OBJECTIVE TEST METHODS TO ASSESS ACTIVE SAFETY BENEFITS OF ESP®

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Paper Number 07-0230

ABSTRACT

Since ABS started in the Mercedes-Benz S-class (W116) in 1978, but mainly by the introduction of ESP® in 1995 in the Mercedes-Benz S-class (W140), Active Safety of passenger cars has been affected by combination of chassis parameters and wheel-brake based systems. Since ESP® has a significant impact on vehicle stability; the evaluation of Active Safety has to be performed in combination with ESP®. Therefore objective tests have been developed to assess the combination of chassis and ESP®. A huge number of tests are used during the development and application of ESP® Systems to vehicle platforms.

Many accident investigations showed an outstanding benefit of ESP® for Active Safety. This raised the interest in objective test methods to assess ESP® performance and finally leads to NHTSA's recently published notice of proposed rulemaking for safety standards for ESP®.

This paper will demonstrate various objective tests and measures for ESP® evaluation. This article will illustrate objective criteria by means of ESP® sub-functions and several operating points (e.g. different speed, lateral acceleration, steering input). The objective behavior of ESP® on high µ will be discussed as well as special demands on low µ.

INTRODUCTION

Current overall ESP® Systems contain several sub-functions to enhance Active Safety in different driving situations. The history of wheel brake-based systems started with braking functions like Anti Lock Brake (ABS). Even to ABS several functions have been added over the last years.

Present systems control the brake balance between front and rear axle by dividing brake force. When it comes to braking in a turn special algorithms are used to maintain yaw stability and provide attainable deceleration. Another part of ABS has the same approach if driver brakes on µ-split. Brake assist recognizes emergency brake situations and supports driver with maximum brake pressure.

The driving functions like traction control represent another category within ESP®. These algorithms assist driver during vehicle acceleration by controlling the maximum wheel slip to maintain stability and if it is driver's intent with achievable lateral acceleration. There are different intervention levels. First engine torque can be adjusted to current driving situation. The second level brakes the driven axle to avoid wheel spin and finally to prevent vehicle spin out it might also be necessary to apply brakes on the front axle to stabilize the vehicle.

The main function of ESP® affects the vehicle dynamics itself. Active yaw control supports driver in situations, where loss of control might occur. In driving situations were vehicle is massive understeering ESP® supports by applying more than one wheel brake to follow driver's intent. Especially vehicles with low static stability factors use additional algorithms to prevent rollover if steering input is very extreme. In these situations ESP® applies vehicles brakes to reduce speed and keep vehicle inside its performance capability.

The sensors and actors of ESP® give the opportunity to implement further functions to enhance Active Safety or to make driving more convenient. In combination with special algorithms ESP® is used to regain stability if a trailer tends to oversteer. Starting on a hill can also be supported be ESP®, if brakes kept applied when the brake paddle is released. Especially in sport utility vehicles ESP® can be used to assist driver in off-road down hill driving by limiting maximum speed and controlling wheel lock.

ACCIDENT STATISTIC

The combination of all ESP® functions increases Active Safety of passenger cars significantly. Investigations of other manufacturers, authorities and institutions on basis of partly different statistics come to comparable results [Aga, M.; Okada, A. (2003) Dang, J. N. (2004) Farmer, Ch. (2004) IIHS (2005) Tingvall, C. et al. (2003)]. ESP® is therefore a system of outstanding influence on the Active Safety of vehicles. Figure 1 shows this impact on Active Safety as the percentage of driving accidents for Mercedes-Benz and vehicles of other brands. Particularly favored by the steep gradients during the introduction of ESP® in Mercedes-Benz passenger cars, 2002 a decrease of the portion of driving accidents of about 30% could be obtained. These are typically serious accidents with a high number of fatalities and severely wounded passengers. In this area of driving safety, ESP® is effective.

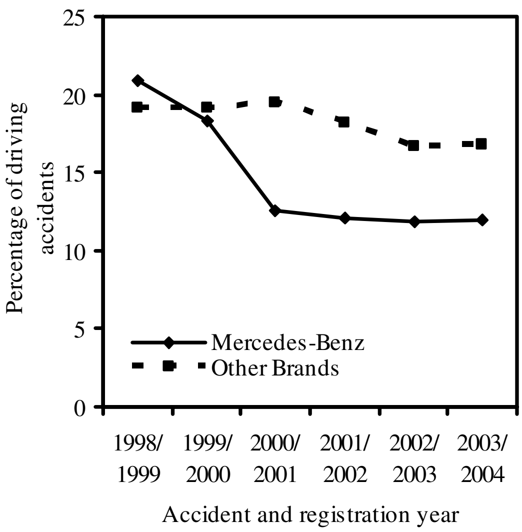

Figure 1: Efficiency of ESP® – accident statistic Mercedes-Benz – Starting 2000 ESP® standard on all Mercedes-Benz Cars –
Source: Anonymous sample of data from Federal Bureau of Statistics Germany 1998 – 2004

This retrospective view from accident statistics can not be used for development and ESP® application directly. Therefore other methods have been established in the past and new ones are still in development. Various tests are described in several standards. Mercedes-Benz updated some tests to reflect current requirements of Active Safety. Several maneuvers used by Mercedes-Benz will be discussed.

OJECTIVE ASSESMENT OF ESP®

In the real world there are innumerable different driving situations. ESP® is constantly comparing driver's intent and vehicle reaction. If a difference between drivers intent and vehicle reaction is observed, ESP® reacts and minimizes the deviation. In many cases conflicts between two or even more criteria arise. After deliberating the criteria of these conflicts, targets can be defined for objective assessment.

Traction Control

A basic conflict exists between acceleration and stability of the vehicle. Mercedes-Benz uses objective measurement on high and low µ to provide driver with excellent stability and a predictable driving behavior while offering highest acceleration capability. First the µ-low test is discussed.

µ-low acceleration in a turn - This objective test represents real world turning maneuvers on low µ. On low µ all rear or all-wheel drive vehicles are able to generate power oversteers, if torque or slip on rear axle is not controlled. In this case there is a conflict between traction and stability. Traction Control supervises rear axle slip and can significantly influence stability but also longitudinal acceleration. To provide the customer with highest acceleration and guarantee stability under all circumstances, Mercedes-Benz uses the objective test "drop throttle in a turn on µ-low" to assess this behavior (Figure 2).

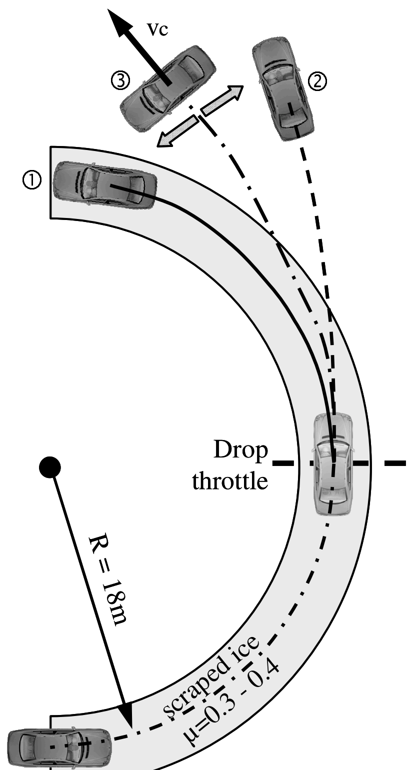

Figure 2: Drop throttle in a turn – ① quasi neural, ② understeering stable, ③ oversteering instable

The initial conditions are adjusted to the coefficient of friction. The maneuver starts with initial steady state cornering on 18 m Radius and a velocity of v = 25 km/h. During this steady state turning accelerator pedal position is immediately increased to a certain level. The rise of accelerator pedal position is stepwise increased until maximum level is reached. All objective measurements must prove at least a certain repeatability level. A significant impact by the coefficient of friction can only be avoided if many measurements on different places are performed. The wheel slip at the drop throttle always polishes the scraped ice surface and has an effect on the result, if a second measurement is performed at the same place. Even with a huge number and attentive execution, level of repeatability is lower than high μ tests.

Data analysis first calculates rise of vehicle course velocity v_c which represents the absolute vehicle velocity along the actual course (see Figure 2). For all data sets the rise of course velocity compared to the initial steady state cornering and rear axel side slip angle two seconds after drop throttle is evaluated. Figure 3 shows the results for three different vehicle setups. The dashed line represents traction control deactivated. The side slip angle increases significantly and loss of control is imminent if velocity rise exceeds 10 km/h. Traction control enhances vehicle stability by controlling the vehicle wheel slip or active brake apply to regain stable conditions. The basic ESP® setup shown in Figure 3 is rather restrictive, only moderate rise of velocity is possible. The optimization of this setup almost allows the same velocity rise as the setup without traction control but on a much higher stability level. The side slip angle at the rear axle does not exceed 10° which is at this speed controllable for any driver.

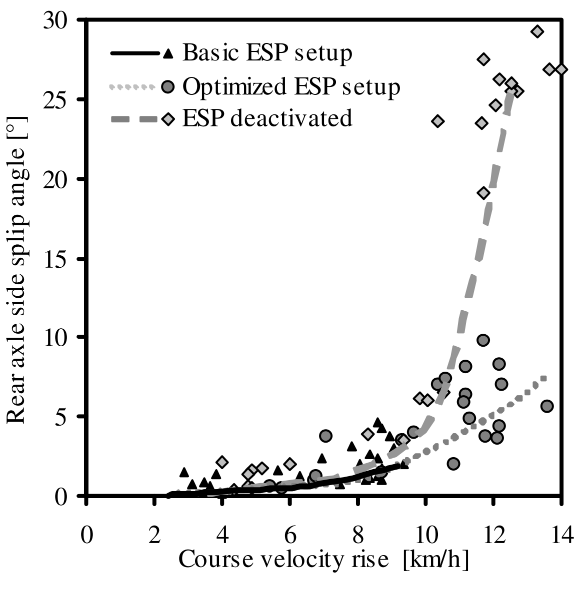

Figure 3: Conflict diagram - drop throttle in a turn

Well attuned traction control systems almost allow the same velocity rise than the vehicle without systems but side slip angle is limited to convenient level. A certain level of side slip is still necessary in order to keep the course of the vehicle on adequate radius. If radius exceeds a certain level, driver will subjectively feel too much understeering.

<u>Acceleration in a turn</u> – A similar test to assess velocity rise and lateral stability is performed on high μ. The initial conditions of the maneuver differ to the test on μ low. The initial radius is reduced to 6.5 m while initial speed v = 25 km/h is the same as on low μ. This leads to higher level of lateral acceleration.

In preliminary tests the maximum rise of velocity is determined. Therefore the vehicle is tested with traction control deactivated. Several tests are performed while at each test the maximum level of the accelerator pedal is increased. Figure 4 shows the velocity rise for the different levels of the accelerator pedal. The maximum velocity rise for the vehicle shown in Figure 4 is reached with accelerator level of 80 percent. Above this level the maximal velocity rise is lower again. If sufficient engine power is available, even on high μ spin out at full throttle is possible. At the test vehicle shown in Figure 4 spin out occurred at almost full throttle. To increase repeatability several test are performed at the accelerator paddle level which provides the maximum velocity rise.

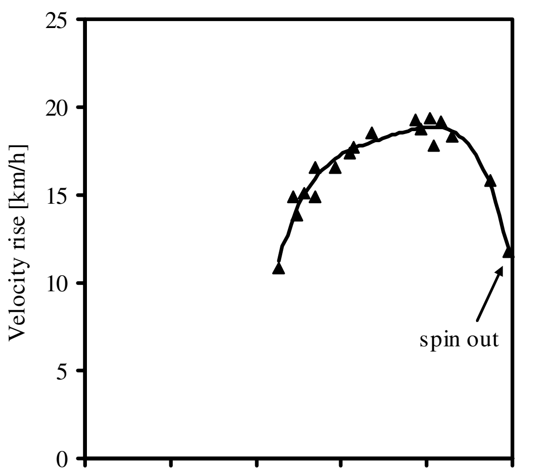

Figure 4: Acceleration in a turn – velocity rise at different throttle levels

The tests where traction control is activated are always performed with full throttle. The exhausting procedure of finding the maximum velocity rise with activated system is so simplified very much. Several tests are accomplished to increase repeatability.

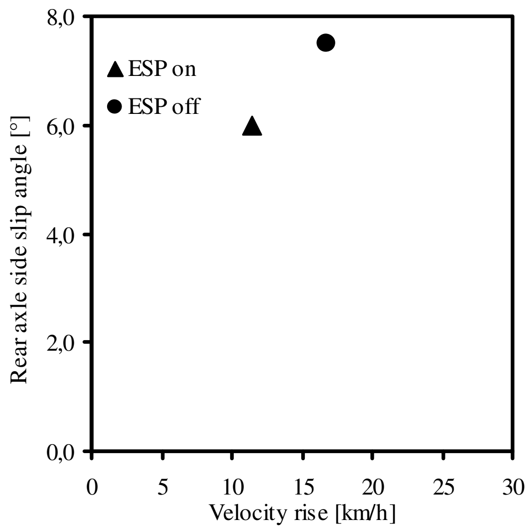

Figure 5: Drop throttle in a turn – maximum velocity rise vs. stability

The summarized results of the conflict velocity rise vs. stability are shown in Figure 5. In this case all measurements with system activated are averaged as well as the measurements with maximum velocity rise and system deactivated. In principle higher velocity rise is possible with traction control deactivated, if driver accelerates by using the optimum accelerator pedal level. Therefore driver needs to control the accelerator pedal to reach this performance and still takes the risk of spinout without ESP®. The velocity rise with traction control activated for the tests shown in Figure 5 is around 70% of the overall maximum level. This velocity rise is reached in a much safer way. Mercedes-Benz uses this test procedure to develop the typical stable and predictable driving behavior.

Vehicle dynamic control

Basically the vehicle dynamic control function builds the core of ESP®. Based on a vehicle model the actual course and driver's intent are compared. The vehicle model uses basically steering wheel angle and vehicle speed to determine driver's intent. Since NHTSA focuses for the evaluation of ESP® systems on the sine with dwell maneuver, this maneuver comes more in focus for ESP® assessment. The conflict between yaw stability and lateral performance is already addressed by this maneuver. Mercedes-Benz uses the sine with dwell maneuver to support application of the dynamic control function.

Especially braking in a turn can lead to an exacting driving situation, if vehicle is running with high speed. In this kind of situations driver needs to be supported. To assess the driving behavior Mercedes-Benz uses the test "braking in a turn at high speed", which will be described next.

Braking in a turn at high speed – Additional to the maneuver braking in a turn, defined in the standard ISO 7975, Mercedes-Benz uses a slightly modified version. In principle all these procedures evaluate conflicting aims between stability and attainable deceleration during the braking. This additional test assesses Active Safety at high speed. Therefore the maneuver starts at a steady–state run at 200 km/h.

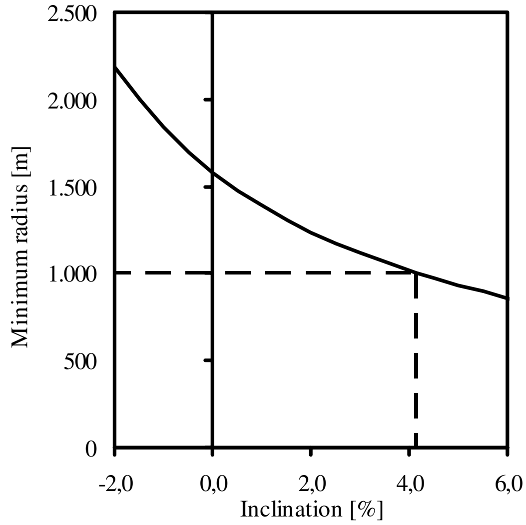

Figure 6: Construction of minimum radius at different inclination for German Autobahn according to RAS-L 1984

The ISO Standard suggests a lateral acceleration of $a_y = 5$ m/s². If this lateral acceleration is used at 200 km/h the vehicle runs on a radius which is typically not used for German Autobahn. The radii on German Autobahns are designed, besides a lot of other parameters, dependant to the inclination (see Figure 6). To reflect a typical German Autobahn profiles the minimum radius is adjusted to R = 1000 m. This leads to a lateral acceleration of $a_y = 3.1$ m/s².

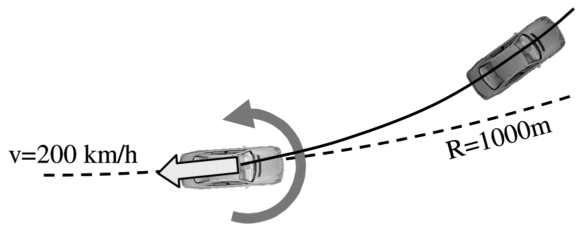

Figure 7: High speed braking in a turn

The brake test starts with the steady-state condition v = 200 km/h and R = 1000 m (see Figure 7). Several measurements at different level of longitudinal deceleration are performed. The deceleration should be kept constant during the single brake maneuver (see Figure 8).

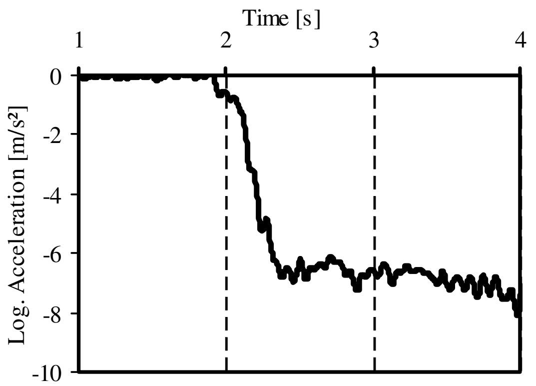

Figure 8: High speed braking in a turn – Example time plot of longitudinal acceleration (brakes applied at t = 2 s).

The yaw reaction is relevant particularly within the first second after the initial brake contact, since the driver, depending on its individual reactivity, compensates course deviations only thereafter. Therefore maximum deviation to the reference of yaw velocity within the first second of brake test is evaluated for every single test (see Figure 9). For this calculation the arithmetic of ISO 7975 is used.

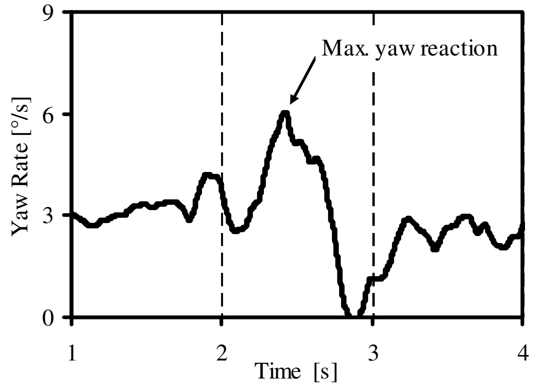

Figure 9: High speed braking in a turn – Example yaw reaction (brakes applied at t = 2 s)

Several braking test on the different deceleration levels and the corresponding yaw reaction is illustrated in Figure 10. Typically these results show the maximum yaw reaction at a deceleration of a_x = 5-7 m/s². Very good car ESP® configurations reach maximum yaw reaction shown in Figure 10.

Physically the yaw velocity as well as the steering wheel angle which are necessary to run with v = 200 km/h on a radius R = 1000 m is quite low. Thus the internal ESP® algorithm also calculates low reference values. Even if the difference between reference and the actual yaw rate is also low, a significant lateral deviation between vehicles course and driver's intent might occur. To support driver in these kind of situation the corner brake control especially controls driver's intent and actual course. To enhance vehicle stability the brake pressure at rear axel is limited to a certain level to increase vehicle stability. Since rear axle does not provide too much brake force the influence of braking distance is not very significant. Brake pressure at rear axle can be increased during the deceleration. If vehicle reaction still is intensive the beginning of the braking maneuver can be influenced to reduce path deviation. Dependent on the corning direction the brake pressure on the front axel is built up slightly asymmetrical. This additional yaw moment works against the vehicle oversteering behavior. Corner brake control enhances vehicle stability and also provides driver maximum deceleration.

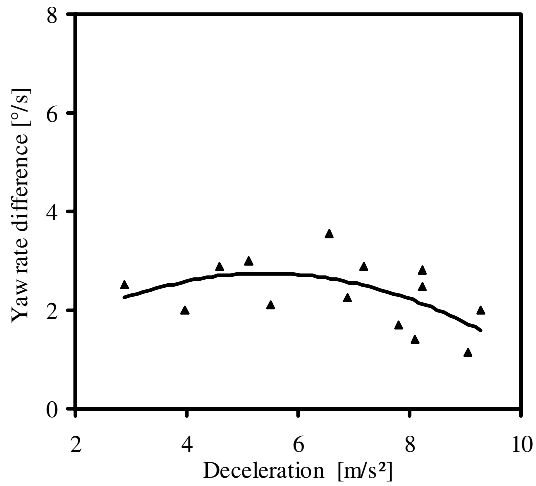

Figure 10: High speed braking in a turn – summarized results

Special functions

Since ESP® becomes more standard in vehicles additional functions are implemented. Some functions make driving more convenient. These kind of functions are not discussed in this paper. Other functions enhance Active Safety.

ESP® Trailer Stabilization is such an additional function. Car-trailer combinations tend to oscillate after excitation from cross-wind, irregular roadway or steering input. The damping of the system decays if speed increases. Therefore the oscillation lasts for a longer period of time if the car-trailer combination is traveling with higher speed. Above the zero-damping speed the oscillations of the rig will not decay anymore (see Figure 11). The level of the zero-damping speed is characteristic for every single car-trailer combination. The mass/inertia moments of the trailer, drawbar length and tires mainly influences the zero-damping speed.

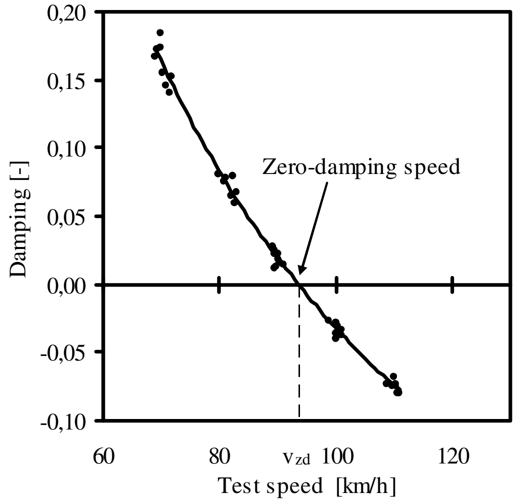

Figure 11: Typical damping of a car-trailer combination at different speed

If a car-trailer combination starts to oscillate at a speed above the zero damping speed, an accident can only be avoided if speed is reduced immediately. After recognizing a car-trailer oscillation situation ESP® Trailer Stabilization applies the brakes of the towing-car to work against the oscillation. This mechanism and reduction of speed increases damping and stabilizes the combination.

A test method to asses the stabilization is illustrated in Figure 12. The driver activates an oscillation of the car-trailer combination by a pulse steer at the towing car. In the first phase of the maneuver the amplitude of the lateral acceleration at trailers center of gravity increases (see Figure 12). After ESP® detects a critical level the brakes are applied in a way that counteracts the oscillation by building up yaw moments in phase with the oscillation. This mechanism additionally damps the oscillation. In this second phase the car decelerates which can be seen in the speed diagram in Figure 12. The speed reduction itself increases the damping of the system and helps to regain stability. This leads to a decay of trailer lateral acceleration amplitudes.

Figure 12 shows two different ESP® setups. The dashed line represents a basic setup. This setup recognizes the trailer oscillation approximately 4 s after the steering input. At this time lateral acceleration already reached 5 m/s², which is a quite high level for trailers. This is already a severe situation; therefore the basic ESP® setup needs to decelerate the car-trailer combination very hard. This test started with an entry speed of almost 120 km/h, after the stabilization of the car-trailer combination the speed was only around 40 km/h. Only if this kind of situation is detected very fast and the braking activations are well controlled the exit speed in this kind of maneuvers remains on adequate level. Nevertheless the exit speed of the maneuver needs to be below the zero-damping speed. Otherwise there is still not enough damping to maintain stability.

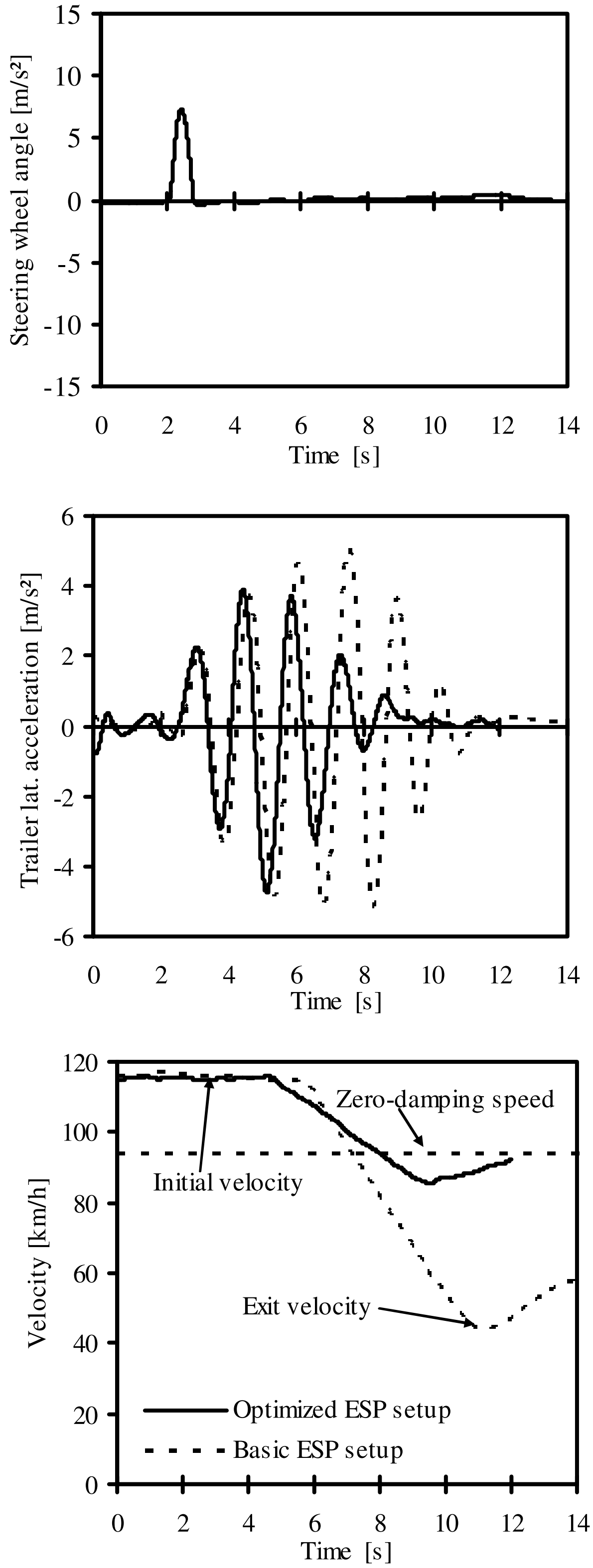

Figure 12: Oscillation and stabilization of a car-trailer combination with different ESP® setups

This conflict of stabilizing and braking the car-trailer combination needs to be assessed during the application of ESP® Trailer Stabilization. Mercedes-Benz uses for this test the already introduced pulse steer maneuver which is based on the ISO 9815 standard. A preliminary test detects the zero-damping speed of the car-trailer combination without ESP® interaction. For that damping of the combination is determined at different speed levels by the test maneuver. Speed is increased till the zero-damping speed is passed.

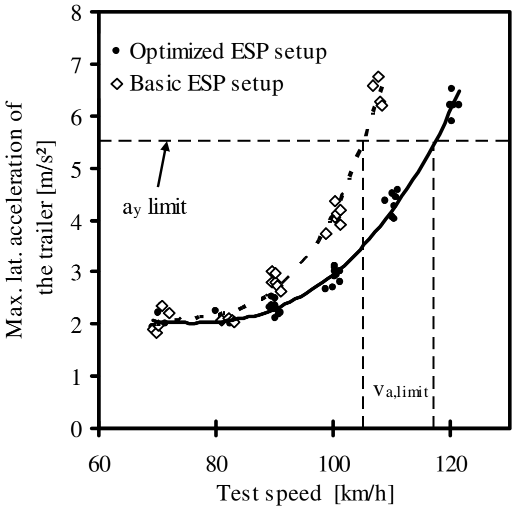

Figure 13: Maximum lateral acceleration of the trailer after pulse input at different speed levels of a car-trailer combination with different ESP® setups

Same test on different speed levels is performed with ESP® interaction. Figure 13 shows the maximum lateral acceleration of the trailer at different speeds and the termination limit. A basic setup which reaches the termination limit at lower speed and an optimized ESP® setup are illustrated. For safety reasons these tests are performed till a certain limit of lateral acceleration of the trailer is reached. Trailers are typically not quipped with high performance tires. This can already at a lateral acceleration level of a_y = 5-6 m/s² lead to a spin out of the trailer. On the other hand trailers with high loading tend to rollover if lateral acceleration overruns this limit.

The speed which reaches the limit of lateral acceleration of the trailer represents a measure for the ESP® Trailer Stabilization performance. This measure is referred to the zero-damping speed to reduce influence of different car-trailer combinations (Equation 1). This stabilization ratio (SR) reflects the stabilization performance of the ESP® Trailer Stabilization.

$$SR = \frac{v_{a,limit}}{v_{zd}} \qquad (1)$$

where

$v_{a,limit}$ is the speed where lateral acceleration of the trailer is equal to the limit

v_{zd} is the zero-damping speed

The second criteria to assess ESP® Trailer Stabilization evaluates velocity drop during the stabilization of the car-trailer combination. Without active mechanisms (e.g. active coupling ball mechanism) a car-trailer combination oscillation above the zero-damping speed can only be stabilized if the speed is reduced immediately. The reduction of speed helps to increase Active Safety in this situation. Of course if the reduction of speed during the stabilization leads to a speed which is way below the common cruise speed inconvenient situation especially for following traffic might occur.

The basic ESP® setup in Figure 12 shows a significant velocity drop during the stabilization. To reduce speed drop during the stabilization phase ESP® Trailer Stabilization needs to detect the trailer oscillation very fast and the application of the ESP® trailer stabilization has to work very efficient. ESP® Trailer Stabilization intervenes by alternating left and right brake application. This intervention lasts for a longer time than conventional ESP® application. This works very efficient against the oscillation of the car-trailer combination. The velocity drop ratio (VDR) assesses the loss of speed. Like the stabilization ratio the velocity drop ratio VDR is also referred to the zero-damping speed (Equation 2) to make different car-trailer combinations more comparable.

$$VDR = \frac{v_{exit}}{v_{zd}} \qquad (2)$$

where

v_{exit} is the speed where the ESP® intervention ends (Figure 12).

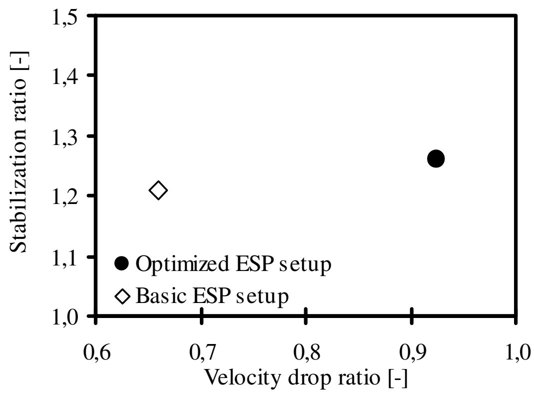

Figure 14: Conflict diagram of stabilization performance and velocity drop of a car-trailer combination with different ESP® setups

The conflict diagram (Figure 14) integrates both criteria. An ESP® setup where the velocity drop ratio is close to VDR = 1 detects trailer oscillation fast and stabilizes the combination quickly.

Nevertheless the VDR needs to be smaller than VDR = 1 (or exit speeds needs to be lower than zero-damping speed) to ensure that the car-trailer combination remains stable even, if the ESP® intervention is terminated.

An ESP® setup were SR > 1 can stabilize car-trailer combination even if the oscillation occurs at speeds above the zero-damping speed. ESP® Trailer Stabilization setups were VDR is close to 1 and SR > 1.2 can be assumed to be well tuned.

SUMMARY

ESP® supports driver in almost every severe driving situation. Several accident statistics show an outstanding reduction of driving accidents. ESP® uses a vehicle model to calculate drivers intend by mainly using steering wheel angle and vehicle speed. These results are constantly compared with the current vehicle course. If a deviation is observed, ESP® will support driver by a specific brake application. The model and several additional features have to be adjusted to the specific vehicle platform. To support and assess this application various maneuvers are used. During application of the system conflicts between several criteria have to be resolved. Several objective tests are used by Mercedes-Benz to support application of the system with objective measures. This paper introduced a selection of these tests. Starting with the driving function, drop throttle in a turn on high and low μ is discussed. This maneuver assesses the conflict between vehicle yaw stability and attainable acceleration. The Active Safety at higher speeds can be evaluated by the test maneuver braking in a turn at high speed. This maneuver focuses on the conflict between vehicle stability and deceleration. The stabilization of a car-trailer combination can be also objectively observed. The optimum ESP® setup must take the stabilization performance as well as the reduction of speed into account.

Of course an ESP® system can not be only attuned by objective testing but a framework is given. Beyond this ESP® application uses single events during subjective pretests or semi-subjective driving to determine the ESP® setup.

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