Advanced Brake Assist – Real World effectiveness of current implementations and next generation enlargements by Mercedes-Benz

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ABSTRACT

The conventional Brake Assist System (BAS) was developed by Mercedes-Benz and became standard equipment of all Mercedes-Benz passenger cars in 1997. In its further development it was supplemented by radar sensors and adaptive brake assist functions to address rear-end collisions. Advanced Brake Assistance Systems were introduced by Mercedes-Benz in the S-Class model 221 in the year 2005 (adaptive brake assist) and completed in 2006 (autonomous partial braking), 2009 (autonomous full braking) and 2011 (expansion of the limits of the functions).

After several years of proving itself in real world accidents situations it is time to compare the prognosis of its real-world effectiveness in avoiding or mitigating the severity of rear-end collisions with the real-world results as well as discussing the expected effectiveness of the enlargements of the advanced brake assist systems to new accident situations. The paper compares the former prognosis of real-world effectiveness of the systems in avoiding rear-end collisions or mitigating their severity with results of the latest analysis based on actual crash data, FOT, insurance data and others. It will be proved that the prognosis was confirmed or exceeded in some cases. A method for a lifetime analysis will be proposed. Advanced technologies in environmental sensing, situational perception and new actuators that allow individual situation-based interventions in braking, in steering or in controlling the chassis characteristics offer new options for the enhancement of automotive safety.

INTRODUCTION

During the first decade of this century road accidents received increasing public interest. The EU set a 50% reduction in the number of fatalities among Europe by 2010 as its common goal and renewed it for 2020. The United Nations announced a “Decade of Action” 2011 to 2020 for Road Safety to reduce the number of 1.3 million people killed in road crashes every year. 90% of them happen in developing countries. Road fatalities are just the tip of an iceberg. They bring a variety of other accidents in their train. However, a multiple of other road users get physically injured. The analysis of accidents showed that rear-end collisions had a big share in all accidents with injuries worldwide. Rear-end collisions are globally considered very significant. Their share in any accident involving injuries or fatalities makes about 23% in Germany, about 28% in the U.S., about 32% in Japan and about 33% in China. (see Fig. 1)

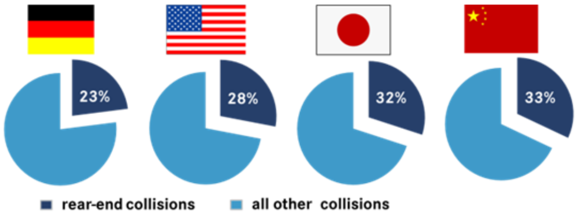


Fig. 1: Share of rear-end collisions in all accidents with casualties or fatalities (Source: 2010; DESTATIS, NHTSA, IATSS, China Min. of Public Safety)

Mercedes-Benz launches very effective primary and secondary safety measures to reduce particularly this type of accident. The systems are called PRE-SAFE® and PRE-SAFE® Brake, Forward Collision Warning, BAS PLUS, Adaptive Brake and Collision Prevention Assist just to mention only a few. In general, these systems are commonly referred to Forward Collision Avoidance Systems (FCA). Within Mercedes-Benz passenger cars FCA interact (if ordered) with PRE-SAFE® – a system offering integrated safety by anticipating an impending accident based on data shared with primary safety measures and activating protective measures in advance e.g. takes the slack out of the seat belts using reversible tensioners and, if a side impact or roll-over is considered likely, closes the power windows and sunroof [17, 18]. Accident research shows that drivers do not always react as quickly as is necessary in critical moments – for example because they are distracted and therefore do not realize the immediate threat of a rear-end crash. Main causal factors are:

- late or no reaction of the driver due to inattentiveness / distraction
- drivers non-awareness of the (increasing) criticality of the pre-crash situation
- misperception of distance and/or deceleration of the lead vehicle resulting in insufficient brake application
- demands resulting from the dynamics within the pre-crash situation exceeds the performance limits of the driver.

In almost 70 percent of these accidents the driver does apply the brake, but too late or too weak; about 30% currently do not brake. Due to this observations a general FCA system consist of at least one module out of FCW (forward collision warning), EBA (emergency brake assist) and AEB (autonomous emergency braking). AEB systems can be subdivided in CMB (autonomous collision mitigation braking) and CIB (autonomous collision imminent braking). Within Mercedes-Benz passenger cars this components have special Mercedes-Benz shaping. (for more details [1,2,4])

FCW: Forward Collision Warning System. Audible and visual warnings are issued when a collision danger is present. Warning is timed to give the driver the chance to avoid collision by braking and/or steering.

BAS PLUS (BAS+): Adaptive brake assistance (EBA) that enhances driver's braking input if necessary based on radar information to avoid a collision with a moving, stopping or stationary lead vehicle.

Adaptive Brake Assist (ABA): Adaptive brake assistance (EBA) that detects an imminent danger of collision with moving/stopping lead vehicle by using radar sensors. If the driver applies the brake in time, the system automatically provides the deceleration required to avoid the collision.

PRE-SAFE® Brake (PSB): Autonomous Emergency Braking (AEB) performed when collision danger is imminent. Stage 1 Partial Braking (CMB), Stage 2 Full deceleration (CIB; when the collision cannot be avoided). Collision can be avoided by stage 1 in combination with BAS PLUS, stage 2 reduces crash severity.

Adaptive Brake (AB): is the name of the brake system that includes support functions to enhance safety and comfort, among others "Brake drying" and "Brake priming". This hydraulic dual-circuit braking system is electronically controlled. In wet conditions the "Brake drying" function applies brief braking impulses to wipe the film of water from the brake disc. Priming means that the system is able to increase the pressure in the brake lines into light contact with the brake discs by itself. Priming supports Brake Assist, Brake Assist PLUS and Adaptive Brake Assist to brake with full force immediately when required.

Currently these safety measures are offered in two bundles as a *basic safety feature* (CPA) or as a *safety net* (DAP) of the Mercedes-Benz adaptive cruise control called DISTRONIC PLUS.

Driving Assistance Package (DAP): is the sales name of an optional bundle of FCA components in which FCW, BAS PLUS and PRE-SAFE Brake® as well as AB are included as a part of DISTONIC PLUS. It is available since 2005. All DPA functionalities cannot be switched off directly by the driver.

Collision Prevention Assist (CPA): is the sales name of a bundle of FCA components in which FCW and ABA as well as AB are combined. It cannot be switched off by the driver. The system is standard on the new B-Class since 2011.

The technical characteristics are contained in Tab.1.

	CPA	DAP
Equipment type	standard	optional
Radar Sensors	1	3
Sensor Range	approx. 80 m	approx. 200 m
Adaptive Cruise Control	-	0 - 200 km/h
Headway warning**	yes	yes
Forward Collision Warning		
Moving/stopping vehicles	30 - 250 km/h	7* - 250 km/h
Stationary vehicles	30 – 72 km/h	7* - 72 km/h
Meets NHTSA requirements	yes	yes
ABA / BAS Plus		
Moving/stopping vehicles	30 – 250 km/h	7* – 250 km/h
Stationary vehicles	-	7* – 72 km/h
Autonomous Emergency Braking	-	7* – 200 km/h
Activation of (optional) reversible PRE-SAFE® functions	yes	yes

All speeds indicate own vehicle speeds.

* The operation speed range for FCW, BAS PLUS and PRE-SAFE Brake were expanded in 2010 from a lower threshold of 30km/h to 7 km/h.

** following distance below 0.8 s for 3 s or longer

NHTSA: Forward Crash Warning System Confirmation Test [12]

Tab. 1: Characteristics of CPA and DAP

In the last 10 years, many systems have appeared on the market. They all address the rear end collision. There are always papers that describe aspects of analysing the effectiveness of these systems. Currently there is no single way to do this impact analysis over the whole life cycle of a system from the concept phase through the development within the use in real world traffic. A holistic suggestion is outlined in Fig.2 [13]. Especially the feedback loop in which the effectiveness in real world is compared with the accident mechanism and a prediction is necessary.

Fig. 2: Continuous evaluation process of real world effectiveness of primary safety measures

Detailed understanding of the *accident mechanism* including the behavior of the driver that runs to the deficit and the injury causation is needed to define standards, requirements and test criterions for the system.

Dynamical tests of the system proofed the technical performance of the system in its use-cases.

Simulator studies are relevant to quantify acceptance and effectiveness of the Driver Vehicle Interaction. However, the results show the effectiveness with which the FCA or its components can address the main causal factors that lead to the accident or can be influenced too an optimal *driver-vehicle* reaction.

Field tests as a part of the development process give a realistic assessment of the change of faulty behavior by FCA components and release rates for each component of FCA and their efficiency of their cooperation in the wide range of the use-cases in the real world.

Efficiency prediction brings together different parameters like the technical performance of the system in relevant test conditions, the performance of the driver vehicle interface and the accident mechanism. Another a posteriori method is a case by case study on representative detailed data that makes use of the estimated performance indicators. However, such studies are found to be complicated and very time consuming, in particular for FCA systems.

Real world evaluation of the system can be done on different ways. An OEM has the opportunity to analyze the *calls of special spare parts* to proof the effectiveness of a FCA system (avoided collision should be reflected in reduced calls). This could be done very early after the market lunch of the system. Another method is the analysis of *insurance claim data*. After 3-4 years depending on the amount of vehicles equipped with the system these figures could be available. However, after the system is introduced it takes several additional years for it to penetrate the market. Only then it is possible to gain information on its efficiency based on real world accident statistics. Many of these systems take more than a decade of years to achieve a sufficient penetration rate.

The proposed process (Fig. 2) is illustrated exemplary for the Mercedes-Benz components of a Forward Collision Avoidance system below.

ACCIDENT MECHANISM & BASIC SAFETY POTENTIAL

The main driver deficiencies leading to rear-end collisions were outlined before. These deficiencies are addressed by CPA´s functions FCW and ABA respectively by DAP´s components FCW and BAS+ (and, to a lesser extent, Headway Warning). Breakdowns of the principal accident mechanisms of rear-end collisions based on GIDAS data shows where these functions have a potential safety impact:

- Collision partners: In at least 80% of all rear-end collisions with injury outcome a passenger car strikes another vehicle (commercial vehicles and coaches struck: approx. 8%, two-wheelers struck: approx. 6%)
- Serious injuries: In at least 90% cases, serious injuries occur in the striking passenger car at collision speeds between 30km/h and 130km/h (own vehicle speed at time of collision). In approx. 2.5% of all cases the striking car has a velocity above 130km/h. For the entire speed range, the risk of serious injury is approx. 1:1 for striking to struck passenger car occupants. The factor for slight injuries is 1:4.
- The main accident types of rear-end collision in longitudinal traffic are “vehicle and follower“, “congestion and follower”, “vehicle waiting mandatory and follower”, “vehicle turning left / right and behind”, “vehicle and lane changer” …[14]
- The amount of multi-collisions in longitudinal traffic is about 30%. The amount of multi-collisions in the case of accidents caused by congestion is above 40% [16].

→ Addressed by CPA (both FCW and ABA & BAS+). It becomes clear that CPA’s speed range clearly targets a potential in which the majority of serious injuries occur in the subject vehicle.

- In approximately 24% the road surface is wet and another 9% ice (i.e. water/salt film on brake).

→ Addressed by AB “dry braking”

- Driver behaviour in the striking passenger car:
  - In 31% the driver does not brake (NB: unknowns included here)

    → Primarily addressed by FCW (producing a braking reaction) and secondarily by ABA / BAS+ (once FCW has led to a braking reaction) if FCW does not generate any reaction addressed by PSB

  - In 69% the driver braked inadequately (too late or not hard enough).

→ “Too late” is addressed by FCW, “not hard enough” is addressed by ABA & BAS+.

Activation rate of the “classic” Brake Assist (BAS) in the striking car:
Tests with “*normal*” driver in a driving simulator in critical situations that could lead to rear-end collisions showed that the drivers activated the brake, but:

  - The BAS activation rate is less than 50% [16] and
  - The BAS activation rate correlates to the criticality. [16]

  → addressed by ABA & BAS+, since its activation threshold (in terms of brake pedal input) is considerably lower than that of the “classic” BAS, given that the additional environment information is available for the situation assessment.

- Analysis of accident data (GIDAS) showed that
  - At least 30% striking passenger cars showed a deceleration above 6m/s² (mean deceleration 7.7m/s²), that could be used as an indicator for activating the classic Brake Assist (BAS)
  - 70% of the striking passenger cars brake with less than 6m/s²; mean deceleration is 5.0 m/s².
  - In 52% of accidents in which the driver of the striking car actually brakes, the collision could have been avoided if the driver had picked a higher but physically feasible braking deceleration. [15]

  → addressed by ABA & BAS+

  Further observations:

  - Advancing the braking reaction by 0.1s would avoid approx. 11% of the first collisions. Another approx. 11% could be avoided for every additional 0.1s braking advancement (almost linear development in the interval [0s to 0.5s]) [3].

  → addressed by FCW & AB

  - In at least 70% of accidents in which the driver of the striking car actually brakes the collision could have been avoided if the driver had picked higher but physical feasible braking deceleration and the reaction had been advanced for 0.3s. [14]

  → addressed by FCW & ABA / BAS+ & AB

- Main accident causes reported by the police for the driver of the striking passenger car:
  - approx. 27% to low headway distance
  → addressed by CPA’s Headway Warning
  - approx. 27% inappropriate speed
  → addressed by FCW as a secondary effect

The most remarkable point is that the components FCW, BAS+ and ABA, PSB in the sum address all topic and causal factors of rear-end collisions. AB gives an additional boost in braking performance. The need of a component that releases an autonomous braking in a bungle is related to the share in which an FCW is able to shift a non-braking reaction to a driver initiated braking. We will return to this problem later.

INJURY MECHANISM

Typical injury mechanisms as addressed by forward collision avoidance systems in the equipped system vehicle (own ship) are reflected well by the dummy parameters monitored in known international frontal certification and rating tests, predominantly with partial, also with full overlap.

Injury criteria include:

- head injuries caused by resultant peak accelerations, accelerations over time (as reflected in the Head Injury Criterion) and concentrated loading through body interior contacts or contact with intruding lead vehicle parts
- Neck disorders due to overloading shear, tension/compression forces or multiaxial extension moments
- Chest injuries caused by high chest acceleration, rib deflections, deflection speed related viscous criteria and concentrated loadings due to intruding objects or hard contacts with body interior parts
- Pelvis and lower extremities injuries, monitored by compression forces and bending moments

The injury mechanisms addressed in the lead vehicle correspond to those assessed in whiplash testing conducted by insurance and rating institutions that rate neck disorders according to occurring shear, tension / compression forces or multiaxial extension moments.

DAP and CPA both target at preventing or at least mitigating these injuries by helping to avoid collisions altogether or at least mitigating their severity by reducing collision speed.

EFFICIENCY PREDICTION - Safety Potential as derived from Real World Data (Prospective Analysis)

Different studies on the basis of GIDAS data show the safety potential of the driver assistance features FCW, BAS PLUS and PRE-SAFE® Brake within DISTRONIC / DISTRONIC PLUS [14], [15]. The first step was to identify a representative set of 839 rear-end collisions with injury in GIDAS data (12-2006). They were used as a base for case-by-case studies with detailed models of the vehicle and the analysed safety measure.

In a collision avoidance efficiency study for rear-end accidents, DISTRONIC and BAS were analysed and compared to DISTRONIC PLUS and BAS PLUS. All systems and the vehicle's dynamic characteristics (current S-Class type BR221) were modelled in detail. The following requirements were made: a fitment rate of 100% was assumed, DISTRONIC as well as DISTRONIC PLUS were activated in extra urban situations on freeways and highways only, driver behaviour remained unchanged, a reaction of the driver to warnings was not modelled. With these conservative assumptions the results of Fig. 3 were obtained.

The predicted efficiency of BAS based on GIDAS data is very similar to the value that was obtained from a retrospective analysis of German national accident data provided by the Federal Statistical Office (DeStatis). For DISTRONIC PLUS / BAS PLUS, a system that is not distributed widely enough in the market to allow retrospective analysis of accident data, a 20% avoidance and a 25% mitigation rate of rear-end accidents with injury are derived. The values for highways and the autobahn are even higher.

Source: * Federal Statistical Office 2006, ** GIDAS 12/2006

Fig. 3: Rear-end Accident Avoidance Potential of DISTRONIC with FCW and Brake Assist Based on Real World Data

CPA is similar to the analysed combination of FCW and BAS+, with the exception that ABA – the adaptive brake assist within CPA is not able to detect stationary vehicles never been detected moving before. BAS+ has this ability (Tab.1)

To compensate this difference between ABA and BAS+, a corrective factor is determined. In 2011 GDV published a study based on insurance data [8]. In this study, the safety potentials of various driver assistance systems were derived. Among others they compared the impact for a FCA system of having the characteristic to detect moving/stopping objects with the characteristic to detect moving/stopping and stationary objects. The Forward Collision Avoidance system consists of FCW, EBA and AEB.

- The FCA system that had the characteristic of detecting moving/stopping vehicles only has an accident avoidance potential of 17.8% of all passenger vehicle accidents with injury.
- The same system including additionally the detection of stationary vehicles has an accident avoidance potential of 19.6% of all passenger vehicle accidents with injury.

While the absolute efficiency percentages are deemed to be generous, it is nevertheless possible to isolate the factor quantifying the detection of stationary vehicles. The quotient of these figures is 0.91 (17.8 / 19.6). To make a rough estimation, 0.91 is applied to the 20% accident avoidance potential and the 25% severity mitigation potential derived in before (Fig.3) we get for CPA:

- an accident avoidance safety potential of 18%
- an accident severity reduction potential of 22%

for rear-end passenger vehicle crashes with injury in the bullet car.

CPA lacks the non-negligible safety spin offs of the adaptive cruise control deceleration. However, this mere comfort oriented "long range" and modest deceleration is of lesser benefit to actual accident avoidance and reliant on DISTONIC PLUS's ACC function actually being in use (primarily on highways / freeways).

DRIVING SIMULATOR TESTS TO RATE THE EFFICIENCY

To assess the effectiveness in which the two combined functions Forward Collision Warning FCW and Brake Assist PLUS are able to improve faulty driver behaviour in the case of rear-end collisions, an experiment was conducted in the Berlin dynamic driving simulator [11]. Brake Assist PLUS is equivalent with CPA's Adaptive Brake Assist with the added capability of detecting stationary vehicles. The results can directly apply to CPA, because the analysed scenarios did not contain stationary objects.

110 ordinary drivers had to cope with three typical driving situations that often lead to rear-end collisions according to accident statistics (see Table 2). They had of approximately 40minutes. One half of the sample drove a vehicle equipped with the conventional BAS, the other half had BAS PLUS available in addition to BAS. In this study, the initial travelling speed of the ego vehicle was always beyond 30 km/h and the target vehicle was always moving. Hence, CPA's Adaptive Brake Assist would have operated in the same way as Brake Assist PLUS.

Nr	Road Type	Speed [km/h]	Initial following distance [s]	Scenario
1	Autobahn	130	1.45 – 1.55	Subject vehicle on left lane, vehicle cutting in from right lane at TTC = 2 s
2	Autobahn	130	1.45 – 1.55	Lead vehicle starts to brake at1 m/s² for 0.7 s and then increases deceleration to 8.5 m/s²
3	Highway	80	1.45 – 1.55	Lead vehicle starts to brake at 1 m/s² for 1 s and then increases deceleration to 9.0 m/s²

Table 2: Scenarios tested in the dynamic driving

Results show that the combination of FCW and BAS

PLUS leads to a 75% lower accident rate (combined) compared to the conventional BAS (Table 3). For those subjects who reacted too late to avoid the accident, BAS PLUS produced a mitigating effect: impact speed was reduced by 35 % on average.

Scenario	Accident Rate with		Impact Speed (if collision occurred) with	
	BAS	*BAS PLUS*	*BAS*	*BAS PLUS*
1	20%	4%	30 km/h	19 km/h
2	55%	19%	60 km/h	45 km/h
3	44%	6%	46 km/h	26 km/h

Table 3: Driver performance in dynamic simulator tests (110 subjects, mean values)

All three potential accident situations would have been addressed by CPA in the same way as they were by BAS PLUS. Hence, the results of this study directly apply to CPA. From the drivers view, the driving simulator contains a "real" car. So the FCA assessed with car environment and/or its settings can be determined. The default setting for BAS PLUS is "on", as is the case for CPA.

Fig. 4: The (old) Berlin moving base simulator of Daimler

For BAS PLUS in combination with FCW it was found that it has high acceptance, a very effective driver vehicle interface and is very effective in reducing collision or collision speed. The results are valid one-to-one for CPA.

FIELD TEST RESULTS

Field tests are usually carried out in the last phase of the development. Mercedes-Benz runs integrated field tests for new and modified systems. They were performed in real world traffic mostly by non-expert drivers and carried out in Europe, US, Japan and South Africa. Generally over 1 million km were driven. The received data base allows an in-depth analysis of the system in cooperation with different driver in the wide range of pre-crash scenarios from critical situations up to near crashes. The results were used in this section to show that Collision Prevention Assist covers most relevant functions of the Driver Assistance Package. Table 4 list the differences.

	PRE-SAFE Brake	Collision Prevention Assist
Headway warning	Yes	Yes
forward collision warning	Yes	Yes
Adaptive Brake assistance	Yes	Yes
Autonomous partial braking	Yes	No
Autonomous full braking	Yes	No

Table 4: Collision Prevention Assist – Comparison with PRE-SAFE® Brake

The main difference is that CPA cannot provide autonomous braking.

To assess the magnitude of this limitation, an in-depth analysis of Mercedes-Benz field test data was carried out. The data set was generated by a special field test carried out for the modified operation speed ranges for FCW, BAS PLUS and PRE-SAFE® Brake (expanded in 2010 from the lower threshold of 30km/h to 7km/h, Tab. 1). The data basis contains 53.100 measurement ascertained in 735,000km driven by more than 400 ordinary (84%) and professional (16%) driver. No rear-end collision occurred within the field test. For more detail see [3]

System	Activation Rate [events per 100,000 km]
Forward collision warning	720
Brake Assist plus (BAS Plus)	15
Brake Assist plus (BAS Plus) AND PRE-SAVE® Brake Stage 1	1
PRE-SAVE® Brake Stage 1 (partial autonomous braking)	2,5
PRE-SAVE® Brake Stage 2 (full autonomous braking)	0

Tab 5: Mercedes-Benz field tests: system activation rates

Tab. 5 shows the activation rates of the different components of the Driving Assistance Package. The Forward Collision Warning in combination with BAS PLUS is by far the most frequently triggered driver support in critical longitudinal driving situations:

- Collision warning resolves many situations
- BAS PLUS alone is activated four times more often than autonomous partial braking
- Even when autonomous partial braking was activated, the drivers braked if necessary (and also received BAS PLUS support, if still necessary)
- No activation of autonomous full braking
- No rear-end collision occurred in the field test

During the field test each system activation was recorded with all relevant physical signal information and with video data captured by several video cameras in the test car.

For the following analysis is restricted to those activation had been qualified as correct. A subset of 379 randomly chosen FCW activations was generated to eliminate statistical influences resulting from the selection procedure. Fig. 5 showed that the majority of warnings occur between 30km/h and 80 km/h.

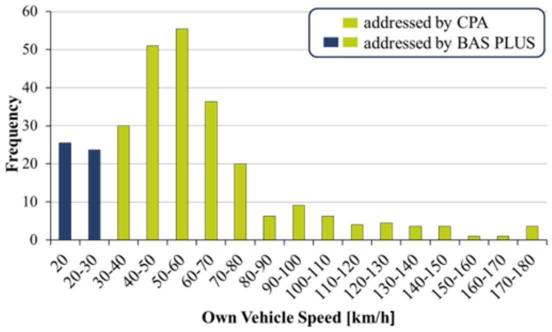


Fig. 5: Mercedes-Benz Field tests: Frequency of forward collision warnings in speed categories (n=379), warnings at speeds above 30 km/h will also be given by Collision Prevention Assist.

The driver was already braking in more than 40% of cases when Forward Collision Warning was triggered (Fig. 6), which correlates well to the results of the GIDAS study outlined in the accident mechanism. Very frequently, the situation occurs in following traffic: The car in front of the test car is already braking when it suddenly increases the deceleration and the following driver unexpectedly also needs to increase his brake force. This observation is also in good correspondence to the accident mechanism.

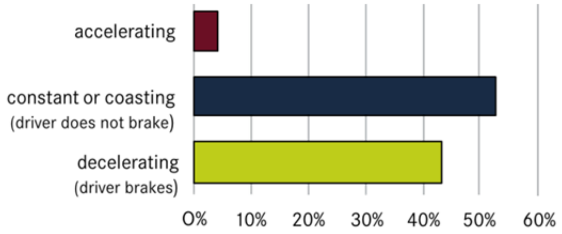


Fig. 6: Mercedes-Benz Field Analysis of field tests: vehicle state when forward collision warning was triggered

Interestingly 44% of all drivers were already braking when a FCW occurred (Fig. 7). Of the drivers who responded to FCW by applying the brake:

- 65% of acted within 0.4s after the warning
- 87% of acted within 0.8s after the warning
- 97% of acted within 1.0s after the warning

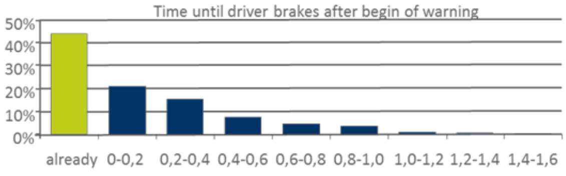


Fig. 7: Mercedes-Benz Field Analysis of field tests: Time between onset of Forward Collision Warning and driver (re)action

No FCW activation without any driver reaction was observed. Hence the audible / visual warning, a combination of warning tone and icon, proves to be very effective. However, no claim for an individual safety potential of FCW, separate from Adaptive Brake Assist, is being made in this dossier. The potential of CPA is always given as a combination of FCW and ABA.

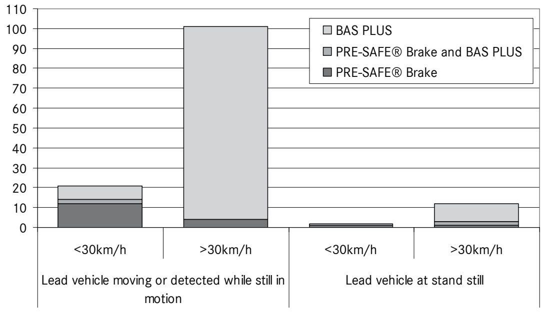


Fig. 8: Mercedes-Benz Analysis of field tests: System Activations in different speed and lead vehicle moving categories (n = 136)

Fig. 8 gives an overview to which extent each system is able to address the critical situations that have occurred during the Mercedes-Benz field tests. The full functionality of the Driver Assistance Package was able to address all of the critical situations.

- BAS PLUS was effective in 87% of all critical situations; so that no accident occurred.
- The CPA functionality had addressed 71% of all critical situations (82% out of the BAS PLUS-situations).
- PRE-SAFE® Brake stage 1 (autonomous partial braking) had addressed 13% of all critical situations.
    - PRE-SAFE® Brake stage 1 had addressed 3% of all critical situations above a threshold of 30km/h.
- Low speed brake assistance (system activations below a threshold of 30km/h) had addressed 17% of all critical situations.
    - PRE-SAFE® Brake stage 1 (autonomous partial braking) had addressed 10% of all critical situations.
    - BAS PLUS had addressed 7% of all critical situations.
- Characteristic feature “detect objects that were not moving during their first detection” for brake assistance had addressed 10% of all critical situations. (good correspondence with the GDV analysis [8])

In order to assess the relevance of these data from MB field tests with regard to real world accidents, a comparison with GIDAS data was carried out. As an indicator the distribution of speed in critical situations in the Mercedes-Benz field test and the speed distribution of accidents with personal injuries taken from GIDAS were used (Fig. 9). The speed profile of system activations in Mercedes-Benz field tests is very consistent with data on real rear-end collisions with one exception: the frequency distribution of PRE-SAFE® Brake situations is different. This finding is not really surprising: no FCW activation without any driver reaction was observed. While PRE-SAFE® Brake Stage 1 is available up to a vehicle speed of 200 km/h; it is nevertheless activated mainly at lower speeds where typically minor personal injuries (would) occur.

Not every critical situation within the Mercedes-Benz field test would have ended in an accident in real world traffic. However, it seems to be plausible that a substantial proportion of critical cases in the Mercedes-Benz field test would have led to an accident without the system's support.

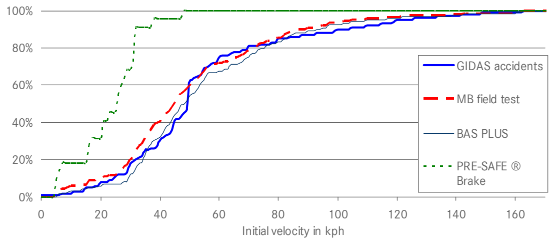


Fig. 9: Comparison between Mercedes-Benz Field test and GIDAS: Velocity at start of braking in critical situations in MB Field test and velocity of rear end crashes taken from GIDAS

The Mercedes-Benz System CPA does not provide the full functionality of the optional Driver Assistance Package consisting of PRE-SAFE® Brake BAS PLUS and FCW. However, it does provide some of the most relevant and most effective functions of the DPA portfolio. Remarkably, the CPA system could address 71% of all critical situations.

REAL WORLD EVALUATION - Mercedes - Benz Spare Part Calls Analysis

The real world evaluation is the final step in the process outlined in Fig. 2. In this paragraph the results of a spare part call analysis are represented. An OEM can analyze the calls over a fixed period and country for a model and compare the calls for vehicles that were equipped with and without a technology. Avoided collisions should lead to fewer calls of (significant) spare parts. Collisions with mitigated severity should lead to shift in spare parts needed for repairs.

To determine the effect of the driver assistance system DISTRONIC PLUS with its integrated assistance features FCW and BAS PLUS an analysis was carried out on the basis of spare part calls. The amount of spare part calls of two equal vehicle models groups equipped / not equipped with the system should differ regarding bumpers, bumpers + cross members and bumper + cross member – front end longitudinal member assembly.

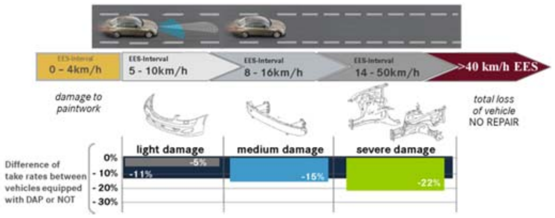


Fig. 10: Reduction of front-end spare parts calls with DISTRONIC PLUS (Model Range 221 in Germany from launch to end of 2008, about 60,000vehicle years in operation)

The evaluation was based on the data of the spare parts calls for the S-Class model 221 delivered by Mercedes-Benz in Germany between launch and end of 2008. In this period about 40,000 cars were sold and registered in Germany. About 40% of these cars were equipped with DISTRONIC PLUS including Forward Collision Warning, PRE-SAFE® Brake stage 1, BAS PLUS and parking assistance. The remaining 60% were equipped with parking assistance only. The results are shown in Fig. 10. The diagram uses the damage of spare parts as an indicator for typical energy levels (given by Energy Equivalent Speed or EES). For all observed chains the highest level is used. The Figs. demonstrate that the rate of repairs for the vehicles equipped with the DISTRONIC PLUS package was reduced in all three ranges of energy equivalent collision speeds. The rate of repairs of front-end bumpers was reduced by 5%, the repair rate of a front-end bumper in combination with a cross member dropped by 15% and repairs involving front-end bumper, cross and longitudinal member assembly dropped by 22%. These data show that DISTRONIC PLUS with the included driver assistance features including PRE-SAFE® Brake is effective in reducing the number and severity of frontal crashes significantly.

Taking the characteristics of the driver assistance safety measures (Tab. 1) into account, a calculation of the efficiency of Forward Collision Warning, BAS Plus and PRE-SAFE® Brake Stage 1 for rear end collisions with injuries or fatalities is possible. The frequency of accidents at a given level of accident severity (measured in EES) occurring in real world accidents can be determined with a cumulative sum of EES taken from a representative accident data sample, such as GIDAS. The number of accidents (respectively cars or injured occupants) occurring up to a certain accident severity can thus be determined. This analysis shows that 53% could be mitigated, as they are in a severity range of up to 45km/h EES. (Fig. 12, for more details see [15])

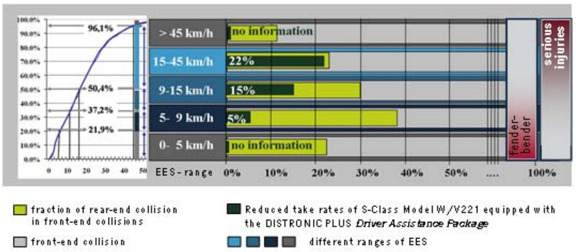


Fig. 11: Effectiveness in reducing front-rear accidents

In detail, the degree of efficiency is about 95% in the EES range [15 – 45 km/h], about 50% in the EES range [9–14 km/h] and about 13% in the EES range [5–9 km/h]. The degree of efficiency denotes the share of spare parts reduction attributed to the system's actions (assumed to be close to 100%, seeing that reference group and control group comprise same type vehicles) versus the computed share of front end damages attributed to rear-end crashes in this EES range (based on the above mentioned GIDAS analysis). The details are shown in Fig. 11.

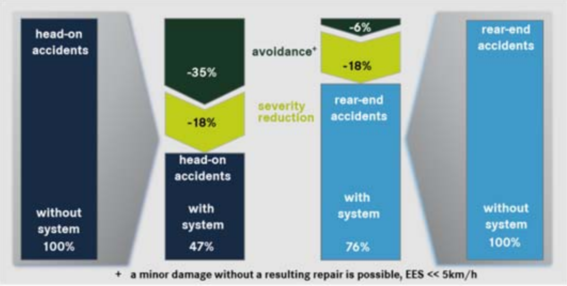


Fig. 12: Effectiveness in avoiding or mitigating the severity of rear-end collisions

This means that severity is shifted at least to the severity of the next (lower) severity range. It is interesting to note that the degree of efficiency is high where the severity of damage is high, i.e. where the speed difference of bullet and target vehicle is high. In other words, especially severe collisions were reduced in their severity.

As a secondary benefit, the calls of rear-end spare parts of the reference group that differ only in the mentioned equipment was also reduced significantly: Equipped vehicles show approximately 24% avoided or mitigated rear-end collisions compared to non-equipped vehicles (Fig.12).

It is assumed that the system has a positive side effect on following traffic prone to rear-end the subject vehicle: Due to the adaptive nature of BAS PLUS and early warnings by FCW, potentially late and hard panic reactions of following vehicle drivers may be changed to earlier, moderate reactions. This attenuating effect is especially helpful in multiple follow-up collisions, usually increasing in criticality because of cumulating late and more intense reactions.

The Adaptive Brake Assist component of CPA includes nearly all capabilities of BAS Plus with the exception of reacting on stationary vehicles that were never seen moving before (see Tab. 1). As stated previously it covers 82% of BAS Plus situations which results in 71% of all situations. Therefore this attenuating effect applies to CPA in a comparable magnitude.

A SPECIALITY: ACCIDENTOLOGY BASED ON SPARE PART CALLS

Effectiveness in avoiding **accidents** or mitigating their severity is **reflected** in the quantities ordered of **characteristic** spare parts.

A *unique* list of characteristic items/spare parts corresponds to a typical extant of a crashed vehicle – and vice versa. (Fig. 13)

Avoided accidents are reflected in reduced take rates. Mitigated severities are reflected in reduced length of orders. (A special spare part is missing in the order – different item list.) By adding “appropriate prior knowledge” –for example results from “classical” accident analysis or system characteristics to such an analysis, new connecting results can be established. This idea is demonstrated in two examples.

Order for **Mercedes-Benz**

- Front-end bumper
- Front-end cross member
- Repair-Set for longitudinal member left
- Airbag (driver)
- Grille plate
- Hood

Fig. 13: Basic Idea of spare part call analysis: call corresponds to damage at a car

An elementary task of each accident research unit is to ascertain the impact energy and characteristic of real world crashes. Currently this is done in the accident research units within the OEM´s or in common comprehensive research projects like for example GIDAS in Germany. Both had the same disadvantage: due to their specific limitations they could not do it for a specific model range. However, the knowledge based approach of analysing spare part calls can do so. In this way an individual characteristic of the impact of *their* real world crashes and changes for example due to the use of primary safety measures could be analysed.

Fig. 14 showed the vertical location of the area of damage of a frontal crash. For the vehicles that were equipped with the *Driver Assistance Package* it moved to the lower region.

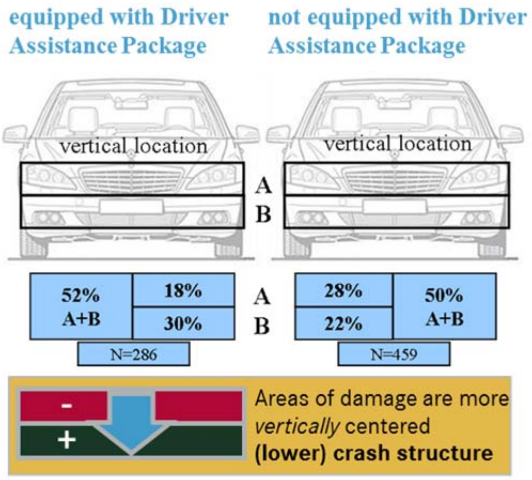


Fig. 14: Vertical damage regions of vehicles equipped and not equipped with the *Driver Assistance Package.*

Fig. 15 showed the horizontal location of the area of damage. Here the comparison of the results for the vehicles that were respectively were not equipped with the Driver Assistance Package showed that the vehicles that were equipped with the system had more overlap with their opponents. Both Fig. 14 and

Fig. 15 showed that the *Driver Assistance Package* leads to a more balanced energy input in the lower crash elements – bumper, cross member and so on.

Fig. 16 showed a comparison of the horizontal location of the impact area for frontal crashes with airbag activations. The differences are reduced overlaps at the right and left sides and an increased share of 100% overlapping.

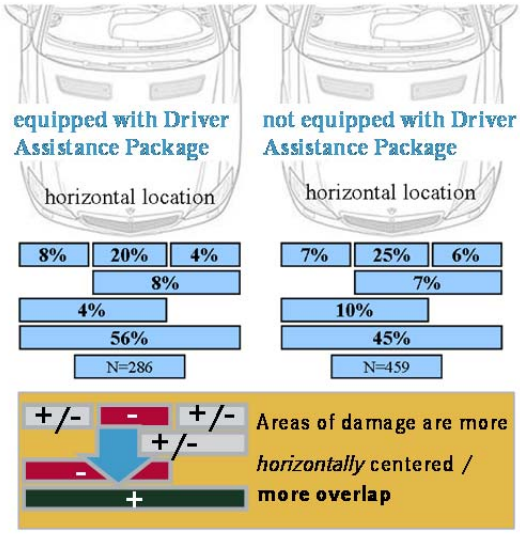


Fig. 15: Horizontal damage regions of vehicles equipped and not equipped with the *Driver Assistance Package.*

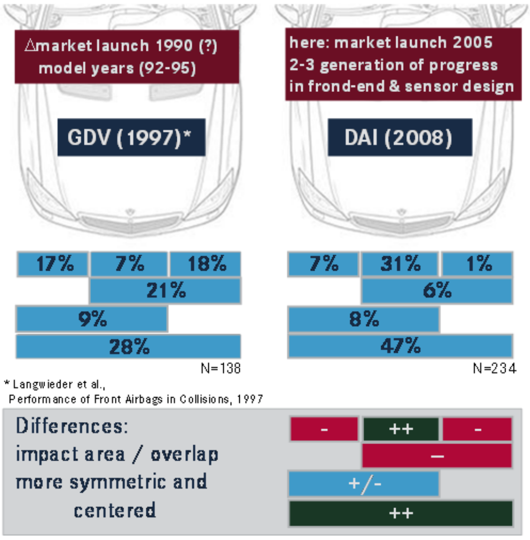


Figure 15: Overlapping of crashed vehicles with airbag activation – differences two studies with 10 years delay.

CASUALTY REDUCTION POTENTIAL BASED ON THE ANALYSIS OF SPARE PART CALLS

The findings are based on the comparison of spare parts calls for same type vehicles with and without DISTRONIC PLUS with FCW, BAS PLUS and PRE-SAFE® Brake stage 1.

To estimate the pertaining potential for casualty reduction, an Injury Risk Function (IRF) is applied to the results of the study [15]. This method is commonly used to estimate the benefit of primary or secondary safety measures. E.g., it was used to prove the equal effectiveness of BAS and secondary safety measures for Pedestrian Protection in [6] carried out for ACEA. For the purpose of this analysis, an injury risk function is required. The needed IRF describes the correlation between MAIS (Maximum Abbreviated Injury Scale) of the passengers of the striking car versus its Energy Equivalent Speed (EES) in a rear-end collision. This IRF was derived from the rear-end accidents contained in GIDAS 12-2008 database.

Two injury classifications were taken into account: slightly injured (MAIS=1) and at least seriously injured (MAIS>1). The class “fatally injured” corresponding to MAIS5+ contains too few entries (n=8). Therefore, only MAIS2+ was considered. Fig. 11 describes the correlation between injury risk (MAIS1+, MAIS2+) and EES.

The driver assistance safety features FCW, BAS PLUS and PRE-SAFE® Brake stage 1 within DISTRONIC PLUS influence the speed difference and thus the EES. This influence does not change the IRF, but the EES as its input. In a case-by-case analysis using the derived degrees of efficiency in the defined EES-ranges, the effect on EES can be predicted. The overall probability of MAIS1+ and MAIS2+ injuries decreases with the reduction of EES or collision speed.

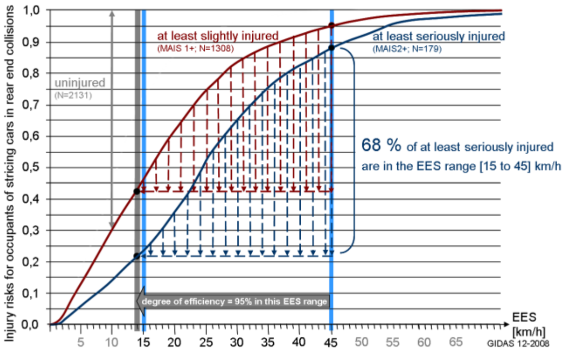


Fig. 16: Injury Risk Function for Bullet Car Occupants in Rear-End Collisions

Fig. 16 shows that about 68% of all at least seriously injured occupants of the striking car are contained in the EES range [15 – 45 km/h]. The degree of efficiency of the driver assistance functions FCW, BAS PLUS and PRE-SAFE® Brake stage 1 within DISTRONIC PLUS is 95% in this EES range.

The degree of efficiency denotes the share of spare parts reduction attributed to the system’s actions (assumed to be close to 100%, seeing that reference group and control group comprise same type vehicles) versus the computed share of front end damages attributed to rear-end crashes in this EES range (based on a GIDAS analysis).

Consequently, this system can reduce the damage level of collisions to at least below the lower limit of the EES range [15–45 km/h], i.e. EES=14km/h or less. Hence, the injury risk for all occupants that actually had an accident within the severity range from [15-45km/h] taken from GIDAS is reduced to the risk of the lower limit of the EES range. Or: The risk of a bullet car occupant of being “at least seriously injured” is reduced by the system from its former value (blue line in Fig. 16) to a new value (dotted blue line in Fig. 16). For each value of EES the downward arrows in Fig. 16 define the reduced injury risk. Adding up the number of occupants which were “at least seriously injured” in a collision with an certain value of EES for all values of EES out of the interval [15-45km/h] multiplied by their reduced risk results in the number of occupants that are no longer “at least severely injured” and so on.

Applying this to the case-by-case analysis yields the injury reduction benefit. The limitation to this EES range indirectly provides an elimination of collisions with initial / collision speeds of the striking car above 130km/h.

As a conservative approach, the system benefit is considered in the EES range [15 – 45 km/h] only. Additionally, it is assumed that the damage in this EES range is reduced to 14km/h EES for all cases (and not less).

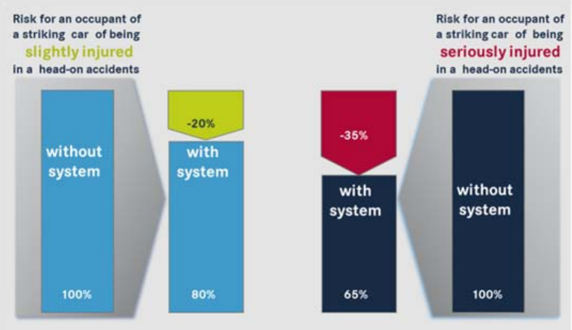


Fig. 17: Effectiveness in avoiding or mitigating the severity of injuries of an occupant of the striking car

Based on these assumptions, a mapping to real world accidents by leveraging a cumulative sum of EES frequencies leads to the following result: For this severity range the number of saved “at least seriously injured” occupants of the striking car is 63. 35 of these “at least serious injuries” were avoided, 28 were reduced to “slightly injured”. Correlating this to the 179 at least seriously injured occupants (derived from GIDAS) yields an effectiveness of 35%.The results are shown in Fig. 17.

MEASURING SYSTEM REAL WORLD EFFECTIVENESS WITH INSURANCE DATA

National Umbrella organizations of insurance companies like the IIHS (Insurance Institute Highway Safety) and the HLDI (Highway Loss Data Institute) in the United States of America or the GDV (Gesamtverband der Deutschen Versicherungswirtschaft) in Germany usually have access to a big share of data of national automobile insurance claim data. Automobile insurance covers damages to vehicles and property as well as injuries to people involved in crashes. Depending on national law, some insurance coverages (including their details) are compulsory for every driver others are voluntary, different coverages may apply depending on who is at fault.

The automotive insurance data is representing the human and economic losses resulting from the ownership and operation of vehicles and the profit or loss that insurance companies gain from it. Consequently, the data covers a very high percentage (>80%) of all annual reported collision, that vehicles had on public roads and private properties. This is a good reflection of road accidents but the data also includes other collisions like low speed maneuvering collisions like parking. This representative large-scale insurance data usually contain data about the at-fault driver’s vehicle and the involved vehicle that was damaged by it, cost in the category of the coverage and no/poor information about the details of the crash (for example point of impact, collision speed, type of crash …). A consequence of the missing detailed crash information is that effectiveness could not be measured against the use cases of the system for example front-to-rear-end crashes for forward collision warning system with collision mitigation braking functionality. Therefore, effectiveness measured with insurance data is always referring to ***all collisions*** regardless of the ability of a system to mitigate or prevent the crash.

Often active safety features are always bundled together on a vehicle and are not available individually. The bundled features vary between vehicle series and by model year. Thus often only the effectiveness of the bundle can be measured.

Another limitation is that the status of a feature is not known at the time of the crash. If a feature can be deactivated by the driver and there is no way to know how many, if any, of the drivers in these vehicles had manually turned off the system prior to the crash. If a significant number of drivers do turn these features off, any reported reductions may actually be underestimates of the true effectiveness of these systems.

General, studies based on insurance data should not be conducted too early. It should be ensured that the exposure rates with active safety features are not to small compared to the probability of accidents; (market introduction, take rates of optional equipment) to make sure that the stability of the results as well as their independence of special weather conditions, their use in correlation to road performance and mileage, the share of inter and extra urban rides are balanced.

Analyses of insurance collision claims are giving early indications of how crash avoidance technologies are working. In 2012 the HDLI [7] published a bulletin that summarized their findings on Mercedes-Benz collision avoidance features. Mercedes-Benz supplied HLDI with the identification numbers of those vehicles that had collision avoidance features, allowing HLDI to compare the insurance records for those vehicles with the same models without the feature. The study is based on property damage liability, collision, bodily injury liability, personal injury protection and medical payment coverages. The different insurance coverages are defined as follows:

- “Collision” pays for damage to the insured vehicle sustained in a crash with an object or other vehicle.
- “Property damage liability” (PDL) pays for damage an at-fault driver’s vehicle does to other people’s property as a result of a crash.
- “Bodily injury liability” pays for medical, hospital, and other expenses for injuries that at-fault drivers inflict on occupants of other vehicles or others on the road;
- “Medical payment” covers injuries to insured drivers and the passengers in their vehicles, but not injuries to people in other vehicles involved in the crash.

Insurance measures are:

- “Exposure”, is expressed in insured vehicle years.
- “Claim frequency”, is expressed as the number of claims per selected number of insured vehicle years (exposure).
- “Claim severity”, represents the average cost per claim.
- “Overall losses”, represents the average cost per insured vehicle (year), calculated by dividing total dollars paid for claims by exposure Insurance measures.

Vehicle damage coverage type	Collision	Property damage liability
Lower bound	-12,8%	-23,3%
Frequency	-7,1%	-14,3%
Upper bound	-1,0%	-4,2%
Lower bound	-$258	-$191
Severity	$145	$126
Upper bound	$578	$479
Lower bound	-$54	-$19
overall losses	-$18	-$8
Upper bound	$20	$40

Tab. 6: Changes in insurance losses in *vehicle damage coverage* for vehicles equipped with DISTRONIC PLUS (incl. Driver Assistance Package) [7]

The results of DISTRONIC PLUS incl. the *Driver Assistance Package* are contained in Tab. 6. There are reductions in the claim frequencies of *collision* of 7.1% and to a greater extend of 14.3% for PDL claim frequency of PDL. Reductions in loss claims are estimated for both first- and third-party vehicle damage coverages, resulting in somewhat lower losses per insured vehicle year (overall losses). Only the frequency reductions for collision and PDL were significant.

DISTRONIC PLUS incl. the *Driver Assistance Package* reduces the frequency of injury claims: -16% in bodily injury liability, -21% in medical payments and -15% in personal injury protection (payment for involved injured persons regardless of who’s at fault in a collision). Under injury coverages, the frequency of paid and reserved claims is lower for all coverage types but none of the differences is statistically significant. Among paid claims, reductions are seen for all coverage types at both low and high severity (Fig. 7).

Vehicle damage coverage type	Collision	Property damage liability
Lower bound	-12,8%	-23,3%
Frequency	-7,1%	-14,3%
Upper bound	-1,0%	-4,2%
Lower bound	-$258	-$191
Severity	$145	$126
Upper bound	$578	$479
Lower bound	-$54	-$19
overall losses	-$18	-$8
Upper bound	$20	$40

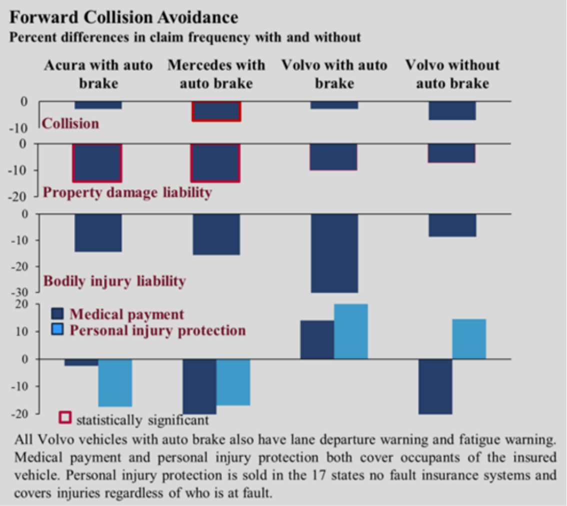
Tab. 7: Changes in insurance losses in *injury coverage* for vehicles equipped with DISTRONIC PLUS (incl. Driver Assistance Package) [7]

As has been deduced before CPA could address 71% of all rear-end pre-crash situations these results are of considerable relevance to CPA.

COMPARISON OF DIFFERENT FOREWARD COLLISION AVOIDANCE SYSTEMS – REAL WORLD EFFECTIVENESS WITH INSURANCE DATA

Insurance data is suitable to compare the real world effectiveness of different systems. The claim frequency under property damage liability insurance, which covers damage to another vehicle caused by the insured vehicle, and collision insurance, which covers damage to the insured vehicle are able to compare the performance of different systems. The claim frequency under property damage liability insurance might be a more objective performance measure compared with the frequency of collision because it this measure is not so strong influence able by economic considerations on the extent of the future such as Insurance Premium.

HLDI analyzed the insurance claim data for FCW systems offered on Acura, Mercedes-Benz and Volvo. The results are displayed in Fig. 18.



All Volvo vehicles with auto brake also have lane departure warning and fatigue warning. Medical payment and personal injury protection both cover occupants of the insured vehicle. Personal injury protection is sold in the 17 states no fault insurance systems and covers injuries regardless of who is at fault.

Fig. 18: Results of the HLDI analysis of insurance claim data [9]

The different systems under analysis had the following specifications:

“Acura with auto brake” means that the Acura were equipped with a Forward Collision Mitigation System that will provide visual and auditory warnings when speed and distance indicates a risk of a crash with the leading traffic and, if the driver does not respond by reducing speed, the system will tug at the seat belt to get the driver’s attention and begin braking to mitigate — but probably not prevent — the crash. Collision mitigation becomes functional at speeds over 15 km/h and deactivates when speed drops below 15 km/h. It is bundled with an Adaptive Cruise Control system.

“Mercedes-Benz with auto brake” means that the vehicles were equipped with DISTRONIC PLUS in combination with the Driver Assistance Package (see Tab. 1) with the lower threshold of the operation speed rage of 30km/h.

“Volvo vehicles without auto brake” were equipped with Adaptive Cruise Control and Forward Collision Warning that uses radar sensors mounted in the front bumper to detect the risk of a collision. Driver warnings are both auditory and visual (red lights in a heads-up windshield display). If the driver brakes the warnings are canceled. The forward collision warning system is active only between speeds of 30 and 180 km/h. Vehicles with Forward Collision Warning also have Adaptive Cruise Control and Distance Alert.

“Volvo vehicles with Auto Brake” were equipped with a Forward Collision Warning system that includes some autonomous emergency braking. With Auto Brake, the system will also provide visual and auditory warnings when speed and distance indicate risk of a crash with the leading traffic and, if the driver’s reaction does not eliminate that risk, the system will begin emergency braking to mitigate – but probably not prevent – the crash. Auto Brake becomes functional at speeds over 5 km/h and deactivates when speed drops below 5 km/h. Auto Brake operates whether or not Adaptive Cruise Control is activated. (All descriptions were taken from HLDI Bulletins.)

MEASURING SYSTEM REAL WORLD EFFECTIVENESS WITH ANNUAL REPORTED ROAD ACCIDENT DATA

The real world evaluation on the basis of federal accident statistics is the final step. Only here the true effectiveness of the safety measure can be verified.

Unfortunately, this step could not yet be performed. The S-class had not enough accidents in Germany for getting statistically significant results. All other models are not long enough on the market. An evaluation based on German accident figures is expected to be available in 2014/2015 for CPA.

CONCLUSIONS

The Real Life Safety evaluation circle (Fig. 2/19) is (nearly) closed for Mercedes-Benz Forward Collision Avoidance Systems. In each step a validation of a former report could be carried out.

Fig. 19: Evaluations made for the Mercedes-Benz systems: Driver Assistances Package consisting of: FCW, BAS PLUS, PRE-SAFE® Brake and Collision Prevention Assist

The Driver Assistance Package consisting of FCW, BAS PLUS, PRE-SAFE® Brake and Adaptive Brake that is available in combination with DISTRONIC PLUS showed in real world evaluations a high effectiveness in avoiding or mitigating the severity of rear-end collisions.

53% of all rear-end collision could be mitigated in their severity, from that 35% could be avoided.

The risk for an occupant of the striking car of being seriously injured is reduced by at least 35%.

Claim frequency reduced by 14.3% in the insurance coverage property damage liability.

It is important to note, that the Collision Prevention Assist CPA covers about 71% cases of the full

Driver Assistance Package consisting of FCW, BAS PLUS, PRE-SAFE® Brake and Adaptive Brake. Hence the effectiveness of the full package applies to CPA in a comparable magnitude.

ACKNOWLEDGEMENT

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