SAFETY SYSTEMS TO REDUCE THE ROLLOVER RISK OF VEHICLES - AN INTEGRATED APPROACH FOR PASSENGER CARS -

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ABSTRACT

During the last years vehicle rollovers have become a major issue to the public interest, the U.S. Government and related organizations (NHTSA). Investigations were conducted by several organizations to analyze the reasons for vehicle rollovers and the measures to reduce the rollover risk. One major outcome of the studies was that vehicles with a small track width and a high center of gravity were especially prone to rollover accidents. As a consequence a "star rating" was defined to give the end consumer a guideline in judging the rollover risk for specific vehicles.

The paper focuses on modern active and passive Safety Control Systems that are able to avoid critical rollover situations and to protect the occupants of the vehicle. In the first part of the paper, the current technologies are described:

- Active Safety Systems
- Passive Protection Measures
- Systems which are able to lower the Center of Gravity, and
- Tire Pressure Monitoring Devices

In addition, an overview of future technologies will be presented:

- Lane Keeping Devices,
- Lane Departure Warning Systems and
- Tire Status Detection Systems.

Today, most systems are used stand-alone. From integration and networking of the systems, new functions and synergies will be realized. These new opportunities will be covered at the end of the paper.

1. INTRODUCTION

Rollover crashes are one of the most significant safety problems for all classes of light vehicles especially light trucks (pickups, sport utility vehicles and vans). In terms of fatalities per vehicle, rollovers are on second place, only catched by frontal crashes in their level of severity. Light trucks, especially sport utility vehicles, have a very serious focus on the rollover problem. Most rollovers result from vehicle leaving the lane and tripping. On-road untripped rollovers due to vehicle maneuvering are responsible for only a small portion of the rollover safety problem. Less than 10 percent of all rollovers are on-road untripped events. Even though this is a small part of the overall rollover crash problem, considerable attention is given to this problem by the automotive industry working with high effort on rollover safety. Untripped rollovers are considered to be preventable by an appropriate safety standard. But also tripped rollovers can be reduced by a significant number when active safety systems are installed into passenger cars with the today's available technology and with the performance increased by network functions.

In this way technical evolution in automotive engineering concerning safety aspects leads to a vehicle equipment, which lowers the risks of a crash (active safety systems) and as well avoid the negative impacts of a crash or reduce the degree of the effects (passive safety systems). The automotive industry works with high pressure developing the safety-increasing potential of the technical equipment.

2. INVESTIGATIONS/RESULTS

In several countries intensive research work was done in the recent years to analyze the rollover causes. Mainly in the U. S. the NHTSA (National Highway Traffic Safety Administration) did a lot of pioneering work [1,2] which at least influenced the legislation (Tread Act). This package of regulations is one of the biggest which occured in regard to traffic in any country of the world. But also in other countries, like in Germany intensive work was done by Prof. Langwieder [3], Director of the "Institute For Vehicle Safety" in Munich and by the car manufacturers (e.g. DaimlerChrysler [4]).

Fig. 1 shows that rollover causes combined with the driving situation and the drivers reaction can lead to a real rollover where - if it is already in process - only passive safety systems can prevent the passengers from serious injuries. The rollover causes can be split into the categories vehicle defects, driving faults, and 3rd party negligences. After all investigations [1], results show that the vehicle speed has the highest impact (s. Fig. 2), but also alcohol, inattention, over-correction, and fatigue have significant contribution

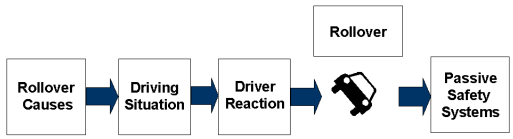

Figure 1. The rollover process.

to such kind of accidents. The vehicle defects have a minor role in these scenarios. The biggest effect in this category have the tires with 3 %. In the category 3rd party negligence "vehicle hit by other" has with a value of 9 %.

The driving situation stands in conjunction with the driver fault. Most of the accidents are happening during straight driving. This means the driver is unattended or fatigue. It is surprising, that in the typical applications for SUV´s (Sport Utility Vehicles), namely under off-road conditions, rollover accidents are very low. If we include the driver reaction, it is evident that the driver is surprised by the situation, because in 46 % of these cases the driver has no reaction.

If the rollover is already in process, only passive safety capabilities, like seat belts or airbags can help. Before this, active safety systems like the Electronic Stability Program "ESP", driver assistance systems like Lane Departure Warning "LDW" or warning systems like the Tire Pressure Monitoring System "TPMS" can assist the driver in overcoming such critical situations.

Prof. Langwieder found out in various investigations [3], done at the "Institute For Vehicle Safety", that mostly driving faults, such as unadapted (too high) vehicle speed, alcohol and step shaped road/bank transitions, interfering with the re-stabilization of a vehicle are causing most of the severe accidents. In the majority of those cases active safety systems help to avoid these situations. The DaimlerChrysler analysis of accident statistics [4] shows a reduction of 15 % accident occurrence since introduction of ESP in all Mercedes models in 1999. In detail the most dangerous type of accidents is losing control in critical driving situations without influence of other vehicles. The percentage of this type of accidents was about 15 % in Germany for all vehicles built between 1997 and 1999. It was reduced by one third to 10.6 % for all Mercedes vehicles equipped with ESP since 1999. ESP (Fig. 3) is able to stabilize the vehicle, to avoid dangerous oversteer behavior, to keep the lane and minimizes the risk of side collisions with severe injuries. Also rollover accidents were reduced by 12 % because of the ESP system.

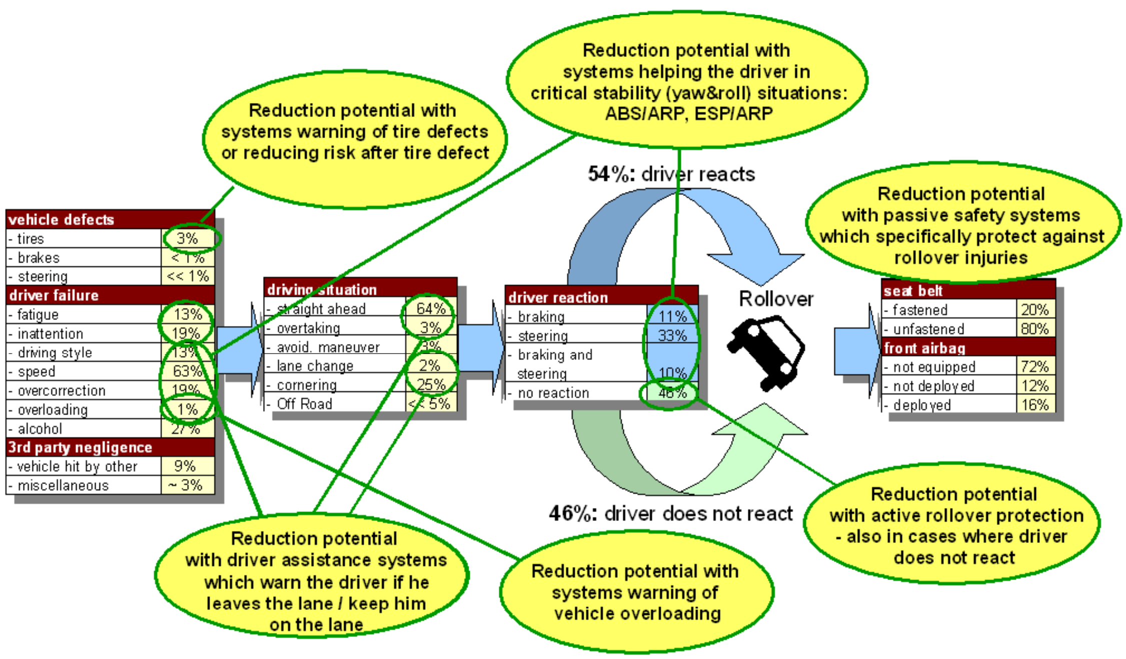

Figure 2. Analysis of rollover causes.

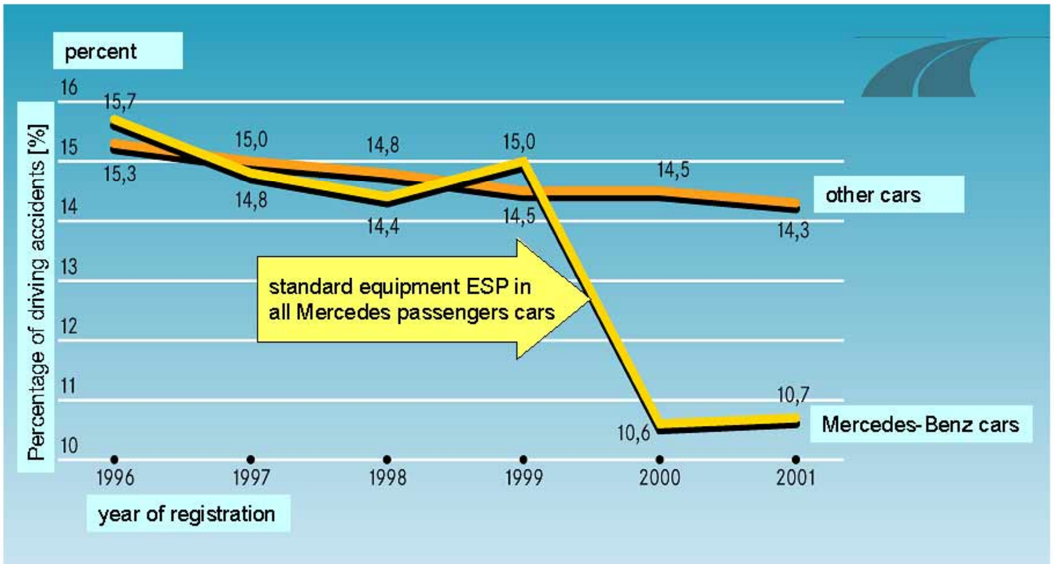

Figure 3. Analysis of driving accidents (Source: Federal Office Of Statistics, Germany).

3. CONSEQUENCES

Several international and national institutions, like NHTSA, insurance companies as well as car manufacturers and their suppliers are working heavily on requirements, proposals, technological means, and laws to avoid rollover situations or reduce the occurrence of these dangerous situations. One of the most pragmatic approaches was the introduction of the Static Stability Factor "SSF" by NHTSA in Jan. 2001 (Fig. 4), where the rollover susceptibility of a vehicle is defined by the half track width of a vehicle divided by height of the Centre of Gravity (COG). By this simple definition all of the vehicles on the market can be judged regarding their rollover risk. The outcome is a star rating where 5 stars represent a rollover risk below 10 % while 1 star represents a rollover risk of more than 40 %.

This NHTSA star rating approach is continuously improved and enhanced. A relatively new enhancement is the integration of dynamic tests, which are essential to provide reliable data concerning the propensity of a vehicle to roll over in real-world conditions. The NHTSA proposal contains two dynamic tests in unladen and laden driving

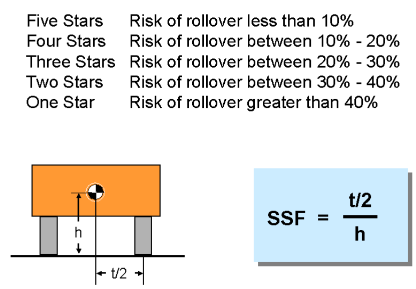

Figure 4. NHTSA star rating.

conditions: A specified fishhook and a J-turn maneuver. Now a worldwide discussion regarding load conditions, maneuvers and many other details between NHTSA, car manufacturers and suppliers has taken place. In discussion is also the centrifuge test as a useful substitute for SSF.

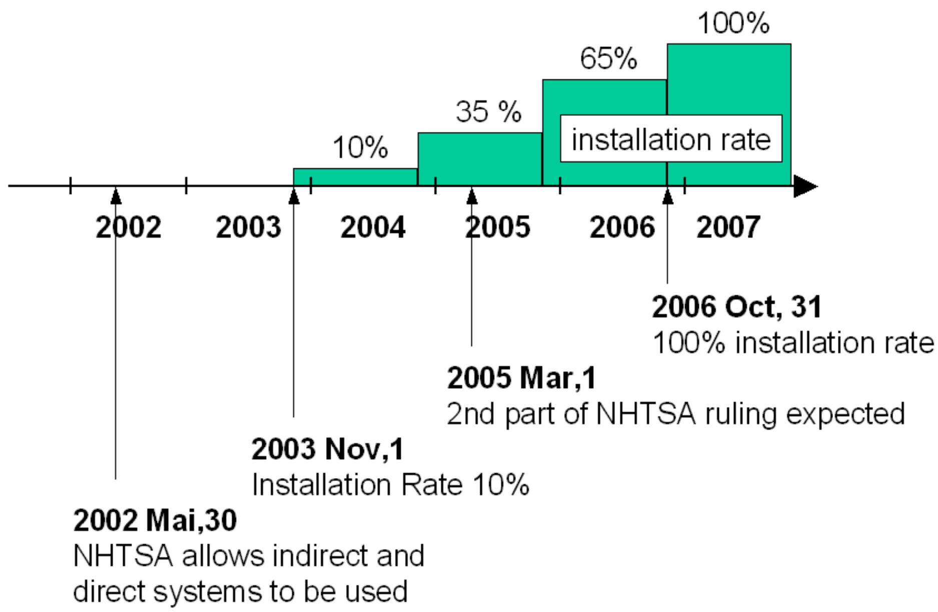

Figure 5. NHTSA rule making procedure.

The additional data of the dynamic tests leads to the question how to combine these results with the known SSF. Two alternatives are possible: an integrated star rating of SSF and dynamic test results or separate ratings for SSF and dynamic test maneuver performance. Overall the NHTSA rollover rulemaking will have an important influence to customer decisions, which will lead to corresponding future vehicle design, suspension set up and EBS (Electronic Brake System) equipment.

Also the requirements for the tire pressure monitoring are in consideration. So the U.S. laws require an increase of the installation rates of tire pressure monitoring systems, shown in Fig. 5.

4. ACTIVE AND PASSIVE SAFETY SYSTEMS

The development over time of active and passive safety systems is shown in Fig. 6. It shows the development in three mainstreams: the passive safety systems, the active safety systems, and the assistance systems. While passive safety systems, such as seat belts, airbags, rollover protection for convertibles, and pre-crash conditioning are in the beginning of a saturation phase, there is still a potential for active safety systems, like ESP, Collision Avoidance (CA), and Brake-By-Wire (BBW). The real driver assistance functions up to automatic driving are in the beginning of their implementation and introduction phase.

The following recommendations can be treated as the answer of the suppliers regarding the rollover problem:

1. In many countries (like the U.S.) the usage of seat belts is not required by law. The results of all the studies show that the **consequent usage of seat-belts** is the most effective way to reduce fatalities during rollover situations.
2. Since in most of the cases the driver is overcharged, **active safety systems, like ESP** which are able to support the driver in emergency situations are very effective.
3. Passive protection measures, like **side airbags and curtains** are able to reduce the consequences of an accident for the vehicle occupants.
4. Since the "static stability factor" plays a major role in the susceptibility of light trucks, SUV`s, and Vans, technical means for **levelling the car body** and therefore reducing the COG are very powerful.
5. **Lane keeping and lane departure warning systems** are preventing the driver from getting off the road and coming into tripped rollover situations.
6. The installation of **diagnostic systems** which are detecting upcoming vehicle or component defects are able to warn the driver driving with an unsafe car.

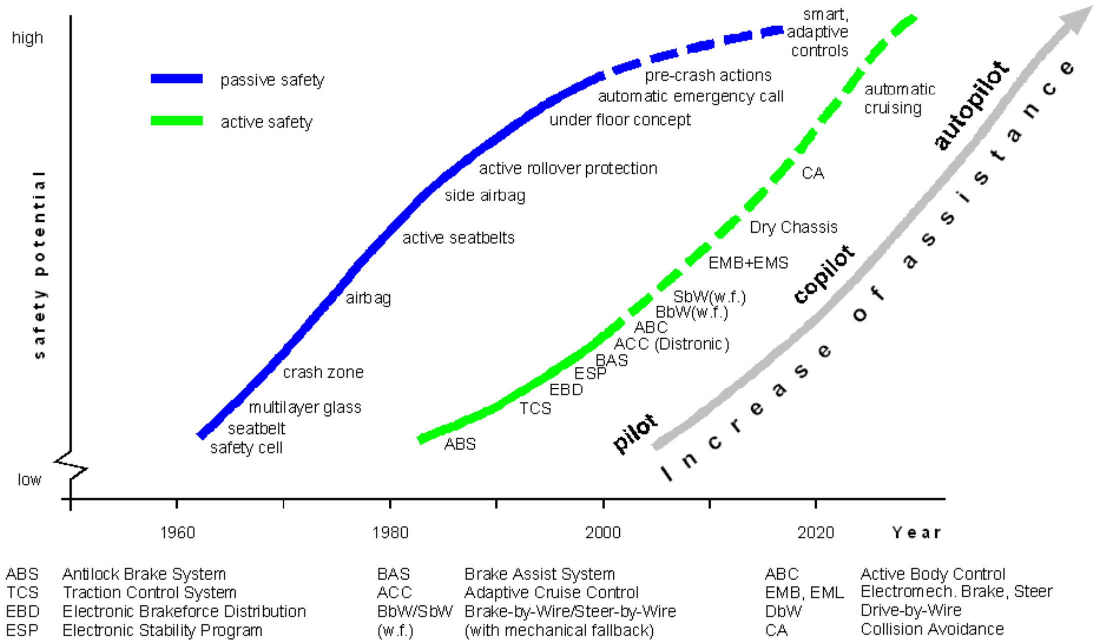

Figure 6. Development of active and passive safety systems.

4.1. ABS, TCS, ESP

The Antilock Brake System (ABS) is meanwhile the classical system, which stabilizes the vehicle under all braking conditions at the adhesion limit. Whenever one or more wheels are losing grip, the ABS takes care and helps also under special conditions, like different friction levels right and left and it can distribute brake torques during normal cornering braking. Due to continuous development and improvement ABS is able to help if the driver is attended and gives him the ability to reduce the speed by full steering capability, so that he can avoid the rollover.

The Traction Control System (TCS) is an enhancement of the ABS and supports the driver during acceleration. Depending on the drive train layout and certain driving conditions TCS is able to hold the car stable or to maintain the steerability of the vehicle.

The Electronic Stability Program (ESP) combines the functions of ABS and TCS, which are more longitudinal dynamics oriented and adds the extremely important lateral dynamic control functions. By this it can support the driver as much as possible during all driving maneuvers. It reduces the rollover risk dramatically. Looking back to Fig. 2 ESP can improve insufficient driver skills during braking, steering, and during combined steering and braking, in cases of too high speed, over-correction, driving style or overloading [4].

In addition to the main system functions other supporting functions like the Panic Brake Assist (PBA), the Electronic Brakeforce Distribution (EBD), and the Engine Drag Torque Compensation (EDC) are on one hand further developments of the existing (sub-)systems, on the other hand effective means of further improvements for the overall capability in reducing the rollover risk [5]. Therefore the ESP can be treated as the nowadays optimum for the reduction of the rollover risk.

4.2. Occupant Safety Systems

Occupant Safety Systems are so called passive systems and they protect the passengers of a vehicle during crashes, collisions and rollovers. In the past up to now an increasing quantity of airbags and inflatable curtains were introduced. Currently such systems are getting more intelligent by using more and more additional sensors or signals and information, already processed in other systems. The introduction of the rollover sensor (ROS) is one example (Fig. 7). This device is sensing the movement of the vehicle around the roll-axis and

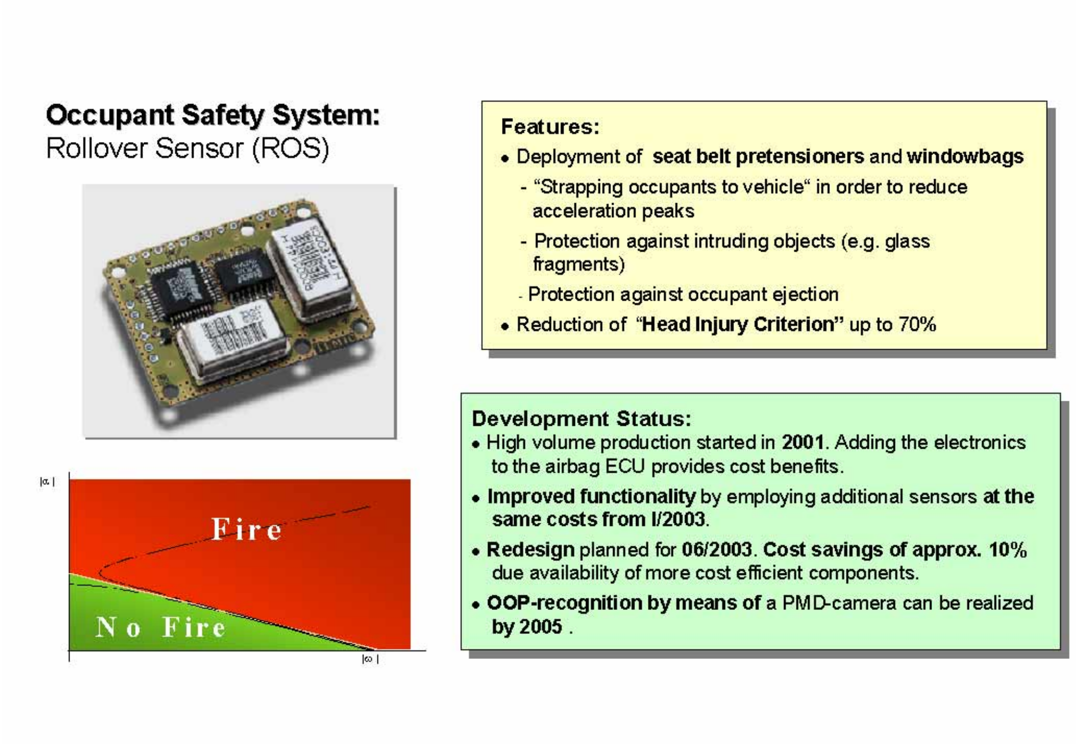

Figure 7. Rollover sensing device.

with this information seat belt pretensioners and windowbags can be energized very accurate and sensitive. As a result the head injuries can be reduced by 70%.

4.3. Electronic Air Suspension (EAS)

The electronic air suspension is the only system nowadays which is able to reduce the COG of a car dynamically. The system as shown in Fig. 8 consists of: air spring/damper modules for each wheel, air supply with reservoir, height sensors and Electronic Control Unit (ECU). By using practical results of the NHTSA star rating as shown in Fig. 9 and calculating the SSF with the same cars but with a reduced COG by 50 mm, we can see that the rating results are improved at least by 1 star.

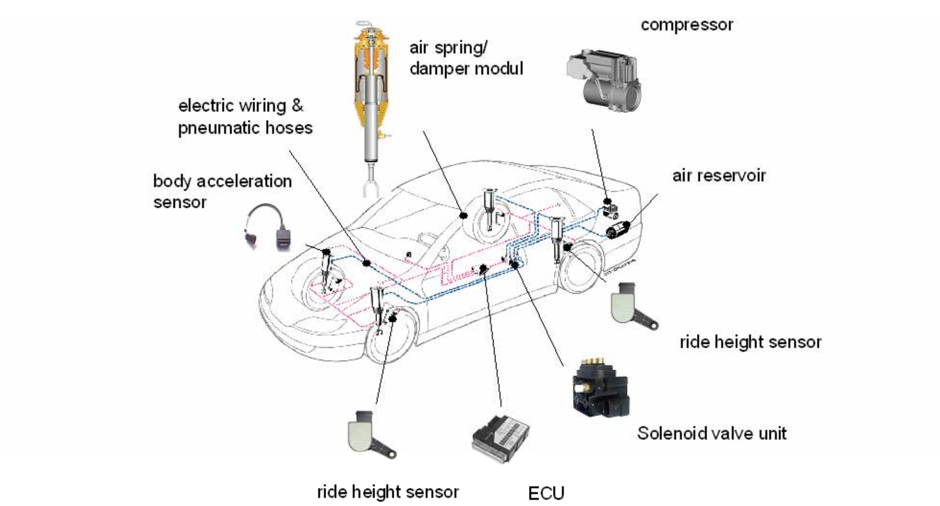

Figure 8. The components of the electronic air suspension (EAS).

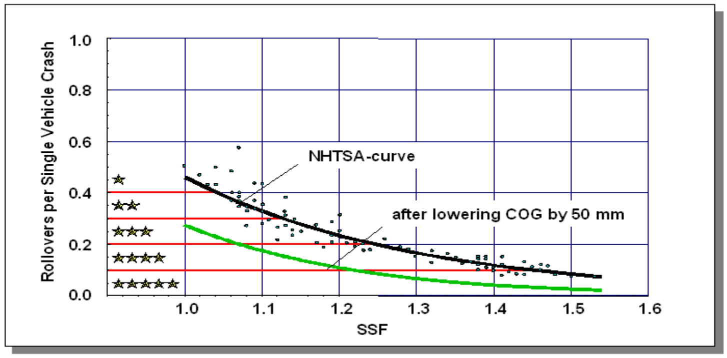

Figure 9. SSF-improvement by lowering the COG.

The EAS system, originally designed for comfort and functionality reasons (height levelling), can be used easily to lower the COG in case of emergency. Here either additional sensors for detecting such situations or data links to other vehicle relevant systems would be necessary. This network approach is discussed further in chapter 5: "The integrated approach".

4.4. Driver assistance systems LDWS & LKS

Many crashes occur because the vehicle is unintentionally leaving its traffic lane. The Lane Departure Warning System (LDWS) assists as soon as the vehicle is in danger to leave its lane. It supports the driver without direct intervention into his driving event. With lane keeping system (LKS) a small camera in the vehicle is monitoring the traffic lane area in front of the vehicle. The gained data are processed by an ECU evaluating the position of the vehicle within the lane.

With this information and together with the vehicle speed it is possible to forecast permanently if there is a risk that the vehicle will leave the traffic lane. If a critical risk threshold is reached the driver will be warned and is able to react. E.g. he can steer the vehicle in a direction to stay within the lane (s. Fig. 10).

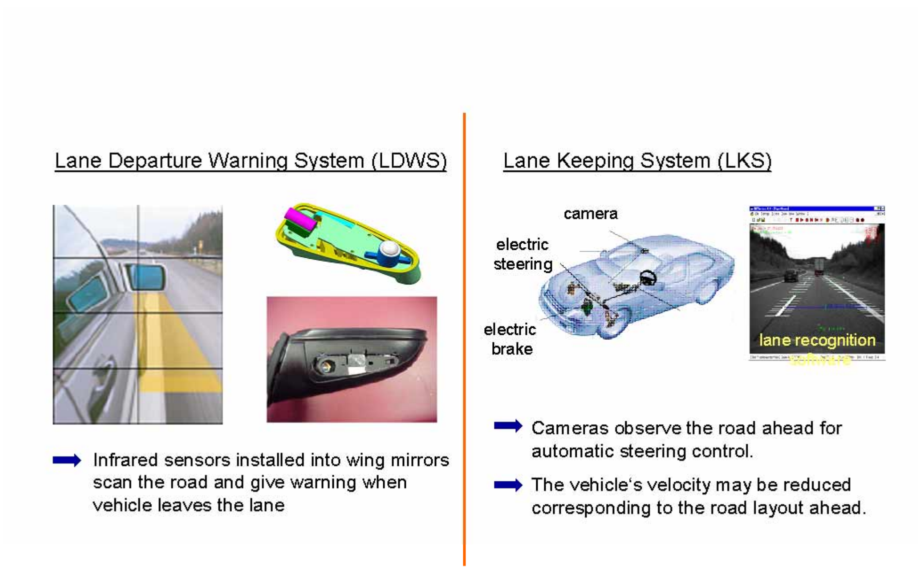

Figure 10. Lane keeping support systems.

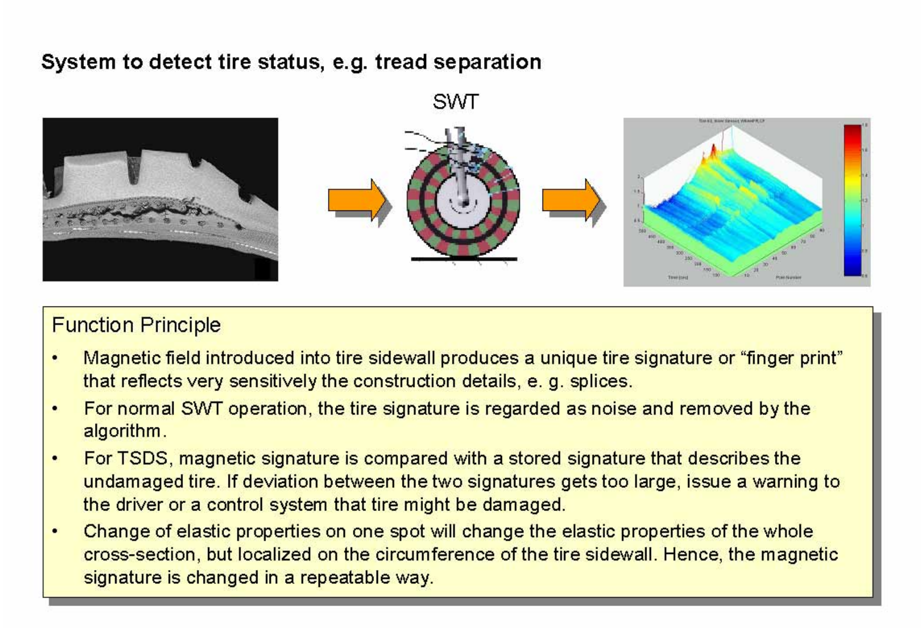

Figure 11. Tire status detection system (TSDS).

4.5. Tire monitoring and diagnostic systems

The wish to control the inside tire pressure is as old as the tire itself. In the first years of the automobile the tire was one of the most unreliable parts of a vehicle.

The situation however has strongly improved until now. The tire has become ordinary to such an extent that attention is hardly paid to that part of the vehicle. Entirely in contrast to the wheel rim which became a design element. This goes as far that the periodical controlling of the tire pressure is often ignored, although it is required in the vehicle operating manual. Even though statistically seen tire defects are extremely improbable.

But the necessity for tire pressure control systems is more important than ever: An incorrect tire pressure or a slow pressure decrease turns out to be fatal just in the case of higher vehicle speeds with which modern vehicles can be driven. With the introduction of the SUV´s and Light Trucks a new category of vehicles has entered the market. This type of vehicles run higher risk of rolling over than common passenger cars. Driving these SUV´s with wrong tire pressure means for the driver accepting a high risk getting into trouble. For this reason the US legislation launched discussions with the aim to make tire pressure monitoring systems a standard defined by law. The specifications for these systems are elaborated by the NHTSA .

A further motivation for the introduction of tire pressure monitoring systems is the removal of the vehicle's spare wheel.

The main task of the direct measuring system TPMS is not only to detect a defect tire but to detect a slow or very slow pressure loss of all tires of the vehicle. E.g. in the case if there occurs little leakage at the wheel rim or the tire valve. For that purpose sensors had to be developed which are able to measure the pressure inside the tire and then transfer the acquired information to a processing device.

In the year 2000 over 100 deaths in the USA were reported in connection with defective tires. The senate decided that tire pressure monitoring systems have to be installed in vehicles as a standard. The NHTSA was ordered to elaborate design proposals. Two alternatives were published in July, 2001 and were taken into discussion.

Estimations of the NHTSA show, that 60 deaths and about 8000 injured people per year in the United States could be avoided, if all vehicles would be equipped with a tire pressure monitoring system and therefore a correct air pressure could be guaranteed in the tires. Tire pressure monitoring systems are able to additionally improve the safety of road traffic [6].

In addition to the tire pressure monitoring devices there are strong research efforts on systems which are able to analyze the tire status and are able to give the driver a warning long before he can usually experience any defects, for instance tread separation. For this task special sensors are required, such as the sidewall torsion sensor which is able to detect discontinuities in the tire mechanics. The development results in the Tire Status Detection System (TSDS) as shown in Fig. 11.

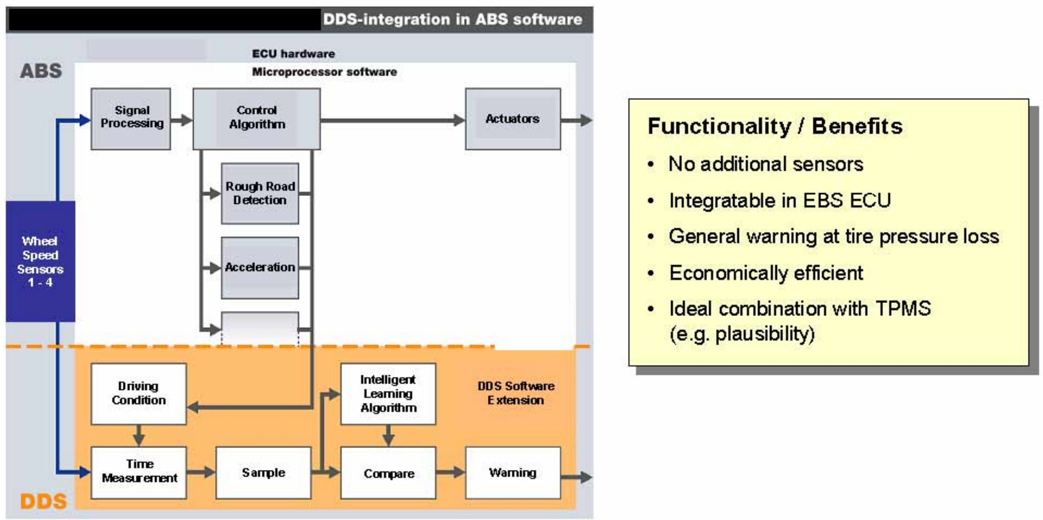

Figure 12. Deflation detection system (DDS).

5. THE INTEGRATED APPROACH

Today passenger cars on the market are equipped with a lot of electronic control units (in high performance cars up to 100), working together with their specific sensors and actuators. Most of the signals derived by the sensors can be used by several control (safety) systems. Also control functions can be performed by one electronic unit and should not be processed separately. So a lot of synergies can be found by analyzing the topology of the distributed control functions in the vehicle [5,7]. It is in addition beneficial using this networking approach for monitoring and moreover for safety reasons as well. So independent processed signals and data from different units can be compared to each other and by means of plausibility criteria judged regarding their validity.

In case of failing sub-systems, the functions can be inhibited while warning the driver or even taken over by other units (depending on the design and the layout of the entire vehicle electronics). In the near future we await in this area a lot of opportunities, but also some risks because the establishment of stable vehicle networks with perfect working data exchange between the subsystems is not an easy task, and not finally solved in the automotive industry. Here we will get soon practical solutions by standardization and international agreements. On the other hand, the advantages are obvious. When we look at the above described systems, we can easily identify the enormous potential, given by the interaction of the systems:

So active safety systems, like ESP, are delivering a lot of data which can be used by other systems, like wheel speeds, vehicle speed, acceleration in longitudinal and lateral direction, surface condition, steering wheel angle and the yaw rate. These signals have different quality. Some are derived from real sensors and are very precise, others are modeled or estimated and therefore more or less rough. It has to be decided case by case whether the quality is sufficient or not.

Whenever the signals are useful they can be used by the airbag unit, by the suspension control, by the lane keeping and lane departure devices and by the deflation detection system (DDS) and TPMS (Fig. 12 and Fig. 13).

The DDS is the best example for gaining synergies, because nearly no additional means are needed, when an electronic brake system is already installed in the car.

There might be additional memory necessary for the function and access to the warning device in the dashboard as well as the information of a calibration button which can be derived via the already installed can bus. These few elements have marginal costs, compared to the benefit for the end user. In addition such systems are fulfilling the U.S. requirements for low costs. They are very robust, because of the few additional parts. The already installed monitoring system of the electronic brake system is able to detect system failures and warns the driver whenever it is necessary.

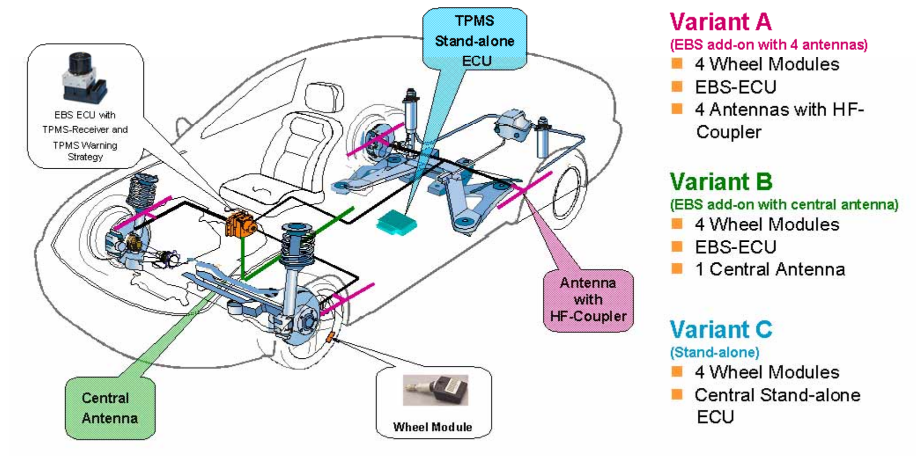

Figure 13. Tire Pressure Monitoring System TPMS and its variations.

In case of the TPMS the networking has several benefits. As an active system with wheel modules, measuring air pressure and temperature in the wheels and sending this information to a receiver unit it can be treated as a stand-alone system, but in combination with an ESP for instance it can use the infrastructure of this system. So the cables for the wheel speed sensors can be used for the transmission of the data from the wheel modules to the receiving unit in the ECU of this system.

The data processing capability of the ESP can also be used for the processing of tire pressure data. If the DDS algorithm is implemented too, this is a back-up, which is able to detect failures in the TPMS, and can be used whenever wheels without wheel modules are in service. This combination of two independent working tire pressure monitoring systems with diversified strategies offers the functionality to influence the ESP. Since the tire pressure monitoring device is now failsafe it can be used to interact with the safety system in the way that it gives a reliable warning to the driver when the speed corresponding to the tire pressure is exceeded, or it can even limit the speed actively.

The interaction between active and passive safety systems offers additional possibilities. ESP functionality can be improved by adding a roll rate sensor. This element, sensing the movement of a vehicle around its roll axis is able to detect early critical driving maneuvers and supports the driver by adequate, selective brake interventions. This information is also helpful for the pre-conditioning of seat belt fasteners or airbags (Fig. 14). So the synergy between both systems is obvious.

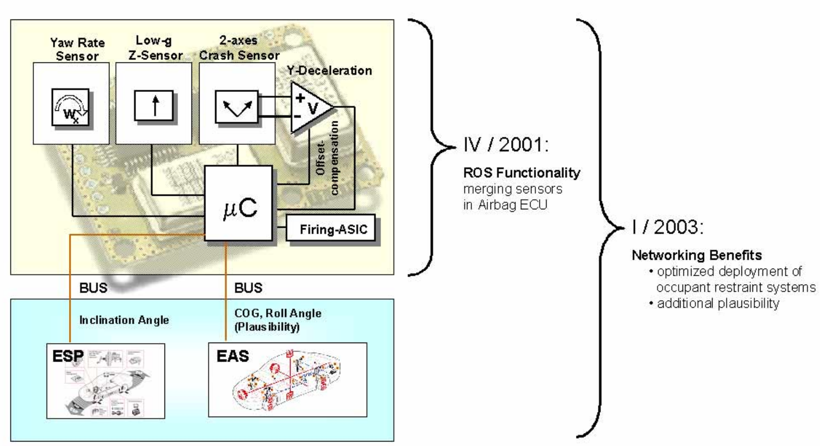

Figure 14. Performance benefit by networking ROS with chassis systems.

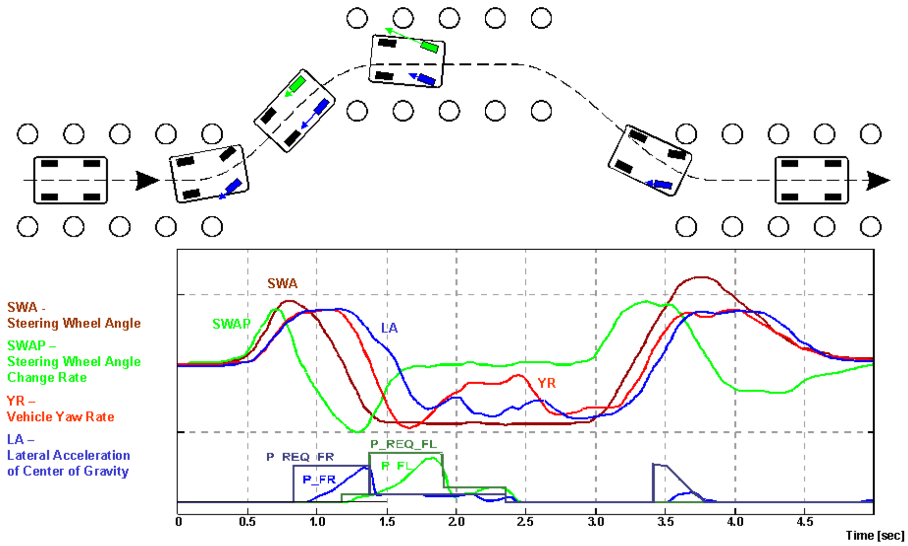

Figure 15. Dynamic lane change with ARP.

A further system approach is given by the so called active rollover protection (ARP) which can be treated as an extension of the ESP, realized with software means only. The main reasons for such a system extension are to reduce the rollover risk during (dynamic) lane change maneuvers and during (steady state) circle driving maneuvers. Here especially lane change, fishhook, J-turn, and circle driving maneuvers are affected. Figures 15 and 16 are showing the effect of such enhanced means.

The electronic suspension control system and the lane keeping and lane departure warning device can use also the signals from the vehicle safety systems sensors or its processed data.

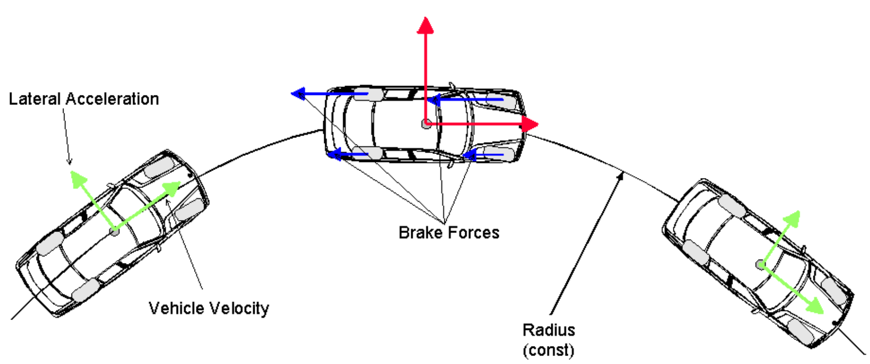

Figure 16. Steady state maneuver with ARP.

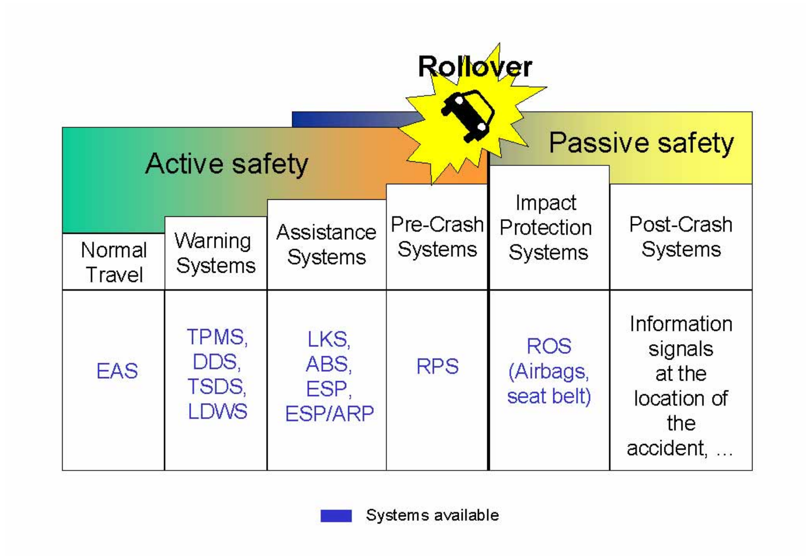

Figure 17. The answer to the rollover problem.

6. CONCLUSION AND OUTLOOK

It turns out that the active safety system ESP is the kernel for many other safety devices in passenger cars. It offers all necessary signals for those systems or can improve these systems significantly. By using networking consequently, new and additional control functions can be introduced for the sake of drivers and passengers safety, leading to an overall reduced risk for the common traffic.

Nevertheless the automotive industry and their suppliers are requested to define standardized, robust and reliable components, sub-systems, systems, and networks, which are able to do their task over the lifetime of the car.

With the current available systems we are able to reduce the risk for all traffic participants. This is shown in Fig. 17.

In the future the electronic control systems will increase and will be the most significant part of a vehicle. Using this potential systematically we are able to improve not only the safety of a vehicle but also the comfort and last but not least the "Fahrspass".

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