Light Commercial Vehicles – Challenges for Vehicle Stability Control

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ABSTRACT

The electronic stability program (ESP®) is increasingly finding acceptance in vans and light commercial vehicles (LCV). Nearly all current models, whose gross vehicle weight is generally between 2.8 and 7.5 metric tons, are now available with this active safety system, either as an option or even as standard equipment.

Many studies have now confirmed that ESP® can prevent a vehicle from skidding or rolling over in nearly all driving situations [1, 2]. This is particularly important in the case of vans, since their design and their use leave them with tighter safety margins. Depending on load, the center of gravity shifts, and consequently the risk of rollover may increase. Bosch has developed a system specifically for light commercial vehicles that automatically adapts its control mechanisms to the current situation.

INTRODUCTION

Worldwide traffic is increasing with more and more vehicles on the road. With further economic growth, we will continue to see more increase in mobility and in traffic density throughout the world. The progress of crash energy absorbing car body design and the standard fitting of airbags significantly improved the passive safety especially combined with the use of seat belts (Figure 1).

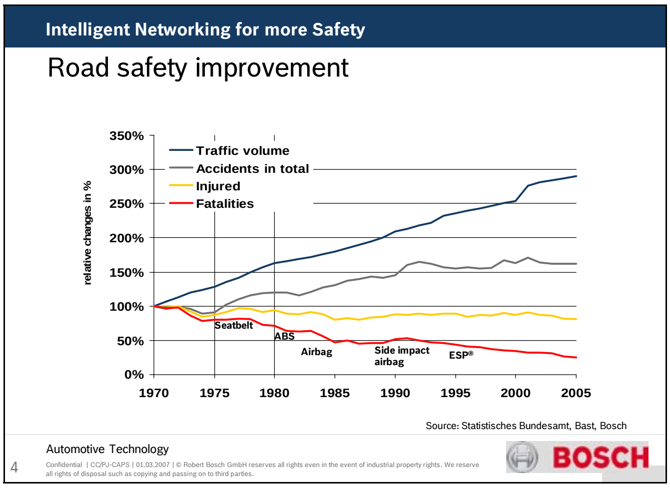

Figure 1. Traffic volume increase and road safety improvement in Germany from 1970 to 2005

But many of the serious accidents happen through loss of control in critical driving situations. When skidding occurs, a side accident is a frequent result. With a reduced protection zone for the occupants compared to front crashes, these accidents show an amplified severity. Especially with vehicles of an elevated center of gravity like vans, sport utility vehicles (SUV) and light commercial vehicles, the loss of control with subsequent skidding may even lead to rollover.

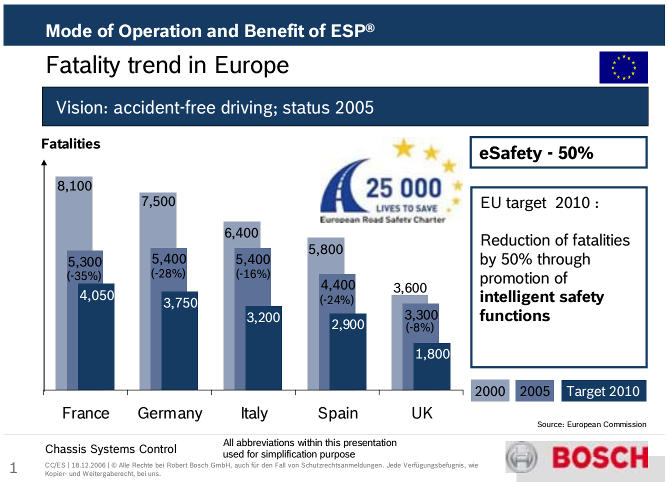

Figure 2. European eSafety initiative of the European Union for 2010 is set to reduce road deaths by 50%

According to accidentology conducted by VW [1], ESP® is considered to avoid 80% of the accidents caused by skidding. VW concludes that the safety benefit of ESP® is even greater than that of the Airbag.

Based on the analysis of Japanese traffic accident statistics, Toyota [2] estimated that the accident rate of vehicles with

ESP® is reduced by approximately 50% for severe single car accidents and reduced by 40% for head-on collisions with other automobiles. The casualty rate of vehicles with ESP® showed approximately 35% reduction for both types of accidents.

Although good progress is shown with a reduction of 21% over the first half decade (Figure 2), the European Union will most likely not achieve the objective. Additional efforts will be required to furthermore enhance the road safety. Bosch supports this with ESP® systems for all vehicle segments including Light Commercial Vehicles (LCV) and furthermore with the combination of active and passive safety systems.

MAIN SECTION

Intelligent safety systems start to support drivers in situations where they are overburdened due to lack of training and driving experience. A study by Prof. Langwieder showed (Figure 3) that in 49% of car-to-car and car-only accidents no braking was applied at all, partial braking was applied in 12% respective 20%, and emergency braking in only 39% respective 31% of the accidents.

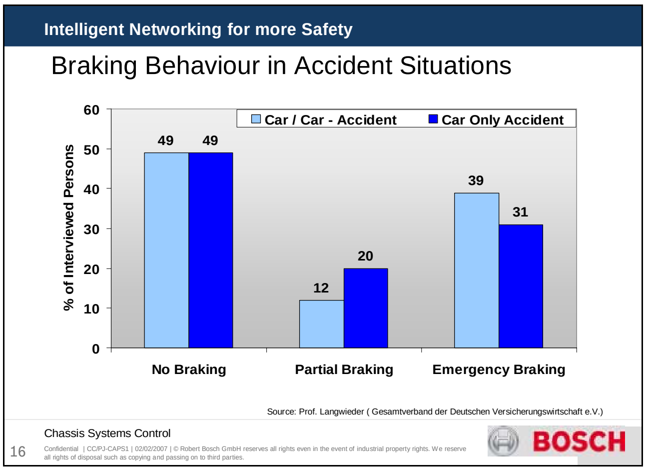

Figure 3. Braking behavior of drivers in car to car and car only accidents in Germany

Although partial braking and to a certain extent emergency braking can be supported efficiently with brake pre-fill and hydraulic brake assist, no braking requires surrounding sensors to enable mitigation functions. First safety systems based on e.g. Radar sensors have already been introduced, supporting partial braking situations with adapted brake assist and brake pre-fill and no braking situations with automated vehicle deceleration.

Still, special emphasize is required to cover the demanding requirements of light commercial vehicles (LCV) and light trucks (LT). For cargo space optimization, LCVs are usually equipped with comparably small wheels. The resulting limitation of brake rotor diameter leads to high pressure ESP® applications with challenging durability requirements.

LT are usually equipped with large wheels allowing remarkable brake sizes with high volume consumption. To ensure full ESP® and rollover mitigation functions and reduced stopping distance, a special brake system design is required. Consequently, Bosch develops the ESP®LT with an optimized

Figure 4. ESP® system for Light Trucks. ESP®LT with optimized motor, pump and valves for improved pressure build-up and better pressure response time during partial braking and ABS intervention; larger accumulator chamber for large brakes with high volume consumption

motor, pump and valves for improved pressure build-up and better pressure response time during partial braking and ABS intervention (Figure 4). Low temperature conditioning is available to ensure full stability performance down to below -25° C. In addition a larger low pressure accumulator chamber is introduced for excellent ABS performance.

Beside typical brake sizes or brake pressure levels, LT and light commercial vehicles share the rather demanding characteristic of high load and mass variances between empty and fully laden vehicle. Specific measures are mandated to ensure full braking, traction and ESP® performance both for the loaded as well as for the empty case. The measure is called Load Adaptive Control or LAC.

LAC – LOAD ADAPTIVE CONTROL

In particular, vehicles with a tare to gross vehicle mass ratio larger than 1.5 such as LCV or LT benefit from LAC. Figure 5 shows the typical load variation for a passenger car compared to a LCV. When the maximum load variance for a car is typically below 40%, it can reach up to 100% and more for a LCV with even stronger relative variations for the Center of Gravity (CoG).

The load configuration has a profound impact on vehicle dynamics. In particular, the load significantly influences:

- braking efficiency incl. ABS- and split-µ performance
- traction efficiency and stability, esp. for vehicles with rear-wheel (RWD) or all-wheel drive (4WD)
- cornering behavior
- rollover tendency

The maximum axle loads are important parameters. They are derived from the mass and longitudinal center of gravity. Since the loading platform tends to be behind engine and passenger compartment, payload mainly increases the rear axle load while only having a minor effect on the front axle load. This also means that front-wheel drive (FWD) vehicles may be as influenced by load changes as RWD and 4WD vehicles.

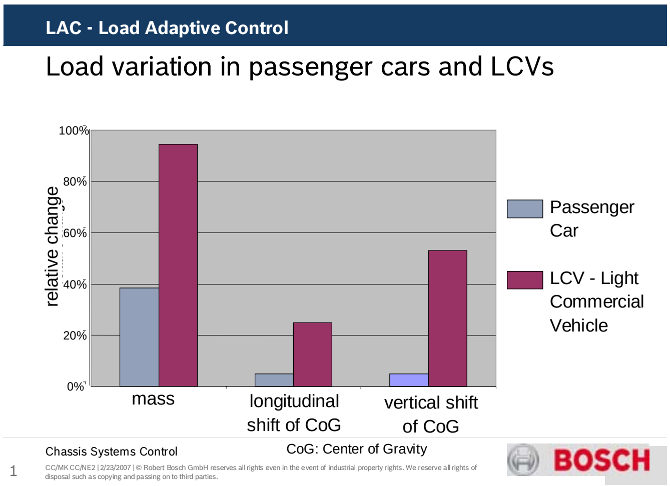

Figure 5. Representative results for relative change of mass, longitudinal and vertical shift of Center of Gravity for empty and loaded cars and LCV

Beside braking and traction performance, different load conditions influence the self-steering and cornering performance of the vehicle. Figure 6 shows the cornering behavior reflected by the yaw gain (according Ackermann) of one and the same vehicle under different load conditions. The empty vehicle shows the expected understeering behavior whereas oversteering is shown with a payload of 1500 kg on the rear axle. A non-adapted target yaw rate would lead to either too early or too late stabilizing interventions.

With LAC, the load impacted characteristic speed is estimated and the target yaw rate and regulating thresholds are adapted accordingly.

The Ackermann yaw gain presumes the free rolling case without longitudinal tire forces. The acceleration causes a pitch effect, thereby shifting load from the front to the rear axle which contributes to increased understeering. The stabilizing effect of traction forces is therefore taken into consideration by LAC.

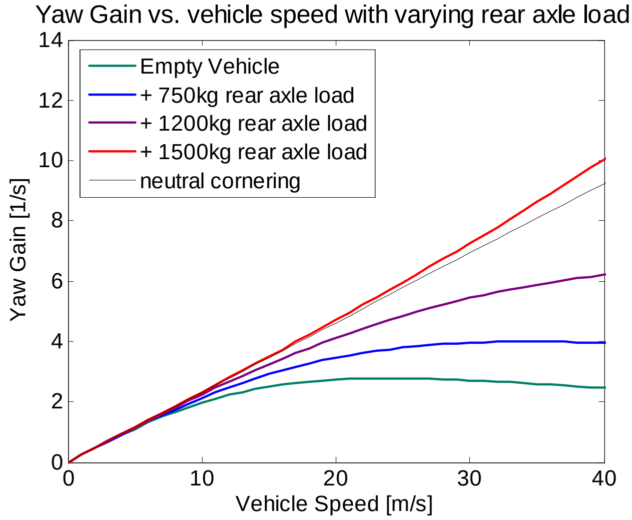

Figure 6. Self-steering and cornering behavior of one vehicle under various load conditions. While the empty vehicle shows the expected understeering, a payload of 1500 kg on the rear axle results in oversteering

LAC consists of algorithms for the estimations of mass, the longitudinal shift of CoG and the change of self-steering behavior reflected by the characteristic speed. The estimation algorithms are centralized while the resulting adaptations are by their nature decentralized and located in various vehicle dynamics modules like the brake slip controller. It is important to note that estimation-based adaptation algorithms need a learning phase, which means that they are never available immediately after key-on. Since estimations will never be 100% accurate, they can only be used to such an extent that a maximum error will not lead to a safety-critical situation. This is to be considered in the FMEA and must be verified in vehicle tests prior to software release.

The following sections describe the positive impact of LAC in different driving situations (for standard ESP® performance and control principles see [3, 4]).

Traction Control and braking performance

The Traction Control System (TCS) determines the target slip depending on the road friction coefficient µ, which is calculated based on the longitudinal and vertical wheel forces. The vertical or normal forces are based on the mass distribution of the vehicle. The high mass variance of LCV in different load conditions would lead to incorrect µ-estimations resulting in inappropriate target slip values. A loaded RWD vehicle during cornering on a low friction surface (i.e. during winter conditions) would estimate a higher µ with the result of excessive wheel slip and the potential of oversteering.

But even with a correct µ estimation, the cornering stability depends on the load and load distribution especially with RWD vehicle. While a vehicle with a low rear axle load may begin to oversteer during acceleration in curves, the loaded vehicle at the same engine torque could still be very stable or even tend to understeer. To adapt for these conditions, ESP®

with LAC calculates an oversteering indicator based on the measured yaw rate compared to the target yaw rate.

With the estimated mass and the longitudinal center of gravity (CoG), the activation thresholds of the rear and front axle torque are adapted. The more the CoG shifts towards the rear axle, the later the torque limitation for the rear brakes will be activated. This results in a more even load distribution between front and rear brakes thereby reducing rotor and pad wear and the risk of fading.

For constantly good braking performance, the actual wheel loads are determined by comparing the braking forces with the prevailing slip values. The higher the estimated wheel loads, the higher the brake controller gains can be selected.

By estimating mass, load distribution, wheel loads and improving the µ-estimation with LAC, the traction and braking stability is optimized for all load conditions.

Fading-detection

Especially with loaded vehicles, fading is more likely to occur. Depending on the design of the front brakes, the dissipated energy may cause excessive brake disc and pad temperatures, leading to fading and - in extreme cases - even to total brake failure. In these cases even high master cylinder pressures will not generate adequate brake torque especially at the front wheels. If front axle fading is detected, the rear axle braking pressure is increased, in case additional rear braking potential is available. Rather than being severely under-braked, the deceleration can be improved and the load on the front brakes reduced.

Load dependent adaptations for split-µ braking

During split-µ braking, different braking forces on the left and right wheels cause a yaw moment which would result in unwanted build-up of body slip angle. With an inappropriate or too late steering correction by the driver, the vehicle might start spinning and potentially rollover in case of vehicles with a high centre of gravity. Therefore the pressure difference between the left and right wheels of one axle is limited to ensure that an average driver can keep control over the vehicle subject to the split-µ caused yaw moment. However, a limit set too low leads to longer braking distance.

Loaded vehicles are more stable during split-µ braking situations than empty vehicles. Therefore, the rear axle pressure difference of a laden vehicle can be increased to higher values at the same stability level. The steering angle information is utilized to adapt the pressure limitation. If small steering angles are sufficient, the rear axle pressure difference is increased and is frozen for large steering wheel angles.

Vehicle dynamics control (VDC)

The changes of self-steering behavior imposed by different loading conditions (Figure 6) are considered by LAC. The VDC activation thresholds to counteract under- and oversteering are adapted as well as the target yaw rate in relation to the Ackermann yaw rate. Prior to or in support of brake interventions, ESP® first adjusts the engine torque to counteract oversteering and severe understeering.

To achieve the required brake slip and the resulting lateral forces in a stability intervention (Figure 7), the brake force must be adapted to the respective wheel load. An empty vehicle requires less brake pressure than a loaded vehicle. Note that the rear outside slip maximum is not changed with LAC.

All these adaptations contribute to optimized stability performance at minimized intrusiveness for the loaded vehicle. Since the payload inflicted changes of the CoG height (Figure 5) can be significant for light commercial vehicles, special

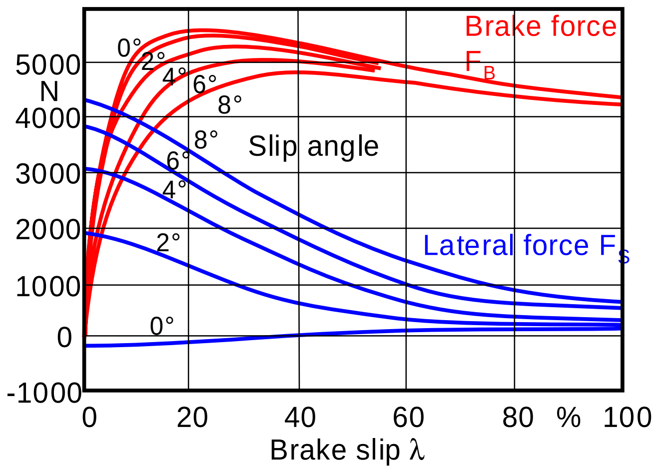

Figure 7. Dependency of lateral forces from longitudinal forces caused by braking for various steering angles. Applying brake pressure controls the maximum possible lateral forces for cornering.

considerations are taken for optimized performance in rollover critical situations.

ROLLOVER MITIGATION WITH LAC

By reading in the estimated mass, the ROM ay-dependent activation thresholds can be adjusted. In this way, the activation thresholds can be increased for empty vehicle and lowered for the loaded vehicle, causing later or earlier interventions, respectively. The figure 8 shows how the threshold adaptation works.

In the US, about 10% of all road accidents are non-collision crashes, but approximately 90% of such single-vehicle crashes account for fatalities [5]. SUV, LT as well as LCV with their elevated center of gravity (CoG) show an amplified rollover propensity, which is reflected in their increased rollover rates.

A vehicle rollover occurs when the lateral forces create a large enough moment around the longitudinal roll axis of the vehicle for a sufficient length of time.

Critical lateral forces can be generated under a variety of conditions. The vast majority of rollover crashes take place after a driver lost control over the vehicle. By skidding off the road, the vehicle may get in lateral contact with a mechanical obstacle like a curb, a pot hole or a plowed furrow which yields a sudden large roll moment. This results in a so called tripped rollover in contrast to an un-tripped or friction rollover. The latter takes place on roads during severe steering maneuvers solely as a result of the lateral cornering forces. Although the ratio of un-tripped to tripped rollovers is small, the un-tripped rollovers account for the most severe crashes.

Accident analysis has shown that the ratio of the track width T and the height of the center of gravity h_{CoG} gives a first indication for the rollover propensity of vehicles.

$$SSF = \frac{T}{2 \cdot h_{CoG}} \qquad \text{Static Stability Factor}$$

The SSF is an important parameter affecting vehicle rollover risk and is both relevant for tripped as well as un-tripped rollover. The track width is a fixed parameter while the center of gravity height varies with subject to different load conditions. Through a one rigid body model - which means no distinction between the mass of the chassis and the sprung mass of the vehicle body – the SSF relates geometrical vehicle data to the level of lateral acceleration that will result in a rollover.

A one rigid body model cannot predict time dependent details of an on-road rollover critical situation. For transient maneuvers involving high lateral accelerations, many vehicle design parameters have an effect on the vehicle handling behavior like e.g. front to rear roll couple distribution, roll axis location, tire behavior, suspension characteristics and roll resonant frequency. These handling characteristics significantly influence the ability of the driver to maintain control in an emergency situation.

The load condition influence on the rollover propensity is shown in Figure 8 in a simplified manner for different types of

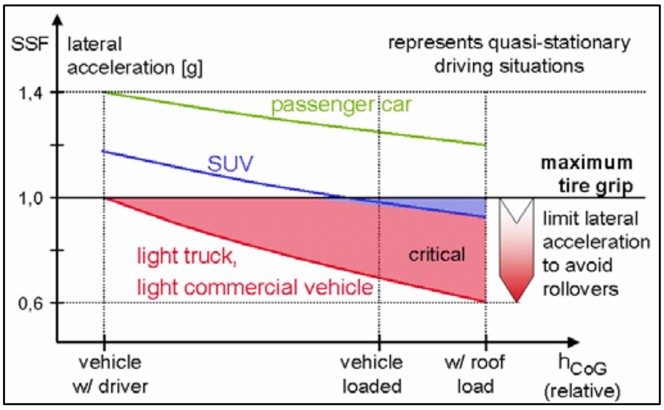

Figure 8. Typical critical lateral accelerations for rollover dependent on loading conditions reflecting different types of vehicles

cars and loading conditions. The static stability factor for typical passenger cars is far above the lateral acceleration which can be transferred by the maximum tire grip. This is the reason why passenger cars are usually not subject to un-tripped rollovers even in extreme loading conditions. If the adhesion limit between the tires and the road surface is reached before the lateral acceleration gets rollover critical, the vehicle starts to skid over the front wheels.

The situation is different especially for light commercial vehicles, where elevated loading may play a major role.

At the physical limit, the tire behavior is extremely nonlinear and the linearized tire-wheel-brake system is even unstable. As a result, the vehicle may suddenly spin and the driver is caught by surprise.

Changing the direction of the resultant tire forces of individual wheels by specific wheel slip demands applies a stabilizing yaw moment (Figure 7) . Besides standard ESP®, active steering can be used as well to increase the vehicle's tracking stability. Both concepts mentioned as well as Active Roll Control [6] or Electronic Damper Control [7] can in general help to avoid critical situations and as a result indirectly help to reduce the rollover risk.

Besides the classification according to the rollover reason, rollover scenarios can be divided into highly dynamic maneuvers, e.g. obstacle avoidance, or quasi stationary maneuvers like circular driving with steadily increasing steering wheel angle. The latter can arise while driving on a highway exit with excess speed.

The Bosch Rollover Mitigation Functions (RMF) are based on the standard ESP sensor set and provide a scalable structure concerning the determination of rollover critical situations and brake/engine control. Other solutions additionally use a roll rate sensor [8]. Further details on the intervention strategy and functional concepts of the Bosch RMF are described in Ref [9].

The Bosch approach uses only existing sensor signals and estimated values to predict the vehicle's rollover propensity. For example, based on the well-known single-track model, an early lead for a subsequent high lateral acceleration is given by

$$c_{pre} = \dot{\psi} \cdot v_x - a_y \approx -\dot{\beta} \cdot v_x$$

$\dot{\psi}$: yaw rate $\qquad v_x$: longitudinal velocity

a_y : lateral acceleration $\qquad \dot{\beta}$: change in body slip angle

With a rapid change of body slip angle weighted with v_x, the lateral acceleration will subsequently increase considerably. The general control strategy is to increase brake pressure at the curve outside wheels to realize the brake slip target values. This reduces the lateral forces as well as the longitudinal speed of the vehicle and results in an increased curve radius. Subsequently the track can be regained due to the reduced speed. In these special situations the brake intervention is usually combined with a cut back on engine torque.

In general, the hydraulic braking system must provide a fast pressure increase over a wide temperature range. For that, the brake tube dimensions, caliper size, and the characteristics of the utilized brake fluid are very important. When a dynamic maneuver is detected, the inside wheel brake on the front axle

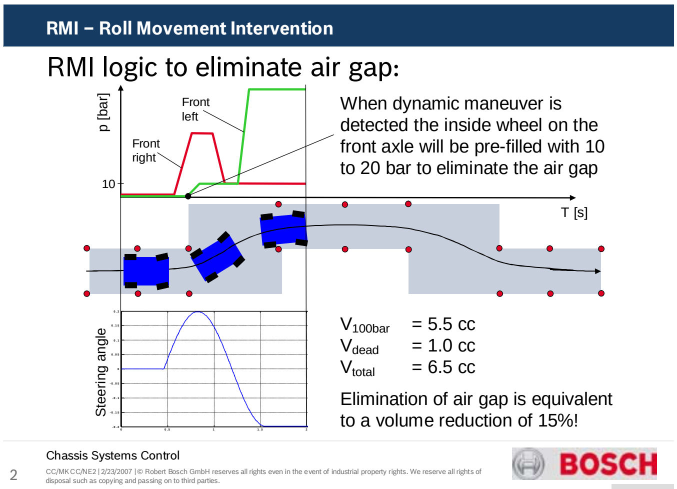

Figure 9. ESP® intervention strategy for increased pressure build-up capability in high dynamic maneuvers requiring Roll Movement Interventions

will be pre-filled with 10 to 20 bar to eliminate the air gap and to cut short on the time needed for a subsequent stability intervention (Figure 9). The elimination of the air gap is equivalent to a volume reduction of approx. 15% depending

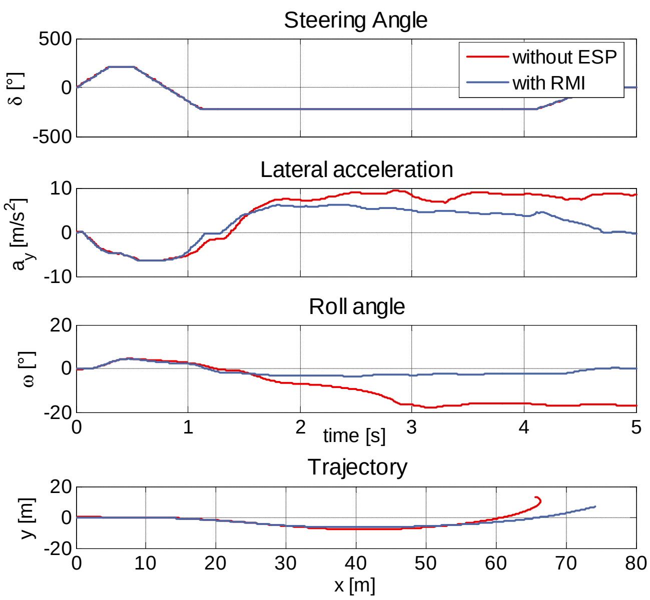

Figure 10. Fishhook maneuver at 80 kph entry speed with a LCV with passenger loads on all seats. Without ESP®, rollover is indicated by two wheel lift off after 2.6 s. With ESP®, the function RMI – Roll Movement Intervention efficiently prevents rollover

on the brake design.

The NHTSA fishhook maneuver with a light commercial vehicle is used as an example to illustrate the rollover mitigation function (Figure 10) compared to the same vehicle w/o ESP® support. Entry speed of the maneuver was 80 kph and the vehicle had passenger loads on all seats. The steering input is depicted in terms of steering wheel angle whereas the vehicle reaction is expressed in terms of lateral acceleration and roll angle. During severe steering back a brake torque pre-control at the curve inside wheel is used to eliminate the air gap for reduced pressure build-up time. While the commercial vehicle with ESP® finished the maneuver successfully, it would have rolled over w/o the Roll Mitigation function.

For vehicles with a high variance of the center of gravity height, an adaptive rollover mitigation strategy is designed. It uses the vehicle's mass and the estimated CoG position to adjust the threshold for brake interventions. This ensures timely interventions with the correct intensity and minimized comfort impairment.

TRAILER SWAY MITIGATION

SUV, LCV and LT are frequently used as towing vehicles for trailers. In typical driving situations, external excitations acting on vehicle and trailer will initiate a sway motion which is automatically attenuated. Above a so called "critical velocity", the sway motion will continuously increase and finally result in serious instability. The appropriate driver reaction would be a reasonable deceleration to a speed below the critical velocity, however some drivers even continue to accelerate, which in short term improves the situation but finally results in aggravated sway and loss of control, as soon as the driver releases the accelerator.

The critical velocity is typically in the speed range between 80 kph and 110 kph. It depends on the geometrical dimensions of vehicle and trailer and their specific load distributions. Especially loading behind the trailer axle affects the critical velocity negatively. Thereby the occurrence of a sway motion may be shifted into a speed range, where the driver never

Figure 11. ESP® function "Trailer Sway Mitigation" to counteract sway movement induced by external excitation (e.g. side wind, road bump)

before experienced any stability impairment. The ESP® function “Trailer Sway Mitigation (TSM)” can effectively counteract the sway motion without need for additional sensors.

The trailer sway results in a periodic yaw motion of the towing vehicle, which is easily detected by the yaw rate sensor. In case the critical velocity is surpassed, the sway amplitude will constantly increase (Figure 12 – top). The TSM function continually monitors the amplitude and decelerates the vehicle with automated brake apply in case a threshold amplitude is exceeded (Figure 12 – middle). Since the required speed reduction can be significant, it might result in undesirable braking of following cars or trucks on the same lane.

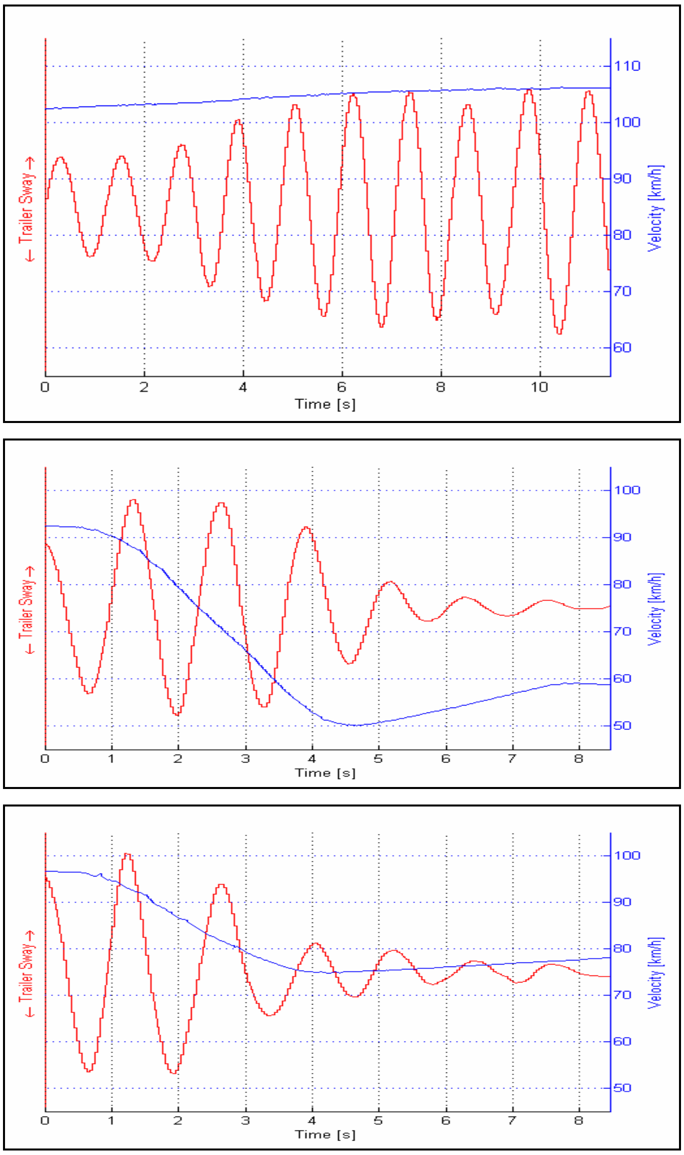

Figure 12. Trailer Sway affects the yaw motion of the towing vehicle. Yaw motion measured with standard ESP® sensor set.
Top: Increasing yaw rate of towing vehicle above critical speed
Middle: Sway damping after symmetrical brake intervention
Bottom: Sway damping after opposite-in-phase brake intervention

The wheel individual brake control of ESP® together with TSM also enables an opposite-in-phase brake intervention with improved efficiency (figure 12 – bottom). The trailer sway is attenuated quickly and the vehicle speed is reduced to just below the critical velocity.

CONCLUSION

The specific characteristics of LCV and LT require special adaptations of stability control due to the load dependent shift of self-steering properties and center of gravity changes. Bosch has developed the Load Adaptive Control that automatically adapts specific ESP® control mechanisms to such changing conditions. In particular, LAC improves the braking efficiency during partial braking as well as in ABS- and split-μ situations. The Drive-away and the overall traction efficiency is improved particularly for RWD and 4WD variants. The stability control is automatically adapted to loading dependent changes of the self-steering properties and the respective cornering behavior. It also supports the driver with an optimized lateral acceleration control to manage rollover critical on-road situations. Together with the TSM function for continually monitoring potential trailer sway, the functional enhancements developed by Bosch ensure that the remarkable safety benefits of ESP® can be fully extended to LCV, LT and heavy SUV.

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ANNOTATION:

All abbreviations within this paper are used for simplification purposes.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

4WD: Four Wheel Drive
ABS: Anti-Lock Control
CCC: Center Coupling Control
CoG: Center of Gravity
ESC: Electronic Stability Control (= ESP®)
ESP®: Electronic Stability Program (= ESC)
FMEA: Failure Mode Effects Analysis
HBA: Hydraulic Brake Assist
LAC: Load Adaptive Control
LCV: Light Commercial Vehicle
LT: Light Truck
NHTSA: National Highway Traffic Safety Administration
RMF: Rollover Mitigation Function
RMI: Roll Movement Intervention
ROM: Rollover Mitigation
RWD: Rear-Wheel Drive
SSF: Static Stability Factor
SUV: Sport Utility Vehicle
TCS: Traction Control System
TSM: Trailer Sway Mitigation
VDC: Vehicle Dynamics Control