

NEW APPROACH OF ACCIDENT BENEFIT ANALYSIS FOR REAR END COLLISION AVOIDANCE AND MITIGATION SYSTEMS

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ABSTRACT

In Germany approximately 12% of all accidents with persons injured and approximately 20% of all material damage accidents are caused by cars in rear end collisions. As a consequence, Bosch is introducing collision avoidance and mitigation systems for rear impact scenarios. Warning, brake support, and autonomous emergency braking are part of Bosch's Advanced Emergency Braking Systems which address such accidents. This study determines the benefit of these assistance and safety systems and estimates the collision avoidance capability considering the driver's behavior. By analyzing representative accidents with injuries from the GIDAS (German In-Depth Accident Study) database, a high potential for collision warning and avoidance systems was determined. For the first time in such a study, this analysis considers the effects of different driver reactions due to warning, braking support, or autonomous braking with respect to the possible driver behavior. For this, a calculation method was developed and used for evaluating the accidents automatically. Both accident avoidance and average speed reduction was determined for different driver types, warning strategies and applications. From the results, an avoidance ratio of 38% for Predictive Collision Warning up to 72% for Automatic Emergency Braking, of all rear-end accidents can be expected for a realistic driver. Therefore it is estimated that 3 out of 4 accidents with severe injuries could be avoided based on the Emergency Brake Assist function and assuming a 100% installation rate. The potential to reduce collision speed in non avoided accidents is calculated on an average basis and is determined to be between 25% and 55% for the realistic driver. The results in the analyses show the high efficiency of the Bosch AEBS functions in avoiding accidents or mitigating injuries by reducing collision speed and should encourage the introduction of

Advanced Emergency Braking Systems across a wide range.

INTRODUCTION

Since active safety systems have become more popular over the past few years, they are now an integral part of new vehicles. The vehicle stability control system ESP® (Electronic Stability Program) is considered to be a representative example of these active safety systems. ESP® supports the driver in nearly all critical driving situations in which an unstable driving condition might occur. By automatically braking individual wheels the system helps to prevent skidding and keeps the vehicle stable. This results in fewer single vehicle accidents with high severity. A large number of international studies by well-known automobile manufacturers and independent institutes have proven the effectiveness of ESP® in reducing the number of accidents. For example Baum *et al* [1] stated ESP® would save 4000 lives per annum assuming a 100% penetration of ESP® for all passenger cars within the European Union (EU25). Furthermore approximately 95.000 injuries would be prevented in such accident scenarios. In the US even up to 9.500 lives and 252.000 injuries per annum could be saved or prevented respectively by a vehicle stability control system like ESP®. Such high avoidance potential could reduce the share of accidents against fixed objects significantly. Figure 1 gives an overview of all accidents with casualties by kind of accident for three different countries.

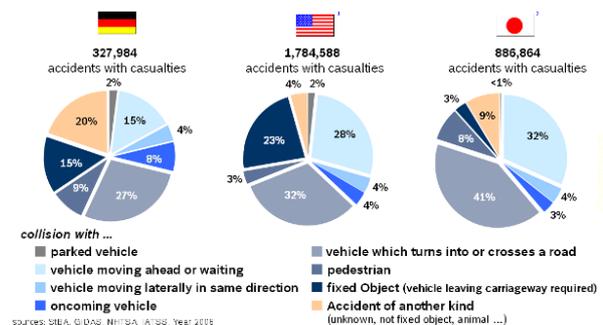


Figure 1. Accidents with casualties by kind of accident [3], [4], [5]

As a result, other types of accidents come to the fore. As shown in Figure 1, a high share of accidents are rear-end collisions against a leading vehicle. With a fraction of 15% of all accidents in Germany, 28% in the US and even 32% in Japan, these accidents cover a high quantity of accidents with casualties. Approximately 4 out of 5 accidents are caused primarily by a passenger car, whereas the remaining accidents are caused primarily by trucks.

In fact, accidents with only property damage are neglected typically, hence their relevance and

potentials are underestimated. Together with Allianz Zentrum für Technik (AZT) - a leading specialist in damage analysis and prevention - we established that approximately 1.1 Million rear-end crashes per annum in Germany occur. This database consists of accidents caused by a passenger vehicle wherein either a police report or individually regulated insurance claim was filed [6]. Such collisions occur mainly at lower speeds but with higher frequency. In summary, a higher need for collision avoidance systems is given. Aside from ESP®, Bosch also provides a family of driver assistance and safety functions which are part of the Advanced Emergency Braking Systems (AEBS). The idea behind AEBS is scalable functionality - from driver warning over optimized braking support to a fully autonomous braking system. To estimate long term effects within the development process, the scope of all functions is a proven benefit within the real world according to their functional specifications.

Real world accidents have to be taken into account to evaluate this benefit. Up to now, other studies considered only one part of the aspects above. For example autonomous braking systems were part of the study from Schittenhelm [7]. He quoted that 20% of all passenger vehicles which caused rear-end collisions would be avoided by the DISTRONIC plus and the Brake Assist System (BAS). Based on semi-autonomous braking and additional braking support by increasing brake pressure, this analysis does not consider any driver reactions due to acoustic or tactile warning strategies. From this point of view it seems to be a more conservative estimate regarding the benefit of predictive safety systems.

In harmony with this concept, the goal of this study is to evaluate the benefit of the Advanced Emergency Braking Systems functions from Bosch using the German In-Depth Accident Study (GIDAS) database. A driver model was developed which considers driver behavior and reaction in order to gain the function's benefit not just based on functional characteristics. As an outcome two major results were obtained - firstly the accident avoidance potential and secondly the reduction of injury severity.

METHODOLOGY

The analysis is based on data from the GIDAS project [8]. Since 1999, accidents with injuries were surveyed within Germany around the region of Hanover and Dresden. Approximately 2000 accidents per year were reviewed and deemed to be valid as representative for accidents with injuries in Germany. For each accident, approximately 3000 details are collected and provided within a database for further analysis. Along with the vehicle damage and personal injuries, information from prior to the

accident also is obtained based on the fact that each accident is reconstructed in detail. Therefore, physical information regarding the pre-, during- and post- post crash phase is available and essential for the analysis of safety systems as AEBS. For this study, 9323 reconstructed accidents with injuries were used. By selecting collisions with significant characteristics, it was ensured that only relevant accidents were taken into account for the AEBS benefit calculation. In this study only passenger vehicles causing rear-end collisions are considered. Thus rear end collisions against a motorcycle caused by a passenger car are also included. Furthermore, accidents were also taken into account wherein a passenger car as the primary cause has had a frontal impact against an opposing vehicle. Hence 1103 relevant accidents (12%) remain from 9323 GIDAS accidents. Those accidents define the so called field of effect. In other words these are the accidents that could be influenced positively by any of the AEBS functions. For Germany, this data represents approximately 39.000 accidents with injuries per annum. In the next step the benefit for each AEBS function is determined by considering driver behavior, functional characteristics and additional system assumptions.

It is apparent that by integrating different driver and sensor characteristics, a complex handling for each accident within the benefit estimation results. Due to this, a tool was developed which allows the handling of sensor parameters, driver reactions and additional system values in a more simple way. By using the Matlab environment from MathWorks™ it is now possible to determine the benefit for a wide range of AEBS functions easily. Modifications within the driver model and functional applications are now easy to handle and it is open for the integration of new applications.

DRIVER MODEL

The effect of predictive collision avoidance systems is directly linked to the driver's reaction. It is evident that a critical situation will be handled in a better way if the driver reacts immediately after warning with a braking intervention. This is also true for autonomous braking systems because the efficiency increases with the braking support of an active driver. For this reason, a driver model was developed and integrated to estimate the driver behavior and reaction.

In the first step, the driver reactions were analyzed in real accident situations. For each accident within the field of effect, deceleration and brake distances were evaluated and classified into three categories. Figure 2 shows the distribution of the classified drivers. 31% of the drivers did not show any (brake) reaction which is assigned to driver type I. Compared to this,

49% of the drivers brake but with less braking performance due to late reaction or light deceleration - this type of driver is categorized as driver type II. Finally 20% of the drivers - driver type III - brake with maximum deceleration but with delayed reaction. Weather and road surface conditions were taken into account.

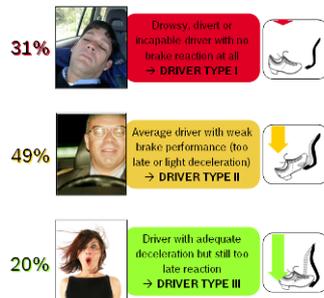


Figure 2: Distribution of the driver behavior for three classified driver types from GIDAS accidents

The question arises why the classification is so important. The reason for classification is that the real braking performance is considered in the functional activity.

In addition to that, Bosch's Advanced Emergency Braking Systems identify the driver's activity to adopt its warning strategy according to his driving behavior. For a less active driver, the warning time is set up earlier relative to a more active driver who reacts faster and therefore the warning strategy could comprise a later warning. The reason for this is clear: Less active drivers need more time to recognize the situation and to employ any brake intervention. Another advantage of this strategy is to minimize false alarms which results in a higher system acceptance and as a result, a higher benefit of the system. As Wilhelm in [9] stated the probability that the driver will subjectively assess the system poorly for providing false warnings rises with the quantity of warnings which precede his own normal personal brake timing. In the benefit analyses, this is considered by separating inactive from active drivers using weighting factors for the benefit calculation. For instance, if a driver was classified as driver type I (no (brake-)reaction) in the real GIDAS accident it is more likely that this is an inactive driver in the real world. For this reason we set the activity level to 30% for these cases. In other words the status "inactive driver" was set to 70% for all drivers classified as driver type I. For driver type II and driver type III other distributions were used. These values were consolidated in other studies, internal investigations, and expert knowledge.

Depending on a driver's activity level and relative closing velocity, the warning strategy is adapted. The

strategy of the Bosch AEBS functions consists of two warning levels. The first level is an acoustic signal, whereas the next level uses a brake jerk to alert the driver. The time delay between first and second level is variable with respect to the driver's activity level. In the calculation, it is also considered that in the real world some drivers will not show any reaction based on simply an acoustic or tactile warning. This is likely due to inattention caused by alcohol, drowsiness or other inactivity. Figure 3 shows the warning level process in a simple way.

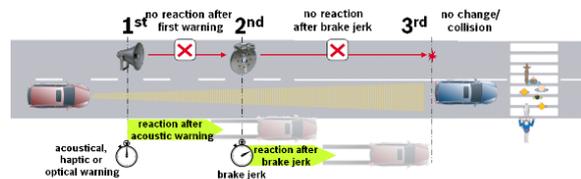


Figure 3: Two-level warning strategy depending on drivers activity and relative closing velocity

Finally, for the driver model it is necessary to know how and in what way the driver reacts after each warning. For this, three driver categories with different behaviors are defined. In Figure 4, the three classes are shown. It was distinguished between a realistic-, lethargic and best-case driver with different reaction times and deceleration levels respectively. Based on [10] and [11] such a driver population is expected whereas the realistic driver has a higher share with mean reaction time and deceleration compared to lethargic and best-case driver with poor reaction and low deceleration or fast reaction and higher deceleration respectively. It is furthermore assumed that the lethargic and the best-driver represent the borderline of the distribution as seen in Figure 4.

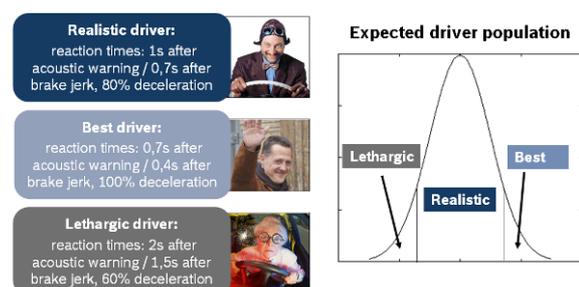


Figure 4: Classes of different driver behaviors

After all in Figure 5 the whole driver model is shown as it is realized for the benefit calculation of the AEBS functions. However it is recognizable how driver type, driver activity, warning strategy and driver behaviors are integrated and work together. As mentioned before, there are different reactions expected if an acoustic or tactile warning is given from the system. It is apparent that for different safety systems these kinds of reaction vary. For the purpose of the AEBS function evaluation we proceed

on the assumptions that a share of 10% will still show no reaction after warning. Another share of 50% will react after the acoustic warning and 40% of the drivers will react after the brake jerk was activated.

Based on the distributions stated above for each driver behavior, a single result is calculated by taking the real deceleration (real driver type), driver's activity, and proposed reaction after warning into account.

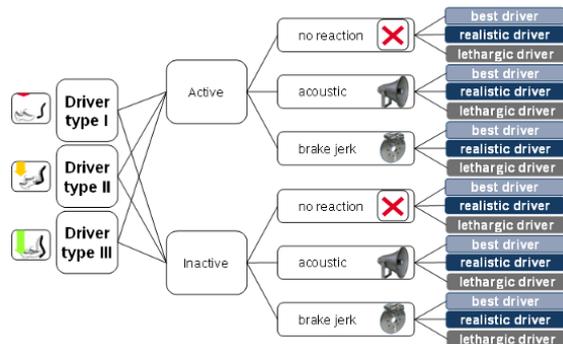


Figure 5: Driver model

The overall benefit is calculated afterward by weighting each single result depending on the driver type which is in focus, i.e. realistic driver.

AEBS FUNCTIONS AND MODE OF ACTION

The main objective of the Bosch AEBS functions is collision avoidance by driver warning. This also includes those cases wherein the driver shows no reaction. In such cases, the system intention is to prompt the driver to react by pushing the brakes. If reaction time was too late or poor brake pressure was measured, an earlier brake intention or a more powerful braking respectively would be the target of the AEBS functions. This is shown in Figure 6.

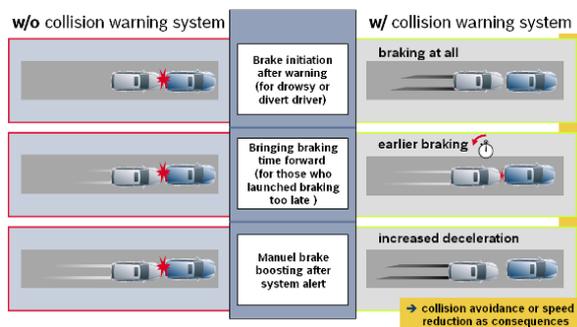


Figure 6: Potential benefit of collision warning systems

The Bosch AEBS functions use radar technology to detect a potential collision object. The sensor is placed on the front end of the car and monitors the

frontal field of the vehicle. If a critical situation is detected indicated by potential opposing obstacles and high closing velocities the system will run through different levels of warning strategies. These strategies again depend on closing velocity and driver behavior. As mentioned above, aside from acoustic warning a tactile warning is given which is realized as a brake jerk. This functionality is called Predictive Collision Warning (PCW) and is part of the Bosch AEBS family.

It is clear that this function can be extended to a target braking function. The system calculates in advance the deceleration which is necessary to avoid any collision but still does not interfere. The target braking will be activated if the driver pushes the brakes. Based on the pre-calculation the optimized deceleration is controlled. If a collision is unavoidable the maximum deceleration will be set for injury mitigation. This function characteristic is helpful for driver type II as seen in Figure 2 due to the fact that their deceleration level was too low. Together with warning and target brake this function is called Emergency Brake Assist (EBA).

As can be seen in the real world (Figure 2), there is still driver type I which shows no (brake-) reaction. To be consistent, the next level of functional characteristic is an autonomous brake initiation. The Automatic Emergency Braking (AEB) function from Bosch fulfills these requirements. This is realized by a multistage intervention. At a very early stage the first level sets a deceleration of 0.3g. Depending on reaction and the ongoing situation, a second level is selected. Finally if a collision is unavoidable 0.5s prior to impact, a maximum brake deceleration will be initiated. It is expected that a driver of driver type III will react eventually due to the multiple interventions and will be prompted to brake on his own. However, comparing EBA and AEB, increased development effort, system costs and foremost liability risks for the autonomously acting AEB have to be taken into account.

BENEFIT ESTIMATION

In order to avoid false alarms, the warning strategy uses different warning times depending on relative closing velocity, classification of the driver as active or inactive, as well as the initial speed of the vehicle itself. It is apparent that the variety of different accident scenarios tend to be complex if they were to be analyzed in detail. Nevertheless to gain the benefit for each function, the collision speeds are recalculated by taking driver reaction (GIDAS) and hypothetical driver reaction (driver model) into account. Furthermore, time of braking as well as deceleration level will be established by fusion of functional intervention and driver initiated braking. In the end, the collision speed is calculated by

numerical integration. As a result for all AEBS functions, the total quantity of accidents avoided as well as the calculated speed reduction is received. A 100% penetration with AEBS functions of the (Ego-) vehicles is assumed. Figure 7 shows the results for avoided accidents for the three different driver types. The benefit calculation is based on a production level application for the PCW and EBA function and an application close to production level for the AEB function. These are optimized in terms of warning strategy and not for maximum benefit. Therefore more efficiency could be possible by other parameter applications.

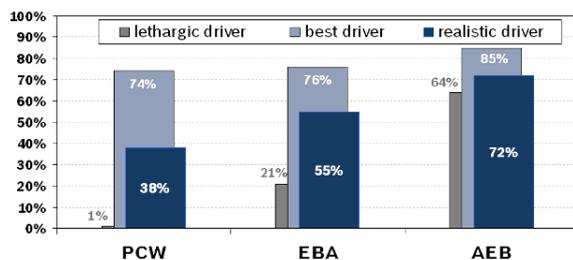


Figure 7: Accident avoidance potential of AEBS functions in rear-end crashes for different driver types

For the Predictive Collision Warning system (PCW) an avoidance benefit of approximately 38% is obtained assuming a realistic driver.

For the Emergency Brake Assist (EBA) function with the target braking, the benefit raises to more than half (55%) of the accidents in the field of effect. This is a remarkable result for a non autonomous function like EBA.

For the full scale characteristic like the Automatic Emergency Braking (AEB) function, 72% of the accidents can be avoided. This is not surprising due to the fact that in an early stage, a braking intervention is initiated if no reaction of the driver is detected by the system. As a consequence, collision speed is reduced significantly and accidents can be avoided.

Focusing on the different driver types in Figure 7, the influence on the accident avoidance potential for the different functions show significantly different potential. Regarding the collision warning functions (PCW) the potential varies from 1% to 74% for a lethargic driver and the best driver respectively. These deviations are caused by different reaction times after warning - 2s reaction time for a lethargic driver and 0.7s reaction time for the best driver. It is apparent that a lethargic driver with poor reaction times and less deceleration does not avoid a collision by means of a pure warning system alone. The analyses show that in real accidents braking was initiated after collision. In comparison to lethargic- and realistic drivers the best driver is able to avoid

more accidents due to fast reaction and high deceleration level.

By looking at the level of automation, another important result is recognized. For the AEB function the difference between lethargic and best driver is 21%. This small gap results in the early activation of the AEB function if no reaction is detected by the system. Hence the biggest benefit of this function is realized for lethargic drivers.

If these results were transferred to accidents at injury level we obtain the effects as shown in Figure 8 taking a realistic driver behavior into account. The first bar shows the distribution of severity level for all rear-end crashes in the field of effect. While the amount of 1% for fatal accidents is low, the remaining accidents are shared between accidents with severe and slight injuries. The distribution herein shows a share of 10% for accidents with severe injuries and 89% for accidents with slight injuries.

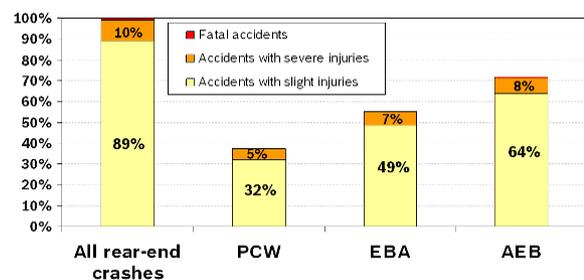


Figure 8: Distribution of avoided injuries by the AEBS functions in avoided rear-end crashes for a realistic driver

The benefit received from the AEBS functions leads to two major conclusions:

- The relations for all considered functions (PCW, EBA and AEB) stay the same regarding all severities for the rear end-crashes.
- The benefit increases enormously by increasing the automation level of the safety system.

For example, the quantity of reduced accidents with severe injuries has a share of 7% for EBA function. With respect to all rear-end crashes with severe injuries about 3 out of 4 accidents are avoided. Furthermore, every 2nd accident with slight injuries is avoided compared to all accidents with slight injuries in rear-end crashes. A prediction regarding fatal accidents is not made due to the lower share within this accident type for the field of effect used. If 39.000 relevant accidents with injuries are considered, in 2006 for Germany the following reduced number of accidents with severe and slight injuries will be avoided (Table 1).

	PCW	EBA	AEB
Accidents w/ slight injuries	12500	19100	25000
Accidents w/ severe injuries	2000	2700	3100

Table 1: Estimated number of reduced accidents with injuries by the AEBS functions for Germany

Furthermore it must be kept in mind that there are still benefits given from the AEBS functions due to accident mitigation by taking the reduced collision speed into account. This is part of the following discussion.

Along with the high accident avoidance potential, the benefit of AEBS functions is especially established in the reduced collision speed. In Figure 9 the average reduction in collision speed is shown for each AEBS function and for different driver types.

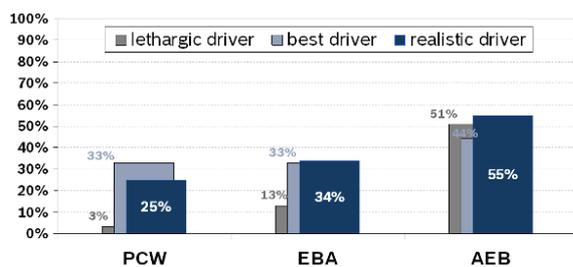


Figure 9: Average Reduction in Collision Speed of AEBS Functions for not avoided rear-end crashes

The average reduction in collision speed is determined based on accidents with reduction in speed and accidents with unchanged course. Therefore, all avoided accidents are excluded. For the realistic driver, a collision avoidance function based on warning only, like PCW, can on average reduce speed by 25%. By an EBA-function (warning + brake boost), the collision speed can be reduced on average by almost 34%. This share even increases to 55% for the AEB function.

It is apparent that minor variations occur regarding different driver types within one functional characteristic. Due to the fact that the best-driver brakes immediately with maximum deceleration this share is less when compared to that of lethargic- or realistic driver

Regarding the collision warning functions (PCW), the potential varies from 3% to 33% for a lethargic driver and the best driver respectively. Again the major difference in reaction time and deceleration level results in a different benefit.

This deviation will be reduced if the automation level is increased. For unavoided accidents, the EBA function reduces the collision speed by about 34%

for a realistic driver. Even a higher reduction is given for the AEB function (55%).

It is expected that the significant reduction in collision speeds will have a considerable positive effect on the injury severities. Ongoing work aims at a comparison of the injuries in real crashes with the injury severities in the same accident with the intervention of a collision avoidance/mitigation system. A statistical model for predicting injury severities is currently being generated with SAS¹. Hereby, a logistic regressions model is setup as a convenient statistical approach for predicting specified injury severities.

With a logistic regression model, the probability of suffering a specified injury severity or not can be estimated. Based on univariate and multivariate frequency and correlation analyses of cars in the field of effect of AEBS functions, variables are selected which have a significant influence on suffering a specified injury severity in a crash.

Two regression models will be identified. The first model² provides the estimation of the probability for suffering minimally “slight injuries.” With the second regression model³ the probability of having minimally “severely injured” car occupants after crash will be estimated.

COMPARISON TO LEGAL REQUIREMENTS

As proposed in the NHTSA review for the New Car Assessment Program (NCAP) from July 2008 [12], new test requirements will be introduced for Forward Collision Warning (FCW) systems. Currently there are three test scenarios defined although two scenarios are in focus of the discussion:

- 1st scenario: Subject vehicle approaches a stopped principle other vehicle at 45mph (72.5kph). The system must give a warning 2.7s prior to collision.
- 2nd scenario: Subject vehicle follows principle other vehicle at 45mph (72.5kph). The other vehicle starts braking. The system must give a warning 2.4s prior to collision.
- 3rd scenario: Subject vehicle at 45mph (72.5kph) encounters a slower principle other vehicle with speed 20mph (32.2kph). The system must give a warning at 2.1s prior to impact.

¹ Statistical Analysis System

² Significant Hosmer-Lemeshow test (0.86), R²=0.62, c-Statistics=0.89

³ Significant Hosmer-Lemeshow test (0.11), R²=0.15, c-Statistics=0.78

The systems in use must fulfill the velocity range which is specified between 30kph and 80kph. Furthermore, it has been claimed that the FCW systems do not necessarily have to work at night and under rainy conditions. As a matter of fact the AEBS functions from Bosch fulfill the requirements. Moreover the speed range is specified through the entire test range and above. Additionally, the Bosch system also works in misty or rainy conditions at both day and night. It is apparent that the systems can be compared to each other. Due to the early and fixed warning times specified in the NCAP requirements it is assumed that more false positive alarms will be given from such a collision warning system. A false positive alarm hereby is defined as a warning given to driver which does not address a potential accident scenario and should be classified as not relevant. Therefore it is more probable that a driver will switch off the system if there is an alarm in a non critical event. As a result, the FCW functionality would be inactive and not available in case it is required. This is why the Bosch AEBS functions use a more flexible warning strategy. The strategy minimizes positive false alarms and a higher acceptance by the driver is realized due to its familiarity and reliability. Nevertheless a comparison of the FCW and the Bosch PCW function was done by setting the requirements for FCW as stated above. In other words for example, accidents which occurred at night are not considered in the benefit calculation for the FCW function. The results are shown in Figure 10 and Figure 11 for the avoided accidents and the average reduced collision speed respectively. The calculation was done for all driver types defined before.

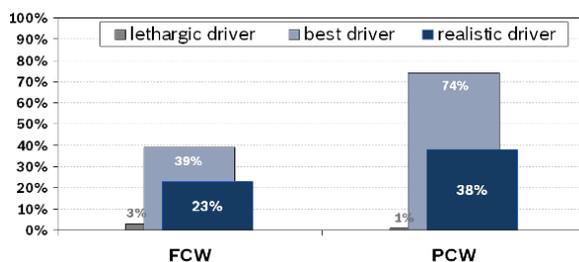


Figure 10: Comparison of FCW vs. PCW in rear-end crashes, Fraction of avoided accidents

As seen in Figure 10 the results show a decreasing benefit if the minimum requirements for FCW functionality were fulfilled. The difference between FCW and the Bosch PCW function for a realistic driver was estimated to be 15%. The same situation is shown in Figure 11 for the average reduction of collision speed. Approximately 16% difference is estimated between FCW and PCW for the realistic driver.

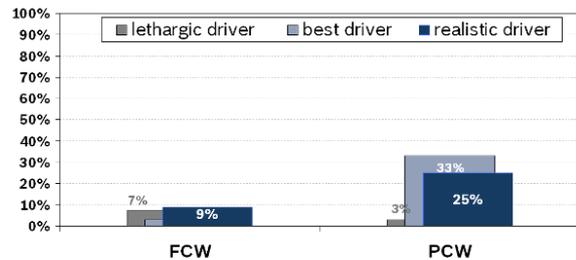


Figure 11: Average reduction in collision speed for not avoided rear-end crashes

CONCLUSIONS

- The study considers 1103 rear-end accidents with injuries from 9323 GIDAS accidents as representative for Germany.
- The analysis is based on three specified applications from the Bosch Advanced Emergency Braking Systems. The PCW and EBA functions are based on production level application whereas the AEB function is based on a market level application. The optimization strategy was to ensure a reduced number of positive false alarms taking maximum avoidance potential into account. Other application settings are also possible by optimizing the accident avoidance.
- A high accident avoidance potential for rear-end collisions is given from the Bosch Advanced Emergency Braking Systems. The share of avoided accidents for a realistic driver was calculated for the PCW system to be 38%, for EBA system to be 55% and for the AEB system to be 72% respectively.
- The efficiency of collision warning systems like PCW depends on driver behavior and on reaction time. The variations are from 1% to 74% for the lethargic and the best-driver respectively.
- An increased system automation level - from PCW, EBA to AEB - reduces the driver influence on the one hand significantly and increases the accident avoidance potential on the other, in particular for lethargic drivers. However, comparing EBA and AEB, increased development effort, system costs and foremost liability risks for the autonomously acting AEB have to be taken into account. Therefore an optimum benefit over cost ratio is expected for the EBA function.
- The number of avoided accidents with severe injuries is estimated to be approximately 2700 rear-end accidents in Germany annually. Furthermore, the amount of avoided rear-end accidents with slight injuries is estimated to be approximately 19100 accidents. Hereby the EBA function for a realistic driver is considered and a 100% installation rate.

- If an accident is unavoidable, the AEBS functions will reduce the collision speed significantly. For the PCW function an average reduction of collision speed is encountered for 25% of unavoided accidents. For the AEB function a rate of even 55% was determined.
- The Bosch Advanced Emergency Braking System functions operate over a wide velocity range, even at night and under rain or bad weather conditions.
- By fulfilling NCAP requirements for FCW systems, accident avoidance potential is reduced from 38% for the PCW system to 23% for the FCW system assuming a realistic driver.
- Furthermore, by fulfilling NCAP requirements for FCW systems, a significantly decreased benefit is determined for the average reduced collision speed for unavoided accidents. For the realistic driver a decrease from 25% to 9% is given based on the PCW function compared to the FCW function respectively.
- A high probability for positive false alarms is expected and hence less acceptance by the driver without variable warning strategy. This strategy should be individually controlled by a driver classification system and taking the relative closing velocity into account.

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