EVALUATION OF OCCUPANT PROTECTION AND COMPATIBILITY OUT OF FRONTAL CRASH TESTS AGAINST THE DEFORMABLE BARRIER

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ABSTRACT

Up to now crash tests highly are restricted to the aspects of self-protection. Due to the fact that compatibility is recognised as an important safety factor in real life car to car accidents a test - and rating procedure is proposed which in addition to self-protection also delivers information on the aggressiveness and compatibility of cars. The test procedure bases on the European frontal crash standard against the offset deformable barrier, but the barrier is modified towards more energy absorption and higher penetration resistance. Vehicle mass in connection with crush zone stiffness and stiffness distribution are assumed to be the influencing factors on aggressiveness, and these effects are quantified by measuring the crush force behind the barrier, the deformation energy in the barrier and the homogeneity of barrier deformation.

Several barrier tests with small and big cars are achieved. With the help of an appropriate rating system self-protection as well as aggressiveness and compatibility of the individual models are quantified. To validate these results additional frontal impacts with big cars against small cars are carried out. The findings, in terms of injury risks for the occupants of the small cars, show sufficient coincidence to the barrier results.

INTRODUCTION

Since the 70s the total annual amount of kilometres travelled on German roads more than doubled from some 250 billion to 606 billion (1996). At the same time fatalities decreased by more than half from 21,332 to 8,758 p.a.- a development demonstrating impressively that our cars are now significantly safer. But we still register 3,801 vehicle passengers killed annually. This figure alone is a clear mandate for accident researchers, car manufacturers and the legislator as well as consumer protection organisations to further improve vehicle safety.

Accident statistics show that 49% of fatalities are related to frontal impacts, 43% to side impacts, 6% to overturning and 2% to rear-end impacts. Therefore it is essential above all to improve frontal and side impact protection. An important key to achieve this is better compatibility of vehicle structures. In other words: vehicle compatibility needs to be improved. Big cars should not be too stiff to make them less aggressive for small cars and small cars should not be too soft in order to ensure passenger protection when hitting a big car.

It is obvious from accident statistics that the crash compatibility of different size vehicles needs to be improved. The figures of Evans/Frick [1] show for instance that the fatality rate for small vehicles in a collision with a vehicle of twice its weight is 50% higher than in a collision with a vehicle of the same weight. Ernst e.a. [2] establish an increase of some 50% also when taking into account seriously injured passengers.

No procedure exists for compatibility assessment. Even consumer protection crash tests [3] do not provide data on the aggressiveness of vehicles. Since the development of passive safety is increasingly influenced by consumer protection tests such tests should as soon as possible be extended to also cover compatibility studies. This will be all the more important as the EuroNCAP tests [4] are conducted at a relatively high impact speed and could therefore tempt car manufacturers to make heavy vehicles even stiffer and thus more aggressive.

In order to contribute to this aspect this study has the aim to examine whether the existing European frontal impact standard against the deformable barrier can be modified to generate not only information on passenger protection but on vehicle aggressiveness and thus compatibility. To get a suitable test configuration in a first step the deformable barrier and impact speed have to be adapted. Then the configuration is tested in barrier tests with several small vehicles and big family saloons. Findings on self-protection and compatibility are finally verified in selected car to car tests.

COMPATIBILITY

Compatibility of a vehicle is defined by both self-protection and partner protection performance. A compatible car must feature good self-protection and low aggressiveness.

Good self-protection always requires high **passenger compartment stiffness** to ensure survival space for car occupants. Also **front-end stiffness** must be balanced. Therefore Baumann e.g. [5] proposes a compatibility curve based on a constant front-end stiffness for all vehicle sizes. Front-ends of the various vehicle classes would then only differ in terms of the required deformation length: 350 mm for a 700 kg car, increasing in relation to the vehicle mass up to 600 mm for 1900 kg vehicles.

From real-life accidents it can be deduced that horizontal and vertical front-end stiffness distribution should be as **homogeneous** as possible. Overriding is particularly dangerous and can be prevented by good vertical stiffness distribution.

Figure 1. gives an overview of compatibility measures and their effect on self-protection and aggressiveness for front and side impact and overriding. This shows that all measures in most cases have a positive or at least indifferent effect on self-protection and aggressiveness. There could be an aggressiveness increase for side impacts where small vehicles would have to be reinforced with the aim to achieve a balanced front-end stiffness for frontal impacts.

compatibility measure	frontal impact		side impact		under-riding
	self protection	aggessiveness	self protection	aggressiveness	self protection
high compartment stiffness	+	0	+	0	+
balanced crush zone stiffness	+...0	+	0	-...+	+...0
homogenous horizontal crush zone stiffness distribution	+	+	0	+	+
homogenous vertical crush zone stiffness distribution	+	+	0	+	+

small...big car small...big car

\+ positive effect
0 indifferent
\- negative effect

Figure 1. Compatibility measures and their effects on self protection and aggressiveness

On the basis of the above compatibility measures two important statements can be made on compatibility assessment:

- Limitation to just one criterion is not enough.
- The applied test procedure in addition to self-protection must also provide findings on front-end stiffness and its horizontal and vertical distribution.

Front-end stiffness primarily effects the energy and force transmitted to the other vehicle. Stiffness distribution determines the degree of plane or local force transfer. The following is a description of how to develop the European (EEVC) barrier in order to get results on these aspects on the basis of its force and deformation performance.

DEFORMABLE BARRIER

As described in paper [6] the EEVC barrier has some weaknesses and is therefore not suited to achieve the objective of gaining compatibility results from frontal impact tests. Its energy absorption and penetration resistance are quite low specially for higher impact speeds than the coming European standard. Some vehicles crash through the barrier and hit the wall behind the barrier. This causes an increase of collision intensity for heavier vehicles at identical impact speed and with growing vehicle mass. Also no conclusions are possible as to energy and force transmission. Penetration against the wall favours vehicles with local stiffness concentrations with respect to the bridge effect of the wall.

The described shortcomings can be avoided by the three-layer barrier with stepped stiffness (Figure 2.). Energy absorption capacity is 2.5 times that of the EEVC barrier. The multi-layer feature ensures a far greater penetration resistance. Force measuring devices behind the barrier allow for registration of the force transmitted by the test vehicle during impact. Here in particular 9 load cells are used to measure total force and to a certain extent also force distribution.

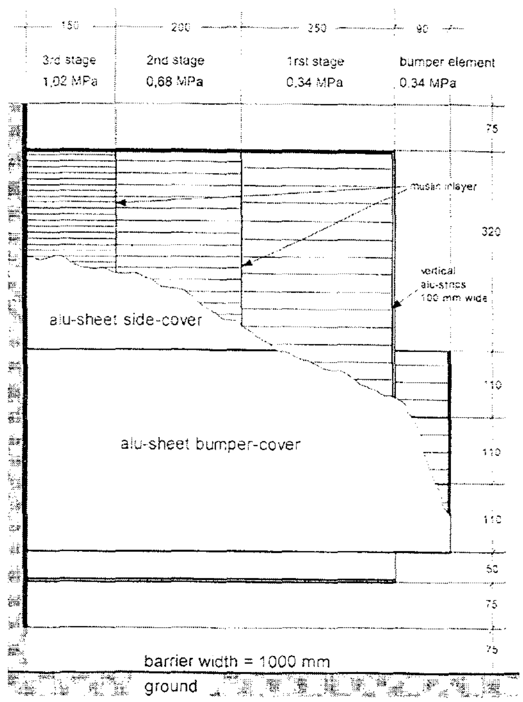


Figure 2. Improved barrier with higher energy absorption and penetration resistance

Energy absorbed by the barrier is determined with the following formula:

$$E_{barrier} = \sum_{j=1}^{7}\sum_{i=1}^{10}\left\{\left[p_{dyn1}\left(\bar{x}_{bumper\_ij} + \bar{x}_{1\_ij}\right) + p_{dyn2}\bar{x}_{2\_ij} + p_{dyn3}\bar{x}_{3\_ij}\right]\cdot A_{ij}\right\}$$

$p_{dyn1,2,3}$ are the dynamic barrier stiffnesses of the layers $1,2,3$. The bumper stiffness is identical with the stiffness of the first layer. A grid divides the barrier front surface horizontally into $i = 10$ and vertically into $j = 7$ surface element rows. A_{ij} are the areas of the surface elements ij. $\bar{x}_{bumper,1,2,3\_ij}$ are the axial displacements of surface elements ij within the bumper respectively the layers.

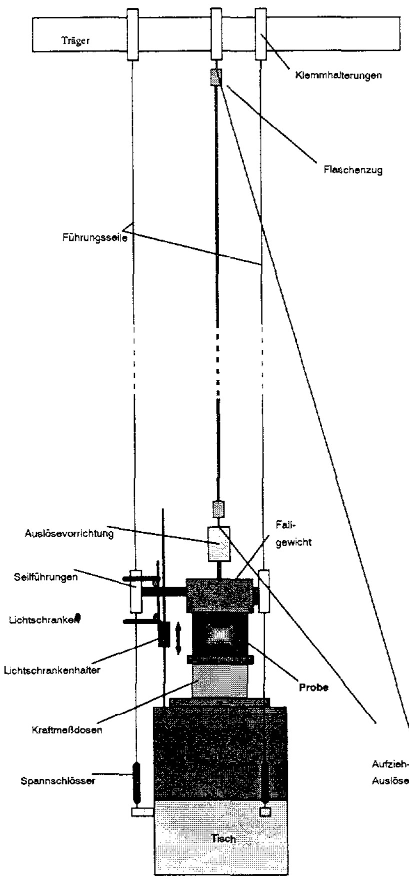


Figure 3. Test bench for proving dynamic barrier stiffness

Dynamic barrier stiffness is determined in a falling mass test, Figure 3.. The measurements are carried out in dependence on impact speed and element displacement. The results show that stiffness increases with raising speed. For 10 m/s the first layer stiffens up from 0,34 to 0,39, the second from 0.68 to 0,71 and the third layer from 1,02 to 1,04 MPa, Figure 4.. The measurements only have been achieved up to this speed. It is expeted that there will not be significant further raise for higher impact speeds. But the findings should be proved on a test sled where the deformations can be brought into the barrier more realistically than with the falling mass.

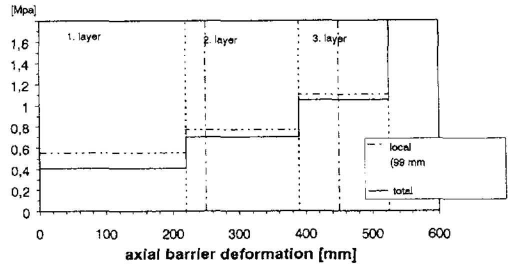


Figure 4. Dynamic barrier stiffness for impact speeds > 10 m/s

IMPACT SPEED

Objectives

Currently vehicles tend to be designed for ensuring good occupant protection in a collision with a vehicle of the same weight. However, as in real life small vehicles far more frequently collide with bigger cars than with those of their own size, smaller vehicles generally experience a higher collision intensity in a car to car collision. In a real-life accident the smaller car is subject to a stronger impact and should therefore undergo stricter testing.

This raises e.g. the question with which speed a small car should be run against the barrier in order to simulate a real-life impact at 50 km/h against a big family saloon. This configuration would cover about 85 % of all all real life frontal collision severities for the small car.

Test procedure

First assessments indicate that 3 tests would be useful to identify the appropriate impact speed:

- Small car at 56 km/h against barrier with 40% offset
- Small car at 64 km/h against barrier with 40% offset
- Small car at 50 km/h against big family saloon with 50% offset.

The small car used was the Ford Ka (test weight 1230 kg) and the big car the Mercedes E (test weight 1665 kg). The two cars were selected since they are relatively new on the market and are said to have already been constructed with a view to compatibility aspects. The cars were equipped with two 50% Hybrid III dummies in the driver and rear right passenger position and two 18 kg cubes in the boot, according to DIN 75410-2.

Injury Severity

From the test results injury risk marks for Ford Ka occupants are determined on the basis of the rating procedure described in the next chapter. Figure 5. gives a comparison of the three tests showing that the 56 km/h impact against the barrier produces the lowest and the Mercedes E impact the highest injury risk. In average the Ka driver risk marks for the 56 barrier test are 0,7 points lower and for the 64 test 0,3 points lower than for the test against the Mercedes. In other words the 64 barrier test is a little bit less severe but quite close to simulate an impact of a small car against a family saloon with 50 km/h.

car model Testcode	Ford KA 5 K 0297 FO	Ford KA 6 K 0297 FO	Ford KA E-K 297 FO	injury risk difference KA/barrier-KA/Mercedes	
V_{Crash} [km/h]	56,2	64,1	50,2	56/50km/h	64/50km/h
	against deformable barrier	against deformable barrier	against Mercedes E		
overlap [%]	40	40	50	40/50	40/50
DRIVER					
body part	risk mark	risk mark	risk mark	risk mark difference	
head	2,7	2,7	3,2	-0,5	-0,5
neck	2,1	2,3	2,4	-0,3	-0,1
arms	3,2	4,3	4,5	-1,3	-0,2
thorax	2,4	2,4	2,8	-0,4	-0,4
abdomen	1,3	1,3	1,5	-0,2	-0,2
pelvis	1,9	2,3	4,0	-2,1	-1,7
legs	3,6	4,4	3,7	-0,1	0,7
injury risk	2,5	2,8	4,0**(3,2)	-0,7	-0,3
rescue risk	3,5	3,7	3,8	-0,3	-0,1
total risk	2,8	3,0	4,0**(3,3)	-0,6	-0,3
REAR SEAT PASSENGER					
head	1,9	2,1	2,5	-0,6	-0,4
neck	2,4	2,5	2,6	-0,2	-0,1
arms	1,0	1,1	1,0	0,0	0,1
thorax	2,2	2,3	2,2	0,0	0,1
abdomen	1,3	1,3	1,5	-0,2	-0,2
pelvis	1,5	1,6	1,9	-0,4	-0,3
legs	1,2	1,5	1,5	-0,3	0,0
injury risk	1,6	1,8	1,9	-0,2	-0,1
rescue risk	3,9	4,0	4,0	-0,2	0,0
total risk	2,2	2,4	2,4	-0,3	-0,1

Figure 5. Injury risk marks for Ford KA occupants

Collision Severity

For the 56 barrier test the deformation energy in the barrier is 30,08 kJ. Assuming rebound energy being 10% of the original kinetic energy the energy absorbed by the Ka is calculated to 103,9 kJ. A Ka to Ka impact with 50 km/h would create an energy absorption of 106,8 kJ in the KA. This shows that the collision severity of the 56 barrier test is very close to the 50 km/h car to car test with vehicles of the same weight.

For the 64 barrier test the deformation energy in the barrier is 44,97 kJ, and the absorbed energy in the Ka is calculated to 129,9 kJ. For a Ka impact against a vehicle with the Mercedes E weight the absorbed energy in the Ka highly depends on the stiffness ratio of the two cars: In the case that the two cars have the same stiffness (compatibility demand in [5] for future vehicle design) the absorbed energy is calculated to 122,8 kJ, if the stiffnesses are proportional to the vehicle masses (approximately today's standard design) the absorbed energy is calculated to 141,2 kJ. From this the 64 barrier test also shows little less severity than demanded to resist today's bigger vehicles but seems a acceptable compromise for next future.

Sum Up

Assuming that the aggressiveness of big vehicles will be reduced for compatibility purposes 64 km/h seems to be the appropriate speed for small cars in order to simulate the 50 km/h impact against big cars.

Under the objective to simulate a 50 km/h car to car impact generally a mass-related impact speed as shown in Figure 6. is proposed. Small vehicles should be tested with 64 km/h to simulate impacts against much bigger models, and very big cars such as mini busses should be tested with 56 km/h to simulate impacts against itself. Reducing the impact speed with increasing vehicle mass will enable car manufacturers to design heavy cars with a softer front-end structure and thus make them more compatible.

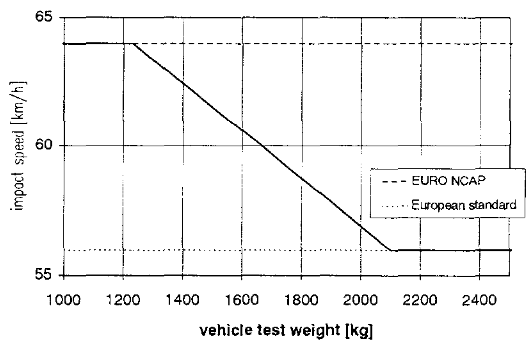


Figure 6. Mass depending impact speed

SELF-PROTECTION AND COMPATIBILITY STUDY BASED ON BARRIER TESTS

Objectives and test procedure

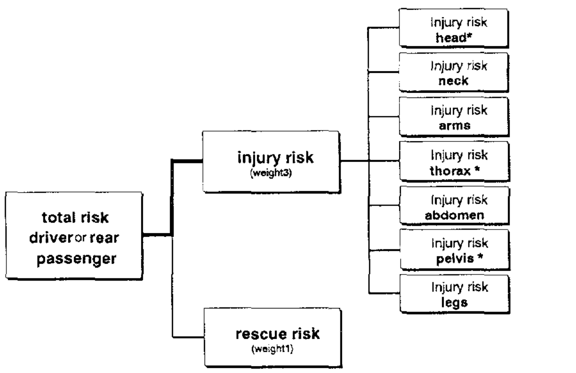
This chapter will attempt to provide information on self-protection, aggressiveness and compatibility from frontal impact tests against the barrier. The test vehicles are current volume models of two different weight classes.

Small car	Citroen Saxo Fiat Punto Ford Fiesta Ford Ka Mitsubishi Colt
Big family saloon	BMW 520i Lancia k Mercedes E 220D Volvo S70 2.0

All vehicles are tested in a 40% offset frontal impact against the barrier. As explained in chapter before the impact speed for small cars is 64 km/h and for big family saloons 60 km/h. The cars are occupied by two 50% *Hybrid III dummies in* the driver and rear right passenger positions and have two pieces of luggage in the boot in conformity with DIN 75410-2. For registration of the force transmitted from the vehicle to the barrier 9 load cells are placed between the barrier and the impact block.

Self-protection rating procedure

This procedure is used to determine the risks for the occupants. The total risk is a combination of the **injury risk** and the **rescue risk** , Figure 7..



* limiting factors for total risk evaluation

Figure 7. Diagram for total risk rating

Injury risk: Assessment of the injury risk is based on a body part related rating system. Risk marks are identified for individual body parts. Generally the injury risk mark for the driver and rear passenger is the arithmetic mean of all body part risk marks:

$$mark_{driver,passenger} = \sum_{head}^{legs} mark_{body\_part} \ / \ 7$$

But where a biochemical limit for the central body parts head, thorax or pelvis is exceeded there will be a down-valuation to the mark of the respective body part.

Body part marks are composed of the marks for individual criteria. Figure 8. shows a list of the applied individual criteria and their allocation to the body parts. There are primary and secondary criteria. Primary criteria always head the list and are printed in **bold,** secondary criteria are listed below and printed in *italics*.

As a rule only primary criteria marks are used to make up the body part mark. Secondary criteria serve as modifiers and will only be considered where this will generate poorer body part marks than the result from primary criteria. [7] gives a detailed description of the body part related rating system.

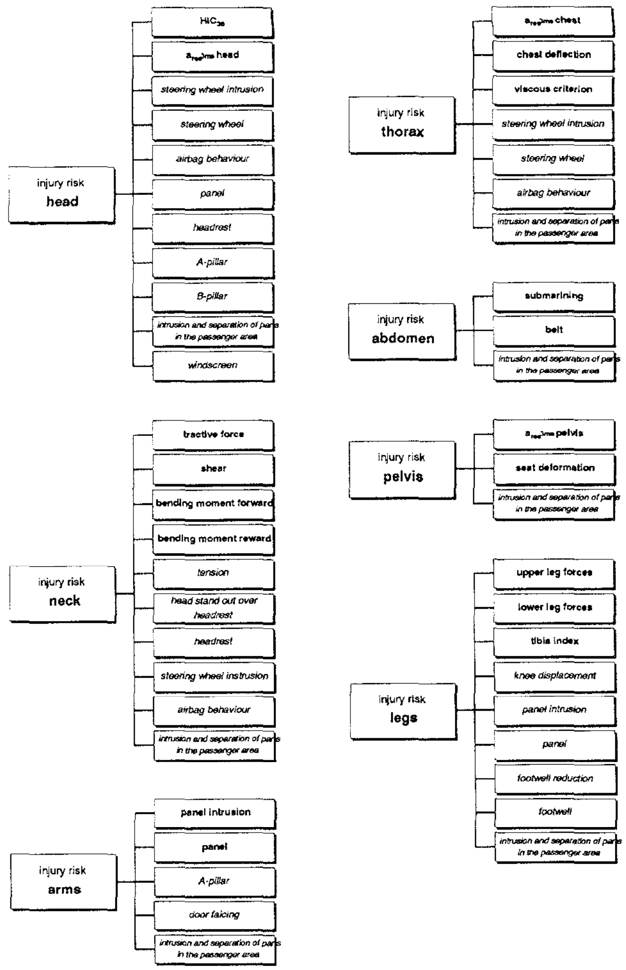


Figure 8. Diagram for body parts injury risk rating

Rescue risk: Figure 9. gives an overview of the assessment criteria for the rescue of occupants of a crashed vehicle. As for injury risk rating the rescue risk total mark is composed of primary and secondary criteria [8].

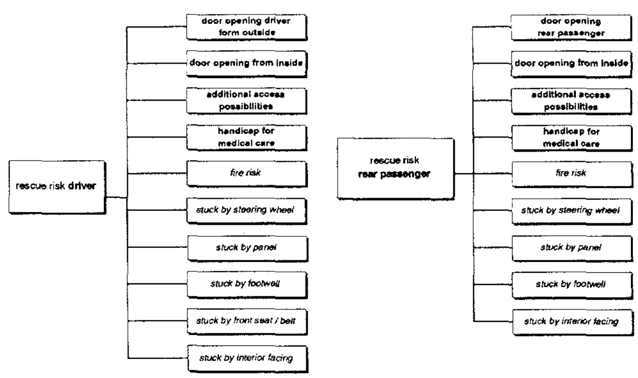
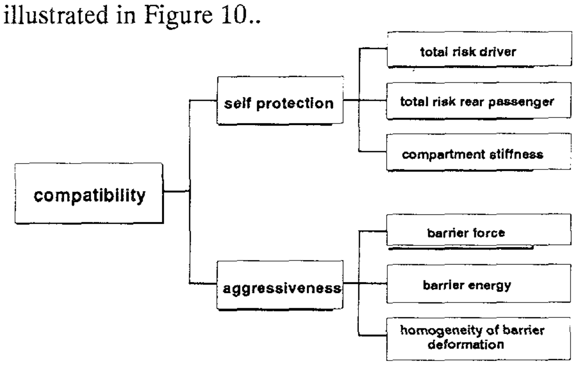


Figure 9. Diagram for rescue risk rating

Compatibility rating procedure

As explained vehicle compatibility is determined both by self-protection performance and aggressiveness [9]. The compatibility rating diagram based on this definition is illustrated in Figure 10..



compatibility mark = worse mark out of self protection an aggressiveness

Figure 10. Diagram for compatibility rating

Only high level self-protection and partner protection performance ensure vehicle compatibility. However, partner protection and thus aggressiveness improvements must not result in a deterioration of the self-protection level. Therefore the compatibility mark is defined not to be better than the worse mark from the two main criteria self-protection and aggressiveness.

Self-protection

Assessment aspects for self-protection are summarised in risk marks are calculated as explained in chapter 5.2. Passenger compartment stiffness is used as an additional

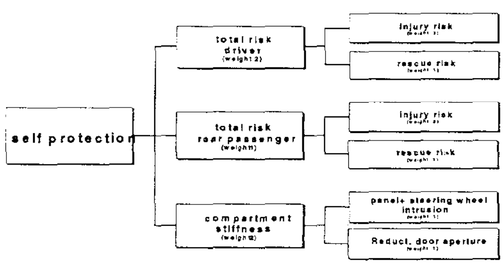


Figure 11. Diagram for self-protection rating

parameter for self-protection assessment (Figure 11.). The mark for compartment stiffness is composed of the horizontal intrusion of the panel and steering wheel and the reduction of the driver door aperture. In order to get precise data targets are affixed to the defined measuring points. There will be measuring before and after the impact. Two mean values are generated from the differences:

1. **Intrusion** mean averaged *from horizontal intrusions of* the measuring points
- panel far left
- panel left of steering column
- panel right of steering column
- panel left of centre console
- steering wheel center.

2. **Door aperture reduction** mean averaged from aperture reductions of measuring points
- lower rim door window level
- horizontal door lock level
- horizontal door sill level.
- diagonal bottom left to top right.

The resulting mean values are marked on the basis of the scale shown in Figure 12.. This will generate a mark for both intrusion as well as for the reduction of the door aperture, the total mark for compartment stiffness is then established in a 3:1 ratio.

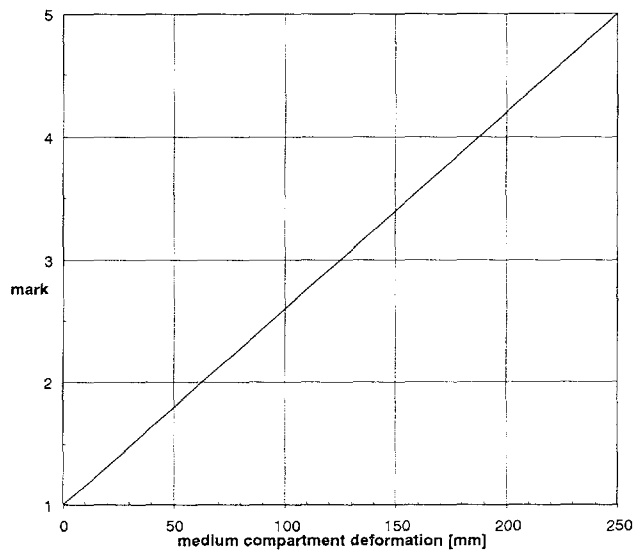


Figure 12. Scale for compartment stiffness

Aggressiveness

Figure 13. shows the diagram for aggressiveness rating. There are the following three main criteria:

Barrier force: For crash testing force measuring devices are placed behind the deformable barrier for registration of the forces impacting the collision partner - in this case the barrier. Rating is based on the maximum value and the total force mean established for a period of 200ms. Figure 14. shows the marking scale for maximum and mean barrier forces.

Barrier energy: From axial barrier surface element displacements the energy absorbed by the barrier is determined according to the formula described in chapter "barrier". Translation of this energy to the rating mark is done on the basis of the scale shown in Figure 15..

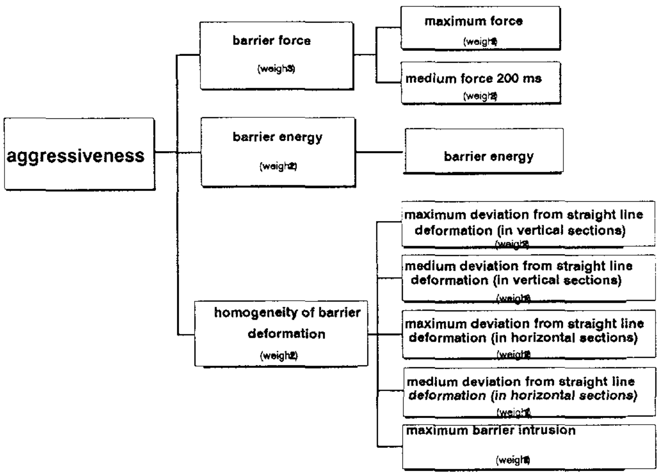


Figure 13. Diagram for aggressiveness rating

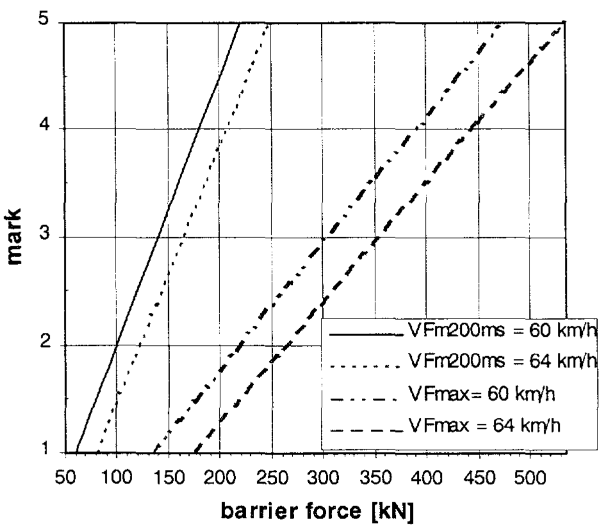


Figure 14. Scale for maximum and medium barrier force

Homogeneity of front-end stiffness: From the deformation pattern it can be read whether the front-end allows for extensive mutual cover and support (shield function) or penetrates the barrier deeply due to stiff protruding vehicle components. For quantification of such homogeneity the horizontal and vertical sections of the deformed barrier surface are examined on the following criteria, Figure 13.:

- maximum deviation from correlation straight line deformation in horizontal direction
- mean deviation from correlation straight line deformation in horizontal direction
- maximum deviation from correlation straight line deformation in vertical direction
- mean deviation from correlation straight line deformation in vertical direction
- maximum intrusion.

Figure 16. shows the marking scales for these homogeneity criteria.

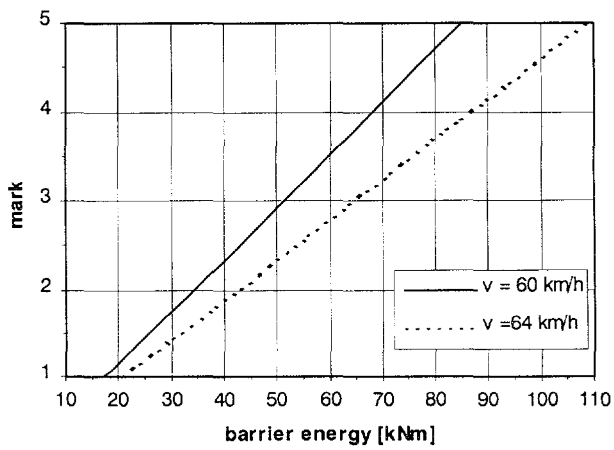


Figure 15. Scale for barrier energy

Findings

Results from barrier tests are translated into assessment marks on the basis of the rating procedures explained before. The findings are presented in Figure 17..

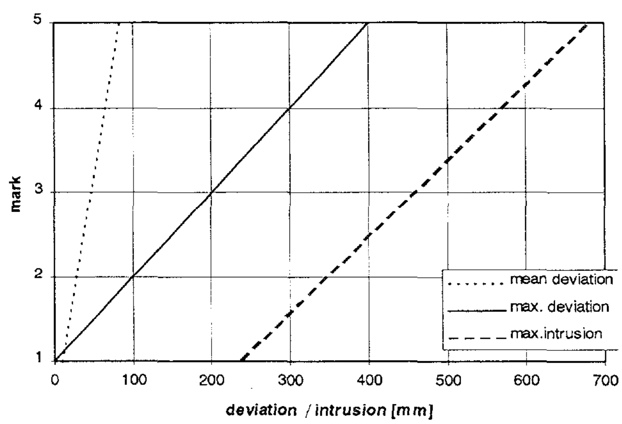


Figure 16. Scales for barrier deformation

		small size cars					upper mid size cars			
	weight	Citroen Saxo	Mitsubishi Colt	Fiat Punto	Ford Fiesta	Ford KA	Lancia k	Volvo S70	BMW 520i	Mer-cedes E
total risk driver	2	4,5	3,2	3,9	2,8	3,0	3,8	2,0	1,8	1,7
total risk rear passenger	1	2,8	4,8	2,7	2,6	2,4	1,8	1,8	1,3	1,5
compartment stiffness	2	4,7	3,9	4,3	3,3	3,5	4,4	1,8	1,6	1,5
self protection		**4,5**	**3,8**	**3,9**	**2,8**	**3,1**	**3,8**	**2,0**	**1,8**	**1,7**
self protection mark cannot be better than total risk driver mark (limiting factor)										
	weight									
barrier force	3	1,2	2,0	1,6	1,8	1,7	2,9	3,1	2,8	3,2
barrier energy	2	1,2	1,4	1,3	1,5	2,1	2,5	2,4	2,5	3,2
homogeneity of barrier deformation	2	2,5	4,1	1,9	3,7	3,0	2,3	2,3	2,4	3,0
aggressivity		**1,6**	**2,4**	**1,6**	**2,3**	**2,2**	**2,6**	**2,7**	**2,6**	**3,1**
compatibility		**4,5**	**3,8**	**3,9**	**2,8**	**3,1**	3,8	2,7	2,6	3,1
compatibility mark=worse mark out of self protection and aggressivity										

Figure 17. Compatibility rating for small cars and big family saloon cars.

The above table illustrates that the self-protection and partner protection performance for the **Citroen Saxo** is rather unbalanced. Resistance at the barrier is too low which has a very negative influence on self-protection. In this test series energy transmission to the barrier is lowest for the Saxo (25 kJ). Also behind the barrier the lowest forces by far are measured. While aggressiveness is low for the Saxo this unfortunately has a fatal effect in terms of self-protection. Because of a too low deformation resistance it absorbs most of the energy itself. At the same time the greater part of the energy is transferred to the passenger compartment which is too weak and collapses totally. For the driver this presents a lethal injury risk. In view of the poor self-protection performance the Saxo is a vehicle with low compatibility.

Like the Saxo the **Fiat Punto** has no sufficient balance between self-protection and partner protection. The low energy input in the barrier (27 kJ) and low reaction forces prove the gentle treatment of the collision partner. From the extensive and balanced deformation of the barrier it can be seen that front-end stiffness distribution of the Punto is very homogeneous. But passenger compartment stability is far too low. Most of the impact energy is transferred to the passenger compartment which means considerable reduction of the driver's survival space. This increases the total risk for the driver and is finally reflected by the relatively poor compatibility mark.

Front-end and passenger compartment stiffness is far more balanced for the **Ford Fiesta.** In terms of partner protection only the non-homogeneous front-end stiffness distribution is to be criticised. The longitudinal is still too stiff in the front section and penetrates the barrier deeply. But the passenger compartment is still stable enough to resist the forces transferred via the longitudinals relatively well. The passenger compartment of the Fiesta shows the least deformation of the small cars tested. This also has a positive effect on the passenger injury risk. As self-protection is on the whole still rated slightly lower than partner protection this is reflected by the compatibility mark. The Ford Fiesta therefore gets a satisfactory compatibility rating. Improvement potential is seen in the deformation performance of the longitudinals. Stability of the passenger compartment could also be improved in order to further reduce the injury risk for passengers.

The **Ford Ka** demonstrates that its partner protection is slightly more developed than that of the Fiesta. Particularly the Ka's front-end stiffness distribution is far more balanced. The modern front-end structure with stable front longitudinals prevents deep penetration of the barrier. However, on the whole the longitudinals are still too stiff and penetrates - if on a broad surface - the barrier very deeply. Thus the Ford Ka transmits far more energy to the collision partner than the other vehicles tested, but this will be an advantage in a crash with a heavier vehicle . Since self-protection rating of the Ford Ka is not as high as for partner protection its compatibility performance can only be graded satisfactory. Particularly in terms of driver survival space the passenger compartment still has some weaknesses. Driver injury risk in the Ford Ka is slightly higher than for the Fiesta. Still, the Ka with its modern design gives the best examples for what compatible vehicles could be like.

Performance of the **Mitsubishi Colt** is much poorer. Serious self-protection deficits are reflected by the compatibility mark. The passenger compartment is so massively deformed that the driver's survival space is dangerously reduced. Due to insufficient securing of the rear seat back rest especially rear seat passengers may suffer lethal injuries. But the Colt also has partner protection weaknesses. The barrier deformation pattern clearly illustrates that front-end stiffness is very unbalanced. The longitudinal is far too stiff, hardly deformed in comparison with the adjacent components and penetrates the barrier deeply. A positive aspect is the low energy transmission to the collison partner. The Mitsubishi Colt gets a low compatibility rating because of the poor self-protection performance.

The self-protection level of the **BMW 520i** is very high. The risk for both occupants is clearly in the non-critical range. The passenger compartment shows hardly any deformation. Despite the lower impact speed the greater mass aggressiveness of the, in comparison to the small cars, much heavier vehicles is clearly noticeable in partner protection performance. Although the reaction forces measured behind the barrier are higher realtively low remaining forces are identified for a car of this weight class. The energy transferred to the collision partner is quite low. Front-end stiffness distribution is also relatively homogeneous. The stable aluminium cross rail keeps the front end firmly together and helps to ensure the evenly sloped deformation pattern. Only in the lower section some chassis parts protrude aggressively from the body contour. The BMW 520i gets a rather acceptable compatibility mark.

The result for the **Lancia k** is much poorer. The serious self-protection deficits are reflected by the compatibility mark. There is a high risk mainly for the driver. His survival space is significantly reduced by the massive deformation of the passenger compartment. The Lancia's partner protection performance is better. The forces measured behind the barrier are slightly higher than for the BMW but the Lancia transmits slightly less energy to the collision partner. Front-end deformation is very balanced and shows no local aggressiveness. Also the lateral stability of the front-end structure indicates a homogeneous stiffness distribution. Despite the good partner protection performance the Lancia k is rated poor for compatibility due to inadequate self-protection.

The **Mercedes E** has the best results for self-protection of the whole series. The passenger compartment is the most stable and shows only minor deformations. For both occupants the total risk is very low. For partner protection, however, it does not reach fully the level of the test competitors. In a crash the highest reaction forces behind the barrier are measured for the Mercedes, and it transmits considerably more energy to the collision partner. The deformation pattern of the barrier clearly illustrates that front-end stiffness distribution is not optimal. Because the front longitudinals are very stiff the front crossrail shows a stepped deformation pattern. This increases the risk of interlocking of the parties involved in a real-life accident. Due to such partner protection behaviour the Mercedes E can only rated satisfactory for compatibility.

The **Volvo S70** does not quite achieve the self-protection level of the BMW or Mercedes. Deformation of the passenger compartment is slightly worse. But the risk for the two occupants is still clearly in the non-critical range. In partner protection performance the advantages of the state-of-the-art design of Volvo become obvious. The front-end structure is supported by four longitudinals and is kept together by a stable aluminium box-section crossrail. Due to this homogeneous stiffness distribution the front end can deform evenly on a broad surface which is reflected by the evenly sloped deformation pattern of the barrier. And the Volvo transmits even less energy to the collision partner than the Lancia.
The Volvo S70 gets a rather acceptable compatibility mark.

VERIFICATION OF COMPATIBILITY FINDINGS BASED ON CAR TO CAR TESTS

Objectives and test procedure

For verification of the compatibility findings from barrier tests various car to car tests are conducted. In each case a small car is crashed against a big family saloon. The findings from car to car tests are compared with the results gained with barrier tests and examined in terms of conformity.

On the basis of compatibility results the following vehicle pairs are selected:

Citroen Saxo (the weakest of the small cars tested) against **Mercedes E** (a little bit aggressive big car)
Citroen Saxo against **BMW 520i** (a comparatively less aggressive big car)
Ford Ka (a comparatively compatible small car) against **Mercedes E**
Ford Ka against **BMW 520i**
Ford Ka against **Volvo S70** (a comparatively less aggressive big car).

Frontal impact tests are conducted with 50% offset overlapping for the small car. The impact speed of both cars is 50 km/h. Only in the crash Ford Ka against BMW 520i a speed of 55 km/h is reached due to a test facility fault. Dummy and luggage arrangements are identical with those of the barrier tests.

vehicle	Citroen Saxo		Ford KA		
V_{impact} [km/h]	50,1	49,9	50,2	55,1	50,1
opponent	Mer-cedes E	BMW 520i	Mer-cedes E	BMW 520i	Volvo S70
head	4,3	3,9	3,2	2,8	3,0
neck	1,9	2,0	2,4	2,4	2,0
arms	4,5	4,3	4,5	3,5	3,8
thorax	3,2	3,1	2,8	2,5	2,6
abdomen	2,5	2,3	1,5	1,5	1,5
pelvis	5,0	5,0	4,0	2,7	4,0
legs	3,9	3,7	3,7	3,7	4,1

injury risk mark $_{Mercede}$ **>injury risk mark** $_{BMW/Volvo}$

Figure 18. Injury risk marks for individual driver body parts of Citroen Saxo and Ford KA crashing against big vehicles

Findings

Figure 18. gives an overview of injury risk marks for individual body parts of the drivers of the Citroen Saxo and the Ford Ka. A comparison of the data shows:

- In the crash against the Mercedes E the injury risk for most body parts is slightly higher than for the crash against the other big cars. This confirms the findings from barrier crashes that the aggressiveness of the Mercedes is slightly higher.
- Also in car to car tests the injury risk in the Citroen Saxo is generally higher than in the Ford Ka. This is another confirmation of the findings of the barrier tests.

SUMMARY AND CONCLUSION

The study had the objective to improve the existing frontal impact test procedure against the deformable barrier in order to not only generate findings on passenger protection but also on vehicle aggressiveness and therefore compatibility.

First compatibility is defined as a vehicle feature which is related both to self-protection performance and aggressiveness towards the other vehicle. The level of aggressiveness depends on the amount of energy and the force transmitted to the other party but also on whether such transmission is distributed over a broad surface or has only a local quality.

The current barrier does not supply this data and thus no information on compatibility. Moreover, this barrier's energy absoprtion is too low for bigger vehicles and penetration resistance is too low for vehicles with a highly non-homogeneous stiffness distribution which can have a negative effect on passenger protection results in terms of real-life accidents.

In order to avoid these disadvantages the barrier will be improved along the following lines:

- higher energy absorption capacity (about 2.5 times) by partition into several layers with gradually increasing stiffness
- higher penetration resistance through multi-layer feature
- force measuring device behind the barrier
- determination of dynamic pressure stiffness of the barrier

These measures provide the opportunity to gain the following additional crash testing information:

- force transmission to the other party (from the behind barrier force)
- energy transmission to the other party (from barrier deformation)
- horizontal and vertical front-end stiffness distribution (from homogeneity of barrier deformation).

A rating system is developed which considers both passenger protection and aggressiveness and thus allows for quantification of passenger protection as well as aggressiveness and compatibility from test results.

The testing of the new barrier and rating system is made within the framework of barrier tests with several small cars and big family saloons. Subsequent car to car tests confirm the compatibility findings from barrier tests.

It can be said that the new barrier is functioning very well and that its performance is by far superior to that of the today's European standard barrier. Energy absorption for all tested vehicles was adequate, there was no bottoming out of vehicle components on the barrier base.

The car to car tests confirm the practicability of the rating procedure. The hypotheses and standards used must however be elaborated and endorsed through additional tests.

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