PROPOSAL TO IMPROVE COMPATIBILITY IN HEAD ON COLLISIONS

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ABSTRACT

All accident studies show that incompatibility has become the main cause of fatal injury. Improving compatibility is the most effective way to reduce the number of road accident victims.
Compatibility is now achievable, mainly because of improved occupant restraint systems. This paper suggests ways in which the stiffness, layout and geometry of vehicles can be improved to achieve good compatibility in frontal collisions between vehicles.

INTRODUCTION

The problems of compatibility have already been the subject of many studies. However, these have all been limited to feasibility demonstration vehicles (CRATCH - UTH Zurich - 1996). If occupant safety is to be improved, however, it is essential to take compatibility into account during the development of current and future vehicles.

The evidence of studies conducted over the last twenty years clearly shows that solving the problems of incompatibility between vehicles is one of the most efficient ways to reduce the number of road accident victims. New regulations coming into force in the end of 1998, as well as various ratings and media tests, lead to a similar level of safety for all vehicles in a frontal impact. Even so, this performance in no way guarantees compatibility in the case of collision between vehicles. Today it is necessary not only to ensure occupant protection during impact against a fixed obstacle, but also against another vehicle.

In addition, research into compatibility must take into account the time taken to renew all the vehicles. Measures proposed for new vehicles must not create dangers for existing vehicles, otherwise the overall benefit of such measures may be severely compromised.

RENAULT'S COMPATIBILITY APPROACH

In this case we are considering only frontal impacts between vehicles, while bearing in mind that the needs of side impact in development must also be take into account.

Today, frontal impact between vehicles is the configuration which causes the greatest number of deaths and injuries (see the table 1). That is why it has been our main concern for several years.

Accidentology (France)

The French vehicle parc today comprises about:

- 25 million private cars
- 4.5 million light commercial vehicles (under 3.5 tons)
- 550,000 trucks, buses and coaches.

It is clear that up to now almost no measure has been taken to look for the differences of mass or stiffness between all these road users. It is therefore not surprising that accidents involving several vehicles represent a large share of road traffic victims.

Accident toll on French roads

These are the main figures summing up the situation on French roads (see Table 1).

Out of the 8,000 dead per year, around 6,000 are private car occupants. The remaining 2,000 victims are for the most part pedestrians, cyclists and motorcyclists.

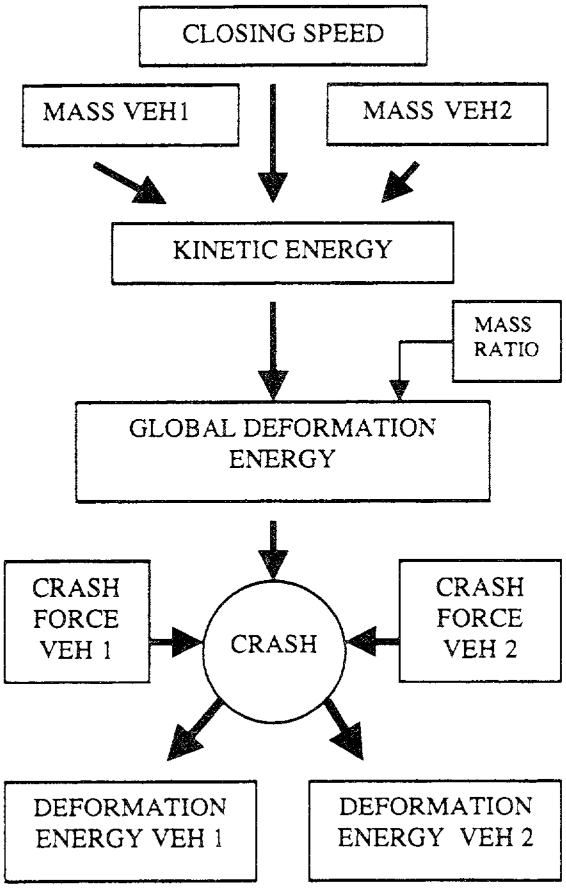
Of the 6,000 car occupants, 1,800 could have been saved if they had been wearing their safety belts. That is by far the most effective and immediate measure to limit the number of deaths.

FUNDAMENTAL PRINCIPLES FOR STRUCTURAL COMPATIBILITY

Theory

Compatibility between structures will depend on a correct distribution of the energy absorbed by the two vehicles. Unfortunately, no simple formula, exists to allow this distribution to be predicted. The only means of doing so are simulation, tests, and experience.

Contrary to commonly accepted ideas, mass plays no part in the way in which energy is distributed between the two vehicles. Only the stiffness, by way of the deformation loads, determines the distribution of energy between the two cars. This process is described in the following flowchart.



However, we have seen that the main cause of death is intrusion. At the same time, it is important to offer the same level of protection in both vehicles. So far as the structure is concerned, this implies that intrusion should be distributed between the two vehicles in a homogeneous manner.

The objective is to offer the same survival potential in both vehicles; in other words, any intrusion should be similar to that observed in a barrier impact at half the closing speed. This is equivalent to say that the EES (Equivalent Energy Speed) is identical for both vehicles. As a consequence, the energy absorbed by each vehicle is proportional to its mass.

Two vehicles are compatible if they have the same EES in a car to car crash

The following numerical example illustrates the different notions of EES and delta V:

Mass of vehicle 1 (W1): 1,000kg
Mass of vehicle 2 (W2): 1,800kg
Speed of vehicles 1 and 2 (S): 50km/hour
Closing speed (Cs): 100km/hour

Kinetic energy

$$0{,}5 * (W1 + W2) * S^2 = 270 \text{ kJ}$$

Energy to absorb

$$GDE = 0{,}5 * \left(\frac{W1 * W2}{W1 + W2} \right) * Cs^2 = 248kJ$$

Energy absorbed by vehicule 1 = compatibility energy

$$\left(\frac{W1}{W1 + W2} \right) * GDE = 88kJ >> EES = 48km/h$$

Variation in speed Vehicule 1

$$\left(\frac{\mathrm{W2}}{\mathrm{W2} + \mathrm{W1}} \right) * \mathrm{Cs} = 64\mathrm{km/h}$$

Energy absorbed by vehicule 2 = compatibility energy

$$\left(\frac{W2}{W1 + W2} \right) * GDE = 160kJ >> EES = 48km/h$$

Variation in speed Vehicule 1

$$\left(\frac{\mathrm{W1}}{\mathrm{W2} + \mathrm{W1}} \right) * \mathrm{Cs} = 35\mathrm{km/h}$$

Those simple calculations show that it is theoretically possible for both cars to have the same EES and that preserves the cabin space of the smaller car. Anyhow, the speed variation is still higher for the smaller vehicle by virtue of the law of conservation of momentum. The impact is always more severe in terms of speed variation for the lighter vehicle. However, the most recent occupant restraint systems allow this effect to be alleviated and we will see further that this speed

For the remaining 4,200, of all impact configurations, collisions between private cars account for 1,250 deaths, while some 1,050 result from collisions between private cars and light commercial vehicles, trucks and coaches.

These figures indicate that 55% of deaths in private cars occur in collisions with other private cars. This study will focus on this very important part of accidentology.

	Deaths	Serious injuries
Number of victims Per year in cars	6000	18000
With 100% Safety belt wearing	4200	16000
PC / PC Frontal impact	700	5750
PC / PC Side impact	520	1740
PC / PC Rear impact	30	240
PC / (LCV + HV) Frontal impact	500	850
PC / (LCV + HV) Other configurations	535	1050
total PC / PC	1250	7730
total PC / (LCV + HV)	1035	1900
Total compatibility (PC / other vehicles)	2285 (55%)	9630 (60%)

PC : Private car LCV : Light commercial vehicle HV : Heavy vehicle (French figures)

Table 1: Distribution of deaths and serious injuries according to collision type

Expected gains

For collisions between vehicles and pedestrians or cyclists, representing over 1,000 victims, the only really effective measures are those which enable such accidents to be avoided (traffic separation, lower speeds in high-risk areas, future accident-avoidance systems . . .).

For the occupants of a vehicle involved in a collision with another vehicle, we have made an estimate of the possible gains with a generalisation of the best available technology in both structural behaviour and restraint systems improvement. This study also uses the statistical distribution of crash severities A global reduction of one-third in the number of deaths and serious injuries (see Table 2).is technically possible by taking coordinated measures on that whole vehicule.range

	Deaths	Serious injuries
PC / PC Frontal impact	350	3450
PC / PC Side impact	70	460
PC / (LCV + HV) frontal impact	225	500
PC / (LCV + HV) Other configurations	170	350
total PC / PC	420	3910
total PC / (LCV + HV)	395	850
Possible gains through improved compatibility	815 (35% of 2285)	4760 (29% of 16630)

Table 2: Possible reduction in number of victims, by type of collision (Renault internal study)

However, this study also shows the potential gains are not the same for each kind of accident. The two areas where the potential is the most important are the head-on collisions between two cars and the car to commercial and heavy vehicles.

For the car to car collisions, it is essential to note that in the majority of cases, cabin space intrusion is responsible for occupant death. This is why it is essential to work on structures in order to guarantee acceptable levels of intrusion. The most representative car to car collision has an overlap of 40 to 60 %. The commonly used overlap of 50% is reasonably representative of accidentology. It should also be noticed that more than 95 % of the fatal accidents occur for a mass ratio lower than 2., higher mass ratios are quite marginal.

Concerning the heavy vehicles, the figures result from a study conducted with Renault VI on the efficiency of anti under-run systems. The major effect of those systems is to put a rigid structure in face of the car in order to enable the car structure to absorb the energy of the crash. Without such a device , only the upper part of the car structures are working resulting in high intrusions for the occupant at a closing speed as low as 45 to 50 km/hour. With an optimised anti under-run system a protection can be obtained up to an impact speed of 70 km/hour.

results in a greater collapse than occurs in a barrier impact (see Figure 6).

- The second is associated with the difference in stiffness between the vehicles at the end of the impact - the main cause of incompatibility indicated by accidentology studies (Figure 8).
- The third is mainly associated with the geometry and/or structural disfunctioning: involving over-riding (Figure 9 and 10).

Energy absorption deficiency

The energy absorption deficiency of the structures results directly from the overlapping of the frontmost elements. The energy absorbed by the frontmost elements is therefore less than occurs in a rigid wall impact.

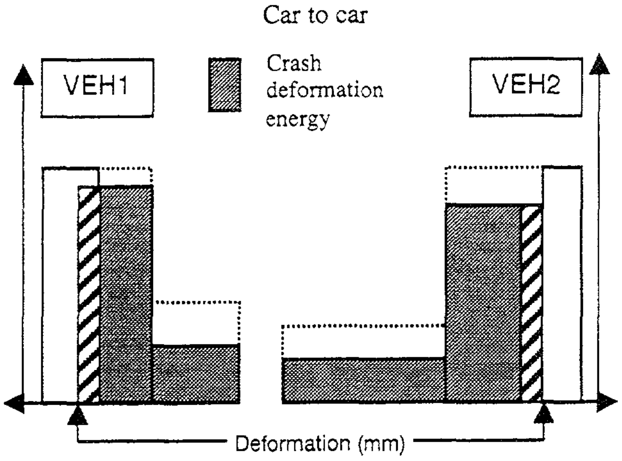


Figure 6: Energy absorption deficiency in initial car deformation

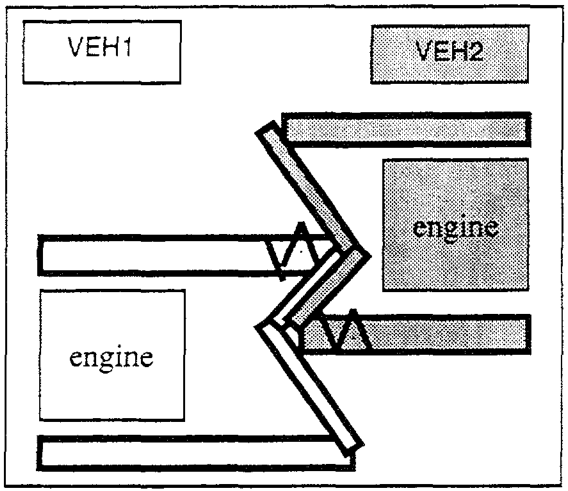


Figure 7: Geometric representation of absorption deficiency sketch in top view

Stiffness at the end of impact

As has already been explained, stiffness determines the distribution of energy between the two vehicles. If one of these vehicles stops, because it is stiffer, then all the remaining energy is absorbed by the other vehicle. In the following example the vehicle 1, by virtue of its greater stiffness, ceases to deform, immediately resulting in a greater deformation of vehicle 2.

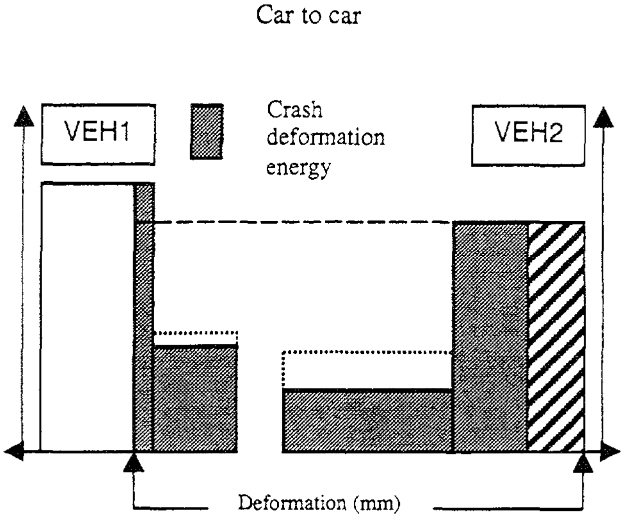


Figure 8: Incompatibility of stiffness between two vehicles

Over-riding

Finally, we must note the existence of a phenomenon whose consequences are more serious than those of absorption deficiency: structural over-riding, in other words when one vehicle passes above the other. Figure 9 shows the energy implications of this effect.

The principle behind over-riding is relatively simple: the geometric difference after the initial impact, and the behaviour of the structures during the transition between the beginning and end of the impact event cause one vehicle to rise higher than the other.

The vehicle which is over-ridden fails to achieve its maximum load potential (since only its upper load paths are stressed). The vehicle thus achieves a much lower load resistance than the over-riding vehicle. This results in large upper-level intrusions. The most significant illustration is the difference in height between the structures of passenger cars and of heavy trucks. Accidentology studies very clearly highlight the problem of embedding or of the over-riding of the heavy truck above the passenger car. It should not be overlooked, however, that geometric incompatibilities also occur between passenger cars themselves.

variation effect is also partially reduced by the duration of the crash event. The basic principle we have proposed is theoretically possible. The major question is to design the cars so that they behave this way

Simplified presentation of compatibility

We define the load force as the force at the interface between the car and either an opposite car or another obstacle (wall or ODB). The load levels in a vehicle during its deformation is globally increasing and can be summarised by a two stages law. The first stage is the initial load of the front structures before the engine becomes involved, and a final load after this event.

The reference we will use is a car to rigid wall crash with the same 50% offset as the car to car crash .We will compare the vehicle-to-vehicle behaviour with that of the vehicle against a rigid barrier (see Figures 4 and 5). The crash against a rigid wall is the ideal possible behaviour of the structure in terms of energy absorption, we shall use it as a reference to describe the various kinds of behaviours that can be encountered on a car to car crash.

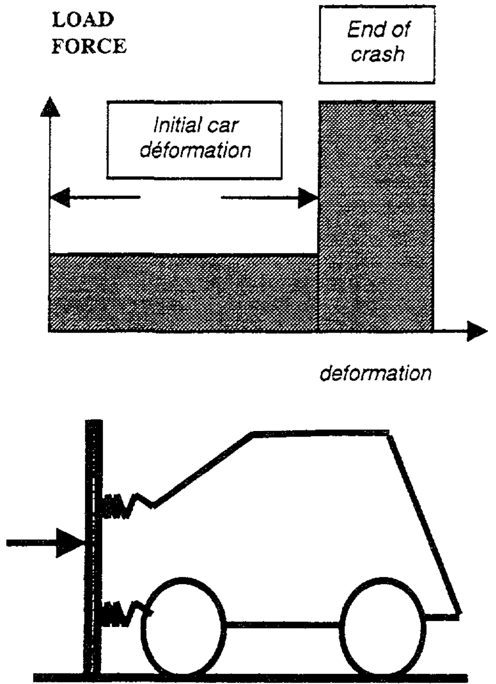


Figure 3: Laws of load/deformation of a vehicle

Let us take first the example of two vehicles in a barrier impact with a 50% offset at the same speed S,

We can draw the energy absorbed by each car as the surface below the force deformation curve.(Figure 4)

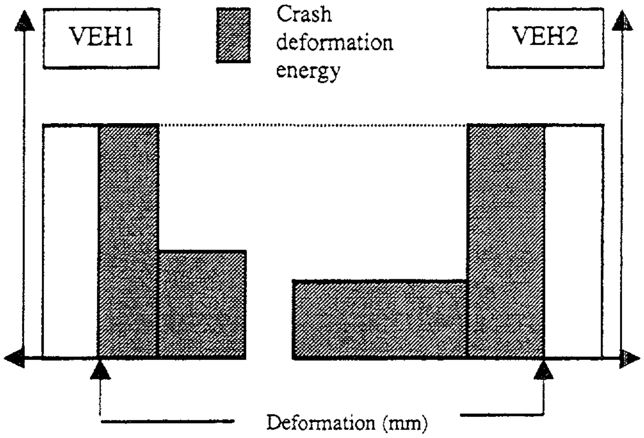


Figure 4: deformation of two vehicles against a rigid barrier

If we take the example of the same two vehicles in a head-on collision with a 50% offset at a closing speed: S x 2. Theoretically, we can obtain exactly the same energy absorption for each car provided that the end crash force is the same for both cars (Figure 5).

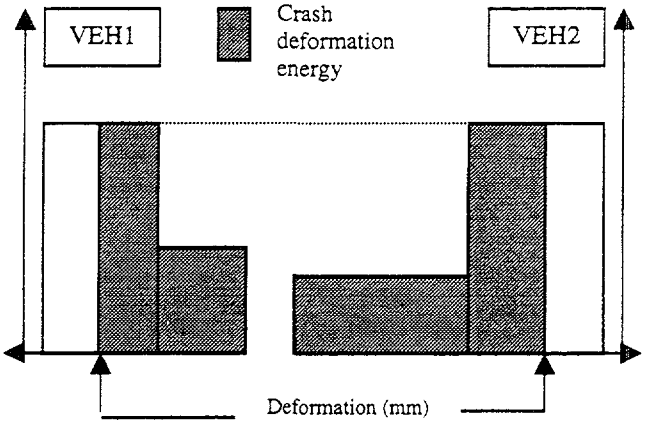


Figure 5: Theoretical compatibility between two vehicles. The collapse of the two vehicles in head-on impact corresponds to collapse in a barrier impact.

In reality, three major problems make this very difficult to achieve.

- The first is associated with the lack of a plane interface between the two vehicles, which results in an energy absorption deficiency (a reduction in the energy absorbed immediately after contact). This deficiency immediately

THE INFLUENCE OF COMPATIBILITY ON OCCUPANT RESTRAINT

The application of compatibility to the structure increases demands on occupant retention. In the most general terms, the control of intrusion is increasing the deceleration. We shall see that the vehicle-to-vehicle configuration is not too severe for the occupants, despite the larger changes in speed for the lighter vehicle. In the 1970s the development of restraint systems was a major problem preventing structural compatibility for light vehicles to take place.

The necessary factors in achieving good retention are already well known. The progress recently achieved in series production vehicles is based on demanding improved airbag performance, in such a way as to limit load levels in the safety belt. This programmed restraint system, developed by Renault, notably allows protection for more fragile subjects [8]. In addition, it completely decouples the occupant from the vehicle. In effect, the large accelerations to which the car body shell may be subjected are not directly reflected in occupant loads.

In the light of several car to car testing, we have been able to determine that the delta-V for mass ratios up to 1.5 is not a major concern in restraint system design.

A parametric study has allowed these observations to be explained, and the influence of mass ratio, closing speed to be investigated more thoroughly.
The model used takes the form of a spring-mass system. This model is based on the behaviour of an average representative car structure design.

Model design

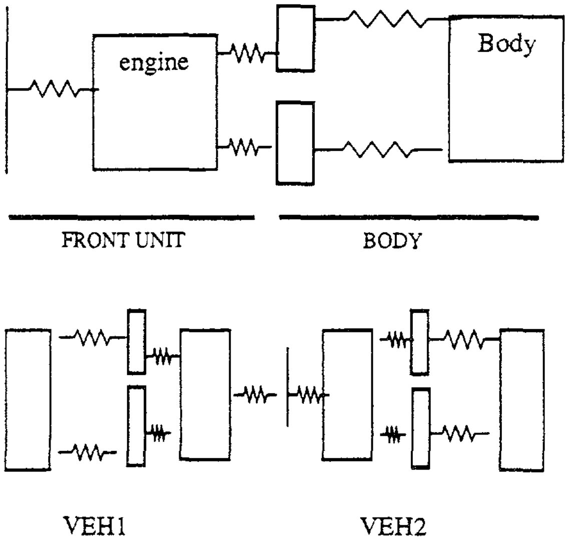


Figure 12: Spring-mass model of structure of car to car

This multi-level model is a good representation of the real dynamic behaviour in a car to car crash.

The average acceleration (γm) of the structure changes less than the delta-V : the increase in δV is partly compensated by an increase of the duration of the impact event (t).

Mass ratio		**1**	**1,44**	**2**
Mass 1	kg	900	900	900
Mass 2	kg	900	1300	1800
Stopping distance on wall veh 1	m	0.49	0.49	0.49
Stopping distance on wall veh 2	m	0.49	0.71	0.85
δV veh 1	km/h	50	59	66
δ t	ms	66	72	77
γm veh 1 (δV/δ t)	g	21.2	23.1	24.5
γm evolution	%	-	9	15

Figure 13. simulation results

Therefore, the severity of a car to car crash is less important than in case of a car to rigid wall with the same delta V.
The following diagram shows how vehicle acceleration increases as a function of the mass ratio. For a reference car to car closing speed of 100 km/h, the severity for the smaller car is not higher with a 1.5 mass ratio than for a crash against an offset rigid wall at 55 km/hour.

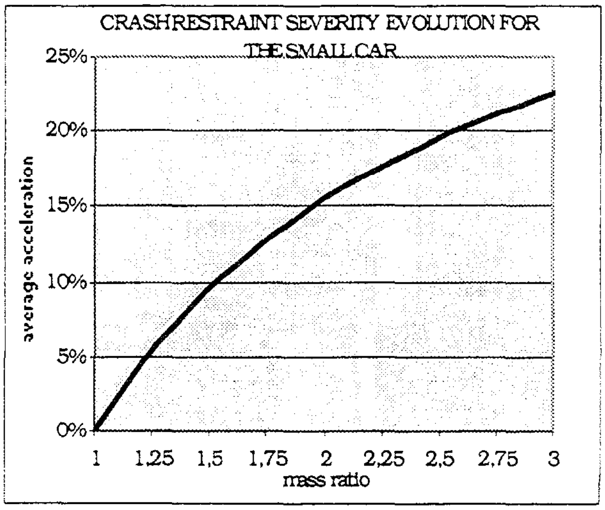


Figure 14: Change in average acceleration as a function of mass ratio

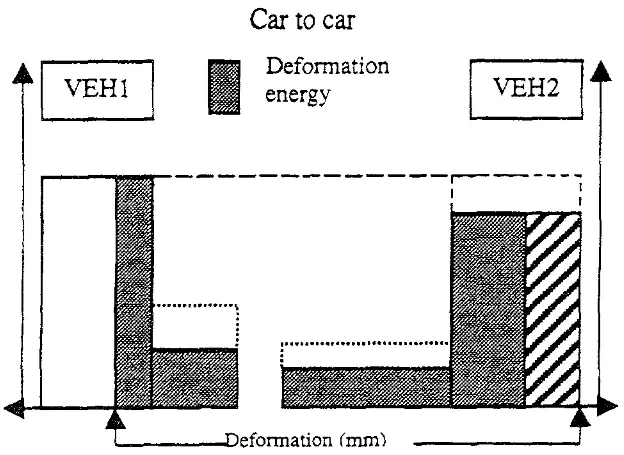


Figure 9: Energy effects of over-riding

In summary, compatibility is a problem:

- of geometry and of layout immediately after impact
- of structural behaviour during the impact event
- of stiffness at the end of the event.

Possible improvements

Geometric improvements

The main concern after the impact has begun must be to ensure that the load paths work as intended. To achieve this, it is essential to distribute the initial impact load across the entire contact surface. This significantly reduces the overlapping of structures, and therefore also the energy absorption deficiency.

As a consequence, it is important to:

- increase the number of load paths
- limit the load immediately after impact
- create a front face spreading out the effort over a large surface.

From the layout point of view, it is therefore desirable to increase the number of load paths and the front contact surface, especially for the highest vehicles. The technical solutions are often very directly linked to the architecture of a car and often difficult to change

Improved end-of-impact load

As we have already seen, when two vehicles collide, the less stiff one absorbs more of the impact energy. The energy distribution is therefore not equal. Generally speaking, the heavier vehicle deforms less because it is stiffer in its design.

This is why a harmonisation of end-of-impact load is needed. Renault therefore proposes an end-of-impact load, which it calls the "compatibility load" of 300kN up to an EES of 55km/hour against a rigid wall or ODB (figure 10 upper view).

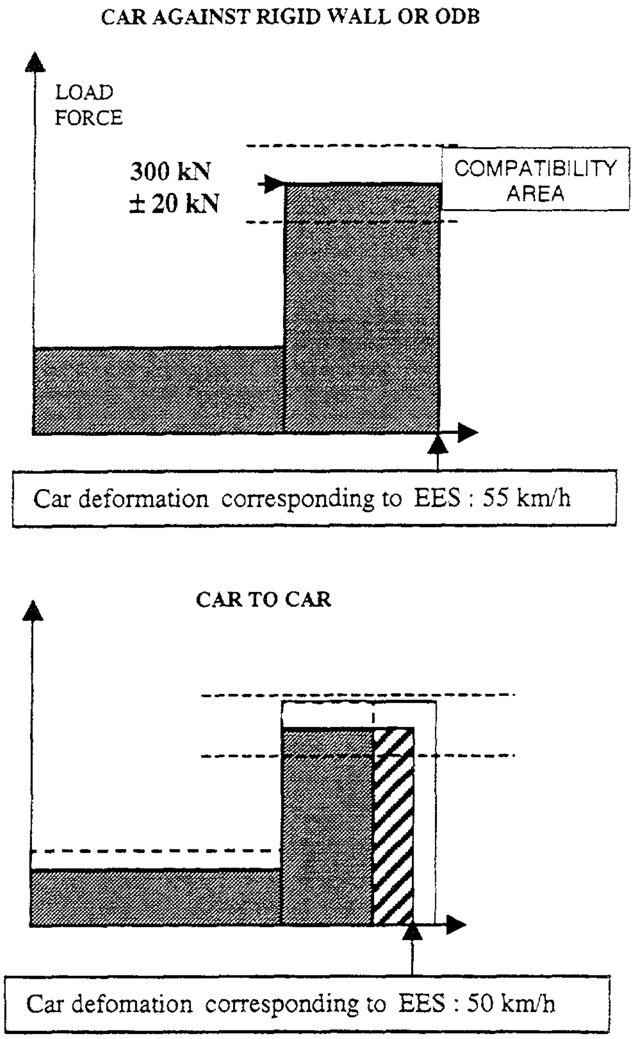


Figure 10: Compatibility load limit

We have also to define a testing procedure to control that a significant part of energy is absorbed before the car reaches the compatibility force. Else, we will have the kind of behaviour shown in figure 6 and 8.

The aim of those two procedures is to ensure that the EES of each car in the car to car test is close to 50 km/hour (figure 10 lower view). This in coherent with our fundamental principles to have the same EES on both cars, at a closing speed of 100 km/h.

Force evaluation in vehicle-to-vehicle impact

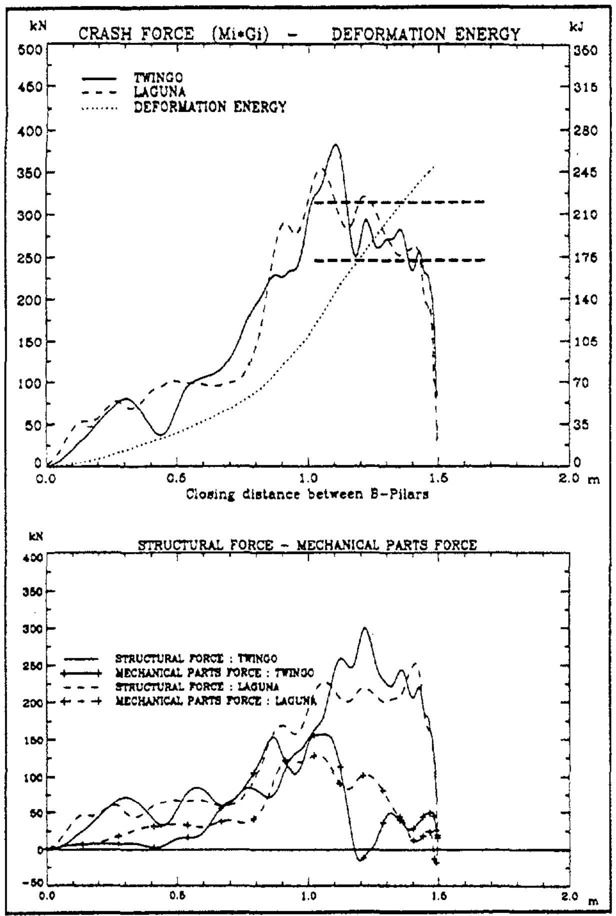


Figure 21: Results of Twingo /Laguna test

The interface force during crash was recalculated for both cars (Figure 21). The principle of action/reaction is respected. The mecanical parts interaction of both cars create a force peak that is slightly above the compatibility force. Anyhow, at the end of the crash we find a force that is very comparable to that measured on the ODB reference tests.

Performance of the New Clio in car to car test

A good performance in compatibility was taken as a design target from the beginning of that new project. The global force capacity of the Clio in the end phase of an offset crash is at the 300 kN value we propose.

In the final development phase, we carried out 6 car to car tests against vehicles representative of the existing parc. Figures 22 and 23 show that in all cases, the two vehicles offered a good protection potential for their occupants. In two cases (VEH A an VEH B), the EES is comparable on both cars, in two cases (VEH C and VEH E), the severity of the crash is less important on the Clio II than on the opposite car. However, we observed that in the last tests against vehicle F, overriding began to occur with a resulting energy absorption deficiency.

The average door aperture reduction lead to the same kind of conclusions. Those results show the progress realised on this new car if we compare them with those published by the ADAC. [11]

As we indicated in the section on restraint systems, the crash severity for the restraint systems remained lower in those crashes than for a crash against an offset rigid wall at 55 km/hour.

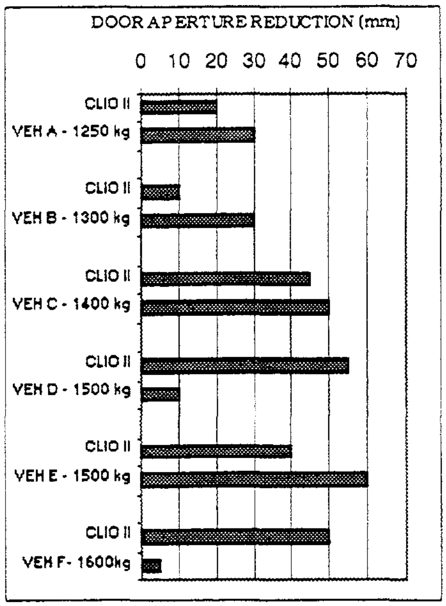


Figure 22: Average reduction of upper and lower door aperture

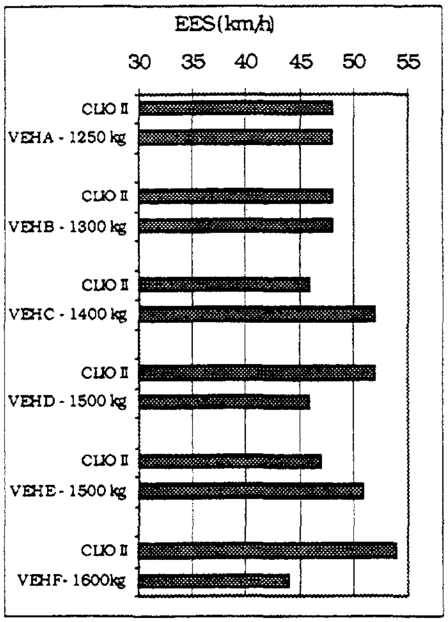


Figure 23: EES of the two vehicles

After the numerical phase, we first tested both cars on a ODB test to measure the interface force. We used also the test anlysis method we developed to compute the interface force from deceleration of a set of chosen points. The results of picture 17 and 18 show both a good corelation between the force measured behind the ODB and the computed force. Further, in the end phase of the crash, both cars have a reaction force that matches the compatibility area we have defined.

Force measurements in the Laguna in ODB

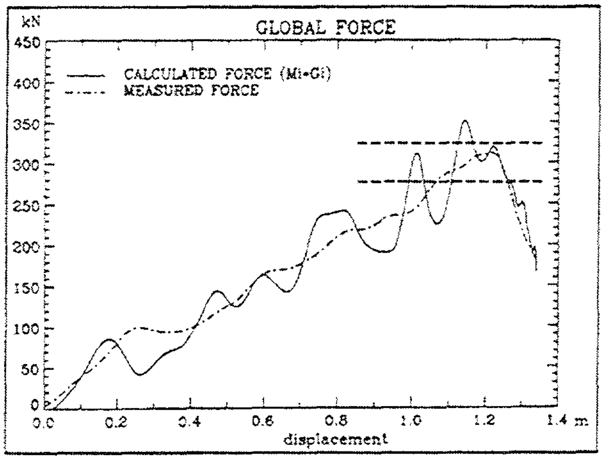


Figure 17: Comparison between measured and calculated forces

Force measurements for the Twingo in BFD

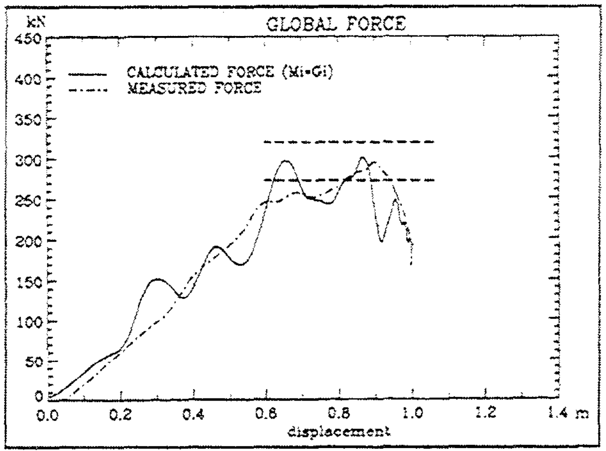


Figure 18: Comparison between measured and calculated forces

Global test validation at 100 km/h closing speed

STRUCTURE	TWINGO	LAGUNA
Groud speed (km/hour)	50	50
Test mass (kg)	1020	1480
Delta V (km/hour)	60	40
Kinetic energy (kJ)	98	143
Deformation energy (kJ)	105	135
EES (km/h)	50	48
Door reduction up (mm)	50	20
Doorreduction down(mm)	80	45

The global test results are in line with the expectations. The estimated EES of both cars is very close although the mass ratio is close to 1,5. The global deformation of the cars is very close to the results of the numerical simulation (figure 19 and 20)

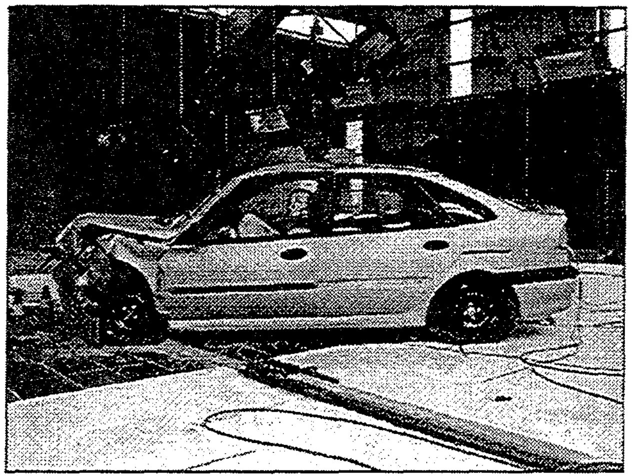


Figure 19 : Laguna after crash

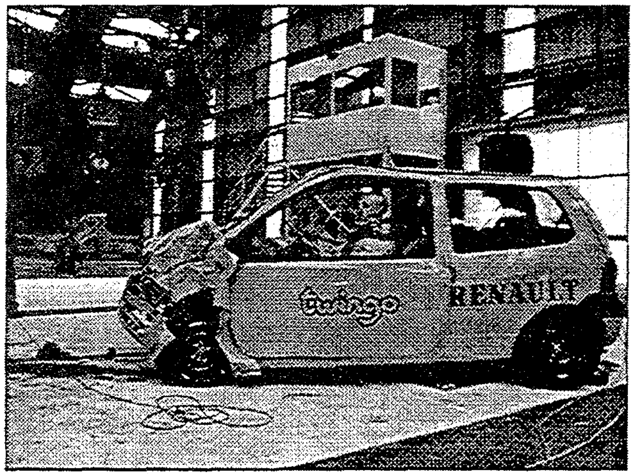


Figure 20 : Twingo after crash

Restraint results

RESTRAINT	TWINGO	LAGUNA
HIC	241	231
Chest acc (g 3ms)	45	40
Pelvis acc (g)	54	50
Shoulder force (daN)	440	470
Femur load (daN)	510	380

The restraint systems of both cars is a Programed Restraint Airbag working with a low force belt load limiter presented by Bendjellal 1998 [10]. That new system gives very good result on dummy valus for both head and thorax. This restraint system and the structural changes tested on the Twingo will be introduced on the new version of that car coming out in september 1998 on the European market.

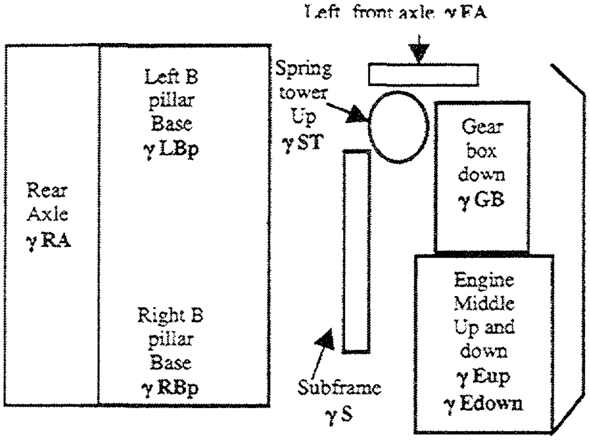
TEST ANALYSIS METHOD

As we have already seen, it is necessary to analyse the structural crushing force in both vehicles in the case of a car to car collision. This is the reason why Renault has developed methods of evaluating this dynamic crushing force. The first method consists simply of measuring the force on a dynamometric barrier which can be used only in single vehicle crash. The second method involves evaluating the inertia forces during the impact event, while measuring the acceleration at various points in the vehicle, and multiplying these accelerations by the mass which suffers the equivalent deceleration. The sum total of all these forces therefore yields the overall crushing force acting on the vehicle during the impact.

The method is based on the principle of action and reaction. A mass represents each part of the vehicle, and of the structure. The multiplication of each of these by the accelerations gives us the forces, and the addition of these forces yields the total force.

Measurement of the crushing force

The total force (Fg) at the interface is made up of the inertia force associated with the mass of the parts (Fm) and the force associated with the structure (Fs).



We were able to verify that these two methods yield correct results for the overall crushing force, both by carrying out an impact test against a deformable barrier and comparing the two approaches, and by carrying out a vehicle-to-vehicle test in order to verify that the crushing force for the two vehicles was the same, in accordance with the principle of action and reaction.

APPLICATION TO THE RENAULT RANGE

Work has been undertaken to apply the principles of energy compatibility to the smaller cars in the range. We have worked mainly on increasing the stiffness of these smaller cars towards the end of the impact. The results achieved are very encouraging. The vehicles concerned are the Twingo and the New Clio.

Application to the LAGUNA/TWINGO test

According to the general principles of compatibility, we have made a first project application on the Twingo, our super mini car. We used a defined opposite car of the upper medium class, the Renault Laguna. This car has already shown in accidentology a good compatibility behaviour.

The first step was to find technical solutions to increase the stiffness of the small car. We experienced various principles using complete car FE numerical simulations. We had to put under control both the industrial feasability and the compliance with some other rigid wall tests to prevent the car from becoming dangerous on such rigid walls.

The end result of that optimisation is presented in pictures 15 and 16. The behaviour of both cars is quite symetrical with an important deformation of both front structures.

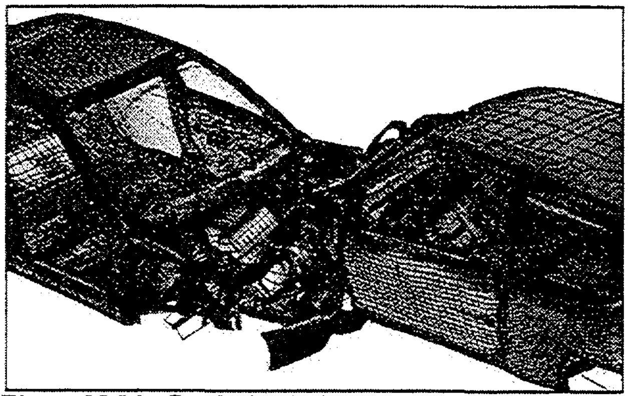
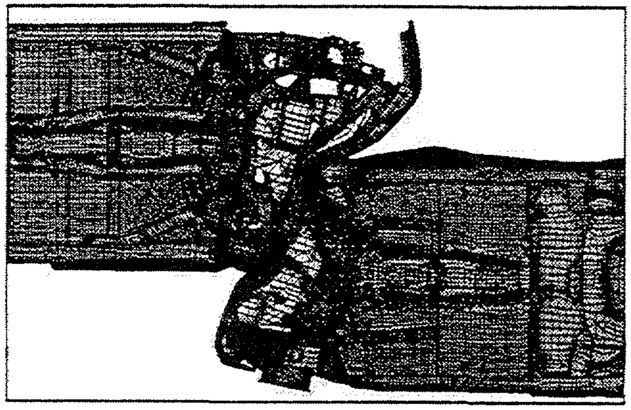


Figure 15,16 : Crash simulation



CONCLUSION

Proposal for a representative compatibility test configuration

No proposed improvements can be effective unless they are applied by all manufacturers and for all passenger cars. The only way to reach that target is of course to define and apply a new regulation project. Several international task forces are working in that direction. We propose here some orientations resulting from the preceding principles that can be discussed in that frame.

The two major principles for a better compatibility are to enforce a minimum resistance of the car body in the end of the crash and to put under control the energy absorbtion of the front end of the car.

For the first principle, testing procedures on deformable barriers have proved to be a good evaluation tool. (the crash force measured directly on a rigid wall is too sensitive to local inertia effects) It is quite easy to measure the force level behind the barrier face and to compare it with a minimum value we can call a compatibility force. We suggest that the barrier used for that purpose has a stiffness distribution that is comparable to a real car, especially concerning the vertical stiffness.

For the second principle, it is important to develop also a testing procedure to put under control the energy absorbed by each car before it reaches the compatibility force. A car designed to be very stiff can reach the compatibility force in an early phase of the crash and be very dangerous because it has not enough energy absorption capacity. The evaluation of that energy on a crash against a deformable barrier requires the capacity to evaluate the energy absorbed by the barrier. According to the strategy we have proposed earlier in this paper, the energy to be absorbed before reaching the compatibility force should also be related to the mass of the vehicle, the heavier vehicles having to absorb more energy than the lighter.

We consider at the present time that two tests are probably needed to cover the two issues of the energy absorption and the compatibility force, those two tests could be on the same barrier with two different speeds.

The increasing demands on the self protection against a rigid wall or an ODB increases dangerously the stiffness of the larger cars. We have seen that a small car can cope with the stiffness of the existing large cars but it will be extremely difficult to face a too strong increase of stiffness of those cars

This is why we have to succeed rapidly in specifying a way of evaluating and controlling that stiffness. It is really urgent to introduce that kind of evaluation in he regulations and ratings,

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