

CRASH TEST USING A CAR WITH AUTOMATIC PRE-CRASH BRAKING

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Abstract - The utilisation of secondary-safety systems to protect occupants has attained a very high level over the past decades. Further improvements are still possible, but increasingly minor progress is only to be had with a high degree of effort. Thus, a key aspect must be the impact to overall safety in an accident. If reliable information is available on an imminent crash, measures already taken in the pre-crash phase can result in a significantly great influence on the outcomes of the crash. With this background preventive measures are the key to a sustainable further reduction of the figures of crash victims on our roads.

This paper aims to show a preventive approach that can contribute to lessening the consequences of a crash by creating an optimum interaction of measures in the fields of primary and secondary safety. To further enhance vehicle safety, driver assistant systems are already available that warn the driver of an imminent front-to-rear-end crash. The next step is to support him in his reactions or if he fails to react sufficiently, to even initiate an automatic braking when the crash becomes unavoidable. Automatic pre-crash braking can, in an ideal situation, fully prevent a crash or can significantly reduce the impact speed and thus the impact energy (and the severity of the accident).

If a vehicle is being braked in the pre-crash phase, the occupants are already being pre-stressed by the deceleration. The information available about the imminent crash can be used to activate the belt tensioners and likewise other secondary-safety systems in the vehicle right before the impact. The pre-crash deceleration also causes the front of the vehicle to dip. Conventional crash tests do not take this specific impact situation into consideration. This is why, for example, the influences of the pre-crash displacements of the occupants are not recorded in the test results. Furthermore, a reproducible representation of the benefit of the vehicle safety systems which prepare the occupants for the imminent impact is not possible.

In order to demonstrate the functions of automated pre-crash braking and to investigate the differences during the impact as a consequence of the altered occupant positions as well as the initiation of force and deformations of the vehicle front, DEKRA teamed up with BMW to carry out a joint crash test with the latest BMW 5 series vehicle. It involved the vehicle braking automatically from a starting test speed of 64 km/h (corresponding to the impact speed set by Euro NCAP) down to 40 km/h. The test was still run by the intelligent drive system of the crash test facility. This required several modifications to be made to the test facility as well as to the vehicle.

The paper will describe and discuss some relevant results of the crash test. In addition, the possible benefits of such systems will also be considered. The test supplemented the work of the vFSS working group (vFSS stands advanced Forward-looking Safety Systems).

NOTATION

a	deceleration
E	energy
m	mass
v	velocity

INTRODUCTION

Primary-safety systems designed to avoid accidents and secondary safety systems for lessening the consequences of an accident used to be considered separately. This isolated approach is omitted because it was recognised that primary-safety systems favourably influence both primary and secondary safety.

One example of this is the Electronic Stability Control ESC. It was primarily developed to prevent accidents following a loss of vehicle control (so-called skidding accidents). Analyses of real-life accidents have, however, shown that ESC not only prevents accidents, but also can mitigate unavoidable accidents and their consequences. [1, 2, 3]. One typical example is the alteration to the impact situation. Normally for occupants particularly lateral impacts are more severe than frontal

impacts. Due to the effect of ESC lateral impacts can be avoided (by changing into less severe frontal impacts resulting in less severe consequences).

Another example is the Brake Assist System BAS. It supports the driver after the initiation of an emergency braking by helping to reduce the speed of the vehicle by a maximum and bringing it to the halt (or until the braking is interrupted) at the highest possible deceleration level. This shortens the brake distance and can avoid collisions. Where the accident cannot be avoided, it reduces the impact speed (and thus the severity of the accident) in collisions with for example stationary obstacles, other vehicles or pedestrians. The potential of a conventional BAS to prevent accidents and to lessen the consequences can be further enhanced by combining it with distance radar [4].

This led to the introduction of the term "integrated safety". Here, a holistic approach is taken to the effect of vehicle safety systems both as regards primary safety as well as secondary safety.

By using information from the pre-crash phase, certain passive systems can already be influenced at an early stage. This improves the effectiveness of the safety measures overall. If the vehicle has already reached a state of dynamic instability, or if a head-on collision is unavoidable, the belts, for example, of driver and front passenger can be pre-tensioned and the seat backs straightened. This brings the occupants into a stress-decreasing position [5].

Despite these additional safety effects that have been verified many times in findings derived from real-life accidents, primary and secondary safety still continue to be evaluated separately in the relevant test scenarios. Crash tests serve to test and evaluate the secondary safety of a vehicle, covering the performance of deformation zones, occupant cell as well as the seat belts and airbags. The primary safety, such as the performance of ESC and BAS, for example is analysed in separate driving tests.

So far there exists no test standard that enables a reliable and comparative assessment on the extended effect of primary-safety systems on the secondary (passive) safety. In order to be able to reproducibly test and evaluate the effects of relevant systems in crash tests according to the holistic approach of integrated safety, the pre-crash reactions of the vehicle must be initiated in a realistic manner well before the impact with the barrier. If, for example, automatic pre-crash braking is initiated before the impact, the vehicle front dips and a displacement of the occupants relative to the vehicle takes place. Both factors are important for the course and the results of the crash test. However, these are not taken into account in today's standards.

VFSS WORKING GROUP

The aim of the vFSS working group (vFSS stands for advanced Forward-looking Safety Systems) is to promote the market penetration of front protection systems designed to avoid accidents and to lessen the consequences of accidents into the volume-model segment and to further improve road safety. To achieve this it is necessary to stipulate test standards for preventative safety systems that reflect real-life situations. In order to attain this, all German car manufacturers, the accident research unit of the German Insurers Association (UDV), the Federal Institute for Highway Safety (BASt), the Allianz Center for Technology (AZT) joint under the chairmanship of DEKRA and the Vehicle Test Institute (KTI), set up the vFSS working group. Honda and Toyota joined the group in 2010. Findings from accident research and definitions of system requirements are divided into three work packages "accident analysis", "pedestrian safety" and "longitudinal traffic safety systems".

The preliminary findings of the vFSS working group gave occasion for a demonstration of the efficacy of an emergency braking system in a vehicle impact with a barrier. The first crash

test with such an automatic braking of the vehicle was carried out in the 2,222nd crash test at the DEKRA Crash Test Center in Neumünster.

HISTORIC DEVELOPMENT OF THE ACCIDENT SITUATION AND OBJECTIVES

Accident statistics show that considerable advances in safety have been made over the past decades. For example, in Europe (EU-27) the number of road deaths per year fell from 1991 to 2001 by 28%, **Figure 1**. The 3rd European road safety action program resulted (as seen by preliminary figures) in a further reduction in the number of annual road deaths from 2001 to 2010 by 43%. That means 85 fatalities per day which is still much too high. The new EU guidelines for road safety until 2020 have set the objective of achieving a further reduction of 50% to approximately 15,500 road fatalities per annum (43 fatalities per day).

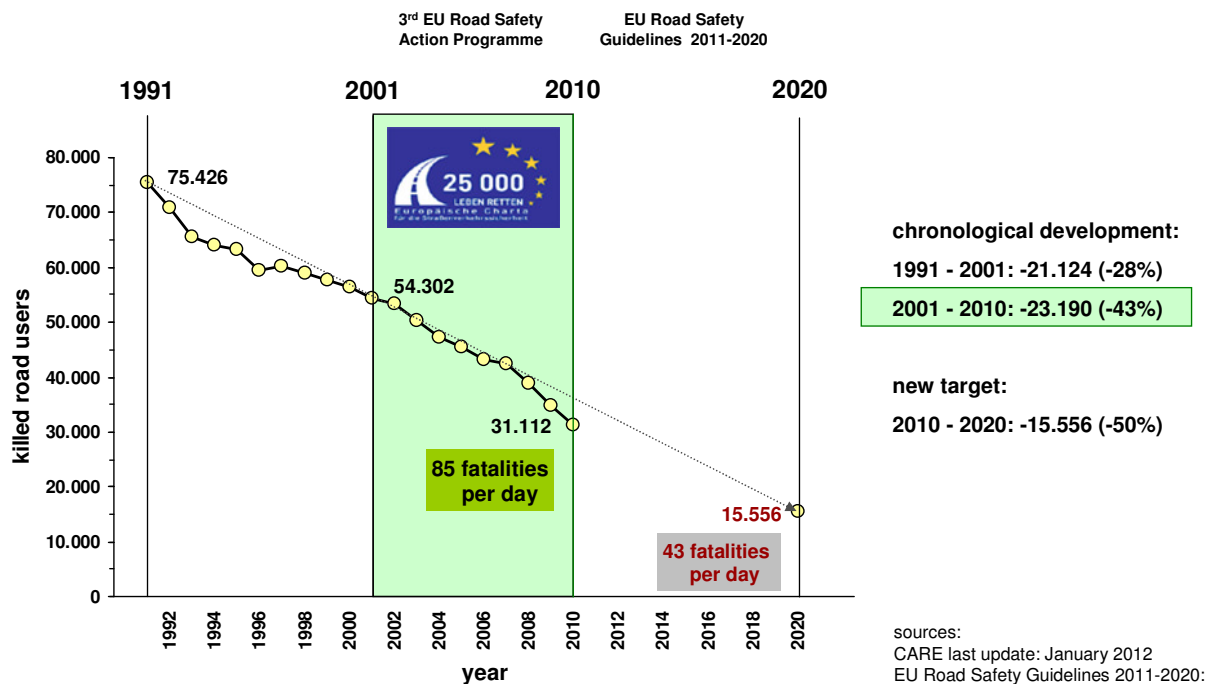


Figure 1. Development of the number of road deaths in the European Union (EU-27) from 1991 until 2010 as well as new objectives

Although a linear continuation of the past trend could possibly see this renewed and very ambitious target being met, it is also just as likely that the previous positive development will reach a “saturation phase” as an effect of the vehicles already equipped with conventional safety technology (including ESC) and will tail away in the future. To ensure that the new objective is met by 2020 it is therefore urgently necessary to introduce new technologies with demonstrable effect to further improve vehicle safety.

EXAMPLE TO DEMONSTRATE THE ENERGY POTENTIAL OF PRE-CRASH BRAKING

A key factor in the severity of a road accidents is the kinetic energy of the vehicles involved at the start of the collision. This energy can be effectively reduced by pre-crash braking. Possible magnitudes of the relevant potential illustrate a simple calculation (see **Figure 2**).

Assumed, that the pre-crash braking is 1.0 s before the collision begins and the vehicle until collision is braked at a medium deceleration of 6.0 m/s². This reduces the speed of the vehicle before the collision by 21.6 km/h. So, the initial speed of 85.6 km/h is reduced to a collision speed of 64 km/h (as in a Euro NCAP crash test). An initial speed of 64 km/h would see the collision speed reduce to 42.4 km/h.

For a vehicle with a mass of 2,100 kg, this means that the kinetic energy in the above mentioned cases would be reduced by 263 kJ (185 kJ respectively) until the collision starts. In a crash test with an impact speed of 64 km/h (Euro NCAP) the impact energy of the vehicle weighing 2,100 kg is 331 kJ. Once the impact has taken place this energy is transformed into deformation work by the "mechanic crumple zone" in the front of the vehicle and in the deformation element on the barrier. Pre-crash braking has therefore produced an additional "virtual deformation zone". Taking the figures assumed in the example, this "virtual deformation zone" can additionally absorb between 56% and 80% of the energy absorbed by the "mechanical deformation zone".

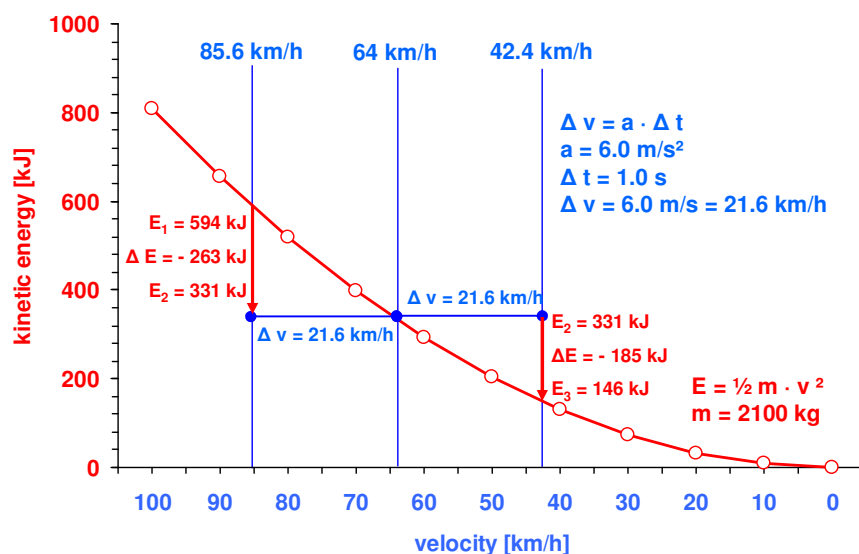


Figure 2. Reductions in the impact energy of a 2100 kg vehicle following pre-crash braking with a deceleration of 6.0 m/s² and duration of 1.0 s at different initial velocities

In order to achieve the same effect using conventional mechanical structures, the vehicle front would need to be considerably longer and/or significantly stiffer. A longer vehicle front would negatively affect the weight, driver vision and vehicle handling. A stiffer front would negatively affect compatibility with regard to the accident exposures of more vulnerable road users. A "virtual deformation zone" does not have such disadvantages. It is merely necessary to be able to safely recognise an unavoidable collision with pre-crash evaluation of signals received by already existing assembly groups in the vehicle, and then, if the driver fails to react, to trigger an automatic pre-crash braking action before the collision.

Such a procedure has already been implemented for collisions in which a vehicle collides with the rear of another vehicle. Such rear-end collisions can be recognised with a high degree of reliability by already existing sensors. Other collision scenarios that can also lead to damage of the vehicle front, such as, for example, front-front scenarios or front-side scenarios cannot be handled in the same way at the moment. However, even if the range of applicability is still currently restricted, these systems represent the launch pad for sustained further improvement.

The basis must always remain the objective of reducing the number of fatalities, injuries and property damage in real-life accident situations for all those involved.

CRASH TEST

In order to represent the effect of a "virtual crumple zone" in an actual crash test, the DEKRA Crash Test Center in Neumünster carried out a test incorporating this aspect. Planning a test involving an automatically braking vehicle poses two challenges: Firstly, the test facility influences object detection by the vehicle sensors and, secondly, the test facility sled system must interact with the braked vehicle.

Most state-of-the-art frontal protection systems detect objects in front of the vehicle using radar sensors. Several problems arise if these sensors operate in a crash-test hall with the crash block has to be reliably detected as a relevant target object. The radar signal can be reflected from all manner of points in the crash-test hall. The hall supports made of reinforced concrete, metal members for the roof as well as supports and stands for providing the crash area with sufficient lighting. All these built-in components represent additional potential detection targets. The crash block also constitutes an upright obstacle. This means that it cannot always be clearly differentiated from other objects as a relevant sensor target. Multiple reflections in the entire hall are likewise possible. To overcome these problems and to conduct a crash test with the vehicle's own environment detection system requires extensive modifications in the vehicle's object detection system. However, the basic principle on which the object detection system works and the reactions of the entire system in the vehicle should not be altered.

In order to hit exactly the pre-defined impact point on the barrier the vehicle guidance system of the facility must be engaged as long as possible. This means not to separate the vehicle from the traction trolley at the moment when the braking is initiated. Thus, the control of the traction cable of the crash facility constitutes a further problem. The desired impact speed is a control variable of crash testing facility. If braking is undertaken on the vehicle during the traction phase, the pulling force of the facility would be simply increased to attain the previously defined impact speed. The regulation of the traction cable drive of the facility had to be altered to prevent this. The software of the modified drive control analyses the additional reaction forces measured in the cable. From this, the traction force momentarily required is computed to, firstly, ensure the longitudinal guidance of the vehicle and, secondly, to follow the deceleration of the vehicle caused by its automatic braking system.

Test Vehicle

The test vehicle was a BMW 530d **Figure 3**. The vehicle is fitted with the currently available active speed regulation system with Stop&Go function including head-on collision warning with braking function. This is a radar-based speed and distance regulation system. The system can also monitor the traffic environment in front of the vehicle if the speed regulation system is not activated. If a critical head-on situation is detected, the driver is warned in two stages. If the critical nature of a head-on collision situation is very high, a visual-acoustic acute warning is additionally activated that initiates an automatic partial braking with a deceleration of 3 m/s^2 . This means the speed is already being reduced during the driver's reaction time. If the driver reacts, he already encounters a pre-stressed brake and swiftly reaches full deceleration with the aid of the brake assistant.

This equipment, which is currently found on production models, was taken as a basis for the development of a prototype front safety system which finally fulfils the requirements of a test in the crash-test hall. This means that it must be first assured that the radar sensor can also reliably detect the target object, in this case the barrier. It is essential that this detection is assured despite the difficult conditions prevailing in the hall.



Figure 3. Test vehicle BMW 530d

Preliminary tests using the production model object detection system have shown that realistic object detection cannot always be reliably guaranteed in the crash-test hall conditions. The sensor is normally configured so that it attains its optimum performance in real-life traffic situations. The laboratory crash test cannot take into account the real-life traffic environment. This is why the object detection system was modified so that the relevant target can be reliably detected in the test-hall environment. Testing in the hall can work with restrictions that are not possible in real-life road traffic, e.g. it can be guaranteed in the test in question that the target object travels will continue in a straight line in front of the vehicle and does not carry out any manoeuvres of its own. It must be noted that the constellation used in the test hall is not suitable for operating the system in real-life traffic, just as much as the production object detection system is equally unsuitable for operation in a crash-test hall.

This alteration in the coordination made it possible to determine the distance to the target object in question, in this case the crash block, as well as the relative speed on the basis of the information provided by the radar sensors of the active speed and distance regulation. It was therefore also possible to trace the entire signal chain from sensor to reaction of the safety systems or to initiation of the automatic emergency braking. Therefore, the safety systems in the test reacted precisely as they would do in a comparable real-life accident scenario.

As the vehicle approached the crash block, different, in part prototype-stage, safety functions were activated, **Figure 4**. Apart from the ACC radar sensor with special object detection, object identification and selection, an ABS with prototype function was also necessary to achieve full deceleration. The vehicle was still equipped with electromotive reversible belt retractors for both driver and front passenger. The strategy employed for the driver warning and the initiation of an emergency braking action was also the subject of a prototype design. Finally, a pre-crash deactivation of the fuel pump was also envisioned. The automatic emergency call function after the crash corresponded to the production standard and was likewise employed as part of the test.

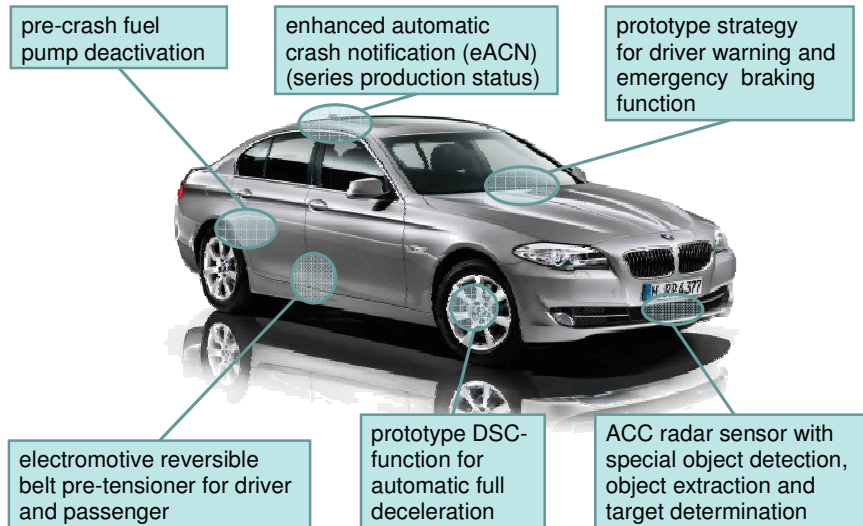


Figure 4. Prototype equipment of the test vehicle with changes to the series production of the BMW 530d

In the course of the test the point was finally reached in which a collision is no longer avoidable by the driver reacting alone (evasion or braking), **Figure 5**. At this point the automatic emergency braking of the vehicle intervenes and reduces the speed at a maximum deceleration stipulated by the friction coefficient between tyres and road surface.

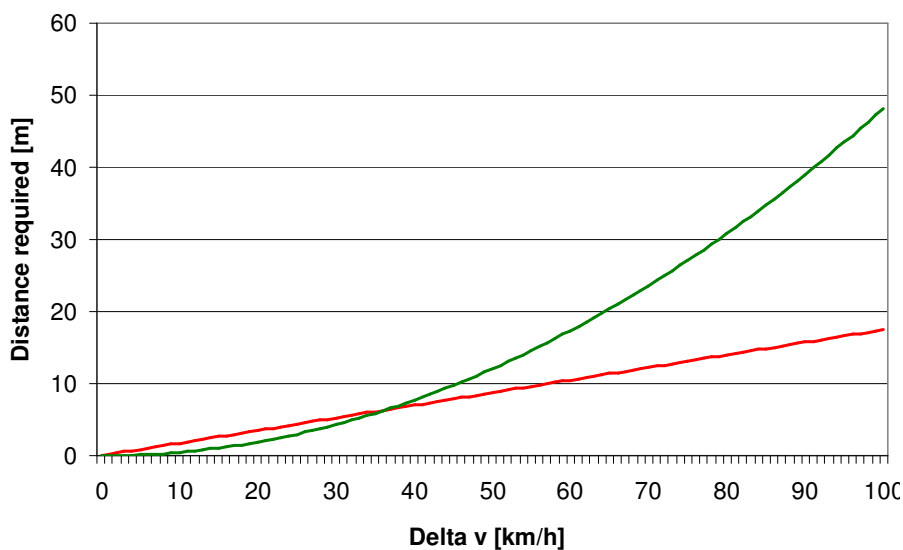


Figure 5. Required distance for an evasive manoeuvre (red curve) and a braking manoeuvre (green curve, $a = 8 \text{ m/s}^2$) to avoid a head-on collision depending on the difference in speed Δv

As a comparison another BMW 5 series car without front safety system was tested conventionally (i.e. unbraked) using the same configuration.

Parameters based on the Euro NCAP or IIHS frontal impact test

A speed of 64 km/h was chosen for the point the automatic emergency braking. This corresponds to the impact speed of the (unbraked) frontal impact test carried out in accordance with Euro NCAP or IIHS. The weight of the vehicle in its test condition was 2,164 kg. The vehicle was tested with a running engine so that it could be assured that all the systems were functioning. As in the Euro NCAP or IIHS test the vehicle overlap at deformable barrier at the crash block was 40%. Driver and front passenger were represented by belted and equipped dummies (Hybrid III 50th percentile male). Children dummies were not used.

In contrast to the normal test procedure in which no pre-crash systems are permitted to be active, they were deliberately activated in this case. Once the vehicle had been accelerated up to the test speed of 64 km/h, the movement continues at a constant speed. At a TTC of 2.1 s (TTC = Time To Collision – time that passes until impact if the speed remains constant) the driver is notified by a visual warning signal of the impending head-on collision. This warning is effected by a red warning light in the instrument panel and by a warning symbol in the head-up display. It means that the driver sees the symbol directly in front of his field of vision. At the same time the brake of the vehicle is pre-stressed and the trigger threshold of the brake assistant reduced.

In the system represented here an acoustic warning to the driver is triggered at a TTC of 1.7 s before the impact. At this time, the system also issues an acoustic alarm in addition to the visual warning. The reversible belt tensioners were activated at a TTC of 1.1 s before impact in order to prevent the occupants from being displaced forward during the braking action. The automatic emergency braking of the vehicle was initiated at 0.9 s before collision. This reduced the speed of the vehicle from 64.8 km/h to 40.4 km/h (-38 %) and corresponds to a reduction of the kinetic energy until collision with the barrier of 61 % from 351 kJ to 136 kJ **Figure 6.**

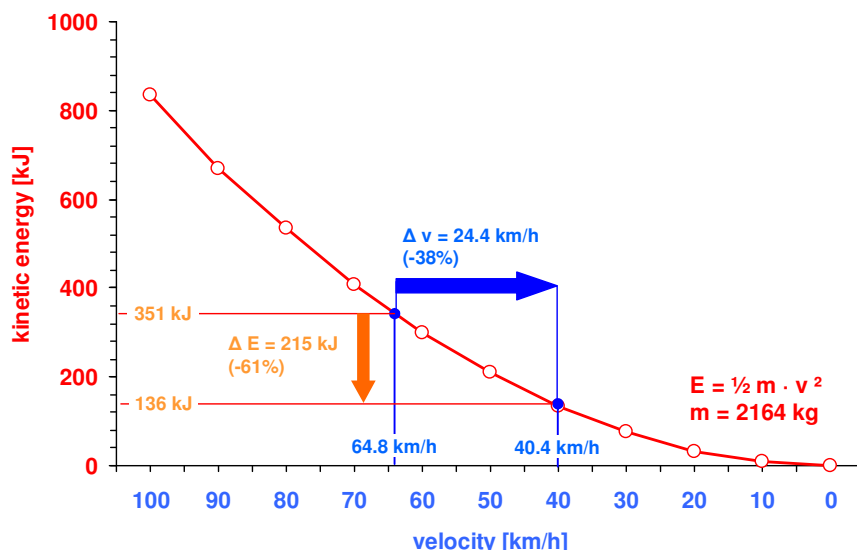


Figure 6. Alteration of the velocity and the kinetic energy of the test vehicle as a consequence of pre-crash braking

The controller of the facility pulling system detected the vehicle deceleration caused by the automatic pre-crash braking and reduced the pulling speed of the drive cable correspondingly. The lateral deviation of the impact point on the barrier was 2 mm only. The dipping of the vehicle front caused by the braking led to a lowering of the impact point by 35 mm, **Figure 7**.



Figure 7. Side view of the braked impact

The comparison vehicle impacted unbraked at 64 km/h into the barrier.

Occupant Loads

Even the production model BMW 5 displayed exemplary behaviour in the unbraked crash test. This is underscored by the superb ratings achieved in the US-NCAP, Euro NCAP and IIHS test procedures. As a consequence of the reduced impact velocity the measured load on the occupant dummies in comparison to the unbraked crash test at 64 km/h was further reduced by a considerable amount. The relative changes of some key load figures for driver and front passenger dummy are shown in **Figure 8**.

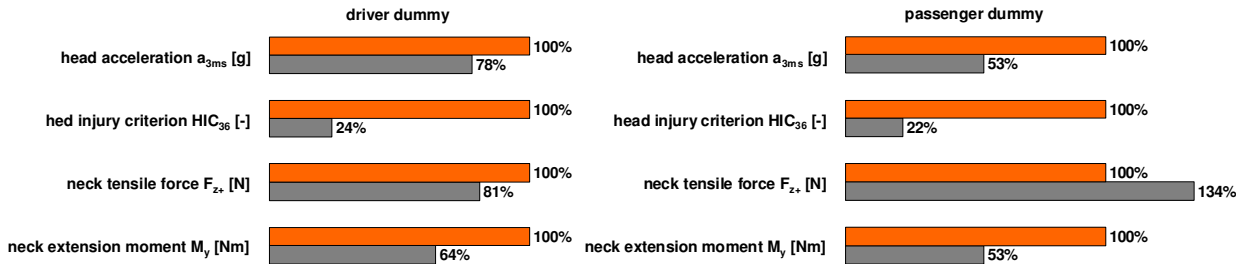


Figure 8. Comparison of the load figures for the driver and front passenger dummy during the unbraked crash test at an impact speed of 64 km/h (100% in each case) and in the braked crash test at an impact speed of 40 km/h

Thus, for example, the head injury criterion HIC_{36} of the driver dummy in the braked crash test fell by 76% in comparison with the unbraked test. The corresponding reduction for the

front passenger dummy was 78%. The characteristic value for the head deceleration a_{3ms} was reduced by 22% for the driver dummy and by 47% for the front passenger dummy.

Vehicle deformation

The deformed vehicles are shown in **Figure 9**. The area around the front left wheel in particular shows the significantly lower deformation of the vehicle.



Figure 9. Comparison of the deformation of the front of the two test vehicles

SUPPLEMENTAL FINDINGS FROM REAL-LIFE ACCIDENTS

As various accident research projects and reports in the media show, the risk of car occupants suffering serious or fatal injuries in frontal impacts continues to be very high. About 50% of the seriously injured and about 40% of the killed vehicle occupants result from a collision at the vehicle front (GIDAS). In about 60% of cases the opponent in the accident was another vehicle (GIDAS) and of these cases a total of 40% are front-rear collisions. This perspective alone is enough to make it sensible to protect the driver in frontal collisions. This is where preventive protection measures offer new possibilities without the disadvantages arising from the mass and dimensions of enlarged or excessively stiffened mechanical deformation zones.

Even so, it must be taken into account that the occupants of the impacting vehicle in a front-to-rear collision are usually not endangered at the most extent. The greatest danger of suffering serious or fatal injuries is assigned to front-to-front or front-to-object collisions, the object frequently being a tree. However, modern sensor technology does make it at least possible to detect front-to-rear collisions and to take corresponding action, which may go as far as automatic emergency braking. Nevertheless, this is an important point of departure for future development. Firstly, however, it is important to identify and utilise suitable sensors, and incorporating them in cooperative systems.

Pedestrians and cyclists are vulnerable road users and are subject to additional risk. Here the protective potential of conventional measures around the car front is already exhausted at impact speeds of 40 km/h (EU directive 78/2009 on pedestrian protection). Preventive safety systems incorporating automatic emergency braking offer additional protection possibilities for this type of vulnerable road user and their efficacy in the real-life traffic environment is potentially even greater than the efficacy of passive-safety protection measures.

In order to estimate the relevant potential benefit it is necessary to know the percentage of the relevant accidents involving car frontal impacts in which the car driver in question either failed to apply the brakes in the first place or not with full force.

As part of the vFSS work package "Accident Analyses" Ford studied the GIDAS database with a view to evaluating the corresponding pre-crash braking behaviour, **Figure 10**. In 24% of the 1,492 cases studied, the car drivers did not brake. In a further 23% of cases the data contained no information on the braking behaviour. In all other cases the cars were braked before the impact. Of the latter, the deceleration was over 6 m/s² in 28% of the cases. An analysis by DEKRA Accident Research confirms these findings.

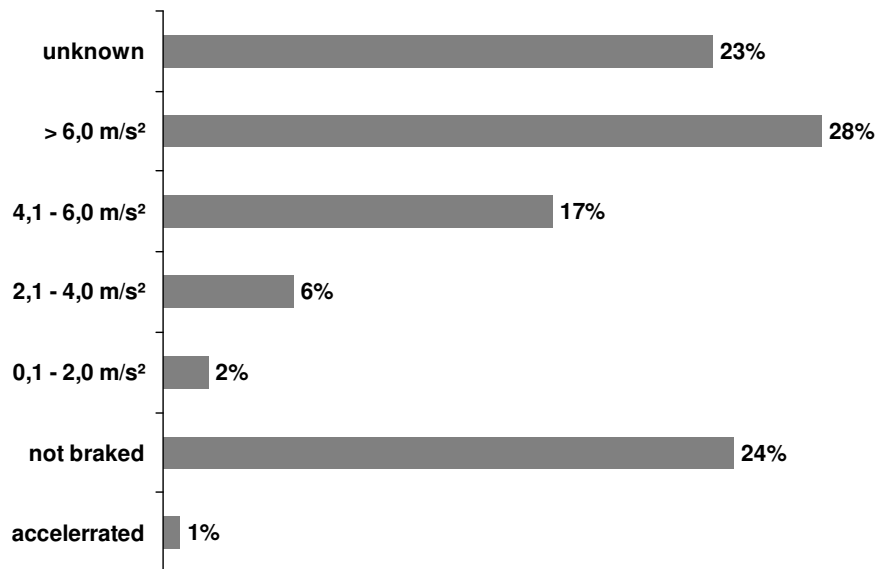


Figure 10. Frequency distribution of braking deceleration in the pre-crash phase (N = 1,492 front-rear accidents, source: GIDAS)

These figures demonstrate the existence of a significant potential benefit of a preventive frontal protection system. In many cases the time warning would cause the driver to brake, otherwise the emergency braking would be applied automatically. An assisting effect of full braking instead of partial braking (less than 6 m/s²) in the pre-crash phase further increases the potential benefit. Furthermore, it can be assumed that even in accidents in which no information on the braking behaviour in the pre-crash phase is available, a percentage of the vehicles were unbraked or subjected to only light braking. This suggests that forward looking front safety systems can make a considerable contribution to further increasing road safety.

Finally, **Figure 11** shows the development of figures of car occupants, motorcycle riders, pedestrians, cyclists and occupants of trucks over 3.5 t killed per year in 15 states of the European Union. For these states the statistics published by CARE (European Road Accident Database) (last update: November 2010) contain a breakdown of the period in question according to the type of road user.

Although the number of killed car occupants fell considerably from 30,799 in 1991 to 12,519 in 2008 by an impressive 59%, car occupant deaths continue to dominate the figures of road user fatalities. In the pedestrian group over the same period the number of fatalities fell significantly by 57% from 10,022 to 3,813. In the states under consideration killed motorcyclists now make up the second largest group. In the historical development there was a fall here of merely 14% from 5,237 in 1991 to 4,481 in 2008. Cyclists form the fourth largest group of road user fatalities by a clear margin. Their figures have developed from 2,063 fatalities in 1991 to 1,540 fatalities in 2008, corresponding likewise to a significant fall of 50%.

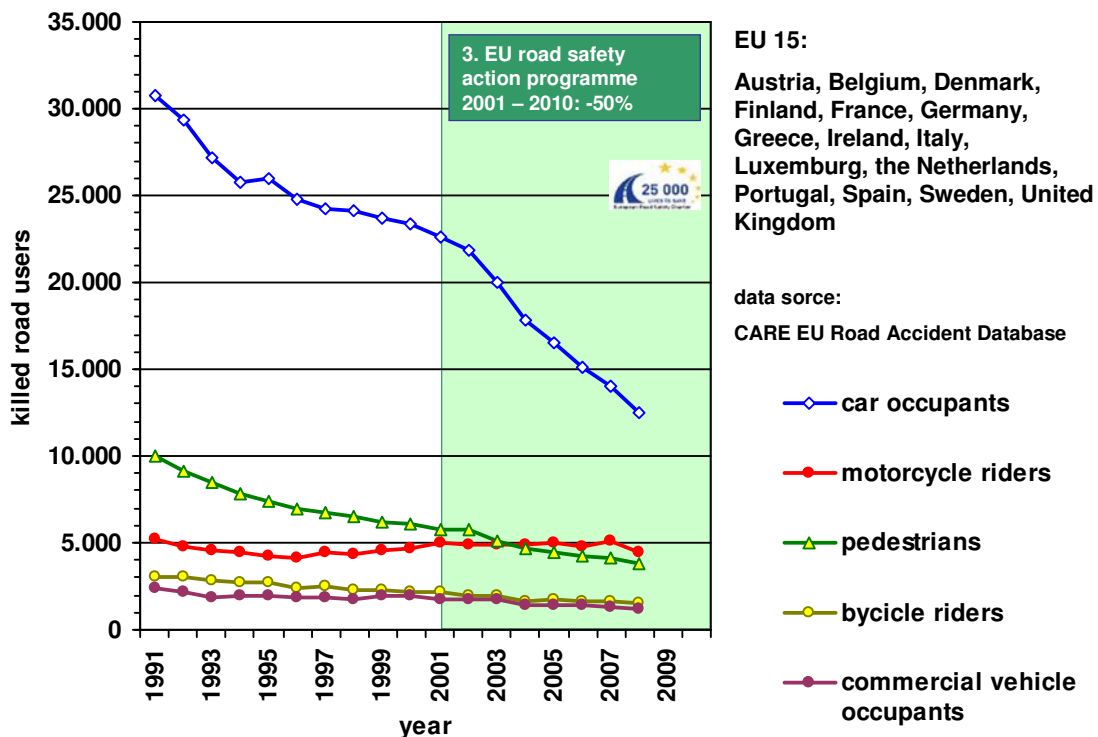


Figure 11: Development of the number of car occupants, motorcyclists, pedestrians, cyclists and occupants of trucks over 3.5 t killed on the road per year in 15 states of the European Union from 1991 to 2008

The magnitudes and the trends of these figures clearly suggest that a further successful reduction of the number of road deaths in Europe can only be achieved if

- the number of killed car occupants continues to fall significantly
- the number of pedestrian fatalities likewise continues to fall significantly
- the number of killed two-wheeler road users, in particular motorcyclists, can be more reduced.

One safety measure that can be particularly effective for car occupants, pedestrians and cyclists is an advanced forward looking frontal safety system like the automatic car emergency braking system outlined in this paper.

The target of further halving the number of road deaths over the period 2011 - 2020 (see Figure 1) requires the introduction of such systems as fast as possible in as many vehicles as possible. This would create the basis for further development of the systems that, in the end, enable automatic energy dissipation in serious frontal collisions in front-to-front or front-to-object scenarios. Current developments have already taken the first steps towards using this future potential.

The precondition for this is detailed definition of the potential benefits depicted and a recognised test procedure with which the performance of the systems can be demonstrated in reproducible form. In this process the evaluation of the systems should not be based on

individual dummy figures but on the actual efficacy in real life. To do this, corresponding evaluation procedures and test methods need to be developed. Based on the examples given here, the vFSS group continues to work at pursuing the necessary accident research and development of harmonized test procedures.

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