PRE-SAFE® IN REAR-END COLLISION SITUATIONS

Ralf Bogenrieder
Michael Fehring
Roland Bachmann
Daimler AG
Germany
Paper Number 09-0129

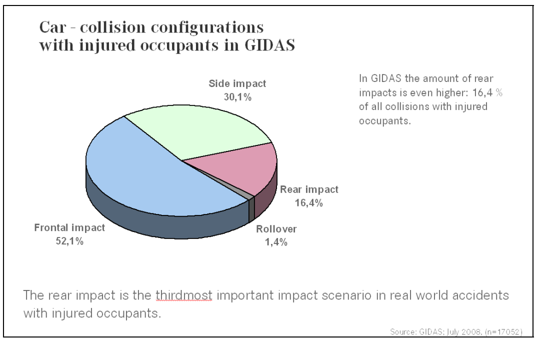
ABSTRACT

In 2002 the first bridge between active and passive automotive safety was built. The MY03 Mercedes-Benz S-Class was the first car in the world that implemented preventive measures for occupant protection which took effect before the actual impact occurred. Meanwhile the name "Mercedes-Benz PRE-SAFE® System" became well known. Since then many other cars from various car manufacturers have adopted this principle of a "natural protection reflex". In order to detect dangerous situations or upcoming accidents, various sensor systems are being used in these cars today. In addition to sensors that keep an eye on the driving dynamics or on the driver reaction, the use of radar sensors or cameras has become common during the past few years. Almost all of those systems observe the area in front of the car and therefore address situations with an increased risk for a frontal impact. Very few systems presented up to now are capable to "look" backwards and thus detect an imminent rear impact. This paper presents the Mercedes-Benz approach to integrate this type of accident into the PRE-SAFE® System. The paper covers the issue of detecting collision objects on the basis of radar data. And it presents a cascade of precautionary actions that can improve occupant protection in rear-end accident situations. In particular, the purpose and benefit of a preventive increase of brake pressure is discussed, as well as taking into account further actuators such as a reversible seat belt pretensioner or an active headrest. In order to substantiate the benefit of such a system several evaluation charts on the reduction of the impact severity, the dummy loads and the estimated risk of whiplash injuries are included. Based on accident simulations there are also evaluations about the reduction of the "accident radius" and thus the risk of a secondary impact. Finally the question of an appropriate electronic architecture for such an integral safety system is touched upon.

INTRODUCTION

Federal German statistics on road accidents show that 15% of all car accidents belong to the category of rear-end impacts, making them the third most important impact scenario after frontal impacts and side impacts.
A closer look into the "German In-Depth Accident Study" (GIDAS) which contains a detailed analysis and documentation of more than 17.000 road accidents that occurred in the regions of Hannover and Dresden, basically confirms this information. Focused on car collisions with injured occupants, the share of rear-end impacts is 16.4% (as of July 2008).

Figure 1: Car-collision configurations with injured occupants in GIDAS.



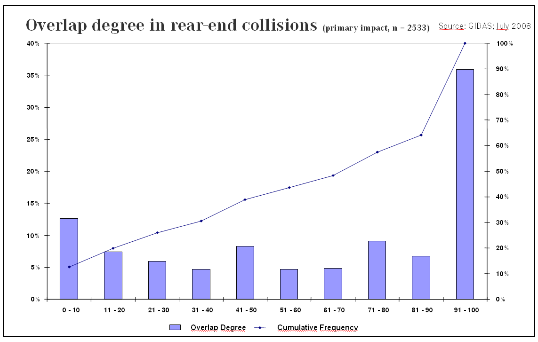
Compared to frontal impacts or side impacts which usually emerge from a broad variety of initial situations, 80% of rear-end collisions result from only four preceding conflict situations:

- Collisions in longitudinal traffic
- Collisions in a traffic jam
- Collisions with a vehicle that stopped at a traffic light
- Collisions with a vehicle that is just about to turn left

ANALYSIS OF REAR-END COLLISIONS

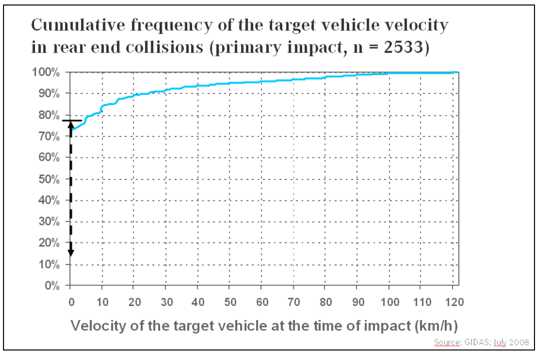
GIDAS also contains data about the overlap. An analysis of this information for rear-end impacts shows that an overlap of more than 90% is clearly the most frequent configuration in this accident type.
Only 20% of all rear-end collisions occur with an overlap of less than 20%.

Figure 2: Overlapping ratio in rear-end collisions



The analysis of the velocity of the target vehicles in rear-end crashes shows that 72% of all rear-end impacted cars are at standstill (v = 0 km/h) at the time of impact.

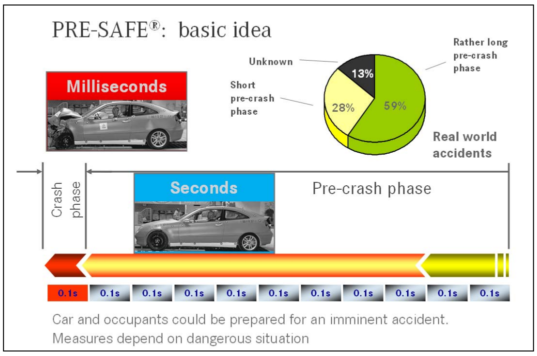
Figure 3: Target vehicle velocity in rear-end collisions



PREVENTIVE OCCUPANT PROTECTION (PRE-SAFE®)

In 2002 Mercedes-Benz launched the world's first protection system that takes action **before** the actual impact occurs and thus improves the safety of car occupants **preventively**. The system called PRE-SAFE® uses sensor data from the Electronic Stability Program (ESP) and the Brake Assistant in order to detect dangerous driving situations in which it is likely that an accident might follow. Two examples of trigger situations for PRE-SAFE® are when ESP detects severe skidding with strong under- or oversteer (beyond the threshold for ESP interventions) or when the Brake Assistant detects an emergency braking.
Comparable to a natural protection reflex the car uses the remaining time before the impact to prepare itself and the occupants for the upcoming crash.
Data from Mercedes-Benz accident research indicate that in almost 60% of all investigated real-world accidents the duration of this pre-crash phase between the moment when a danger becomes imminent and the actual impact is longer than 1 second. PRE-SAFE® makes use of this time span which is much longer than the span of the actual crash itself.

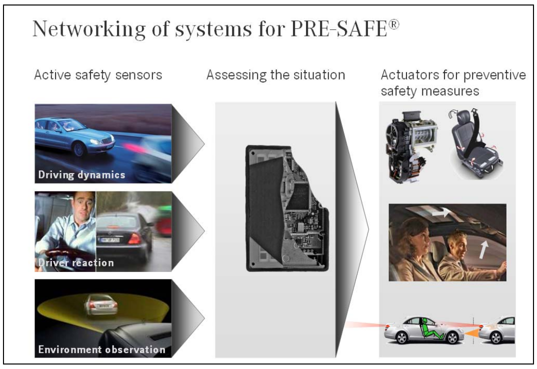
Figure 4: Basic idea of PRE-SAFE®



The PRE-SAFE® master software is located within the ESP control unit and makes use of the CAN network which is standard in modern cars today. The system gathers data from various sensors and at the same time communicates with different actuators. Depending on the equipment available in the vehicle the system takes the following actions:

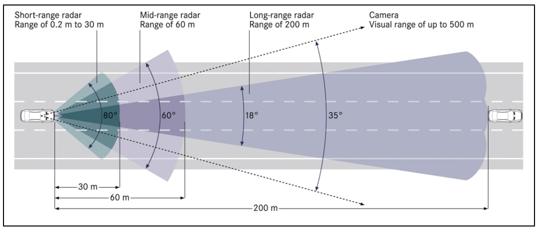
- The seatbelts of driver and front passenger are tightened to a force level of 140 N in order to reduce belt slack and to keep the occupants in a safe position for potential restraint deployment.
- The front passenger seat is moved to a more favorable position for possible restraint system deployment (in case it had been adjusted to a less optimal position before).
- The side bolsters of the multicontour seat are inflated in order to improve the lateral support of the occupants and keep them in a safe position for possible restraint deployment.
- When the system detects that a rollover crash might be imminent the sliding roof and the side windows are closed (until only a small gap remains) in order to minimize the risk that occupants are ejected from the car.

Figure 5: PRE-SAFE® system network



These measures are aimed at reducing the risk of injury for the car occupants and enhancing the efficiency of the conventional restraint systems. In this way PRE-SAFE® virtually builds a bridge so to speak between Active and Passive Safety.
All PRE-SAFE® measures are reversible, so they can easily (or even automatically) be reset in case the accident could successfully be avoided. The system is then ready for action again instantly.
However PRE-SAFE® does not replace any of the conventional safety systems because it cannot detect each and every accident before it takes place. PRE-SAFE® is designed to provide additional safety in as many cases as possible.
In 2005 the system's capabilities to detect dangerous situations were expanded by making use of radar sensors that scan the area in front of the car.

Figure 6: Use of environment observation for PRE-SAFE®



While those sensors are mainly used for the application of an Adaptive Cruise Control (ACC), they can also provide data for Active Safety Functions like Brake Assist Plus or for collision mitigation systems like "PRE-SAFE® Brake".
A vehicle equipped with "PRE-SAFE® Brake" can detect objects in front of the vehicle and, when detected, can continuously measure the distance to those objects. When the system detects that this distance drops dangerously low, it starts a sequence of escalation steps:

- 2.6 sec before a potentially imminent crash the driver gets a warning by optical and audible signals
- 1.6 sec before the possible crash the car initiates an autonomous braking at a level of 40% of the maximum brake force. At the same time, the PRE-SAFE® measures for preventive occupant protection are activated.
- In case the driver still fails to react and take control the car automatically implements full braking 0.6 sec before the imminent impact, which at this time is unavoidable.

As a result of the autonomous braking the system can reduce the impact energy by up to 55%.
Further details on the PRE-SAFE® system were presented during the ESV 2005 Conference in Washington DC [1].

REARWARD ENVIRONMENT OBSERVATION

Today a typical rear-end accident can not be detected by PRE-SAFE®. According to Figure 3 many of these accidents take place while the target vehicle is at standstill, so the ESP sensors don't indicate any driving dynamics. Objects approaching from behind can also not be detected by the present radar sensor equipment because these sensors typically are mounted in the front bumper or behind the front grille to observe the area in front of the car only. Even the sensors that are mounted in the corners of the rear bumper in some cars are not applicable to detect vehicles approaching in the same lane, because those sensors are designed and adjusted to monitor the so called "blind spots" beside the car on the adjacent lanes.
On the other hand the high offset rates in most rear-end impacts (see Figure 2) provide relatively good conditions for rearward facing environment observation sensors. Therefore the Mercedes-Benz approach to integrate rear-end accidents into the PRE-SAFE® system is to mount a radar sensor in the rear bumper. The field of view of such a sensor should be adjusted mainly to the area right behind the car, since in most cases the impacting vehicles approach in the same lane.
Regarding the necessary working range two main aspects have to be taken into account:

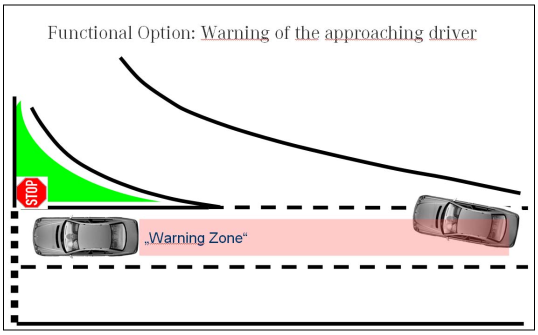
1. Is the system designed to send any warning signals (either to the vehicle driver / occupants or to the driver approaching from behind)?
2. Activation time of the actuators that are triggered by the system (i. e.: period of time that those actuators require to provide their functions).

Both aspects are discussed below.

THE “WARNING DILEMMA”

Any sort of warning only makes sense when it takes place early enough to leave sufficient time for appropriate and effective reactions.
When a potential collision object approaches from behind there are two possible warning scenarios: Either the driver / occupants are warned – for example by visual, audible or haptical signals – or the warning is aimed at the driver in the approaching vehicle.
In both cases the timeline is roughly the same. Mercedes-Benz studies with test subjects in a driving simulator showed that a warning should be triggered 2.6 sec before the predicted impact in order to leave enough time for average reaction delay and an adequate preventive action.
At usual city speeds of 40-50 km/h this means that a warning has to start when the distance to the approaching vehicle is 29-36 m. In other words: The necessary extension of the “warning zone” is so large, that the detection of another vehicle within this zone will be a very frequent event (as the example scenario in Figure 7 shows).
So the so called “warning dilemma” becomes obvious: On the one hand a warning only makes sense when it takes place early enough, on the other hand a warning should only be a rare event, because otherwise it would be annoying and would fail to generate the designated reaction.

Figure 7: Necessary extension of the “warning zone”



Due to this general dilemma the functional option of sending warning signals today is not the main focus of the Mercedes-Benz approach to improve safety in rear-end accident scenarios.

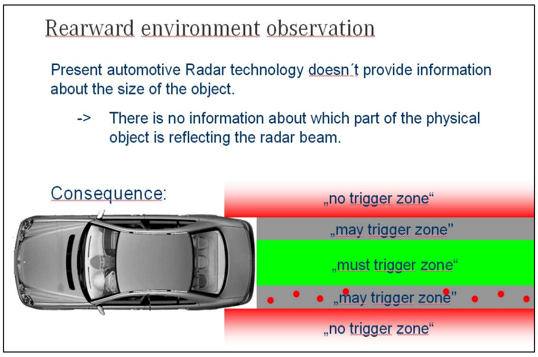
RESTRICTIONS OF RADAR-BASED ENVIRONMENT PERCEPTION

The design of a safety system that uses radar signals always has to keep in mind the limitations of this technology.
The most relevant limiting factors are:

- The degree of reflexion varies between different materials. Some materials (e. g., dry wood) poorly reflect radar beams and thus are more difficult for radar sensors to detect.
- A cover of snow or dirt dampens radar beams. Thick snow covers can even make a sensor “blind”.
- Radar technology does not provide any information about the mass of detected collision objects.
- Present automotive radar sensors do not provide reliable information about the size of the detected objects.

The first two points show that a radar sensor can not detect <u>all</u> collision objects. Radar data can therefore only provide additional assistance for occupant protection systems, but these systems can not be designed such that radar data is indispensable for their trigger decisions.
The last limiting factor mentioned above also has an impact on the design of automotive safety systems based on radar sensors. Since the radar systems available for automotive applications today detect objects only in the form of a singular spot without any extension, it is impossible to definitively distinguish between objects that will actually hit the vehicle and objects that will only closely pass by.
As a consequence a “grey area” will be inevitable. This means that for an object located in this grey area and approaching the vehicle, the system can not clearly predict if the object will hit the vehicle or pass by.
Depending on the preventive measures to be triggered based on the radar information, the trigger strategy for objects in the grey zone may be different. If the impact (or rather the “annoyance potential”) of a certain measure is rather low, then it can also be activated in doubtful cases. If a certain measure causes a considerably adverse effect on the comfort of the driver or the occupants (like, for example, preventive seat belt tensioning), then the activation should rather be suppressed. This, however, means that there will be accidents in which the measure has not been activated even though it would have been useful.

Figure 11: The grey "may-trigger-zone"

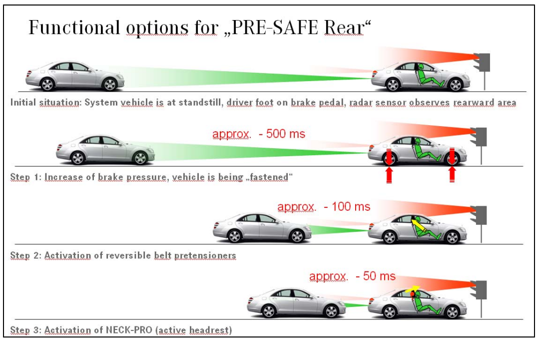


Regarding the PRE-SAFE® system, Mercedes-Benz therefore has always made one thing absolutely clear: PRE-SAFE® only provides **additional** safety. It cannot and will not claim to detect every single accident in advance. In cases when the danger of an imminent accident can be detected early enough, PRE-SAFE® can provide additional protection. But there will also be accidents without a preceding PRE-SAFE® activation. In these cases the full range of all conventional restraint and protection systems remains available.
Under this prerequisite radar sensors can be used for PRE-SAFE® in spite of their limitations.
The idea is to provide additional safety whenever possible. Even when it is not possible to provide additional safety, the use of radar sensors for PRE-SAFE® in rear-end collision situations still causes no harm.

PRE-SAFE® REAR

Given that an environment sensing system observes the area behind the car and can detect potential collision objects approaching from behind, it will be useful to calculate the "time-to-collision" ("TTC") based on the tracking data of the observed object. This allows for the triggering of a sequence of measures within an integral escalation concept in a way that each measure can provide its protective function at the right moment in the potential crash sequence.
At the present stage of discussion the Mercedes-Benz approach mainly addresses the following steps.

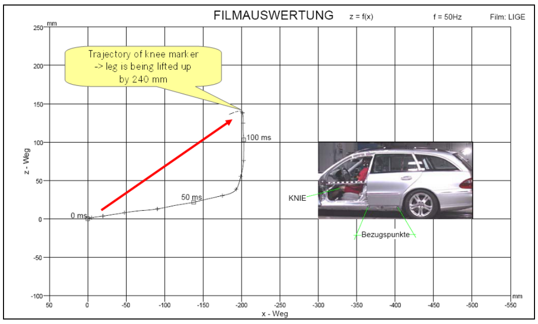
Figure 8: Functional options for "PRE-SAFE® Rear"



Step 1: Increase brake force

Analysis of rear impact crash test films showed that during the impact the inertial force led to a significant rearward movement of the occupants relative to the occupant compartment. This movement also includes the driver's legs. Even if the driver has his foot on the brake pedal before the rear-end impact, the inertial forces of the crash can lead to a lifting of the foot from the pedal. In a heavy rear impact this lifting can reach an amount of more than 200 mm.

Figure 9: Crash film analysis of the relative movement between leg and brake pedal

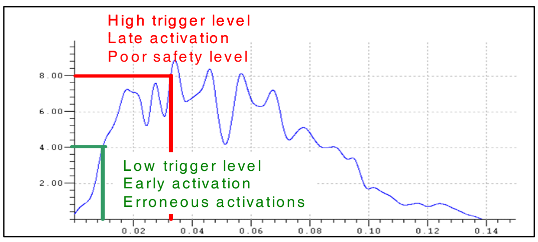


So in a heavy rear impact (impact speed in the example: 50.7 km/h) the driver may not be able to keep his foot on the brake pedal even when he wants to.
In a less severe rear impact the inertial crash force reduces the force that the foot exerts on the pedal. Unfortunately this inertial force effect has adverse consequences for the crash. Both during the impact itself and also during the following seconds it would be beneficial overall if the impacted car had applied the brakes as hard as possible (see separate paragraph on the benefits). Thus the active and preventive boost of the brake force in situations of an imminent rear-end impact is an advantageous PRE-SAFE® measure. Due to the usual time requirements for brake force enhancement, this measure should typically be activated at a time-to-collision ("TTC") of approx. 600 ms in order to be fully effective at the time of impact.

Step 2: Reversible seat belt tensioning
The activation of reversible seat belt tensioners, which is mainly useful in situations with imminent frontal crashes, also makes sense when a rear-end impact is about to happen. The electric motor in such a belt system takes out the belt slack and thus fixes the occupants tighter to their seats and to the passenger compartment. This reduces any dynamic displacement and improves the efficiency of all conventional restraint systems and brings significant advantages in case a secondary impact should follow (which would usually be a frontal or side impact).
With respect to the typical activation time of reversible seat belt tensioners this measure should be activated at a TTC of approx. 100 ms.

Step 3: Activation of the active headrest
The Mercedes-Benz approach also includes the activation of the headrest. Usually the airbag control unit triggers this headrest. For this trigger a relay switch is released and the headrest is moved forward and upward by means of a spring force within 30 ms.
Since this system is also fully reversible, it can also be activated before impact The main benefit of this measure is that preventive activation fully avoids the usual trade-off from which acceleration-based trigger algorithms suffer. On the one hand the activation shall take place as early as possible, but on the other hand the acceleration signal usually only allows non-ambiguous classifications of the crash severity after several milliseconds.
Another aspect is that a preventive activation of the headrest also avoids interference between the movement of the headrest and inertial forces affecting the seat during the impact. Triggering the headrest early enough before the impact guarantees a release movement unaffected by any impact-related forces.

Figure 10: Trade-off in the acceleration-based trigger decision for an active headrest



With respect to the short activation time of the Mercedes-Benz active headrest, this measure should be activated at a TTC of approx. 50 ms.

BENEFITS OF A PREVENTIVE ENHANCEMENT OF THE BRAKE FORCE

1. Benefit during the impact

Applying the brakes in the target vehicle in car-to-car collisions influences the impact in various ways (compared to the situation with no brakes applied at all):

- The net impact forces between the two vehicles are higher.
- The deformations are higher.
- Delta v and mean acceleration are higher for the bullet car.
- Delta v and mean acceleration are lower for the target car.

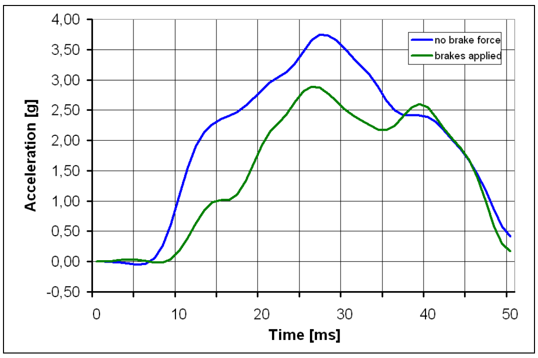
Since the forces imposed by brakes and tires are relatively low compared to the impact forces in a severe rear-end impact, the effects mentioned above can usually be disregarded in many cases. However: The slower the impact is, the more relevant these effects are.
With regard to whiplash injuries it is important to note that these injuries can already occur at relatively low impact speeds.
Various studies in the 1990´s investigated the relation between impact severity and the occurrence of neck injuries. Studies by McConnell et al (1995) [2], Eichberger et al (1996) [3], Ono and Kaneoka (1997) [4], Siegmund et al (1997) [5], Krafft et al (2002) [6] and Kullgren et al (2003) [7] allow us to reach the conclusion that the risk of whiplash injuries already rises significantly at a rather low impact level. The threshold found in these studies is at a level of delta v = 10-12 km/h for the target vehicle and a mean acceleration of only 4 g.
At the ESV2005 conference Krafft et al [8] showed that even rather small differences in the mean acceleration obviously can make a big difference for the risk of whiplash injuries and especially for the duration of the symptoms. Table 2 (taken from the Krafft study) shows that only 0.4 g reduction in the mean acceleration can result in the reduction of symptom duration from 1-6 months to less than one month. And a reduction of 1.1 g in mean acceleration can result in being uninjured instead of suffering from neck pains for 1-6 months.

Table 1: Numbers of male and female drivers and front seat passengers and average delta v and mean acceleration for different symptom durations.

	Males			Females		
	N	Δv	Mean acc.	N	Δv	Mean acc.
All	90	10.6	3.7	105	10.4	3.7
Uninj.	64	9.0	3.4	58	9.0	3.5
< 1 m	17	12.5	4.2	32	9.6	3.6
1-6 m	2	13.5	4.6	5	17.3	5.6
>6 m	7	19.9	5.2	10	17.6	5.1

So whiplash injuries typically occur at an accident severity level in which the occupants in the impacting cars usually can expect to remain completely uninjured. Even more: They still will not face significantly increased risk of injury when their impact becomes slightly harder because the car in the front applies its brakes. The appreciation of values here shows that the benefit for the occupants in the impacted car clearly outweighs the small disadvantage for the occupants in the second car.
A Mercedes-Benz Crash Simulation showed which reduction in acceleration can be achieved when the brakes are fully applied in an impacted vehicle on a high grip surface (μ=0.95). In this example the modelled impacted car was a fully loaded Mercedes-Benz S-Class (m=2835 kg) hit by a moving deformable barrier (m=1367 kg) at a speed of 10 km/h.
The black graphs in Figure 12 show that the maximum acceleration in the S-Class decreases from 3.8 g to less than 3 g. Following the results from Krafft this is a scale that can significantly be beneficial for the risk of neck pains and most likely can reduce their duration.

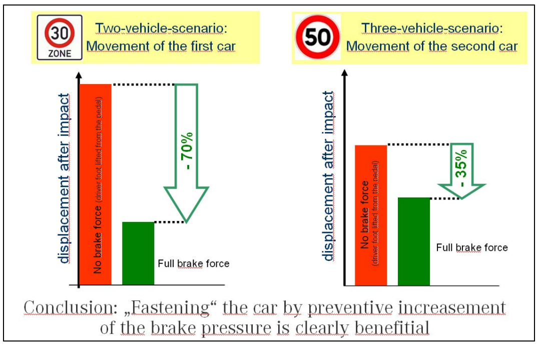
Figure 12: Reduction of the acceleration of an impacted car by enhancement of the brake force



2. Benefit after the initial impact

The analysis in figure 9 shows that in a severe rear-end impact it is likely that the driver's foot will be lifted from the brake pedal. So during the few moments until the driver can react and put his foot back on the brake pedal again, his car will be pushed away and roll on freely. Any object in the impacted vehicle's path will likely be hit, so that after the rear-end impact, a secondary frontal impact may follow. The car may even be pushed into the lane of oncoming traffic, so that this secondary impact may be very severe.
If, however, the impacted vehicle could automatically apply and hold its brakes (either for a certain duration or until the driver touches the accelerator pedal), this would significantly reduce the risk of a secondary impact, simply by reducing the "radius" of the post-crash movement of the impacted vehicle.
The benefit of this PRE-SAFE® brake-force enhancement in rear impacts was demonstrated in two different accident scenarios, using an accident simulation software. In a scenario in which the second car crashed at a speed of 30 km/h into a vehicle that was at standstill, the post-crash movement of the impacted car was reduced by 70%. In a scenario with an impact speed of 50 km/h, the reduction was still 35% (see figure 13).

Figure 13: Reduction of the uncontrolled post-crash movement of an impacted car by enhancement of the brake force



SUMMARY

In the most frequent rear impact scenarios the target vehicle is at standstill while the bullet vehicle approaches in the same lane. The crash mostly takes place with an offset ratio of 90% or more.
In this constellation a pre-impact detection of the upcoming danger can neither be achieved on the basis of driving dynamic sensors nor on the basis of driver reactions. Instead of that the use of environment observation sensors will be necessary

for the activation of preventive protection measures.
Today PRE-SAFE®, the preventive occupant protection system of Mercedes-Benz, is not able to detect an upcoming rear-end impact. But the integration of a rearward-facing radar sensor will enable the system to cover a considerable share of real world rear-end impact scenarios.
When such a sensor detects a potential collision object a sequence of preventive measures can be activated.
Especially the enhancement of brake pressure is a measure that can both reduce the risk of whiplash injuries and also the risk or energy of secondary accidents.
In further pre-crash escalation steps the activation of reversible seatbelt tensioners and active headrests are additional measures that can improve occupant protection in real-world rear impact accidents effectively.

REFERENCES

[1] Schöneburg R, Breitling T
Enhancement of Active and Passive safety by future PRE-SAFE® systems
2005 ESV Conference
Washington DC
Paper 05-0080

[2] McConnell W E, Howard R P, v. Poppel J
Human Head and Neck Kinematics after Low Velocity Rear-End Impacts – understanding "Whiplash".
Proc. Of the 39th Stapp Car Crash Conference, San Diego, 1995
pp. 215-238

[3] Eichberger A, Geigl B C, Moser A, Fachbach B, Steffan H, Hell W, Langwieder K
Comparison of different car seats regarding head-neck kinematics of volunteers during rear end impact
Proc of the Int. IRCOBI Conference on the Biomechanics of Impacts,
Dublin, 1996

[4] Ono K, Kaneoka K,
Motion analysis of human cervical vertebrae during low speed rear impacts by the simulated sled
Proc of the Int. IRCOBI Conference on the Biomechanics of Impacts,
Eindhoven, 1997
pp. 201-212

[5] Siegmund G P, King D J, Lawrence J M, Whjeller J B, Brault J R, Smith T A
Head/Neck Kinematic Response of Human Subjects in Low-Speed Rear-End Collisions
Proc. of the 41th Stapp Car Crash Conference, Lake Buena Vista, FL, 1997, pp. 357-371

[6] Krafft M, Kullgren A, Ydenius A, Tingvall C
Influence of crash pulse characteristics on whiplash associated disorders in rear impacts – crash recording in real life crashes
Traffic Injury Prevention
3:141-149, 2002

[7] Kullgren A, Eriksson L, Boström O, Krafft M
Validation of neck injury criteria using reconstructed real-life rear-end crashes with recorded crash pulses
Proc. of the 2003 ESV Conference
Nagoya 2003

[8] Krafft M, Kullgren A, Malm S, Ydenius A
Influence of crash severity on various whiplash injury symptoms: A study based on real-life rear-end crashes with recorded crash pulses
2005 ESV Conference
Washington DC
Paper 05-0363