Compatibility Considerations for Low-Mass Rigid-Belt Vehicles

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Abstract

According to published accident and injury statistics a negative correlation exists between vehicle mass and injury severity in car-to-car crashes. Yet, certain vehicles have been demonstrated to deviate from this general rule, in that a favourable safety performance is documented in spite of a relatively low mass. This fact corroborates the hypothesis, that appropriate design strategies facilitate an acceptable safety standard also for low-mass vehicles (LMVs) in the strict sense (curb mass less than 600 kg).

A number of staged impacts performed by our group with the aid of a LMV test device indicates that a Rigid-Belt Body (RBB) represents such a design strategy. Providing that an advanced restraint system be used and the occupant compartment be appropriately designed, it is expected that an adequate occupant safety performance is reached in a RBB vehicle also for the higher Δv environment which is anticipated for LMVs in crashes with conventional vehicles. The RBB concept raises the problem of compatibility, however.

Ideally, the deformability of car front structures should increase with increasing vehicle weight in order to ascertain compatibility. Published data on frontal deformation characteristics indicate however that conventional cars today exhibit an opposite behaviour. To address this problem, two crash experiments were performed together with a theoretical model analysis. A LMV with a mass of 680 kg (incl. batteries, 50% mass of two dummies, instrumentation) designed according to the RBB concept and a conventional car of 1320 kg (equivalent loading conditions as LMV) were crashed at 56 km/h against a deformable barrier (FMVSS 214). Furthermore, a mathematical model was based on estimated deformation characteristics of conventional vehicles to predict intrusion distances into the FMVSS barrier in hypothetical frontal crashes with 56 km/h. The results indicate that due to its low mass a LMV does not represent an excessive compatibility problem for other car occupants in spite of the stiff RBB characteristics.

Introduction

In the analysis of vehicle-vehicle collisions, the concept of mutual compatibility is a major issue which is given increased attention at present. In qualitative terms vehicles are denoted as collision-compatible if their deformation characteristics are such that they do not impose excessive loads on the occupants of the collision partner under a well-defined set of crash conditions. In particular, a collapse of the passenger compartment of the impacted car has to be avoided. Structural as well as geometric properties are thereby of importance and a distinction is usually made between structural and geometric compatibility. Yet, a need exists to characterize compatibility more quantitatively than has been done to date and this communication is to be viewed as a step towards this goal.

The present paradigm of crashworthiness of passenger cars [1] includes a stiff passenger compartment and a frontal crush zone which exhibits carefully designed deformation properties in a frontal barrier crash with typically 50 km/h (*e.g.*, according to FMVSS 208) allowing for a controlled "ride-down" of the occupant. As a result of this concept, the overall frontal stiffness of a vehicle increases with weight because a barrier crash is equivalent to a collision with a static undeformable "vehicle" of infinite mass. To maintain a mean deceleration level which does not essentially exceed 20 g in a crash with 50 km/h into a rigid barrier, a permanent crush distance of at least 50 cm is necessary and the overall stiffness of the impacting vehicle has to increase about proportionally with the vehicle mass. Published data on frontal deformation characteristics [2] substantiate this general rule.

However, the overall stiffness of a car front should in contrast decrease with increasing vehicle weight in order that the vehicle be collision-compatible. Geometrical compatibility would moreover require that the variation of deformation characteristics over the vehicle hight would obey some defined guidelines (in order to prevent underride-effects). In side collisions, finally, the problem of structural and geometrical compatibility is virtually unsolved today.

Impact and injury analysis document a negative correlation between vehicle mass and injury severity in car-to-car crashes [3], which can in part be attributed to insufficient compatibility. Yet, certain vehicles have been demonstrated to deviate from this general rule, in that a favourable safety performance is documented in spite of a relatively low mass [4]. This fact corroborates the hypothesis, that appropriate design strategies facilitate an acceptable safety standard also for low-mass vehicles (LMVs) in the strict sense (mass less than 600 kg).

A number of staged impacts performed by our group with the aid of a LMV test device indicates that a Rigid Belt Body (RBB) represents such a design strategy [5]. Providing that an advanced restraint system be used and the occupant compartment be appropriately designed, it is expected that an adequate occupant safety performance is reached in a RBB vehicle also for the higher Δv environment which is anticipated to result for LMVs in crashes with conventional vehicles. The RBB concept raises the problem of compatibility, however.

To address this problem, two crash experiments were performed together with a theoretical model analysis. A LMV designed according to the RBB concept and a conventional car were crashed at 56 km/h against a deformable barrier with deformation properties which are representative of a typical vehicle front. The tests were conducted at the *Bundesanstalt für Strassenwesen (BASt)* in Bergisch Gladbach, Germany. Furthermore, a mathematical model was based on published deformation characteristics of conventional vehicles ([2], [6]) to predict intrusion distances of passenger cars into the deformable barrier in hypothetical frontal crashes.

This investigation is limited to the problem of structural compatibility. The important aspects relating to geometrical compatibility, in particular in side collisions, are not addressed here. It can be anticipated, however, that the RBB concept substantially diminishes also this problem providing that the rigid belt extends over a sufficient height (typically 80 cm) and includes the door area. Furthermore, the RBB vehicle may be less dangerous in side impacts into conventional cars. Due to the nearly uniform stiffness of the impacting front, load transfer and deformations are imparted uniformly over the entire contacted area such that local intrusions are prevented.

Material and Methods

A LMV (Horlacher City II) with a mass of 510 kg (empty), respectively 680 kg equivalent crash mass (incl. batteries, 50% mass of two Hybrid III occupants, instrumentation) designed according to the RBB concept and, in a second test, a conventional car (Audi 100) of 1210 kg (empty), respectively 1320 kg (equivalent loading conditions as LMV) were crashed in a frontal direction at 56 km/h against a deformable barrier. As barrier exhibiting a deformability which is representative of passenger car fronts, the side impact barrier according to FMVSS 214 was chosen. In order to have sufficient deformation space available, two such barrier elements were placed behind each other. Figure 1 shows the experimental installation. The LMV (Horlacher City II) was equipped with driver and passenger airbags and pretensioned belts, while the driver and passenger of the Audi 100 were solely protected by conventional seat belts (according to the original equipment). As ATD the Hybrid III was used.

The conventional passenger car with a typical frontal crush zone is dimensioned such that it undergoes a mean deceleration which does not exceed 20 g in a rigid barrier impact with 50 km/h. In turn, the LMV is expected to exhibit a roughly four times higher mean deceleration level under the same impact conditions. Permanent deformation distances are approximately 60 cm for the conventional car and 15 cm for the LMV, respectively.

Furthermore, a mathematical model was based on typical deformation characteristics of conventional vehicles to predict intrusion distances into the FMVSS barrier in hypothetical frontal crashes. For this purpose, a 6-mass model was used (Figure 2) consisting of masses, nonlinear elastic-plastic elements including damping and gap distances. Parameters were chosen such as to mimick a typical passenger car with a frontal deformation zone. As "typical" in this context we considered a permanent frontal crush distance of 60 cm resulting from an impact with 56 km/h against a rigid barrier. A mean deceleration of 20 -25 g is thereby reached with peaks of up to 35 g (Figure 3). The pulse duration is about 80 msec.

To model the characteristics of a specific vehicle in detail, a higher number of degrees of freedom than is assumed here is necessary [6]. Providing that enough parameters are available for fitting purposes, any specific deceleration pattern can of course be correctly reproduced. However, for the purpose of this investigation the detailed deceleration curve associated with a particular vehicle is of minor interest, rather, an approximate average behaviour which is representative of a large number of existing vehicles was attempted to be modelled. A six-mass model produces relatively smooth deceleration curves lacking the high and narrow deceleration peaks which are normally recorded in real crash tests. In particular, lumped parameter models representing a system with relatively little internal structure do not allow for wave propagation phenomena.

The question therefore arises, to what degree the details of a deceleration curve, in particular short (< 3 msec) but large deviations from an averaged smooth curve may influence the intrusion distance into a **deformable** crash barrier under the condition that the aberrations from a given deceleration curve are such that all equivalent crashes into a **fixed** barrier yield the **same** permanent vehicle deformation. Because all distances results from a double integration of the model equations, the influence of scatter and high frequency components is minimal. However, the gross pulse shape exerts an appreciable effect upon the intrusion distance into the barrier. By parametric variations of the model parameters such that the **rigid** barrier deformation remained constant, i.e., using various deformation characteristics leading to different deceleration pulses but equal total vehicle crush, it was found that the mutual crush distances in crashes into the **deformable** barrier can vary up to 15%.

The barrier was modelled as a single mass exhibiting a uniform viscoelastic-plastic behaviour producing a constant force during collapse (constant collapse pressure with an inertial threshold). No attempt was made to develop a more sophisticated mathematical model for the barrier itself because this would require an extensive experimental analysis of the collapse process. Moreover, the mathematical model describes in essence a one-dimensional intrusion process and does as such not include any effects associated with the size of the contact area, in

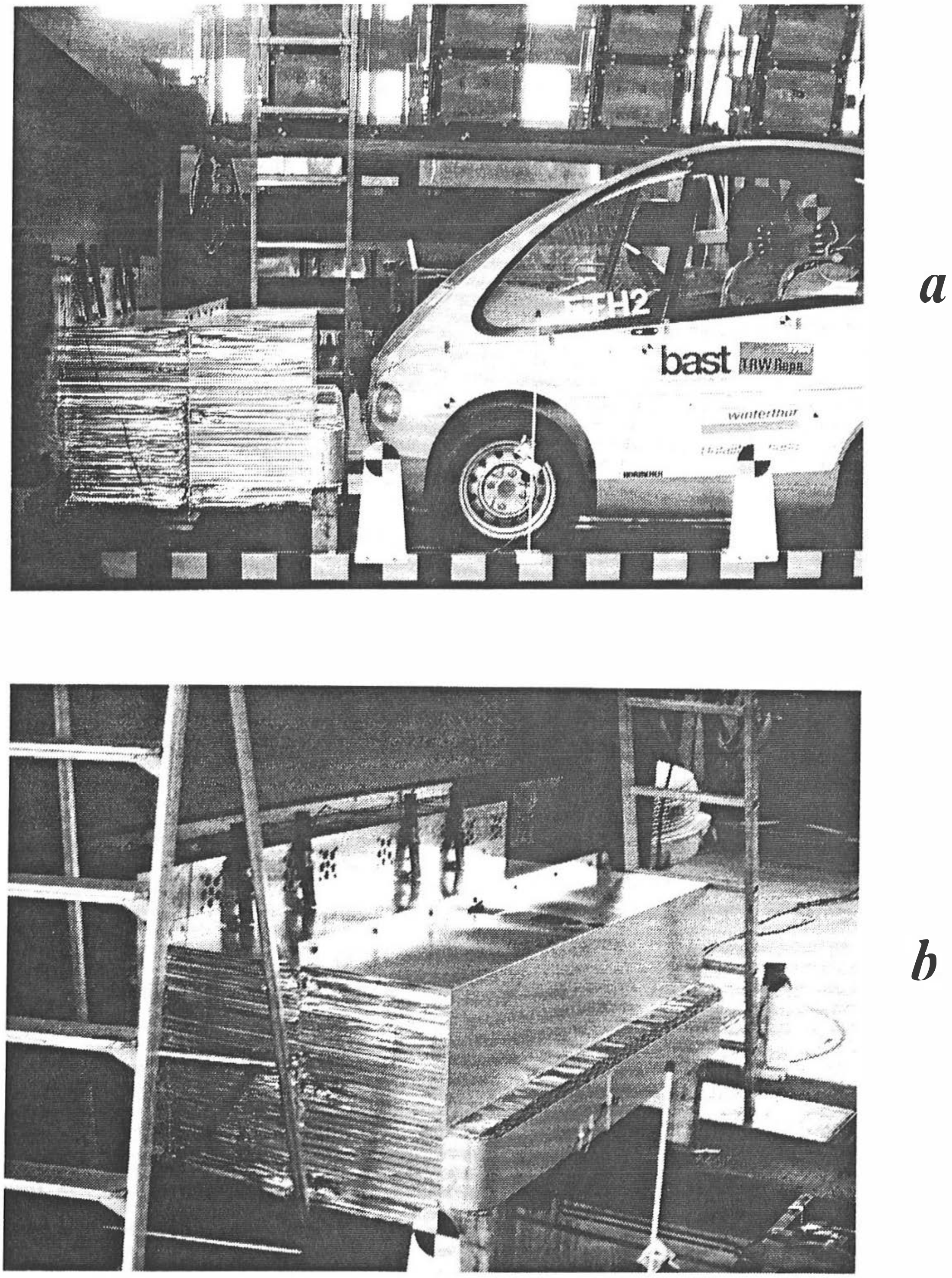


Fig. 1: Crash configuration with LMV Horlacher City II (a) and deformable barrier (b)

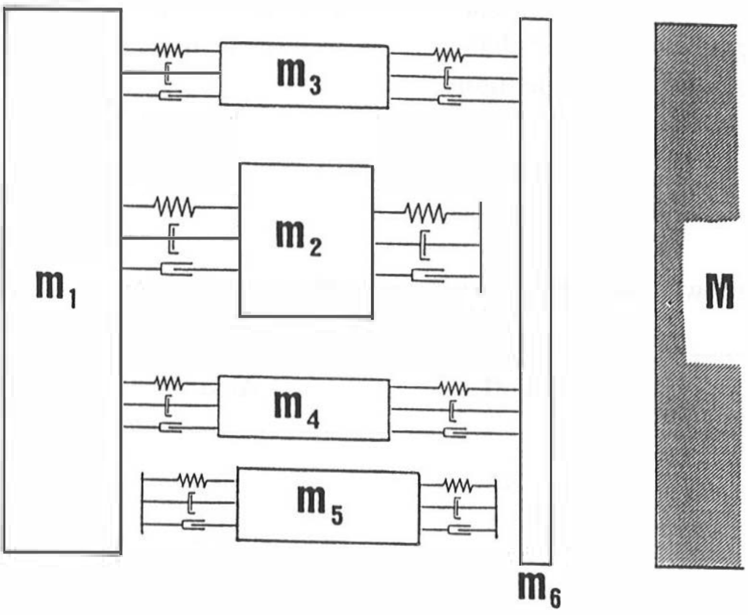


Fig. 2: Lumped parameter model of vehicle front

m_1 : passenger compartment
m_2 : engine
m_3 : frame rails
m_4 : hood
m_5 : wheels, axle
m_6 : bumper, radiator
M : barrier

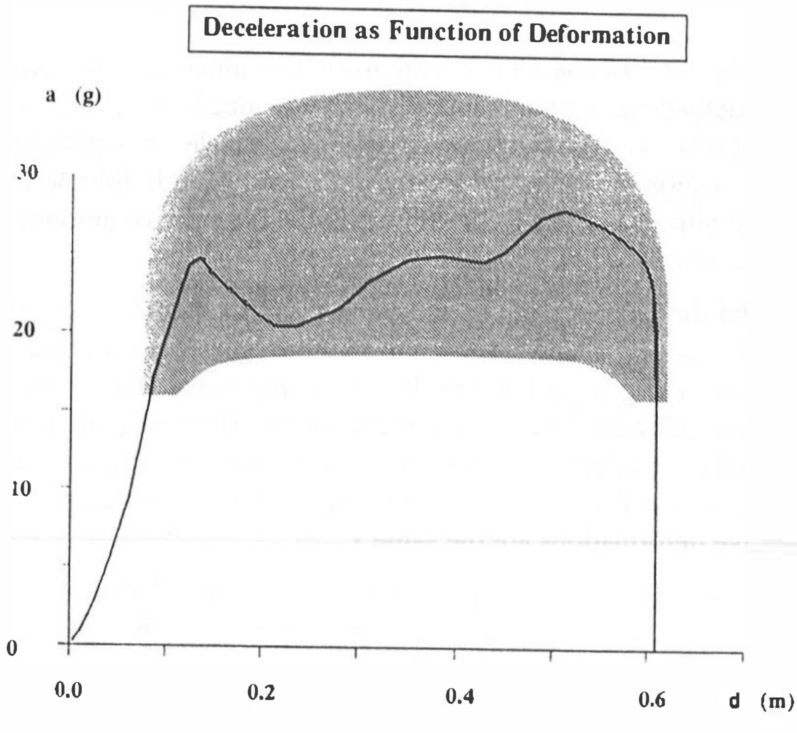


Fig. 3 : Simulated deceleration of vehicle body as a result of an impact with 56 km/h into a rigid barrier (mathematical model according to Fig. 2). The shaded area includes the range of typical deceleration pulses.

particular, local differences of deformability over the car front are not modelled. It was therefore somewhat arbitrarily calibrated (see below) such that compatibility is reached for a model vehicle of 1000 kg crashing into the hypothetical barrier with 16 m/sec.

However, in the tests performed, local variations of the deformation pattern in the deformable barrier were considerable (see results). This important aspect which can be included under the problem area of geometric compatibility is not included in the analysis at this stage but needs particular attention and an in-depth analysis in the future.

Results

Some representative results of the two crash tests are summarized as follows:

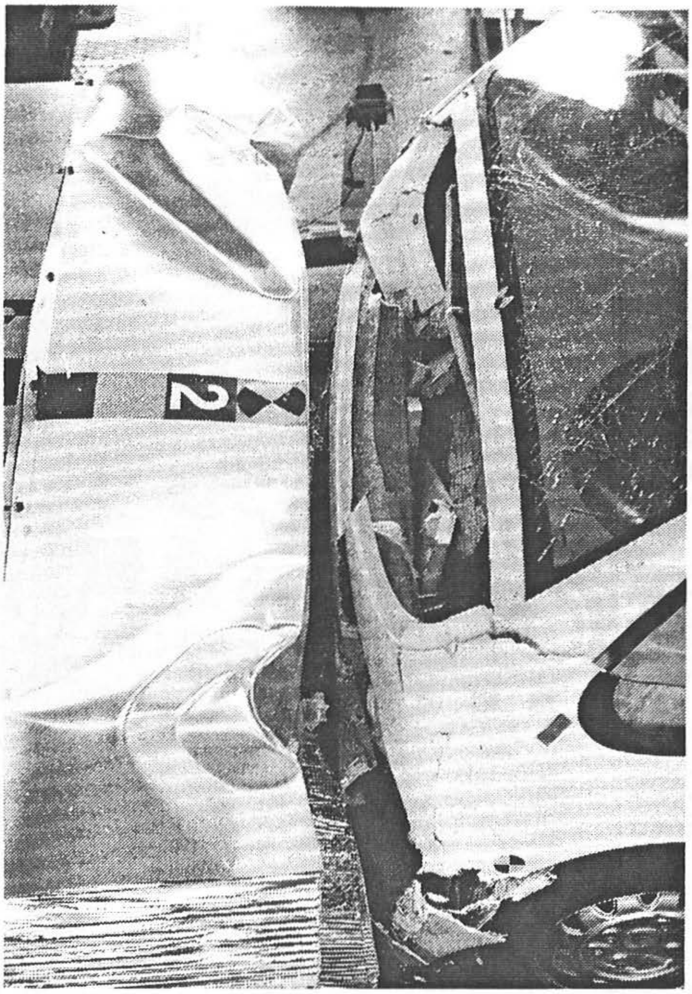
	City II	**Audi 100**
Total kinetic energy	**82 kJ**	**160 kJ**
Absorbed energy by barrier	**24 kJ**	**25 kJ**
% of total energy	**29 %**	**16 %**

	City II		**Audi 100**	
	driver	**passgr.**	**driver**	**passgr.**
HIC	**1050**	**940**	**920**	**760**
Acc. head (3 msec)	**81 g**	**73 g**	**118 g**	**57 g**
Chest def.	**5.4 cm**	**4.3 cm**	**3.2 cm**	**3.3 cm**
Femur load (avg. l/r)	**2.9 kN**	**2.9 kN**	**1.5 kN**	**1.6 kN**

Figures 4a-d exhibit the deformed barriers of the City II and Audi 100 impact, respectively. The enormously inhomogeneous deformation patterns document the need to include the aspects of geometrical compatibility in future assessment of vehicle compatibility. Nevertheless, it is observed that the energy absorbed by the barrier is comparable for the two impacts. As a result of the increased stiffness of the RBB, almost twice the relative amount of energy is imparted to the barrier in case of the LMV impact.

With the aid of the theoretical model the influence of impact speed was first examined (Figure 5). Due to the initial threshold of the barrier, at low speeds the average barrier deformation is less than the vehicle crush. With increasing impact speed, however, the barrier deformation shows a stronger increase than the one of the vehicle. This effect indicates that compatibility at a given impact speed, *e.g.*, at 16 m/sec (Figure 6) does not imply compatibility at other collision velocities. (In the sense of an *ad hoc* definition, structural compatibility is assumed here to be ideal if the mutual effective deformations are the same.)

Second, the influence of the vehicle mass was analysed. It was thereby considered that vehicles of a smaller mass are usually also shorter than heavier cars, such that there is less space available for frontal crush. Accordingly, the overall stiffness of a small vehicle is in general somewhat higher than would correspond to a linear extrapolation from the values of a heavy car. Figure 7 shows the results obtained for the calculated deformations of vehicle and barrier, respectively, as a function of the vehicle mass. The compatibility problems are readily seen in



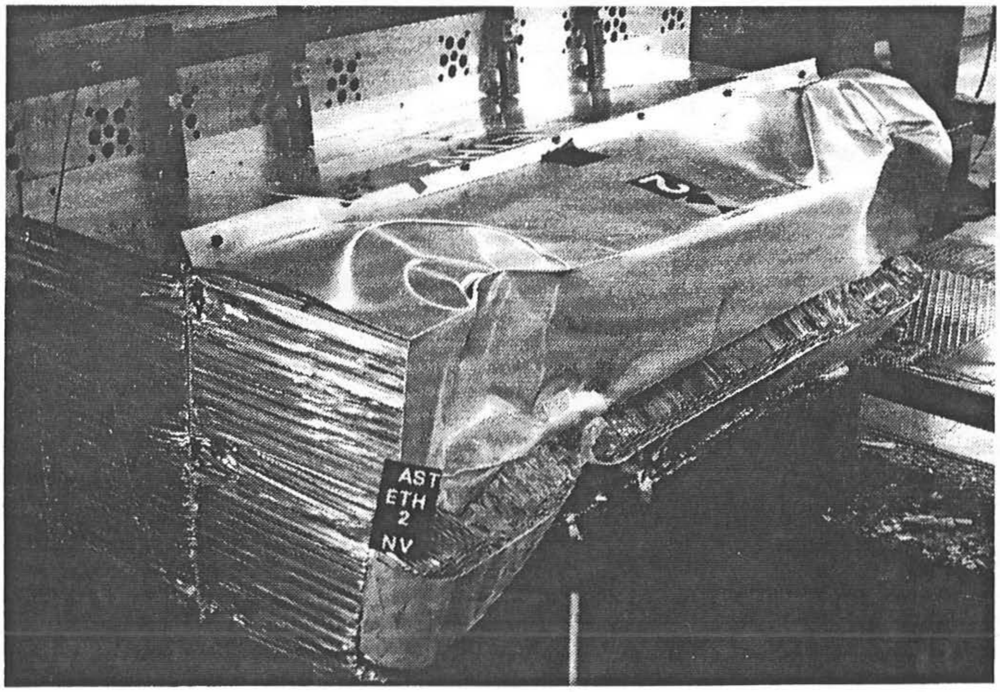
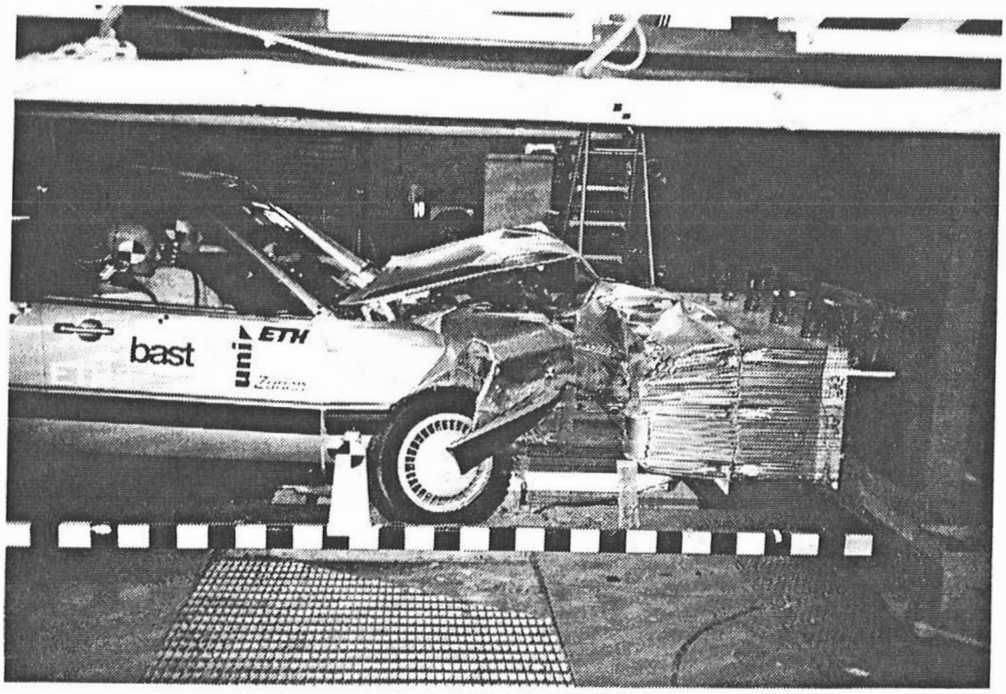


Fig. 4a: *Crash of LMV into deformable barrier (56 km/h)*
4b: *Deformed barrier*



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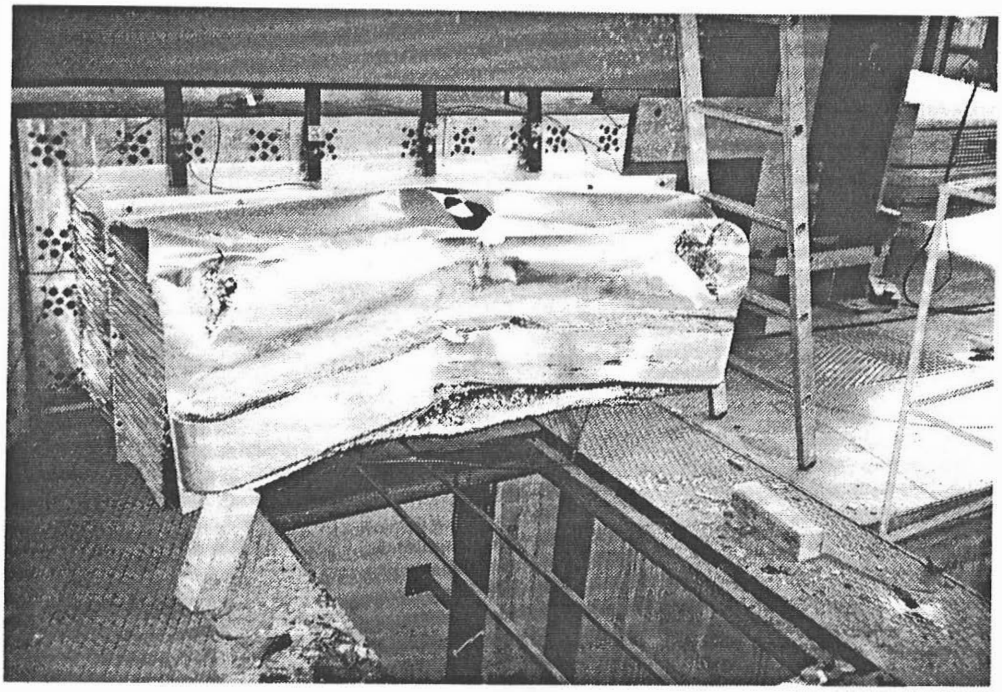

d

Fig. 4c: Crash of Audi 100 into deformable barrier (56 km/h)
4d: Deformed barrier

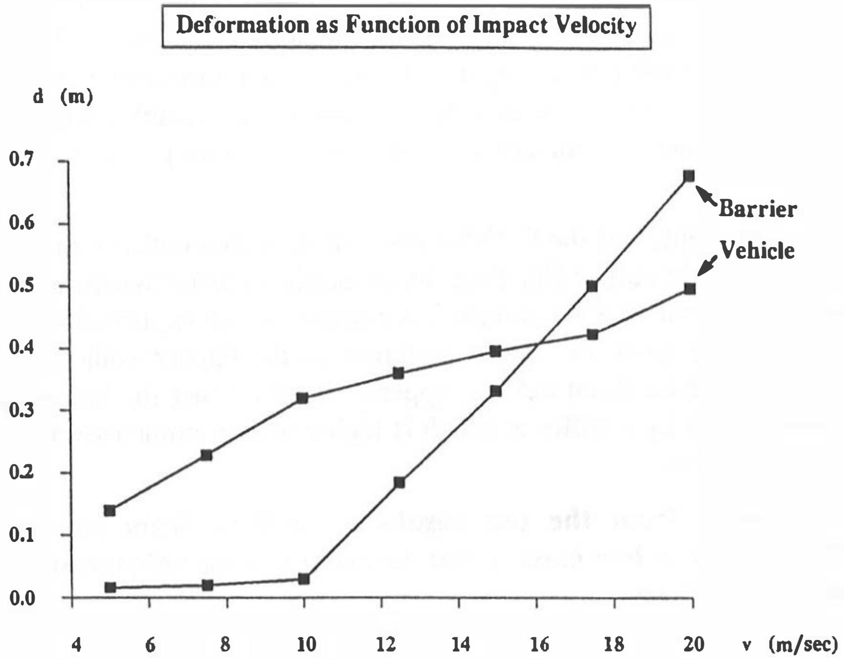

Fig. 5: Calculated deformations of theoretical vehicle front and barrier, respectively, as function of impact speed according to mathematical model of Fig. 2. Compatibility was chosen for 16 m/sec (see Fig. 6).

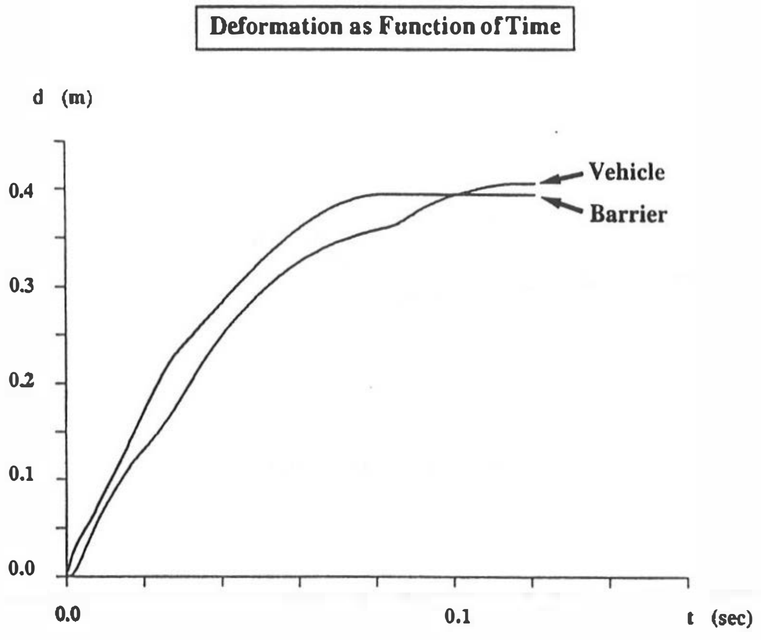

Fig. 6: Calculated deformations of theoretical vehicle front and barrier, respectively, as function of time for an impact speed of 16 m/sec (mathematical model) showing compatible collapse behaviour.

that the barrier deformation (which represents another, impacted car) strongly increases with the mass of the striking vehicle, while its own deformation decreases. Although Figure 7 exhibits theoretical curves which may vary under realistic circumstances, a basic structural compatibility conflict remains. In particular, it is seen that a considerable margin for increasing the stiffness of a vehicle exists without compromising compatibility providing that its mass be sufficiently small.

It should be noted at this point, that the FMVSS 214 barrier with a collapse pressure of 45 PSI as used in the tests is considerably stiffer than the theoretical barrier which is assumed in the mathematical model and which exhibits compatibility properties as explained above: Only 16% of the kinetic energy of the Audi 100 was transferred to the barrier while according to the mathematical model it would be about 60%. It appears therefore that the barrier defined in the FMVSS 214 is characterized by a stiffness which is higher also in comparison to most vehicle fronts of present passenger cars.

As an overall conclusion from the test results as well as from the results of the simulation, a LMV, due to its low mass, is not expected to pose substantial compatibility problems in spite of its stiffness.

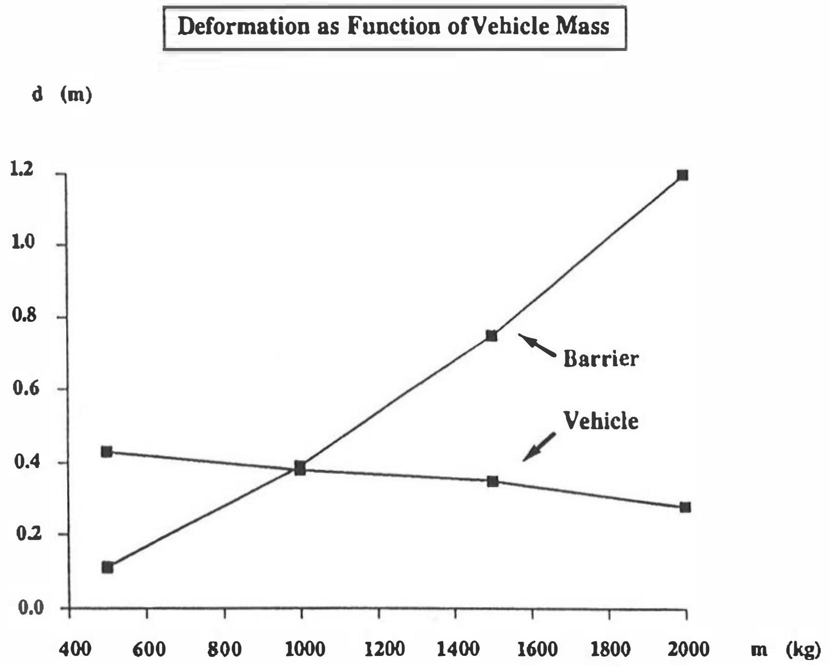

Fig. 7: Calculated deformations of theoretical vehicle front and barrier, respectively, as function of vehicle mass according to mathematical model of Fig. 2. Simulated impact speed is 16 m/sec. Explanations see text.

Discussion

On the average, frontal deformation characteristics of present cars are such that the overall stiffness increases with increasing weight. This circumstance results from the necessity of having a controlled deceleration pattern in a crash into a rigid barrier with typically 50 km/h. In spite of the fact that the space available for permanent frontal deformation in a smaller vehicle is also smaller in comparison to a larger car, and therefore the relative stiffness has to increase somewhat with decreasing vehicle mass, an unfavourable behaviour in view of structural compatibility is inevitable. The smaller a vehicle, the stiffer it should be if compatibility is required. That such a feature need not compromise occupant safety has been shown in various tests conducted so far [5].

A deformable barrier lends itself to be used for assessing the compatibility of vehicles in spite of the fact that a deformable barrier with a constant collapse load does not represent a real vehicle as far as deformation characteristics are concerned. Providing that the collapse load be appropriately chosen, it can still be regarded as representative. This goal was in fact attempted to be reached when the FMVSS 214 barrier which was applied here was dimensioned. However, it appears that this barrier is somewhat stiffer than corresponds to present car fronts. Likewise, in the mathematical model used, the simplified representation of the barrier can be questioned. The results of the model study are however primarily used for comparison purposes rather than as a simulation which describes the detailed intrusion process into an actual vehicle.

Of primary importance is the finding, that a RBB vehicle of sufficiently small mass (around 500 kg) does not represent a serious threat to a conventionally designed heavier vehicle in spite of its increased stiffness. In turn, occupant protection in side collisions is improved because the RBB includes lateral sections of the vehicle as well.

Pedestrian safety has to be considered furthermore when RBB vehicles are studied. Under urban circumstances, an RBB vehicle will have to be equipped with a soft outer layer of about 10 cm thickness which has been shown to be sufficient for adequate pedestrian protection [7].

Finally, the two tests involving the deformable barrier demonstrated on the one hand the need to include the aspects of geometric compatibility in the analysis of vehicle-vehicle interaction as well as on the other hand the usefulness of a crash into a deformable barrier for this purpose.

Acknowledgements

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