Automotive Active Safety & Comfort Functions using Radar

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***Abstract* — Increase of safety and comfort is a main objective of car manufacturers as well as of their suppliers and a substantial distinguishing feature in the international competition. Active safety systems as well as driver assistance systems are becoming more and more important. They help to recognize dangerous situations at an early stage, and thus, help to avoid accidents or at least to reduce the accident severity, especially within the permanently increasing traffic density. Radar sensors play a decisive roll for the environment perception. After an introduction to the evolution of automotive systems, commonly implemented functions using radar will be discussed. Finally, as an example, the arrangement of the radar sensors in the new Mercedes-Benz E-Class and their role in the adjacent environment perception system - as a part of the safety and comfort functions - will be outlined.**

Keywords- automotiv; radar; passive safety; active safety; comfort functions; UWB

I. Introduction

In 1951 Daimler-Benz filed a patent entitled “Motor vehicles, particularly for the transportation of people” [1]. This referred to nothing less than the invention of the crumple zone. The ingenious originator of this idea was Béla Barényi, who was not at all impressed with the prevailing maxim that “a safe car must be robust and not unstable.” He was the first to recognize that kinetic energy occurring during an impact must be absorbed by deformation to protect the occupants.

This was the beginning of the progress developing passive safety features for the automobiles to mitigate the severity of accidents. Mercedes-Benz drove an important role from this time on and continuously improves the high safety level of their automobiles. In 1973 they equipped their automobiles with the three-point seat belt as standard. With the development of active safety features to prevent accidents the anti-lock braking system (ABS) was introduced in 1978. With this assistant system, developed jointly with Bosch, the car remains fully steerable even during drastic braking. After a 13 years development Mercedes-Benz went an epoch-making step towards greater passive safety by introducing the airbag in 1981. In 1995 the world premiere of the electronic stability program (ESP) took place. This program is able to control all wheels separately to detect and prevent skids.

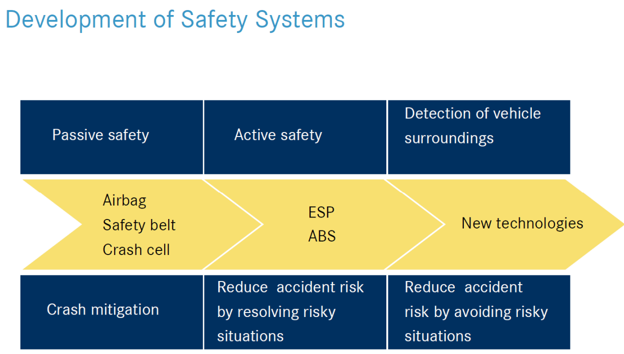

Figure 1. Development of Safety Systems

Until now there are many enhanced safety features established in automobiles by combining passive and active elements. New technology safety systems are improved by sensors observing the environment to reduce the risk of accidents (see Figure 1). These sensors have to achieve high requirements to be robust, capable of real-time use, weather-proofed and invisible to fulfil safety demands. Furthermore they have to be extraordinary accurate in angle and range to locate obstacles and measure their velocity. One sensor which is capable to handle all these requirements is the ultra-wideband radar. Nowadays UWB radar sensors for automotive applications are operating in the ISM-band with the centre frequency at 24 GHz, and in the future additionally from 76 GHz to 81 GHz. With the combination of radar information and active-passive elements an electronic protective shielding is established for greatly reducing the severity of an accident.

II. Active Safety & Comfort Functions Using Environmental Sensing

High-performance assistance systems are helping to defuse dangerous driving situations and avoid accidents. With their help it is possible to determine if a driver fails to respond correctly or responds too late, and to correct such mistakes in a targeted manner. The main tasks of active safety systems are to prevent accidents and reduce the risk of injury to vehicle occupants. Until now there are various active safety and comfort functions available in the automobile sector and radar sensors supply them fundamental data. Mercedes-Benz uses two short-range radars (SRR) in the front and two in the rear bumper, one mid-range radar (MRR) and one long-range radar (LRR) to realize the following functions:

- Brake Assist and Brake Assist PLUS
- DISTRONIC PLUS for Adaptive Cruise Control and Stop&Go
- PRE-SAFE Brake
- Blind Spot Assist
- Lane Keeping Assist

A. Brake Assist and Brake Assist PLUS

The Brake Assist (BAS) interprets the driver's braking behaviour and builds up the full braking force automatically when it recognizes a panic braking situation, even if the driver applies the brakes cautiously. Introduced in 1996, this development is based on the finding of Mercedes-Benz accident research that motorists, though they do apply the brakes quickly in critical situations, do not step on the brake pedal with sufficient force. Rear-end collisions are among the most frequent and severe types of traffic accidents. The more widespread use of Brake Assist could prevent thousands of rear-end collisions and pedestrian related accidents each year. However, only about 58 percent of all new vehicles are currently equipped with braking assistance in Europe [2].

The Brake Assist with radar (BAS PLUS) delivers even better performance. Seconds, sometimes even fractions of a second, make the difference between an accident happening and being averted. In these critical moments it is crucial both to recognize the danger in good time and to act quickly and decisively to avoid a collision. On recognizing a potential accident situation, help is provided to both systems by two short-range radar sensors behind the front bumper operating at 24 GHz and one long-range radar in the middle of the radiator grille working at 76.5 GHz. Together, they continually monitor the traffic activity in front of the car. The radar data of both systems are fused in the electronic control unit (ECU) analysing the traffic situation. If the distance to the car in front is not sufficient, a red warning symbol lights up in the instrument cluster [3]. If the vehicle in front, which is registered by the radar, brakes suddenly, creating the risk of a collision, an additional warning tone also sounds. This is the clear and unmistakable prompt for the driver to brake. The system automatically determines the brake pressure required in this situation to prevent the collision. In other words, the system helps the driver to recognize the risk and makes the calculated brake boosting force instantly available, even if the driver does not step on the brake forcefully enough. Depending on the speed and distance, BAS PLUS therefore allows controlled, targeted braking. If necessary, the system increases the braking force up to full braking.

Wide-ranging tests of the effectiveness of Brake Assist PLUS carried out in the simulator show that this system reduces the accident rate in typical situations involving the risk of a rear-end collision from 44 to 11 percent. However, it should be noted that support is only provided by BAS PLUS if the driver gives the braking command, by stepping on the brake pedal

B. DISTRONIC PLUS

The DISTRONIC was presented in 1999. With this proximity control system Mercedes-Benz extends the functions of retaining a constant driving speed. DISTRONIC automatically maintains a constant distance between the car, it is installed in and other road users. The radar measures the distance to vehicles ahead and compares this value with the car's own speed. DISTRONIC computes its response based on this data, maintaining or reducing speed. At the beginning the DISTRONIC stood as a synonym for long-range radar systems used in automobiles, with the next stage in evolution DISTRONIC PLUS turned into a distance control function because of not only using one radar sensor anymore. Mercedes-Benz introduced the DISTRONIC PLUS in 2005.

The DISTRONIC PLUS proximity control operates at speeds of between 0 and 200 km/h and is therefore coping with Stop&Go traffic. It keeps the car a set distance behind the vehicle in front, applies the brakes as required and can even bring the car to a complete halt, depending on the traffic situation. DISTRONIC PLUS works in combination with Brake Assist Plus. Even in slow-moving traffic DISTRONIC PLUS maintains a constant interval to the vehicle ahead and brakes the car, if need be, to a full stop. If the gap to the vehicle in front narrows too quickly, the system gives the driver an audible warning and, as soon as this first warning signal sounds, automatically calculates the brake pressure required to prevent a collision in this situation.

Mercedes-Benz uses a newly developed long-range radar sensor with a range of 200 metres. In addition, this sensor has medium-range detection capability, allowing to monitor the area up to 60 metres ahead of the car with a 60° field of view (FOV). This technology enables precise monitoring of the traffic situation in front of the car and even better detection of dynamic events such as a car in front swerving suddenly. The two wide-beam short-range radar sensors with a range of around 30 metres and a FOV of 80° are employed controlling the range with high accuracy. Mercedes-Benz offers DISTRONIC PLUS in combination with Brake Assist PLUS as an optional extra.

This technology can prevent a fifth of all head-to-tail crashes in Germany alone. On motorways, the accident rate can be reduced by as much as around 36 percent. Every year in Germany there are over 50,000 serious head-to-tail crashes, in which some 5,700 people are either killed or seriously injured. One in six traffic accidents in which people are injured is down to a head-to-tail crash. The situation is even more serious in the US, where this type of collision accounts for around 30 percent of all serious road accidents [3].

C. PRE-SAFE brake

Unfortunately, drivers do not always react as quickly as needed in critical moments, for example they are distracted and fail to register the warning signals. The PRE-SAFE Brake intervenes in situations, if there is acute danger of an accident. Radar sensors provide the location and support the electronic control unit to predict the time to collision and induce a full braking autonomously after several warning.

The timeline in Figure 2 represents a typical rear-end collision. If the assistance systems recognize a potential accident situation, the driver will be warned visually and acoustically, approximately 2.6 s before the impact. If the driver doesn't intervene and avoid the accident there is a further audible warning three times at approximately 1.6 seconds. Is this warning cascade kept unnoticed and the driver has not responded, partial braking will be initiated automatically. With this autonomous partial braking process a deceleration of up to 0.4 g (approx. 4 m/s2) is provided. That is around 40 percent of the maximum braking performance. During this sequence the driver can carry out an emergency stop or can take evasive action to avoid an accident. Approximately 0.6 s before the crash the driver has the last opportunity to avoid an accident through evasive manoeuvre or emergency stop. Subsequently a full braking will be triggered automatically to shrink the severeness of the accident. However, it has to be considered that the PRE-SAFE brake function ignores oncoming cars or any obstacles which may suddenly appear [4].

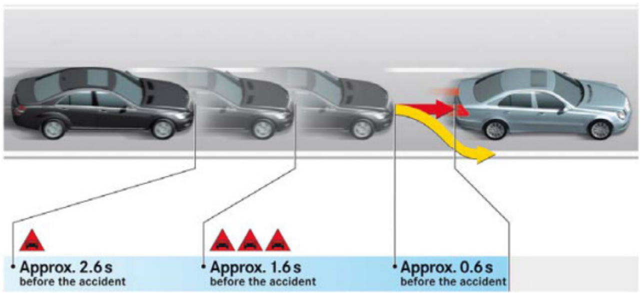

Figure 2. Timeline of a Typical Rear-End Colision using PRE-SAFE brake

The Autonomous PRE-SAFE partial braking has a twofold effect: the intervention of the PRE-SAFE Brake makes distracted drivers aware of the situation, alerting them to the acute danger and indicating that immediate action is required. The driver is further aided in the attempt to avert the accident by the safety systems. During emergency braking, Brake Assist PLUS instantly calculates the optimum braking force for the given situation. If the car veers rapidly to one side, ESP stabilizes the vehicle and reduces the risk of skidding. If the collision cannot be avoided, the PRE-SAFE Brake will help to minimize the consequences of the accident.

Driving tests conducted by the engineers from Germany's Automobile Association ADAC showed that autonomous partial braking reduced the impact speed by 12.5 km/h. In other words, instead of making impact at 50 km/h, the vehicle equipped with the PRE-SAFE Brake struck the rear of another car at 37.5 km/h, reducing the force of impact on the occupants in the front by about 30 percent, and by 45 percent for occupants in the rear seat [2]. In the future, this technology could also serve as a basis for an autonomous braking system that will implement full braking automatically if there is acute danger of an accident, which can greatly reduce the force of impact. In 2006 the PRE-SAFE brake came on the market in the Mercedes S-Class and CL coupe.

D. *Blind Spot Assist*

The Blind Spot Assist, developed by Mercedes-Benz, uses radar technology to indicate obstacles in the indiscernible field vision of the driver. It warns the driver when changing lanes would be too dangerous. Their new systems are intended, for example, to make lane changes safer, improve safety at intersections and support the driver when turning into another street or road. Every year, around 9,500 serious road accidents in Germany are caused by motorists who fail to take heed of the traffic behind when changing lanes or cut across in front of another vehicle too soon after overtaking [3]. The Mercedes assistance system can help drivers to change lanes safely. With two UWB short-range radar sensors housed on each side of the rear bumper the areas directly alongside and behind the car are monitored with high resolution. This process enables them to see if there is another vehicle in the next lane, in the so called blind spot. In such situations, the system informs the driver by illuminating a red warning signal in the glass of the exterior mirror. If the driver fails to notice the red light and uses the turn signal to indicate a lane change, the warning light will begin to blink and a warning alarm will be sounded.

E. *Lane Keeping Assist*

The Lane Keeping Assist is a newly developed Mercedes assistance system which warns the driver if the car leaves its lane unintentionally. Until today the camera on the inside of the windscreen monitors the road markings and detects when the car leaves its lane. In future applications this assist can be supported or substituted by UWB short-range radar sensors because they are able to scan the road surface accurately. Until now this assist is made possible by evaluating the difference in contrast between the road surface and the markings. The image-processing system sends data to the electronic control unit (ECU), which determines the position of the car and detects when it leaves its lane on the left or right. Furthermore, the ECU assesses whether the car has left its lane intentionally or unintentionally. There is therefore no warning if, for example, the driver accelerates before overtaking or joining a motorway, brakes heavily or steers into a bend.

If the system determines that the car is leaving its lane unintentionally, it will activate an electric motor, causing the steering wheel to vibrate. This is a high effective way of prompting the driver to countersteer. The timing of the warning depends on the width of the road and the type of lane markings. If the car crosses over a continuous line on the road, as opposed to a broken one, the system emits its warning earlier [3].

The Lane Keeping Assist operates at speeds of between 60 and 250 km/h as soon as the system has detected a lane marking. The steering wheel does not vibrate to warn the driver if the driver cuts a corner intentionally, uses the turn indicators, moves back into the original lane after overtaking. Furthermore, Lane Keeping Assist is deactivated immediately if ABS, ESP, Brake Assist or another safety system intervenes [3].

III. AUTOMOTIVE RADAR SENSORS

A. *Why (UWB-) Radar?*

Radar technology has proved its ability for automotive applications for several years. When compared to its optical counterpart video (with image processing) or lidar, the advantages of radar are obvious:

- Direct distance and speed measurement
- Robust against weather influences and pollution
- Unaffected by light
- Measurement of stationary and moving objects on and in the vicinity of the road
- Invisible integration behind electromagnetically transparent materials (for example bumpers).

The need for a UWB bandwidth is given by the application. Therefore, the prediction of a possible collision needs a reliable object tracking capability. Thus, SRR sensors have to have sufficient high range resolution (for example centimeter range) to detect smaller objects and vulnerable road users such as motor cyclists and children.

B. *Types of Radar Sensors*

In the automotive branch three types of radar sensors have to be distinguished for diverse applications of environmental perception. Each radar sensors contains different ranges in distance and fields of view (FOV). In this constellation an approaching target can be tracked easily even from a far distance, handed over to the mid-range and finally to the high-resolution UWB short-range sensor.

There are different mounting positions to attach radar sensors, for example the long-range radar (LRR) can be integrated in the centre of the radiator grille. Mercedes-Benz uses a radar sensor containing a long-range radar as well as a mid-range radar in one device. Both are operating at the centre frequency of 76.5 GHz. The long-range radar is able to detect obstacles with a FOV of 18° and is capable of scanning a three-lane, 200 meter-long stretch of highway. In addition the mid-range radar has a wider opening angle of +/- 30° with a maximum range of 60 m (see Figure 3).

UWB short-range radars (SRR) offer high resolution in distance due to the occupied large frequency bandwidth. Hence they are capable to determine the exact position of potential obstacles. To illuminate the lane sufficiently SRR sensors can be installed on each side of the front and rear bumper, in total 4 sensors. Mercedes-Benz uses SRR sensors operating at the centre frequency of the ISM band at 24.125 GHz and occupy a bandwidth of 5 GHz. Each sensor covers a target range of 30 m with an aperture angle of +/- 40° resulting to an effective angle of 80 degrees (see Figure 3).

IV. ESTABLISHED ACTIVE SAFETY&COMFORT FUNKTIONS

In its new E-Class Mercedes-Benz has implemented all radar based functions presented in chapter II. This is a markable transfer of safety functions from the premium segment to medium class passenger cars. The new E-Class has

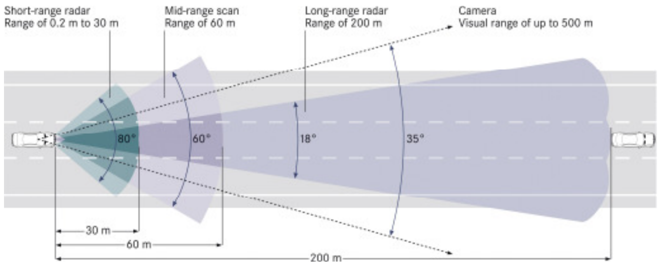

Figure 3. Field of view of UWB-SRR, MRR and LRR in the new E-Class

attached 5 radar sensors explained in Chapter III: two UWB-SRR and one LRR (MRR is included) are installed in the front of the new E-Class and two side-looking UWB-SRR at the rear (see Figure 4).

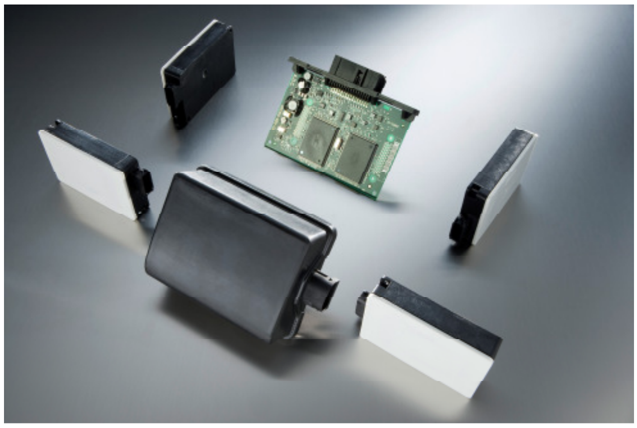

Figure 4. One LRR in between of two UWB-SRRs, followed by 2 sidelooking UWB-SRRs in the new E-Class

The new E-Class, available since spring 2009, synergises sophisticated safety technologies and makes new Mercedes models part of sensing the environment and acting autonomously. In case of a forthcoming collision new assistance systems have the ability to prevent or mitigate severe accidents by observing the environment. They take into account the distance to other vehicles, speed, drowsiness, darkness and lane departure.

Mercedes-Benz offers in the new E-class the PRE-SAFE occupant protection system as a standard equipment for passenger cars [5]. Based on information received from radar sensors, it identifies situations that might turn into accidents and instinctively activates preventive occupant-protection measures, allowing the seat belts and airbags to deploy with maximum effect in the event of an impact. PRE-SAFE therefore bridges the gap between active safety and passive safety. It is networked to the Brake Assist and the Electronic Stability Program, whose sensors recognise potentially dangerous driving situations (see Figure 5). This information is transmitted to the electronic control units within milliseconds. To reduce the force exerted on the front passengers, the seat belt tensioners are triggered at the very last moment before an unavoidable collision occurs.

To mitigate the degree of automobile accident Mercedes-Benz introduces in its new E-class the PRE-SAFE Brake. It acts like an "electronic crumple zone" offering the car occupants even greater protection. In case of an unavoidable accident the severity can be reduced extensively, because it induces emergency braking milliseconds before the collision takes place. However, the driver has always the sovereignty to counteract.

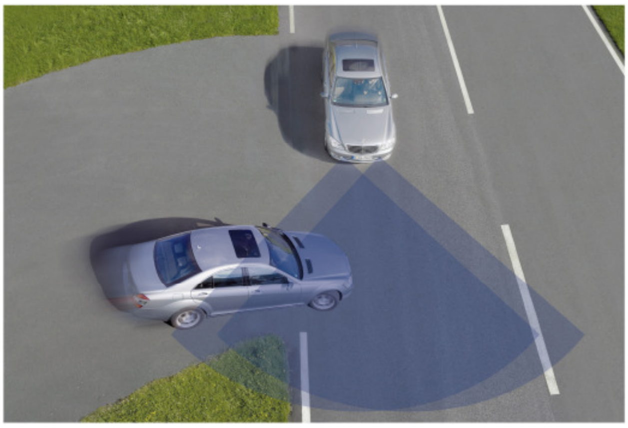

Figure 5. PRE-SAFE occupant protection system with two UWB-SRRs

Radar technology, installed in the new E-Class can assist in emergency braking of a pending head-to-tail crash. The sensors are networked with Brake Assist PLUS, which automatically calculates the brake pressure required to prevent an imminent collision. This braking assistance, available as soon as the driver hits the brake pedal, allows controlled, targeted braking or – if necessary – emergency braking, depending on the car's speed and the distance to the vehicle in front.

Occupant protection is one of the fundamentals of Mercedes-Benz. Hence, over 150 crash tests are accomplished for the highest possible level of Mercedes safety. During the course of development, the new E-Class has successfully come through over 150 high-speed crash tests and more than 17,000 realistic crash simulations, including around 40 different crash tests which the saloon had to pass in order to gain world-wide approval and nine extremely demanding, in-house impact tests, some of which go well beyond the statutory requirements [3].

The new E-class additionally offers the Blind Spot Assist using short-range radars to highlight passing vehicles in the indiscernible field vision of the driver (see Figure 6). If changing the lane would be too hazardous, the driver will be warned by a red warning triangle in the rearview mirror.

Furthermore, radar technology, providing short-range, medium-range and long range data, are used for the DISTRONIC PLUS and the Brake Assist PLUS. These assistance systems are highly effective at helping to prevent accidents and to allow Stop&Go traffic. The DISTRONIC PLUS keeps the distance constant between the own car and the vehicle in front, while the Brake Assist PLUS intervenes if the distance to the car ahead will be reduced to fast or an accident can only be avoided by braking with sufficient break pressure.

With a total of seven airbags fitted as standard, not to mention seat-belt tensioners, belt force limiters and NECK-PRO crash-responsive head restraints, the new E‑Class will offer an extensive package of safety equipment to protect their occupants. Self-adaptive belt-force limiters in the rear, which adapt automatically to suit the size of the rear passengers, will be introduced for the first time in autumn 2009 [3].

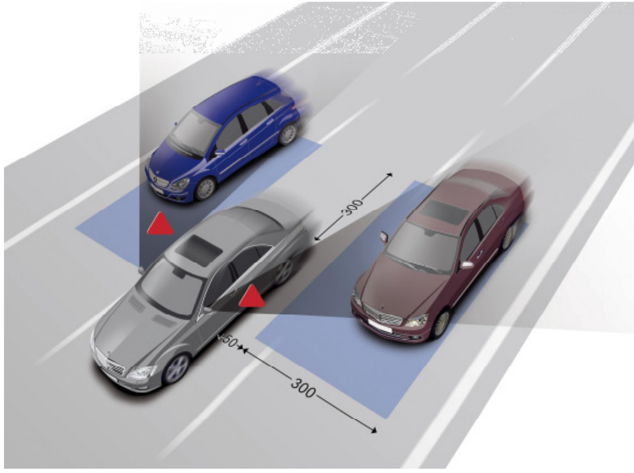

Figure 6. Blind Spot Assist with two sidelooking UWB-SRRs

V. Conclusion

Automotive radar is a key technology improving driving safety in the future, especially due to its inherent advantages such as weather independence, direct acquisition of range and velocity and benefit of ground reflexion. In this contribution actual active safety and comfort functions have been introduced and their integration and application in the novel Mercedes-Benz E-Class has been presented. Novel LRR developments aim to increased system sensitivity, higher range, angular resolution and to a wider FOV. This enhancement over existing automotive radar sensors will allow a new quality of environmental sensing. In combination with UWB SRR new perspectives of comfort and safety features in future automobiles are opened up. To meet the technological challenges with respect to small size, low weight, easy packaging, and low cost for future LRR and SRR sensors research projects like the project Radar on Chip for Cars (RoCC), funded by the German Ministry of Education and Research (BMBF), have been started.

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