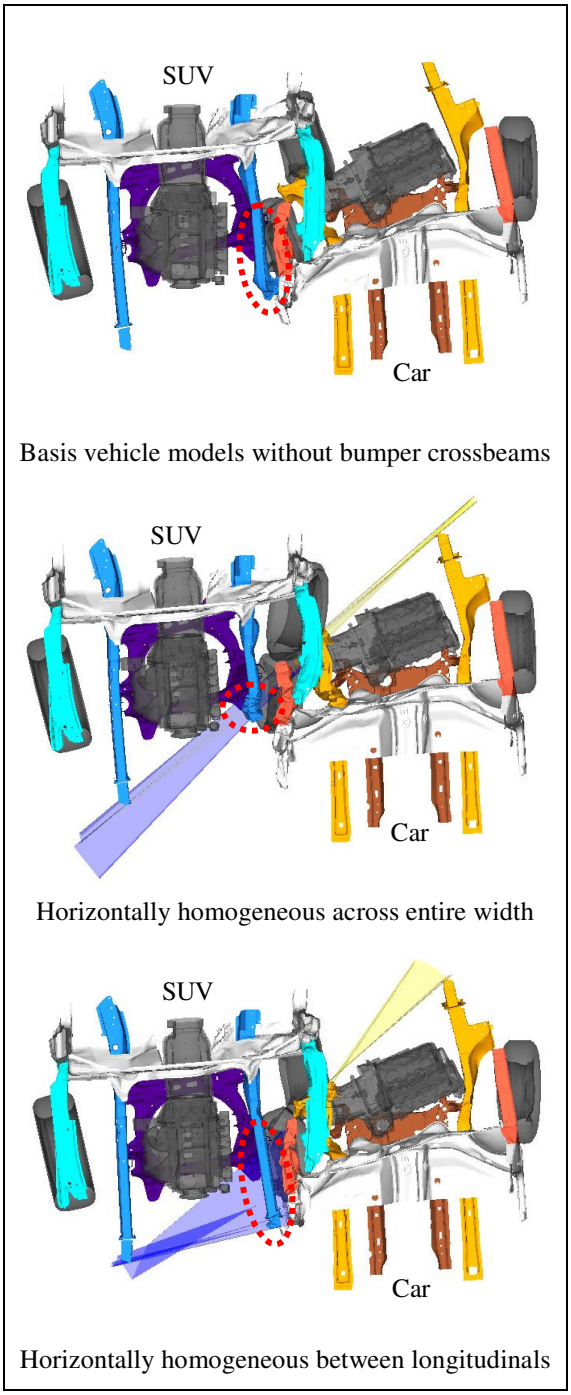

Figure 7. Front-to-front collision with 33% overlap. Top view after 85 ms.

and improved vertical homogeneity. If vertical homogeneity is achieved, horizontal homogeneity between the main load paths does not provide additional benefit and hence this should not be prioritised in a compatibility assessment. The assessment of horizontal homogeneity is only relevant for small overlap collisions outboard of the vehicles' longitudinals.

The validity of the conclusions above is limited by the underlying characteristics of the car and SUV

models, which are not inhomogeneous and have certainly influenced the outcome of the simulations. However, given that the designs of the car and SUV are typical for modern vehicles, it is reasonable to generalise the conclusions to other vehicle types.

ASSESSMENT OF COMAPTIBILITY

In the preceding sections, it is shown that the priorities for the assessment of frontal impact compatibility are vertical alignment of primary structures, improved vertical homogeneity, and improved horizontal homogeneity outboard of the longitudinals. Design characteristics related to vehicle mass and horizontal homogeneity between the longitudinals should not be prioritised for evaluation. In this section, the assessment of compatibility using various barriers and test procedures is discussed.

Offset Deformable Barrier (ODB)

The ODB is used worldwide in regulation and consumer information programs. Tests using the ODB place high demands on the vehicle structure, and the strength of the passenger compartment is a key factor in meeting the requirements [18]. The ODB is sometimes criticised for having a mass-dependent test severity, but the accident statistics in Figure 2 do not reflect any negative consequences to support this criticism.

Research has shown that load cell wall measurements from ODB tests may be inappropriate for the evaluation of vertical force distributions [19]. This was attributed to interaction between the load cell wall edge and the engine and crossbeam, but at that time the evaluation of structures was based on the peak forces measured throughout the entire impact. Recent research in Japan [8] and Europe [9] has focussed on solving similar force measurement problems with the FWRB by only assessing the initial part of the collision. Even if this were implemented for the ODB, the measured force distribution may still be affected by the transfer of shear forces within the aluminium honeycomb that makes up the barrier. However, the honeycomb used in the main block of the ODB has a stiffness of 0.34 MPa, and load spreading has typically only been observed with stiffer honeycombs such as the 1.71 MPa rear layer of the FWDB [14].

The offset nature of the test ensures that the horizontal connections between main load paths are stable, but further assessment of horizontal homogeneity does not appear feasible with the existing barrier design.

Full width barrier

Full width barrier tests are used in many vehicle regulations worldwide, but Europe is notable for having abolished the full width test when the ODB was introduced. Full width tests apply loading to both longitudinals of a vehicle, which maximises the effective stiffness of the front-end and hence places higher demands on the restraint system.

As mentioned in the introduction, research in Japan and Europe has led to the development of several metrics for the evaluation of vertical structural alignment. However, as shown in Figure 4, vertical homogeneity can further improve the interaction between structures even when initial, geometrical alignment of the structures is provided. Neither the FWRB nor the FWDB can assess the way that a vehicle structure reacts to inhomogeneous loading because they are both flat and homogeneous themselves. The FWRB is only capable of applying forces normal to the barrier face, and although the deformable element in the FWDB can induce some shear forces within the vehicle structure, the load cells behind the deformable element are unable to directly evaluate this. The situation is similar for horizontal homogeneity: the FWDB can induce shear forces in the vehicle structure and hence detect a horizontal spreading of loads, but this evaluation is only valid within the 300 mm depth of the deformable element. Once the FWDB is bottomed out, or in any test with the FWRB, no further evaluation of homogeneity is possible.

Full width tests encourage optimisation of the vehicle stiffness to minimise the severity of the pulse. For high speed collisions, it has been shown that minimal occupant loading is achieved with high initial stiffness levels in the vehicle front-end. As the collision velocity increases, so too does the stiffness level required to achieve minimal occupant loading. In contrast, at lower collision velocities, it is preferable to have lower front-end stiffness [20]. With current technology, the stiffness of a vehicle front-end cannot be modified with respect to the collision severity, and hence a compromise must be found that provides the optimum protection across all likely collision velocities. A high severity full width test that is not representative of the accident environment may have negative effects on the total number of casualties and should therefore be avoided.

Progressive Deformable Barrier (PDB)

The PDB has a deep deformable element that may be used to evaluate the stiffness distribution of a vehicle front-end. Various metrics have been

developed that evaluate the deformation of the barrier face. However, to enable an assessment of deformation, the design of the barrier compromises many other aspects of robust test design.

The PDB is larger than the ODB, which helps to avoid vehicles bottoming out the barrier. This is a fundamental design aspect, because barrier deformations cannot be used to delineate between vehicle structures once the maximum degree of barrier deformation is reached. However, the deformation of the barrier dissipates a part of the collision energy and hence reduces the quantity of energy that must be dissipated by the vehicle itself. A crash test barrier has the primary purpose of guiding the design of new vehicles, but the PDB would allow new vehicles to be designed so that more energy was deformed by the barrier and less by the vehicle itself. The bottoming out of the ODB limits the quantity of energy that can be dissipated by the barrier and hence ensures that current vehicle designs are capable of dissipating collision energy in the accident environment. The requirements of the ODB test also ensure that current vehicles deform in PDB tests. However, simulations with modified vehicles [21] and concept tests [22] have shown that a new generation of vehicles could be designed to exploit this aspect of the PDB design. The combination of FWRB and PDB tests has been suggested as a way to limit this behaviour, since the vehicle must dissipate all of its energy in the rigid barrier test. However, a full width test is less severe for the structure because the entire front-end is loaded. Furthermore, as discussed above, a high severity full width test encourages high initial stiffness levels, which would enable further exploitation of the PDB deformation.

The dissipation of energy in a crash test barrier creates a divergence between impact speed and front-end deformation. In real accidents, this may result in suboptimal performance of the vehicle structure and the restraint system. For the ODB, a test speed of 56 km/h corresponds to an Energy Equivalent Speed (EES) of 50 km/h, i.e. it represents a front-to-front collision at 50 km/h [23]. For the PDB, this EES is achieved by at a test speed of 60 km/h. The depth and stiffness of the PDB may also create a divergence between the vehicle front-end stiffness and the compartment decelerations. Even after major modifications are made to a vehicle structure or front-end package, it has been shown that the compartment decelerations observed in PDB tests remain similar [24]. As a consequence, restraint systems that are designed to perform well in a PDB test may or may not perform appropriately in real accidents.

Current proposals for the evaluation of the PDB deformation are focussed on crossbeam stiffness and the presence of lower load paths. Neither of these design characteristics is considered in this paper to be a high priority for the evaluation of compatibility.

Mobile Deformable Barrier (MDB)

A MDB has the appearance of an ideal compatibility test, but an appropriate evaluation of the results is impracticable. According to the collision based approach to the evaluation of a compatible collision, it would be inappropriate to require all vehicles to provide the same occupant protection in a MDB test. Instead, the occupant protection in the test vehicle and the hypothetical risk to the occupants of the MDB would need to be evaluated together. Pass/fail criteria would then apply to the combined score and not to the individual parts. Although this is theoretically possible, it would be extremely difficult to validate an occupant injury risk curve for a MDB with the same accuracy as is currently expected for crash test dummies.

Small overlap barrier

The IIHS is developing a small overlap barrier that directly loads the structure outboard of the vehicle longitudinals. The test configuration may be capable of improving horizontal homogeneity in this part of the structure, but the IIHS assessment is limited to dummy measures and compartment deformation [10]. The very high test severity used in the research program heavily loads the passenger compartment, but it is too severe to demonstrate the benefits of homogeneous structures that are further forward in the front-end. Ideally, new test procedures should be representative of the accident environment and encourage the design features that provide the most benefit.

The specifications of the IIHS small overlap test are, at the time of writing, not finalised, and hence a full evaluation is not possible in this paper. The potential for a lower severity small overlap test to improve horizontal homogeneity outboard of the longitudinals may warrant further investigation.

Low speed bumper tests

Low speed tests are not able to determine the behaviour of structures that only deform in high speed collisions, and they are hence often neglected in discussions of compatibility test procedures. However, the structures loaded in low speed collisions must be supported by those that are also

deformed in high speed collisions, and hence low speed tests play a significant role in determining the design of an entire vehicle. For example, the Part 581 bumper tests in the USA indirectly encourage all passenger car longitudinals to be at a similar height. Two classes of vehicles that are typically not subjected to these tests, light trucks in the USA and minicars in Japan, have been identified as having poor vertical alignment with the passenger car fleet [24]. The new RCAR bumper tests are more stringent than the Part 581 bumper tests and specifically address the dynamic performance of a vehicle and its ability to prevent override and underride. The RCAR bumper tests are therefore the only current or proposed evaluation of vertical homogeneity.

CONCLUSIONS

Priorities for the assessment of frontal impact compatibility are vertical alignment of primary structures, improved vertical homogeneity, and improved horizontal homogeneity outboard of the longitudinals. Design characteristics related to vehicle mass and horizontal homogeneity between the longitudinals should not be prioritised for evaluation. Further improvements in vehicle safety can be also be achieved by focussing on improved self-protection for all vehicles, which is applicable in all collision types.

Vertical alignment may be evaluated by measuring load cell forces in either the ODB or the full width test procedures. Other options exist, but these two tests are already established in worldwide regulations. Vertical homogeneity is currently being addressed by the RCAR bumper test, and further research is warranted to determine if alternative low speed tests can bring about improved horizontal homogeneity outboard of the vehicle longitudinals.

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