PROGRESS OF PASSIVE SAFETY IN CAR-TO-CAR FRONTAL COLLISIONS: RESULTS FROM REAL-LIFE CRASH ANALYSES AND FROM CRASH TESTS

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ABSTRACT

The progress of passive safety in car-to-car frontal collisions can be seen very clearly from the results of crash tests with old and new car models. The published federal accident statistics show an overall effort in passive safety, which is obvious by decreasing figures of killed and severely injured car occupants per year on German roads. But it is not possible to exclusively focus on car crashes with frontal collisions because the characteristics investigated in official statistics are not detailed enough. Therefore additional in-depth studies are necessary.

The paper shows results of car-to-car and car-to-barrier frontal impacts for old and new car models. Some results of evaluations using the federal German statistics show historical trends in a more general view. Interdisciplinary real-life crash studies are focused on car-to-car frontal collisions. Results of connecting assessments using vehicle deformation index (VDI), energy equivalent speed (EES), velocity change (delta-v) and occupant injuries (injury severity, AIS) for old and new cars certify an effort of passive safety.

Finally compatibility aspects "new car to old car" caused by different front-end stiffness and mass are discussed.

INTRODUCTION

Safety of cars has been improved for decades now. In general this can be seen in a long-term view on the number of killed or severely injured occupants in accident-involved cars. Examples are given by the German Federal Statistics [1] (Figure 1 and 2).

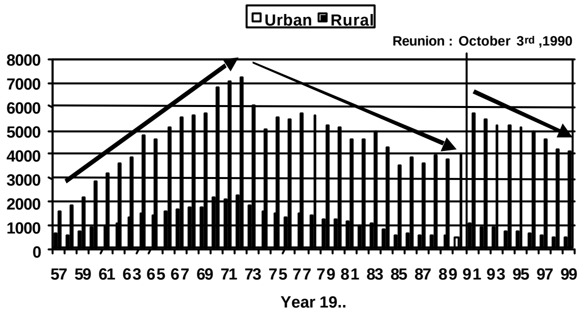


Figure 1. Fatally injured occupants in accident-involved cars on German roads from 1957 to 1999 (Source: Federal Statistics)

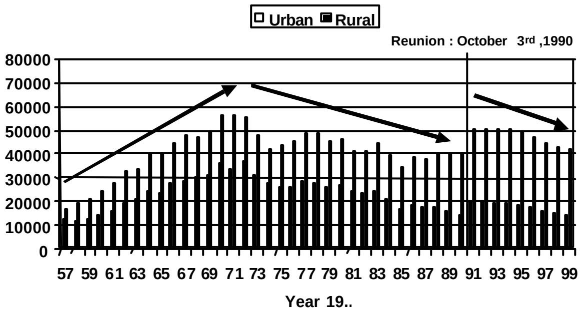


Figure 2. Severely injured occupants in accident-involved cars on German roads from 1957 to 1999 (Source: Federal Statistics)

In the Federal Republic of Germany the number of killed car occupants rose till the beginning of the 70ies. The year 1972 showed a maximum of 2,259 killed car occupants urban and 7,198 rural. In the following years the figures decreased up to the German reunion in 1990.

After that the decreasing trend continued again. For 1999 the statistics recorded 420 fatally injured car occupants urban and 4,120 rural. Similar trends show the figures of severely injured car occupants. For 1970 the statistics recorded 36,054 severely injured car occupants urban and 56,177 rural. For 1999 there are 14,420 severely injured urban and 41,824 rural.

The absolute figures have to be weighted with the number of registered cars and their kilometrage, [2] figure 3. These figures have risen during the years so that the specific risk of car occupants of being killed or severely injured in a traffic accident actually sank much more than it can be seen by the total number of victims only.

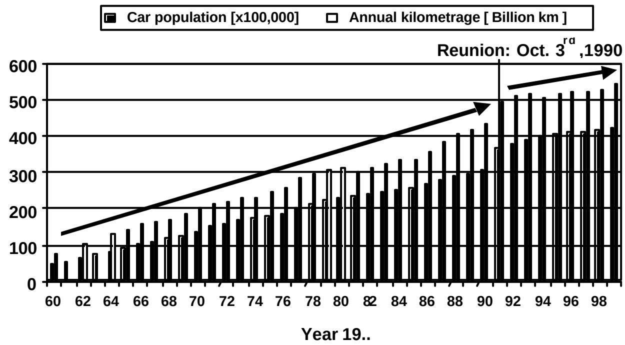


Figure 3. Car population and annual kilometrage of cars in the Federal Republic of Germany (Source: Federal Statistics)

The relative risk of a car occupant of being slightly injured (no stay in hospital), severely injured (stay in hospital) or fatally injured (death within 30 days) in an accident is indicated by the percentage of the figures within these victim groups relating to all victims (sum of slightly injured, severely injured and killed). As shown in figure 4, the percentage of severely injured and killed was nearly constant at about 30 % during the 60ies and 70ies and began to decrease at the beginning of the 80ies. Up to the reunion in 1990 this percentage reached almost 20 %. After the reunion the percentage increased shortly with a following trend down to 20 % again.

As described with these examples, an overall effort in the passive safety of cars is obvious. Reasons for this are multiple: E.g. improvements of roads, rescue service, driver education, surveillance, general infrastructure and of course improvements of car safety.

Car manufacturers first focused on improving passive safety in frontal impacts. At the beginning in the late 80ies and early 90ies, consumer crash tests first focused on frontal impacts, too. Therefore it is of interest, to ask whether the improved frontal impact performance of cars has any positive effect upon real world crashes. It is not possible to detect any special benefit only by examining federal accident statistics because these statistics are not detailed enough [3].

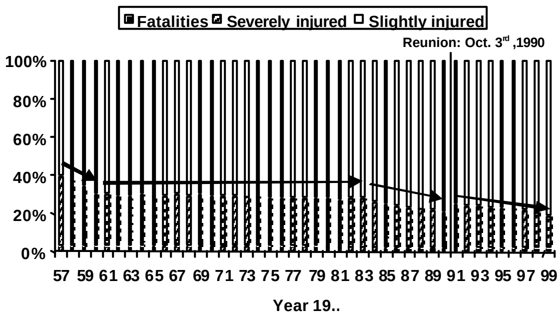


Figure 4. Percentage of fatally injured, severely injured and slightly injured car occupants in relation to all of these victims per year in Germany from 1957 to 1999 (Source: Federal Statistics)

Using an in-depth accident database, the authors looked for a method to detect progress of passive car safety in real world frontal impacts. The idea was to focus only on car-to-car frontal impacts. In such head-on collisions the effort of frontal crash performance becomes visible when comparing the accident outcomes of both vehicles involved as well as the damages and injuries of the occupants. The database used, the method of analysis and first results are shown in this paper.

In order to illustrate the effort of passive car safety which is obvious by the results of crash tests, some of such tests with old and new cars and their results are included in the paper. This gives additional impressions of the differences of structural performance and occupant loads (measured as dummy responses). Discussing the study and their results, there are some aspects dealing with compatibility, too.

CRASH TEST RESULTS

Efforts of the body structure performance of a car can be seen at the different model generations of the Volkswagen Golf. This is an example similar to the improvement of passive safety of many other cars within the very popular compact class. The Golf I (1974 – 1983) showed some distinguishing marks of a safety design: The front end was equipped with a solid transversal member fixed to the longitudinals. Depression ribs at the longitudinals controlled an energy-absorbing crumple process of the sheet metal during a frontal impact [4]. The structure of the Golf II (1983 – 1991) looked similar, with some more reinforcements to sustain higher crash test loads [5].

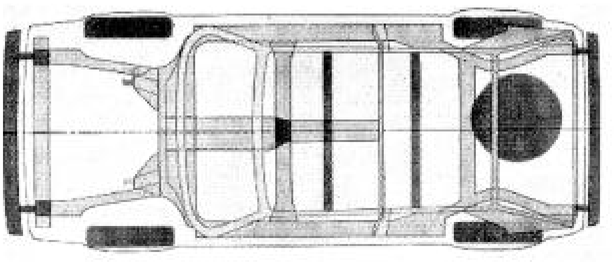


Figure 5. Body structure of Golf I (1974 – 1983) [4]

Some substantial enhancements showed the structure of the Golf III (1991-1997), figure 6. Several load paths lead to a more homogeneous load distribution even in asymmetrical frontal impacts [6]. The current Golf IV (since 1997) shows the latest evaluation step of all Golf models and represents the state of the art in passive safety of modern compact cars [7].

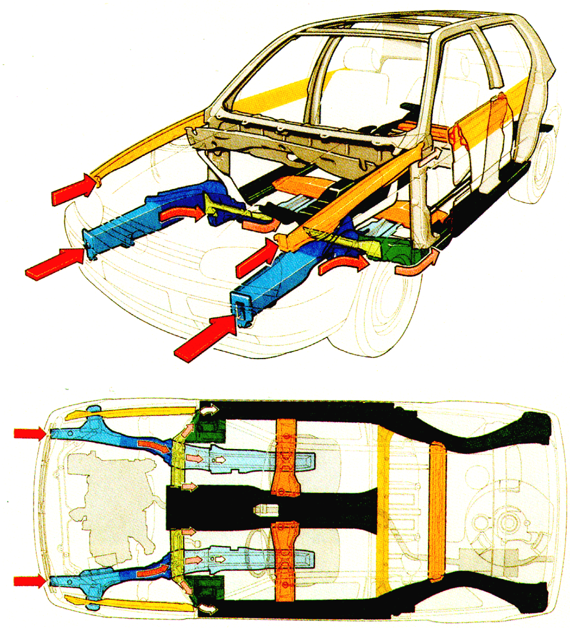


Figure 6. Body structure of Golf III (1991 – 1997) [6]

Results of consumer crash tests with the Golf II, Golf III and Golf IV, published in the magazine "auto motor sport", supply evidence of effort of the structure performance, [8, 9, 10] table 1. For all these tests the car impacted at 55 kph with 50 % frontal overlap on a fixed rigid barrier. Despite higher masses, the intrusions into the passenger compartments, e.g. steering column, dashboard or pedal decrease for the newer models.

Together with structural improvements, the restraint system was improved, too. The Golf I was equipped with static belts, later with automatic belts. The Golf II showed improved belt geometry with the buckle fixed to the seat base. The belt system in the Golf III was additionally fitted with pretensioners. Starting in 1993 the restraint system of the Golf III was supplemented by front airbags for driver and front passenger. In the Golf IV the restraint system consists of airbags and a belt system which is equipped with pretensioners and additional force limiters.

Table 1. Results of rigid barrier crash tests regarding the structure performance of different model generations of the Volkswagen Golf (55 kph, 55 %) [8, 9, 10]

	Golf II	Golf III	Golf IV
Vehicle Mass [kg]	1,145	1,252	1,390
Test Velocity [kph]	55.2	55.2	55.0
Steering Column Displacement Vertical [cm]	-19	-4	-5
Steering Column Displacement Horizontal [cm]	-18	-8	-4
Dashboard Displacement Vertical [cm]	-11	-7	-2
Dashboard Displacement Horizontal [cm]	-32	-24	-9
Pedal Displacement Vertical [cm]	-23	-5	-7
Pedal Displacement Horizontal [cm]	-32	-24	-14
Reduction Compartment Length [cm]	-46	-27	-11
Force To Open Right Door [N]	∞	> 500	430

Of course there are not only improvements regarding frontal impacts of the different Golf model generations. For Golf III and especially Golf IV some other improvements of the passive safety in side impacts and rollover protection have been established [6, 7] which are not mentioned here because this paper deals only with frontal impacts.

Improvements of the passive safety of cars in frontal impacts are obvious in car-to-car crash tests with old and new car models. An example gives a frontal impact Ford Fiesta ´85 (1,117 ccm, 50 hp) versus Ford Fiesta ´98 (1,388 ccm, 90 hp), carried out by DEKRA in 1998 [3] (see figure 7).

Figure 7. Car-to-car crash test Ford Fiesta model ´98 (1,388 ccm, 90 hp) versus Ford Fiesta model ´85 (1,117 ccm, 50 hp) both at 55 kph, 50 % frontal overlap

The cars impacted at a speed of 55 kph against each other (closing velocity 110 kph) with 50 % frontal overlap. Hybrid-III dummies (50^{th} percentile male) represented driver and passenger in both cars.

Characteristics of the passive safety of the model ´98 are reinforced compartment structure and load paths in the front structure to distribute asymmetrically impact forces as in an offset crash test. The occupants were restrained by safety belts with belt-stopping elements and pretensioners. Anti-dive ramps in the front seats prevent a sliding under the pelvic belt (submarining). Airbags for driver and passenger supplement the belt system. The same Fiesta model got 3 stars in the 4-star-rating EURONCAP frontal crash test series “superminis” in 1997 [11].

The Fiesta model ´85 was equipped only with automatic belts without additional subsystems such as pretensioners. The structure of this model was drafted in the 70ies. At that time such cars were not designed with regard to offset crash. Figure 8 shows a frontal offset crash test with the same model ´86 carried out by DEKRA in 1998 [3].

The impact velocity in the barrier test was 55 kph, that is the same as in the car-to-car test (figure 7) and 9 kph less than in a 64-kph EURONCAP frontal crash test. It is obvious that the energy absorption capacity of the front structure was totally used-up and the passenger compartment began to collapse. The horizontal intrusion of the brake pedal was measured at 227 mm, the horizontal intrusion of the steering wheel lay at 236 mm and of the footwell left at 287 mm.

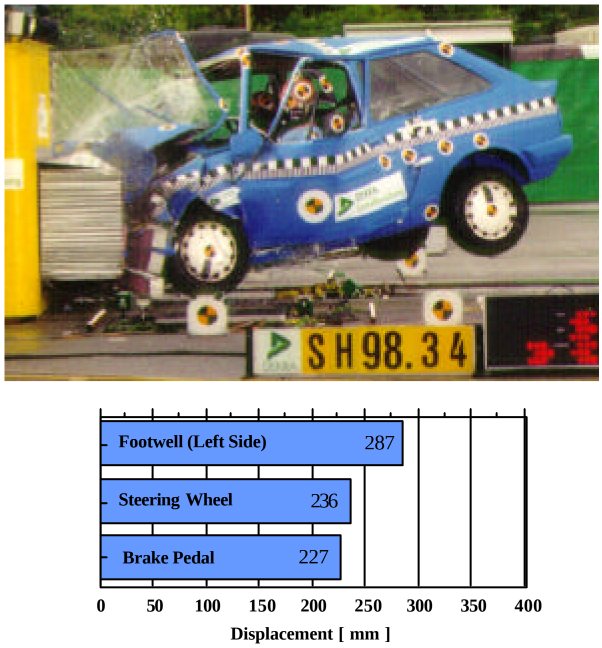
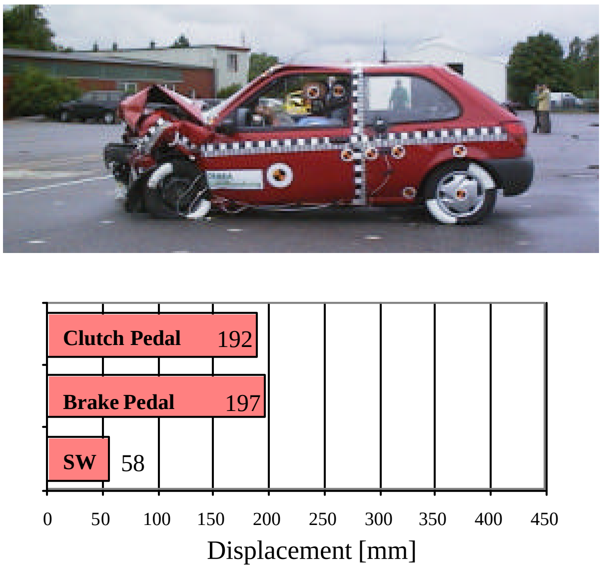


Figure 8. Offset crash test of a Ford Fiesta model ´86 (1,117 ccm, 50 hp) at 55 kph impact velocity with 40 % overlap against a deformable ECE-R-94 barrier

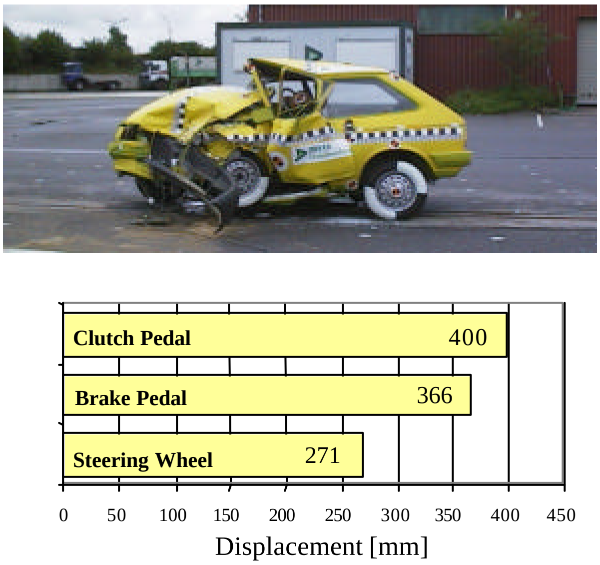
Results of the car-to-car test for the Fiesta model ´85 are shown in figure 9. The clutch pedal intruded horizontally 400 mm, the brake pedal 366 mm and the steering wheel 271 mm. Compared to corresponding intrusions in the 55 kph impact on the deformable barrier (figure 8) it is evident to see that for this car model the car-to-car crash was more severe. Reasons for this are given by the vehicle masses (test mass 970 kg for the Fiesta ´85 and 1,198 kg for the Fiesta ´98). The collision-induced velocity changed: delta-v was 60 kph for the Fiesta ´85 and 53 kph for the Fiesta ´98. Also of importance for the damage severity is the stiffer front end of the Fiesta ´98.

Compared to the Fiesta model ´85 it is obvious that the deformation of the Fiesta model ´98 is significantly less severe, figure 10. The clutch pedal intruded horizontally 192 mm, the brake pedal 197 mm and the steering wheel 58 mm.



Measured Value	Driver	Passenger
HIC	281	225
Resultant Head Deceleration (3ms-Value)	41 g	36 g
Resultant Chest Deceleration (3ms-Value)	38 g	32 g
Chest Deflection	22 mm	-
Resultant Pelvis Deceleration (3ms-Value)	51 g	38 g
Femur Force (Left Side)	8.0 kN	-
Femur Force (Right Side)	2.7 kN	-

Figure 9. Results of the car-to-car crash test (see figure 7) for the Fiesta model ´98



Measured Variable	Driver	Passenger
HIC	977	743
Resultant Head Deceleration (3ms-Value)	116 g	86 g
Resultant Chest Deceleration (3ms-Value)	92 g	40 g
Chest Deflection	39 mm	-
Resultant Pelvis Deceleration (3ms-Value)	63 g	28 g
Femur Force (Left Side)	8.8 kN	-
Femur Force (Right Side)	4.9 kN	-

Figure 10. Results of the car-to-car crash test (see figure 7) for the Fiesta model ´85

In the Fiesta model ´98 the dummies were loaded far below the corresponding biomechanical limits. For example HIC = 281 for the driver and HIC = 225 for the passenger (see figure 9). Only the left femur of the driver was loaded with 8.0 kN closer to its limit 10 kN, but did not reach it.

Significantly more severe were the loads of the dummies in the Fiesta Model ´85, see figure 10. HIC = 977 for the driver and HIC = 743 for the passenger lay below their limit HIC = 1000. But the deceleration of the head a_{3ms} = 116 g for the driver and a_{3ms} = 86 g for the passenger lay above its limit 80 g. The chest deceleration of the driver a_{3ms} = 92 g was also considerably above its limit 60 g.

To sum up the results of the car-to-car crash tests, the effort of passive safety of cars in frontal impacts are clearly visible. There is a more proper performance of the structure of the Fiesta model ´98 than of the Fiesta model ´85 so that the passenger compartment in the newer model fulfils its function as a safety cell much better. This was the prerequisite for belt and bag to work as an effective restraint system for driver and passenger.

REAL WORLD CRASHES

With the background described in the chapter above it is of interest whether the efforts in passive safety of cars in frontal impacts can be seen in real world crashes, too. This question is not trivial. Real world accident scenarios are much more complex than crash tests. There are variations of overlap, impact angle and impact velocities. And it has to be kept in mind that (less expensive) older cars are more often driven by younger people than (more expensive) newer cars and that the individual injury tolerances of younger people are higher than those of older ones. For such reasons the outcomes of real world crashes could be surprising in some cases. Two examples shall give insights into real world crash scenarios of frontal impacts. The technical reconstructions were done by DEKRA engineers who are trained technical experts for accident reconstruction. The description and assessment of the injuries were made in cooperation with medical doctors who are members of the Society of Real Life Accident Analyses.

VW Polo III (´96) versus VW Golf II (´87)

As shown in figure 11 a VW Polo III (model year ´96, 1,390 ccm, 60 hp, mass 1,000 kg) impacted frontally a VW Golf II (model year ´87, 1,760 ccm, 90 hp, mass 1,050 kg). The Polo impacted at 46 kph, the golf at 66 kph (closing velocity 112 kph). Both vehicles overlapped at 50 %. Golf and Polo were occupied only with a driver each. The Polo was equipped with an airbag. Technical reconstruction came to EES = 52 kph, delta-v = 55 kph for the Golf and for the Polo EES = 55 kph, delta-v = 53 kph.

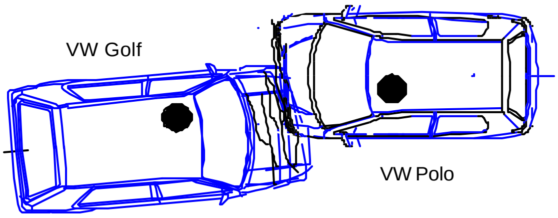


Figure 11. Impact situation with a VW Golf II (66 kph, 1,050 kg) impacting a VW Polo (46 kph, 1,000 kg) both at 50 % frontal overlap

The damaged Golf is shown in figure 12. It was classified as VDI 5 = 4 (VDI = Vehicle Deformation Index with reference to SAE J 224a). In this car the male driver was trapped and the fire brigade had to use spreaders to rescue him. He suffered fractures at knees and femur bones left and right and cuttings in his face. His maximum AIS was classified as AIS 3. He stayed in hospital for 9 weeks. After that a rehabilitation followed with unknown duration.

Figure 13 shows the damaged Polo. The damage was classified as VDI 5 = 3. For the rescue of the female driver, the door could be opened by hand. She suffered a fracture at the left knee (AIS 2), stayed in hospital for 4 weeks and after that she was under medical treatment for some more weeks.

Figure 12. Damage to the Golf II Model year ´87 (1,760 ccm, 90 hp) after rescue of driver (EES = 52 kph, VDI 5 = 4)

Figure 13. Damage to the Polo III Model year ´96 (1,390 ccm, 60 hp) after rescue of driver (EES = 55 kph, VDI 5 = 3)

This example confirmed that in a frontal car-to-car impact the driver in an older car is essentially more endangered than in a new one. The female driver in the Polo model ´96 was in fact less severely injured than the male driver in the Golf model ´87. The Polo was designed with regard to the frontal offset crash. Its front structure deformed under control and the compartment did not collapse. Under this circumstances the restraint system with SRS Airbag saved head and chest properly.

The front structure of the older Golf II did not work with the same efficiency. Behind the footwell and at the dashboard some intrusions reduced the survival space in the compartment. Head and chest of the driver were not saved by an airbag, therefore a head impact on the steering wheel could occur.

Opel Kadett E (´88) versus Golf III (´94)

Figure 14 shows the impact situation of an Opel Kadett E (model year ´88, 1,998 ccm, 112 hp, mass 1,100 kg) which impacted at 100 % overlap against a Golf III (model year ´94, 2,792 ccm, 165 hp, mass 1,230 kg). Impact speeds were 95 kph for the Kadett and 35 kph for the Golf (closing velocity 130 kph). The Opel was occupied with driver and passenger, the Golf only with driver. In the Golf an airbag was installed as supplement to the belt system. As a result of the technical reconstruction an EES = 65 kph was given for the Kadett and EES = 55 kph for the Golf. Delta-v was 67 kph for the Kadett and 58 kph for the Golf.

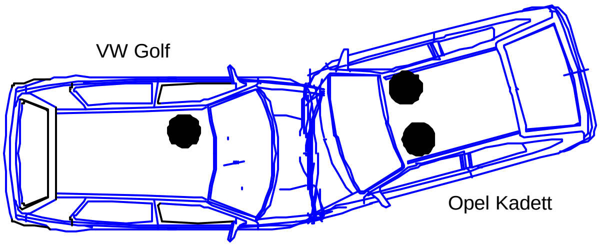


Figure 14. Impact situation with an Opel Kadett E (95 kph, 1,100 kg) impacting a VW Golf III (35 kph, 1,230 kg) both at 100 % frontal overlap

The damage of the Kadett was classified by VDI 5 = 5, see Figure 15. VDI 5 = 4 was the damage classification of the Golf, see figure 16.

The driver in the Kadett was belted. He had contact with the steering wheel, suffered severe facial injuries and fractures at the 3rd and 4th lumbar vertebrae. The maximum AIS was 3. The passenger of the Kadett was not belted. He impacted with his head roof and windshield, suffered severe head injuries (AIS 6) and died at the accident scene.

The driver of the Golf was belted, too. He suffered a whiplash neck injury and a pelvic fracture (AIS 3).

The front structure of the Kadett was totally deformed and severe intrusions into the compartment behind had to be diagnosed. Due to this, the survival space was reduced significantly, so that driver and passenger impacted intruding structures with their heads. This lead to fatal injuries of the unbelted passenger.

In contrast to the Kadett, the Golf absorbed deformation energy almost completely by its front structure. The compartment remained stable without severe intrusions.

Figure 15. Damage to the Kadett E Model year ´88 (1,998 ccm, 112 hp) after rescue of driver and passenger (EES = 65 kph, VDI 5 = 5)

Figure 16. Damage to the Golf III Model year ´94 (2,798 ccm, 165 hp) after rescue of driver (EES = 55 kph, VDI 5 = 4)

This example shows that the damage to an older car model generation in a frontal collision with a newer car model generation of the same class is more severe even in fully overlapped impacts. But it also shows that for belted drivers the AIS classification could be the same (AIS = 3 for both drivers). Also remarkable is the fact that an unbelted passenger runs a much higher risk of being more severely or fatally injured (passenger in the Kadett died).

STATISTICAL ANALYSIS

Keeping in mind the variations of real world crashes it is obvious that just by looking at car-to-car frontal impacts, there can be found single cases with surprising outcomes. The interesting point now is to see whether the analysis of a sample of such accidents can have any statistical benefit. If such a benefit becomes evident, not only in a qualitative but also in a quantitative manner, it can be stated that the improvements of passive safety of cars in frontal impacts had surely lead to injury reductions and life savings in real world crashes. To analyse this, a pilot study was carried out.

Database

An existing database of DEKRA Accident Research containing 1,120 car accidents was used. The accidents happened all over Germany within the years 1996 to 1999. In a first step, all cases which are not of interest for the pilot study were excluded:

- accidents with pedestrians and two-wheelers
- accidents with involved heavy vehicles (vehicle mass more than 2.8 tons)
- accidents with multiple impacts
- accidents with not only frontal car-to-car impacts

The remaining sample contains 146 accidents. In a second step, cases were excluded which did not fulfil the following requirements:

- frontal overlap 50 % or more (no glance of)
- impact direction frontal (VDI 1 = 12 ± 1)
- information about accident severity, vehicle deformation and occupant injuries of good quality for both cars

That finally leads to a sample of 74 accidents used for the pilot study.

Then it was necessary to define “old” and “new” cars. An individual assessment, for example regarding results of NCAP tests, could not be done because the remaining number of cases would have become too small. It was decided to take the model year ´93 as the border between old and new cars since the historical passive safety efforts of cars delivered for the German market with regard to frontal impacts showed remarkable progress at the beginning of the 90ies (for example VW changed from Golf II to Golf III or Opel from Kadett E to Astra). Since 1993 almost all new cars coming into traffic in Germany have been equipped with front airbags. To tune a supplementary restraint system (belt & bag), a lot of crash tests had to be done. These tests also had led to further optimizations of the car body structure. Thus for the pilot study cars with the construction year before 1993 are classified as “old”. Cars with the construction year 1993 or later are classified as “new”. Amongst the 74 cars used for the pilot study 52 (70 %) are old and 22 (30 %) new. Figure 17 shows the distribution of the damage to the cars within the two groups classified by Vehicle Deformation Index VDI 5.

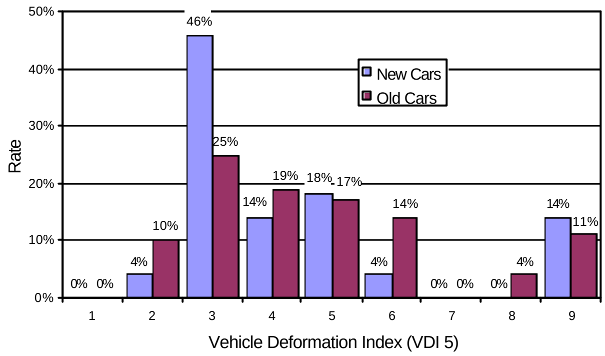


Figure 17. Distribution of damage classified as Vehicle Deformation Index (VDI 5 = 1 to 9) for the 52 old cars and for the 22 new cars

65 % of the old cars have a deformation VDI 5 = 4 or more. For the new cars this percentage is 50 %. VDI 5 = 5 (deformation depth up to A-pillar) or more (behind A-pillar) are given for 29 % oft the old cars and 18 % of the new cars. This shows that in general the old cars were deformed more severely than the new cars.

Similar results are given by the injury severity of the occupants, figure 18. 80 % of the occupants in new cars suffered injuries with AIS 3 or less. This was the case for 52 % of the occupants in old cars. In the old cars 30 % of the occupants were killed. For the new cars the share of killed occupants was at 17 %.

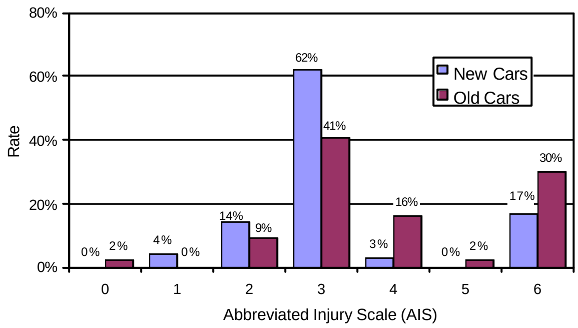


Figure 18. Distribution of the injury severity (AIS 1 to 6) of the occupants in the 52 old cars and in the 22 new cars

Correlation between vehicle deformation VDI, deformation energy EES, collision-induced velocity change delta-v and injury severity AIS

For the two car groups a Spearman Rank-Correlation Coefficient was calculated with results as shown in table 2. This indicates what quality of a functional coherence is given between AIS and VDI, AIS and EES and AIS and delta-v within the two groups [13, 14, 15]

Table 2. Spearman Rank-Correlation Coefficient for AIS, VDI and EES for the two car groups

	Old Cars	New Cars
AIS and VDI	0.57	0.77
AIS and EES	0.6	0.6
AIS and Delta-v	0.43	0.57

Using the method of minimal fault square, the best function was found as an exponential function:

$$y = p_0\, p_1^{\,x}$$

Parameters p_0 and p_1 were estimated with 500 steps of iteration with a standard estimation fault of 0.02.

Figure 19 shows the single values determined for the accidented cars and the calculated values of the correlation curve. The spread of the single values is here recognizable.

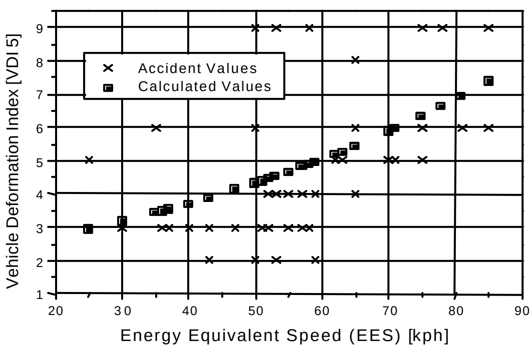


Figure 19. Correlation between vehicle deformation VDI 5 and Energy Equivalent Speed EES for old cars (Accident values and calculated values)

The correlation between VDI and EES which was found for old and new cars in the pilot study is shown in figure 20. The curves go nearly in parallel. Old cars show higher VDI at all EES values. This means that absorbing the same deformation energy, the front structure of old cars is more deformed than those of new cars. In other words: The frontal structure of new cars is stiffer. This qualitative result had been expected.

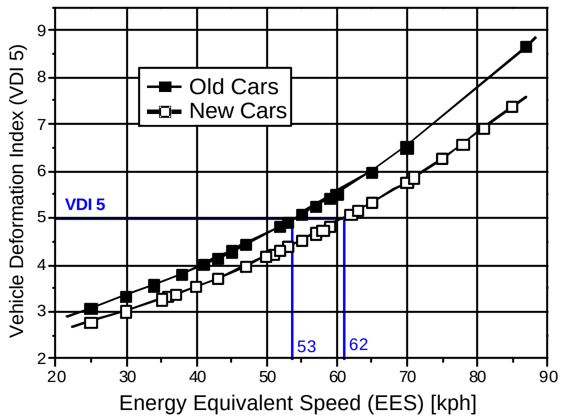


Figure 20. Correlation between vehicle deformation VDI5 and Energy Equivalent Speed EES for old and new cars

For the cars of the pilot study this could be quantified as follows: A deformation energy which is equivalent to EES = 53 kph leads to VDI 5 = 5 for old cars. A damage of new cars with the same VDI requires an EES = 62 kph.

Figure 21 shows the correlation which was found for VDI 5 and delta-v for old and new cars in the pilot study.

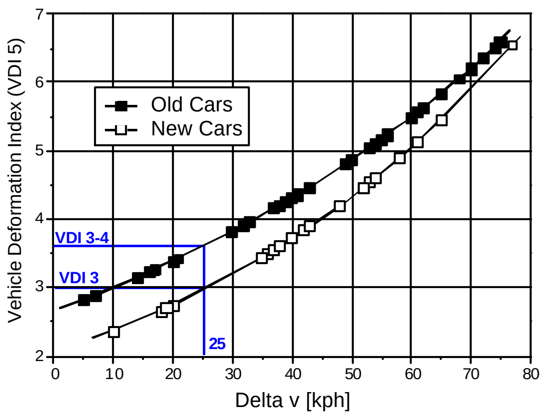


Figure 21. Correlation between vehicle deformation VDI 5 and collision-induced velocity change delta-v for old and new cars

The grades of deformation for old cars are higher at all velocity changes. At a delta-v of 25 kph a new car is classified by a deformation of VDI 5 = 3 whereas an old one have VDI 5 = 3-4.

Figure 22 shows the correlation which was found for AIS and delta-v for old and new cars.

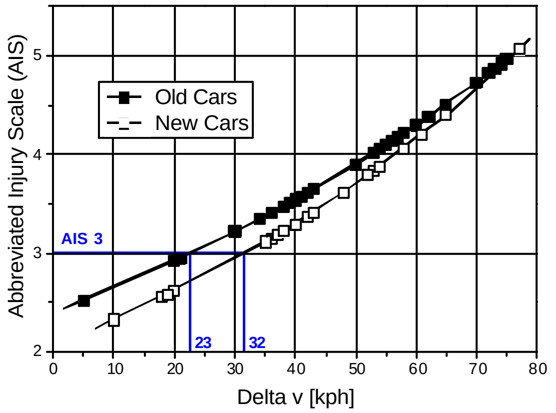


Figure 22. Correlation between collision-induced velocity change delta-v and occupant injury severity AIS for old and new cars

At the same value of delta-v, the AIS value is lower for new cars than for old ones. The difference is greater for lower values of delta-v and decreases with higher values. This qualitative result had also been expected. It has to be taken into account that at high delta-v values above 70 kph there are a lot of so-called “catastrophic accidents”. If cars are involved in such accidents, the risk of being severely injured or killed is extremely high even in new cars. The real safety benefit of new cars is given at impact velocities up to the relevant test speeds which is for example 65 kph in an EURO NCAP frontal crash test (40 % overlap, deformable barrier).

For the cars in the pilot study this can be quantified as follows: A delta-v of 23 kph leads to AIS = 3 for occupants in old cars. For occupants in new cars the same AIS = 3 is given by a delta-v of 32 kph.

Figure 23 shows the correlation which was found for VDI 5 and AIS. Discussing the result, first it was not satisfactory that at higher values of VDI 5 (5 - 7) the AIS was higher in new cars than in old ones. But it has to be kept in mind that VDI 5 = 5 indicates a deformation of the car front up to the A-pillar. VDI 5 = 6 and more indicates severe intrusion into the compartment. These again are “catastrophic accidents” with extreme risks for the occupants to be severely injured or killed regardless whether the car is old or new.

With a deformation severity less VDI 5 = 6 the occupants in old cars suffer more severe injuries than those in new cars. This result is as expected. For the cars in the pilot study this can be quantified for example with AIS = 3. In old cars for this injury severity the deformation lies near VDI 5 = 2. For new cars to the same AIS = 3 corresponds VDI 5 = 4.

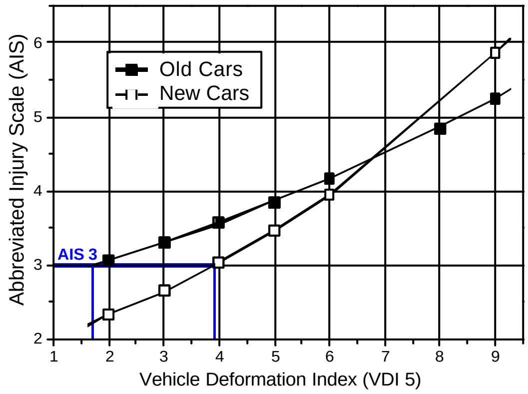


Figure 23. Correlation between Vehicle Deformation Index VDI 5 and occupant injury severity AIS for old and new cars

Of special interest for medium severe frontal impacts are VDI 5 = 3 (reduction of the front length approximately up to the front wheel) and VDI 5 = 4 (reduction of the front length approximately up to the front axle). Table 3 gives the corresponding EES and delta-v for old and new cars in the pilot study.

Table 3. Energy Equivalent Speed EES and collision-induced velocity change delta-v for old and new cars which are deformed with VDI 5 = 3 and VDI 5 = 4

	VDI 5 = 3	VDI 5 = 3	VDI 5 = 4	VDI 5 = 4
	Old Cars	New Cars	Old Cars	New Cars
EES [kph]	10	25	34	44
Delta-v [kph]	23	30	42	47

For the old cars in the pilot study VDI 5 = 3 was given at EES = 10 kph and delta-v = 23 kph. For new cars and the same VDI 5 = 3 there were EES = 10 kph and delta-v = 30 kph. Looking to VDI 5 = 4 and old cars there is EES = 34 kph and delta-v = 42 kph. For new cars and the same VDI 5 = 4 there is an EES = 44 kph and a delta-v = 47 kph. In general this shows that for the same deformation severity VDI 5 = 3 to VDI 5 = 4 the collision-induced velocity change delta-v is between 7 and 5 kph higher for the new cars than for the old ones in the pilot study. The EES is between 15 and 9 kph higher for the new cars than for the old ones.

Taking into account that the front structure of new cars is stiffer than that of old cars, these results are as expected as far as quality is concerned. The method used to generate functional relations shows a possible and, as seen so far, successful way to give additional quantitative information.

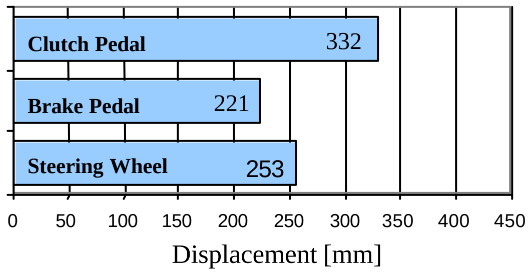
COMPATIBILITY ASPECTS

The effort of passive safety of new cars in frontal impacts is based fundamentally on a good performance of the front structure. To catch good results in consumer tests for example the requirements in an EURO-NCAP frontal crash test with 64 kph have to be fulfilled. Therefore compared to older cars the front stiffness of new cars has increased. This was also the result of the analyses of real world crashes. Additionally the masses of new cars have increased. This gives the background to discuss compatibility aspects regarding frontal impacts with old and new cars.

To demonstrate a car-to-car frontal crash situation which could have happened in the 80ies, DEKRA carried out a car-to-car frontal crash test with two VW Golf II (1,570 ccm, 75 hp) in the year 2000, Figure 24. Both vehicles impacted at 55 kph (110 kph closing velocity) with 50 % frontal overlap against each other. The year of construction of both cars was 1987. Hybrid-III dummies (50^{th} percentile male) represented driver and passenger and were restrained by safety belts.

The damages to the cars and the dummy loads are shown in Figure 25 and 26.

Figure 24. Car-to-car crash test VW Golf II model year´87 (1,570 ccm, 75 hp) versus VW Golf II model year ´87 (1570 ccm, 75 hp) both at 55 kph, 50 % frontal overlap



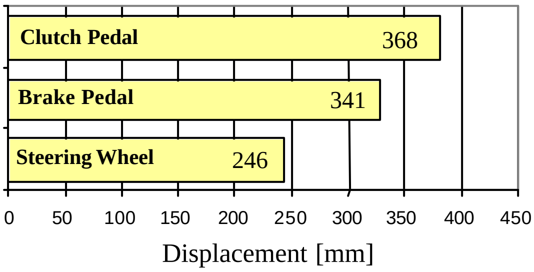
Measured Value	Driver	Passenger
HIC	457	115
Resultant Head Deceleration (3ms-Value)	73 g	26 g
Resultant Chest Deceleration (3ms-Value)	44 g	21 g
Chest Deflection	49 mm	17 mm
Resultant Pelvis Deceleration (3ms-Value)	42 g	28 g
Femur Force (Left Side)	7.4 kN	-
Femur Force (Right Side)	1.9 kN	-

Figure 25. Results of the car-to-car crash test (see figure 24) for a VW Golf II ´87

The frontal structures of both cars were severely damaged and were not able to absorb all the deformation energy. Therefore the compartments began to collapse. The clutch pedals intruded 332 mm respectively 368 mm, the brake pedals 221 mm respectively 341 mm and the steering wheel 253 mm respectively 246 mm.

Depending on the impact situation the measured dummy loads indicate more severe injury risks for the drivers than for the passengers. With a_{3ms} = 104 g one of the measured head accelerations was above the limit a_{3ms} = 80 g. It must be realized that the risk of being severely injured or killed in such an “accident of the 80ies” with typical cars of that time is evident.

During the years the mass of such compact-class cars increased considerably, figure 27 shows this for example for the different Golf model generations. Therefore and because of fundamental physics in frontal impacts with potential crash opponents in the same class, the collision-induced velocity change delta-v increased for an old car during the years.



Measured Variable	**Driver**	**Passenger**
HIC	759	292
Resultant Head Deceleration (3ms-Value)	104 g	58 g
Resultant Chest Deceleration (3ms-Value)	42 g	28 g
Chest Deflection	19 mm	-
Resultant Pelvis Deceleration (3ms-Value)	46 g	37 g
Femur Force (Left Side)	6.2 kN	-
Femur Force (Right Side)	5.5 kN	-

Figure 26. Results of the car-to-car crash test (see figure 24) for a VW Golf II ´87

If in the 80ies a Golf II with a mass of 900 kg impacted with the front fully overlapped the same car, each with 55 kph, its delta-v was 55 kph (supposing a fully plastic impact). If today the Golf II impacts a Golf IV with a mass of 1,300 kg under the same circumstances (55 kph each car and full frontal overlap), for the Golf IV the delta-v is 45 kph and for the Golf II it is 65 kph. Due to this, the injury risk of the occupants in the old car increases during the years.

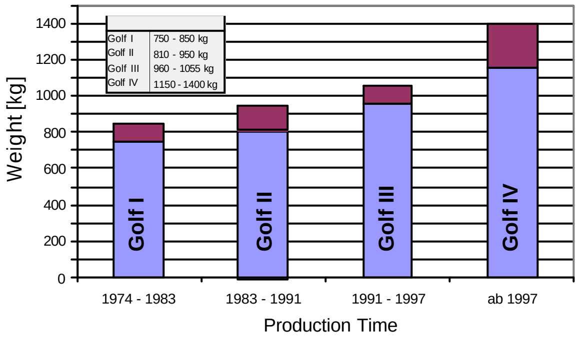


Figure 27. Curb weight of the VW Golf model generations during the years 1974 to 1997

Taking into account that modern compact cars have stiffer front ends than older ones, there is an additional risk of severe damages and intrusion into the compartment of the old car with corresponding increased injury risk.

These compatibility aspects should also be taken into account while discussing the progress of passive safety of cars in frontal impacts. Finally this process must be understood as an evolution. The better performance of modern cars in frontal car-to-car impacts and of course in single accidents like frontal impacts against rigid obstacles – is bound to border old cars. An overall passive safety of the car fleet which is recently on the streets depends not only on the crash performance of the newest vehicles. In car-to-car crashes with frontal impacts for both opponents in total it depends at least on an average performance. It is this average performance that leads to more and more passive safety which can be seen by less severely injured and killed car occupants registered in the annual statistics. The more old cars leave the fleet and the more new ones enter it, the more will this average performance of passive safety increase in the future.

SUMMARY AND CONCLUSIONS

From point of view of the development engineers it is well known that improvements of crashworthiness of cars had be done during the years since the 70ies with a first focus on frontal impacts. This development was like an evolution process. Consumer crash tests in Germany began at the end of the 80ies with a first focus on frontal impacts, too. In 1993 most of the new cars coming into traffic on German roads were equipped with airbags to supplement the belt system. To tune supplemental restraint systems, a lot of crash tests had to be done and this was also helpful to some further optimizations of the car front structure even in offset crash tests.

The results of crashtests show these efforts of passive safety by measured car damage and dummy responses under defined test circumstances. This becomes clearly visible by comparing the results of frontal car-on-barrier impacts and frontal car-to-car impacts of old and new cars. Examples are shown in the paper.

Regarding this technical background from an accident researcher's point of view it is of interest whether the progress of passive car safety in frontal impacts can be noticed in real world crashes, shows that too - not only in a qualitative but also in a quantitative manner. This is of special interest because of the variety of real world crash scenarios. Even the focus on crashes with frontal impacts only speeds and impact angles could vary in a wide range. Taking into account different individual constitution and resistance of occupants against crash loads, the outcome of some real world crashes could be surprising. Finally it is of interest whether a remaining positive statistical effect can be noticed.

For the Federal Republic of Germany the accident statistics show an overall progress of passive safety since the beginning of the 70ties with decreasing figures of fatally and severely injured car occupants in general for all accident types. It is not possible to focus only on frontal impacts because the federal statistics are not detailed enough. Therefore additional in-depth studies are necessary.

Using an in-depth database with 1,120 accidents which happened in the years 1996 to 1999 in Germany, the authors have looked for a method to detect progress of passive safety of cars in real world frontal impacts. In a pilot study a sample of 74 accidents involving only car-to-car frontal impacts were analysed. The cars were separated in "old" cars with the year of construction before 1993 and in "new" cars with the year of construction in 1993 or later.

Using an exponential function $y = p_0 \; p_1^x$, correlations between vehicle deformation index VDI, deformation energy EES, collision-induced velocity change delta-v and injury severity AIS were found for the old cars and new cars in the used sample. The results show that for the old cars compared with the new cars:

- at the same value of EES the vehicle deformation VDI 5 is greater
- at the same delta-v the Vehicle Deformation Index VDI 5 is greater
- at the same delta-v the maximum AIS of the occupants is greater within the relevant range of delta-v up to 70 kph
- at the same Vehicle Deformation Index VDI 5 the AIS is greater within the relevant range of VDI 5 up to 6.

These results are as expected and indicate that the front structure of new cars at the same deformation depth absorb more deformation energy, is stiffer and at least in conjunction with the safety cell and the restraint system protects the occupants better than old cars. With the functions found this could not only be described in a qualitative manner – it gives additional quantitative information, too.

These quantitative results are described in the paper, but cannot be generalized yet. Therefore it is planned to continue the study by using greater samples in the future. It is also planned to separate old and new cars not only by the year 1993 but – if possible – by results of EURO-NCAP rating tests.

spects of compatibility "old against new cars" are being discussed in the paper, too. During the years, increasing masses and stiffer front structures of new cars have lead to a greater accident severity for old cars in front-to-front collisions than it was the case when old cars impacted the same "old opponent" under the same circumstances. With this background efforts of passive car safety in frontal impacts have to be understood as an evolution process. An overall passive safety in the car fleet which is recently on the streets depends not only on the performance of the newest car generation. It is an average performance that leads at the end to more and more passive safety which can be seen from lower numbers of severely injured and killed car occupants in the annual statistics. The more old cars leave the fleet and the more new ones enter it, the more will this average performance of passive safety increase in the future.

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