

# Vehicle Structural Crashworthiness with respect to Compatibility in Collisions

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## ABSTRACT

This paper is focusing on frontal collisions with respect to compatibility, since such collisions make more than 50% of all car accidents according to accident statistics. Frontal collisions also show the highest velocity change among different collision situations. Furthermore, published accident and injury statistics show an inverse correlation of vehicle mass against injury severity in car to car collisions, above all in head-on collisions. This is in part related to a lack of compatibility among currently circulating cars.

Some basic considerations on the concept and the structural stiffness of car cabins and car front ends are outlined with respect to compatibility. A few aspects on rear end and lateral collisions are mentioned as well.

Results from research work of our working group [1] are given and test results of some recent production cars are mentioned. These examples show, that head-on collisions at closing speeds of up to 100 km/h with a mass ratio of 1:2 of the collision opponents are survivable with occupant loads well below the limits of actual injury criteria (FMVSS 208, ECE R 94), if compatibility requirements are met with regard to car structure as well as restraint systems.

## INTRODUCTION

Compatibility is the key aspect to be considered if the best possible safety for cars of different size and weight is to be achieved. Compatibility is an important issue especially for the design of low mass vehicles (LMV) without excessive reduction of safety level compared to heavier cars. LMV's could contribute to reduce fuel consumption in urban traffic, provided that they are able to offer a level of safety comparable to larger cars. Published accident and injury statistics however show an inverse correlation of vehicle mass against injury severity in car to car collisions, above all in head-on collisions. This inverse correlation is in part caused by current crash test standards, where compatibility in collisions between cars of different size and weight is not a requirement. Compatibility in frontal collisions calls for significantly different deceleration-time curves in rigid barrier impacts for cars with different weight. Cars designed according to

compatibility criteria can change future accident and injury statistics in a way that injury severity in LMVs can be reduced significantly. This lack of compatibility is considered to be the main reason for the unfavourable appearance of small vehicles in accident statistics [2].

## BASIC CONSIDERATIONS

The reasons for the higher injury risk for occupants of small vehicles can be found in the low mass, which results in a higher total change of velocity in car to car collisions, and, in comparison to heavier cars, in a usually lower stiffness of the crush zone and the cabin structure. Furthermore, the design of the car structure and the restraint systems are - according to current FMVSS and European standards - still being optimised for a head-on collision of a car against one of its kind<sup>1</sup>, or, in the case of an impact on a deformable barrier, against a fictitious car<sup>2</sup>, and not against the statistically most probable counterpart. These compatibility issues have been addressed by various authors in the past 25 years [3], [4].

Besides mass and structural stiffness, the geometry, i.e. the positioning of the structurally stiff parts with relation to their counterparts on e.g. the impacting car, is important as well. Cars are geometrically compatible in frontal, rear and side collisions, if the energy absorbing structure of these cars is arranged in a 'belt' at a uniform height around the car. Typical geometric incompatibility in collisions is given for passenger cars against trucks or against off-road vehicles. Today, this 'belt' is only defined for front bumpers. The mean bumper height above ground is 450 mm. Usually, an important energy absorbing part of the front structure is placed at the same height, behind the bumper. The configurations for rear end collisions are quite variable, since car rear ends change their height considerably depending on passenger and baggage load and when 'nose diving' due to hard braking occurs.

<sup>1</sup> an impact on a rigid barrier is comparable to a collision against a 'mirror image' of the impacting car, e.g. with the same mass, same speed, and the same front stiffness.

<sup>2</sup> infinite mass, zero speed, standardised front stiffness

The basic principles for the structural design of LMV's, as well as first results of crash tests, have been published earlier by our working group [1] [5] [8] [9]. A minimum curb weight for the LMV of 600 - 650 kg appears to be feasible. In frontal collisions, such a LMV should be compatible with 70 - 80 % of the currently circulating cars. In Europe, the mass of collision opponents to be considered for the LMV (i.e. the European 'compact' class) ranges between 1300 - 1400 kg, which leads to a design mass ratio of approximately 1:2. In such a frontal car to car collision with 100 % overlap and 100 km/h closing speed, the LMV is subjected to a  $\Delta v$  of 20 m/s and a mean car deceleration level of 40 - 50 g. A highly optimised restraint system is needed to reach the same degree of occupant protection as encountered in conventional cars. The results of mathematical modeling and sled tests of such an optimised restraint system have been presented earlier [6]. They clearly indicate the feasibility of the procedure, in that the envisaged protection criteria could be met with ample margins.

## COLLISION MECHANICS

**GENERAL** - A small, light car will always experience a higher deceleration level in a real car versus car collision compared to its heavier opponent, as the deceleration for each of the colliding cars can be calculated with a simplified model from the crush load at the interface of the two cars. Both cars experience the same crush load vs. time curve with this simplified model.

$$\text{deceleration} = \text{crush load} / \text{car mass}$$

Furthermore, this type of frontal collision will subject the lighter car to a higher total change of velocity. The velocity change of both cars can be calculated with the law of conservation of momentum. In real collisions, the observed  $\Delta v$  lies 5 - 10 % above the theoretical value due to residual elasticity of the deformed structures.

$$\Delta v_1 = m_2 * (v_1 + v_2) / (m_1 + m_2)$$

$$\Delta v_2 = m_1 * (v_1 + v_2) / (m_1 + m_2)$$

As this paper shows, the main reason for the higher injury risk for the occupants of currently circulating small cars in frontal collisions is not intrinsic in these two physical constraints. Instead, it is given by the lack of compatibility in frontal collisions among cars of different size and weight.

The restraint system of any car will only be able to deploy its effectiveness if the passenger compartment does not collapse in a collision. Intrusion of structural components into the cabin and deformation of the passenger compartment must be kept small. An extremely important parameter for the development of the restraint system is the mean deceleration level of the car cabin with its restraint system interface points and surfaces impacted by the body of the occupant during the collision.

Current crash test standards still encourage to design the car front stiffness for moderate cabin deceleration

pulses, allowing the use of conventional restraint system components. This approach creates car front stiffnesses that are more or less proportional to the car mass. A low mass vehicle, designed in such a way, will be disadvantaged twofold in case of a collision with a heavier vehicle. Not only will it experience a higher  $\Delta v$  due to the mass ratio, but its frontal deformation space, which is relatively soft (according to the reasons mentioned above), will be crushed before significant deformation of the heavier car even starts.

In conclusion, the frontal structural stiffness of a low mass vehicle must be at least equal or slightly *higher* than the stiffness of its heavier counterpart [7] [8].

**COMPATIBILITY** - Structural compatibility in collisions means that the different cars should have geometric compatibility and that these cars should deform at the same load level, yielding a length of the deformation zone proportional to the mass of the car. This even helps to design a short and light LMV, since the interior of a LMV's dimensions are given by ergonomical constraints. The demand for a small overall length leads to shorter as well as more densely packed frontal and rear deformation zones.

Analysis of advanced restraint systems indicate that such an 'universal' deformation load level should be defined in a way that mean deceleration levels of LMV's do not exceed 40 - 50 g. The maximum load level in a frontal collision at a given speed is experienced with 100 % overlap. With smaller overlap ratios, the load decreases. The length of the crushable zone is defined by the amount of energy that has to be absorbed. Since frontal crash tests against a rigid barrier are performed at the same speed with 100 % and 40 - 50 % overlap, the maximum required deformation length is determined by the 40 % overlap condition. Under all conceivable conditions, the LMV's crush zone must be capable of absorbing the LMV's own kinetic energy. In a collision against a heavier car, some of the LMV's kinetic energy might also be dissipated through deformation of the heavier car, if the front stiffness of the LMV is designed according to the considerations mentioned above. Such a concept is reasonable, since the heavier car experiences a considerably smaller change in velocity in this type of collision than in a test against a rigid barrier. Earlier tests with an ultrastiff lightweight structure crashed against an Audi 100 have confirmed this concept [5].

Figure 1 shows, schematically, deceleration pulses during an impact on a rigid barrier with an initial velocity of 15.5 m/s for a LMV designed according to compatibility criteria in comparison to a typical compact car. Deformations in this example would be in the range of 300 mm for the LMV vs. 800 mm for the Compact Car.

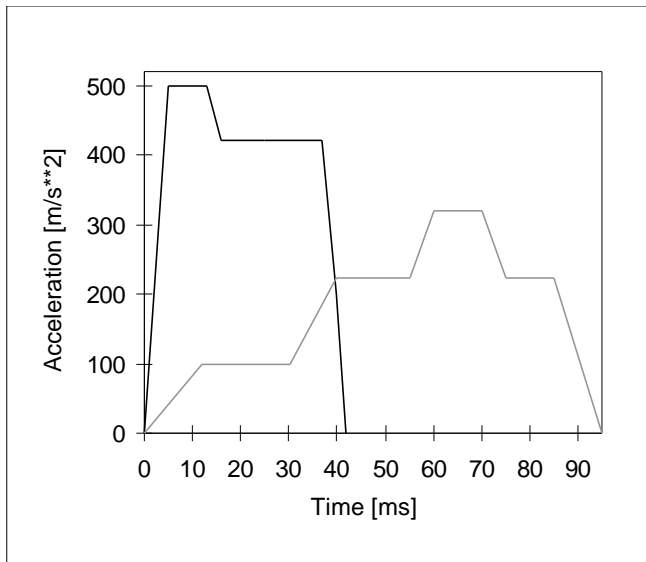


Figure 1: Schematic representation of the deceleration pulses of a typical Compact Car (gray) and a compatible LMV (black) against a rigid barrier at 15.5 m/s (56 km/h).

### COMPATIBILITY IN FRONTAL COLLISIONS

**GEOMETRIC COMPATIBILITY** - must be given for all configurations discussed in the following paragraphs. Usually an important energy absorbing part of the front structure is placed at the uniform height of front end bumpers.

**COMPATIBLE LOW MASS VEHICLES** - As mentioned in "Basic considerations", a reasonable minimum curb weight is 650 kg. According to figure 1, the maximum average design deceleration (frontal collision with 50 km/h and 100 % overlap against a rigid barrier), for a curb weight of 650 kg should be around 45 g. A general formula for design decelerations for compatible cars can be given, based on the values from this end of the range. Approximately half of the drivers weight (coupled mass) must be added to the curb weight, to calculate the crush loads at the interface according to "Collision mechanics". Using the values mentioned above, the crush load for 100 % overlap becomes:

$$F_{cr,100\%} = 690 \cdot 9.81 \cdot 45 \sim 300 \text{ kN}$$

with the corresponding design deceleration:

$$a_{design,100\%} = 300 \text{ kN} / (\text{curb weight} + 40 \text{ kg}) = 435 \text{ m/s}^2$$

LMV's have small, light drive trains with little contribution to structural and inertial stiffness. The front structure must be capable to absorb most of the collision energy including lateral load components, since deformation of the cabin and intrusion of components into it should be avoided. The reason for this requirement is, that the full undeformed space in the cabin must be available to the restraint system to decelerate the passenger, since the cabin is decelerated at a higher level compared to heavier cars, as explained in "Collision me-

chanics". An ideal design of a deformable front structure would distribute energy absorption to all its structural elements even for a 40 % overlap situation, thereby substituting the part of a heavier car's engine, which offers much structural and inertial stiffness in the center area of a car front. The inertia loads of the engine help to prevent the front structure from folding to the side, when subjected to lateral load components in frontal oblique collisions.

**COMPATIBLE HEAVIER CARS** - As mentioned before, the heavier car in a collision is aggressive though its mass, even when designed for compatibility. The curb weight of these cars should not be higher than 1400 kg (max. mass ratio 2:1). The front end should be designed for a homogeneous stiffness distribution over the frontal area, to offer the lowest possible structural aggressiveness to a colliding car of lower mass. The highest average design deceleration, for such a car is:

$$a_{design,100\%} = 300 \text{ kN} / 1440 \text{ kg} \sim 200 \text{ m/s}^2$$

Peaks in the curve deceleration vs. deformation should be avoided or at least occur only in the second half of the deformation range, thus allowing a lighter colliding car to make use of most of the heavier car's deformable length (more ride down distance) and to force the heavier car to absorb energy in the magnitude of 90 - 100 % of its initial kinetic energy.

**VERY HEAVY CARS** - Cars with a curb weight of 1800 kg up to 2000 kg are dangerous to occupants of cars of less than 900 kg curb weight (mass ratio over 2.1:1). Such cars can only in part compensate for their mass aggressiveness through a long, deformable front end with a reduced average crush load:

$$F_{cr,100\%, \text{ heavy}} \leq 220 - 240 \text{ kN}$$

$$a_{design,100\%} = 220 \text{ kN} / 2040 \text{ kg} \sim 110 \text{ m/s}^2$$

Still, a frontal collision with 100 % overlap of such a car against a car with a curb weight of 650 kg, both running at 50 km/h, is hard to survive for driver and passengers of the light car, since a high cabin deceleration (100 % overlap) is combined with a very high velocity change.

### COMPATIBILITY IN REAR COLLISIONS

**GEOMETRIC COMPATIBILITY** - The rear end geometric compatibility is more complex, compared to that of the front end. The configurations for rear end collisions are rather variable, since car rear ends change their height considerably with passenger and baggage load and during braking.

**STRUCTURAL STIFFNESS AND MASS** - Compatibility considerations concerning the front ends are valid for rear ends as well.

### COMPATIBILITY IN LATERAL COLLISIONS

**GEOMETRIC COMPATIBILITY** - Most cars show a geometric incompatibility in lateral collisions,

since front end bumpers are located higher than the stiff side structure. The stiff A-pillars and B-pillars can only impose narrowly localised loads onto the colliding car front, thus allowing the remaining parts of the car front to strongly deform the less stiff door. The intruding parts of the striking car front can hit the passenger at speeds of almost up to the initial speed of the striking car.

**STRUCTURAL STIFFNESS AND MASS** - A compatible car must have very stiff side structure elements at the height of the striking car's front bumpers. These elements must be capable of resisting the mentioned crush load for the full width of a compatible car front (300 kN) with small deformations only, since there is little space to deform between door and passenger. The stroke should have little elastic energy to keep the velocity change as low as possible. The front of the striking car must absorb the collision energy.

### THE EXPERIMENTAL LMV CRATCH

**GENERAL** - The working group on accident mechanics at the Universities Zürich started a research project with the title "Safety of Low Mass Vehicles" in 1991. An experimental LMV called CRATCH was designed and built, to verify and demonstrate our ideas in the field of compatibility. The project has been described e.g. in [1] [5] [6] [7] [8] [9]. Details concerning the LMV CRATCH are given in [1].

**STRUCTURE** - The primary structure is shown in figure 2. A stiff transversal beam directly behind the front bumper across the full width of the experimental LMV CRATCH can react to various load conditions (point load or distributed load) and overlap situations in frontal and frontal oblique collisions. The beam is located at the average bumper height of 440 mm above ground with a width of 120 mm. The beam transfers the crush load onto the deformation elements of the front structure. The structural interface between cabin and deformation elements is a second stiff transversal beam, connecting the two A-pillars in front of the floorpan.

The deformation elements are thin-walled tubes with a rectangular cross section. They are attached rigidly to the 'bumper' beam and the 'A-pillar' transversal beam, all together forming a stiff frame. This frame is designed to transfer longitudinal as well as lateral loads. The deformation modes for a 100 % and a 40 - 50 % overlap situation are shown in figures 3 and 4. The length of the deformation elements is determined by the average crush load and the amount of energy to be absorbed in the various collision situations.

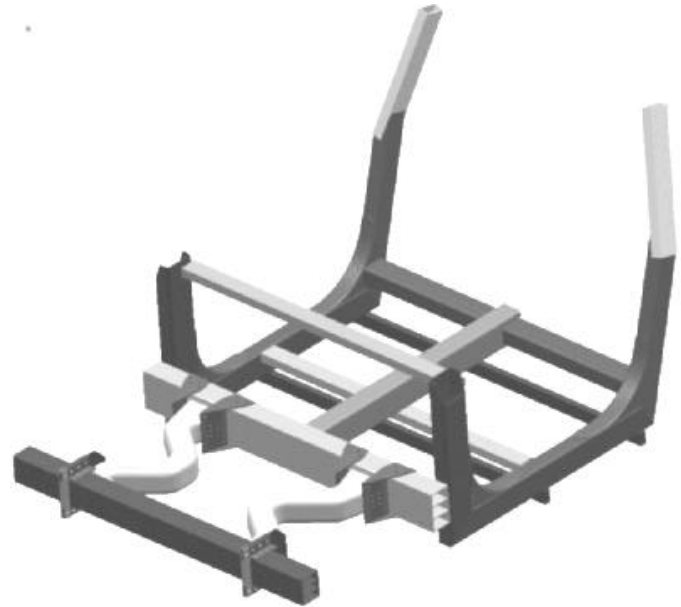


Figure 2: The CRATCH spaceframe

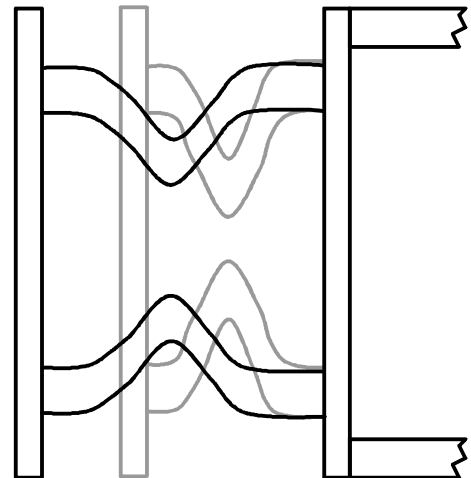


Figure 3: Deformation of front structure (100 % overlap)

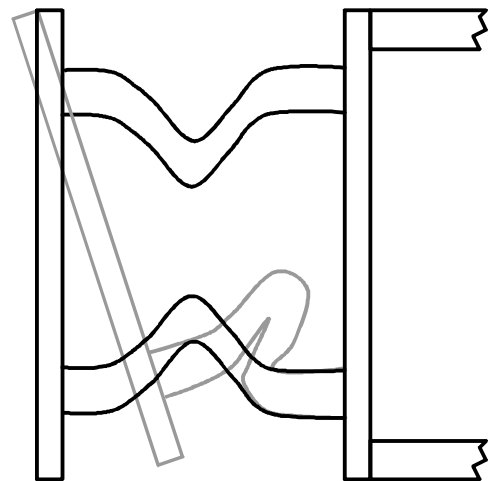


Figure 4: Deformation of front structure (40 - 50 % overlap)

DESIGN DATA OF THE STRUCTURE - The experimental LMV CRATCH is designed according to the following design requirements:

- cabin for 2 occupants plus luggage
- length 3.0 m
- width 1.65 m
- height 1.7 m
- space for a hybrid drivetrain
- space for 250 kg batteries
- max. curb weight 650 kg
- design frontal crash pulse for 50% and 100% overlap according to figure 5
- max. deceleration level for the cabin 60 g.
- collision angles maximum +20° and -20° to the longitudinal axis
- Stiff cabin structure, structural elements arranged such, that drivetrain or chassis components, bumpers and obstacles cannot intrude into the cabin in frontal and side collisions

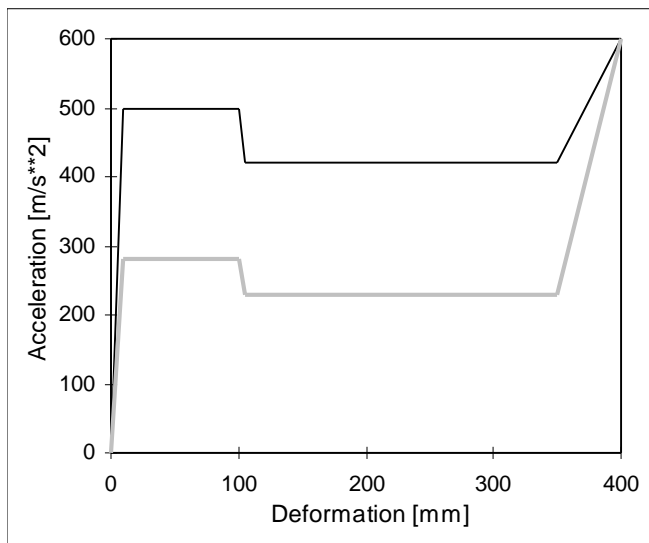


Figure 5: Frontal crash design pulses for the experimental LMV CRATCH, 100 % (black) and 25 % (gray) overlap against a rigid barrier. These 25 % correspond to 40 - 50 % overlap against a deformable barrier due to the nature of this structure.

## VERIFICATION OF THE THEORETICAL FINDINGS

Due to limited resources, only one fully equipped experimental LMV CRATCH could be manufactured, i.e. only one frontal collision situation CRATCH vs. an average compact car (in our case a Renault LAGUNA) could be tested. Therefore, it seemed adequate to use the estimated design pulse for a head-on collision with 100% overlap and a  $\Delta v$  of 20 m/s for the development of the restraint system and the subsequent sled tests [6]; this is the worst case for the restraint system. A frontal collision with 50 % overlap at 0° collision angle and a  $\Delta v$  of

20 m/s, on the other hand, is considered to be the critical load case for the crush zone; only 50 - 60 % of the deformable structure is crushed and absorbs energy. This latter load case yields a lower and longer crash pulse but it shows the maximum deformations with a possible stiffening of the structure at the end of the crushable zone, and also an eventual intrusion of components into the foot space of the driver. Accordingly, this load case was selected to be tested in the final collision test CRATCH vs. LAGUNA.

## COMPATIBILITY CRASH TEST CRATCH vs. LAGUNA

GENERAL - The French car manufacturer Renault was a highly welcome partner in the project, as this car manufacturer has a long tradition in offering a model range of largely different size and weight. Compatibility in collisions, at the very least among the currently circulating fleet of their own make, is a central issue for this manufacturer [10][11]. Therefore, the LAGUNA already exhibits an adequate stiffness of the crush zone considering frontal collisions against small cars. Moreover, in terms of mass and exterior dimensions, the LAGUNA is representative for the current European 'compact' class cars.



Figure 6: The collision opponents

The driver and passenger positions of the CRATCH as well as the driver position of the LAGUNA were occupied by instrumented 50<sup>th</sup> percentile Hybrid III dummies. A uninstrumented Hybrid II dummy was used for the passenger position of the LAGUNA, since occupant loads were expected to be well below actual protection criteria.

		CRATCH	LAGUNA
Length	[m]	3.05	4.508
Width (without mirror)		1.65	1.752
Height		1.7	1.433
Empty weight incl. measuring equipment, no fuel	[kg]	671.7	1356.6
Driver & passenger dummies	[kg]	160.3	153.4
Collision weight	[kg]	832	1510
Collision speed	[km/h]	50.5	50.5
Overlap (0° collision angle)	[%]	50	46.8
theoretical $\Delta v$ (w/o rotation)	[km/h]	65.12	35.88

Table 1: Test parameters

The test was performed successfully. The high center of gravity of CRATCH caused a remarkable rotation about the lateral axis, i.e. the rear bumper was lifted by 0.5 m approx. Both cars rotated about the vertical axis, the CRATCH by 140°, the LAGUNA by 80°.

As predicted, the CRATCH cabin showed no measurable deformation and no intrusion. The left deformation element was totally crushed and, after full deformation had occurred, the rear folding joint broke. Future improvements of the deformation elements should eliminate such ruptures.

The LAGUNA cabin showed very small deformation and intrusion into the driver's floorpan (5 - 20 mm).

		CRATCH	LAGUNA
measured $\Delta v$	[km/h]	71.6	32.76
kinetic energy	[kJ]	81.9	148.6
absorbed energy	[kJ]	65	140

Table 2: Energy balance

The energy absorption capability for this type of collision of the CRATCH has been exhausted in the test. Further investigation is needed with respect to the energy absorption in other collision situations, e.g. against rigid barriers.

	CRATCH		LAGUNA	limit
	driver	pass.	driver	
HIC <sub>36</sub>	632	546	257	1000
a <sub>3ms</sub> head [g]	58,4	62,6	38	80
a <sub>3ms</sub> chest [g]	39,7	33,3	35	60
F femur l/r [kN]	2.1 / 1.6	1.6 / 0.3	n.m	10.1

Table 3: Occupant loads

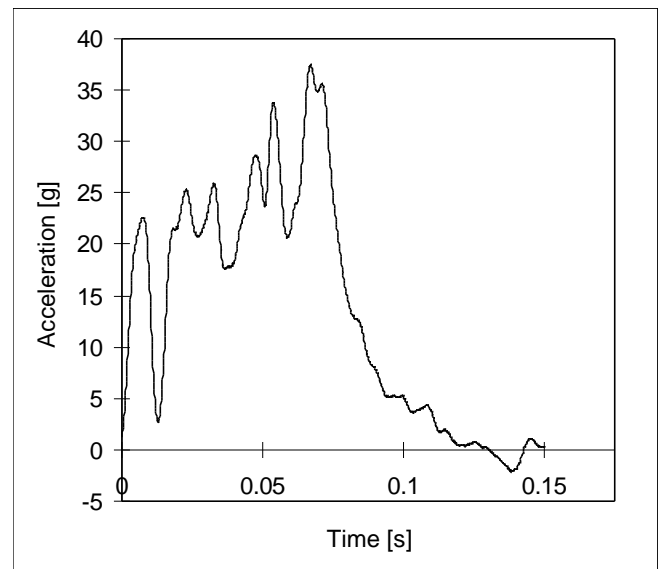


Figure 7: CRATCH - deceleration of car cabin

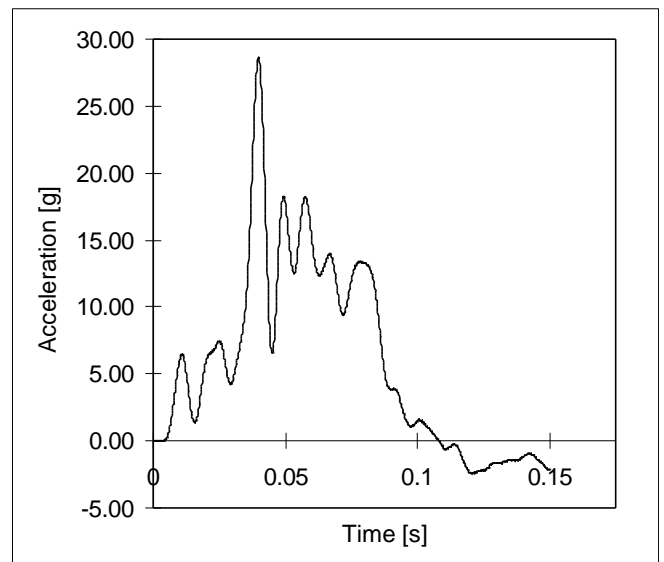


Figure 8: LAGUNA - deceleration of car cabin

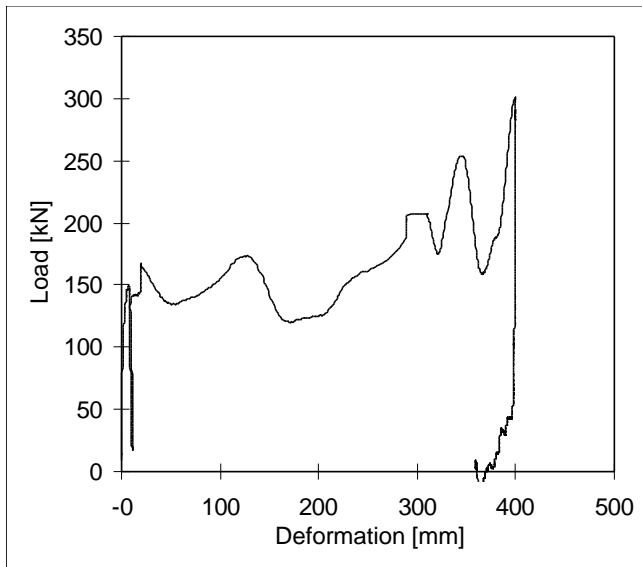


Figure 9: CRATCH - load at the interface



Figure 10: Maximum deformation of the two cars



Figure 11: Situation after the collision



Figure 12: CRATCH - deformation of the front beams.

### ADDITIONAL EXAMPLES OF COMPATIBILITY

**RENAULT** - As already mentioned, this car manufacturer has a long tradition in this field. Today Renault offers a fleet of their own make, that is fully compatible from the models Clio II and Twingo up to the models Laguna and Espace [10][11].

**DAIMLER - CHRYSLER** - Some of the concepts mentioned above were adapted for the MCC Smart. The design of the structural stiffness and also of some parts of the restraint system (deformable steering column) is in agreement with the ideas published in [5] [6] [7] [8] [9].

A compatibility crash test between a MCC Smart and a Mercedes S-Class was recently performed and published [12].

**VOLKSWAGEN / AUDI** - Two compatibility crash test between cars of different weight and size were performed and published: Audi A8 versus VW Polo, and VW Passat versus VW Lupo [13].

### CONCLUSIONS

The safety deficits of small cars observed in accident statistics today can be alleviated if the structure and the restraint systems of these cars are designed and optimised for the situation they will most likely encounter in a real world situation, e.g. a collision against a heavier car. Current testing methods for the assessment of occupant safety in frontal collisions (FMVSS 208, ECE R94, Euro-NCAP) do not take this aspect fully into account. Moreover, the rising percentage of Vans and Pick-Up trucks of the car population leads to (mainly geometrical) compatibility problems even with passenger cars of average size and weight.

For the extreme example of a low mass vehicle with a curb weight 25 % lower than current subcompact cars, it was shown that the development of a rigid light weight structure with well defined properties of the crush zone is feasible and that a restraint system which can meet occupant protection criteria even at a  $\Delta v$  of 21.5 m/s (77.4 km/h) and car mean deceleration levels of 400 - 500 m/s<sup>2</sup> can also be conceived [6].

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