A REALISTIC CRASH TEST SETUP TO ASSESS THE REAL WORLD PERFORMANCE OF ADVANCED ROLLOVER SENSING SYSTEMS

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ABSTRACT

To protect occupants during a rollover event, restraint control modules with integrated Rollover Sensing (RoSe) function have been developed. These devices are able to trigger belt tensioners and curtain airbags if the vehicle's roll angle and roll rate indicate that the vehicle is going to tip over. Especially in the case of tripped rollovers, however, the optimum deployment time for curtain airbags is before the vehicle has build up a significant roll angle. To cope with this challenge the advanced rollover sensing function from Bosch uses the lateral velocity of the vehicle as additional input to its deployment decision.

Based on a new crash test setup developed by Dekra the performance benefit of this advanced rollover sensing system can be shown under realistic circumstances. The test does not only cover the rollover phase but also the skidding phase before the vehicle passes onto the soil and rolls over. First tests have been performed to investigate both the repeatability of the movement and the behaviour of the vehicle during such tests. To steer the car, an optically controlled guidance is used combined with a time-based activation of the steering without braking. The vehicle with rightwards steered front wheels runs for a short time on a μ-split path. Several sensors are used to measure the relevant kinematics (velocity, acceleration, yaw-, roll- and pitch-rate). Additionally the movement is filmed by several high-speed cameras.

In the article the authors describe the test method and the results and discuss the benefit of this new method to assess the performance of an algorithm for advanced rollover protection.

INTRODUCTION

According to the NHTSA Traffic Safety Report 2005 [1] rollover crash events still contribute significantly to the crash fatalities on the roads of the United States. Although only 2.6% of all vehicle crashes can be attributed to rollovers, 21.1% of the occupant fatalities in 2005 are related to vehicles having a rollover crash. These statistics dramatically illustrate the severity of this crash type.

RESTRAINT DEVICES FOR OCCUPANT PROTECTION DURING ROLLOVERS

The best way to protect occupants from any rollover injury is to prevent a rollover. Electronic stability control (ESC) systems can help to reduce the risk of rolling over. However, such systems mainly address so called on-road rollovers induced by lateral tire friction occurring e.g. in massive skidding situations. In case of a vehicle leaving the roadway, stability control systems come to the limit, since they cannot prevent wheels from furrowing into the ground resulting in a rollover. As crash statistics show these so-called soil trip rollovers account for a significant number of the rollovers in the USA.

In case a rollover cannot be prevented, the vehicle's passive safety design has to prove of value: A high roof stability as well as intelligent restraint devices like rollover curtains and belt tensioners can help to reduce the occupants' injury level. Special rollover curtains that remain inflated for several seconds can prevent occupants from being fully or partially ejected during a rollover. Belt tensioners can fix a buckled occupant in the seat thereby keeping the occupant's head at the maximum possible distance from the side windows and from the vehicle's roof which might be subject to intrusion.

ROLLOVER SENSING - MAKING A TRIGGER DECISION FOR ROLLOVER RESTRAINTS

The protection potential of rollover related restraint devices like rollover curtains or belt tensioners is strongly correlated to the time they are triggered: The

earlier these devices are deployed, the higher their protection effectiveness can be. On the other hand an inadvertent deployment must be avoided under all circumstances, even in the case that a vehicle already has started to roll but doesn't roll over completely in the end, i.e. not reaching a roll angle ≥ 90°. Making an early but robust deployment decision is a question of the rollover sensing performance. Today the RoSe function is an integral (but for most vehicles still optional) part of the restraints control module.

Existing RoSe systems typically calculate a deployment decision using a roll rate sensor that is integrated into the restraints control module. The deployment decision is based on a comparison of the vehicle's actual roll rate with a critical roll rate threshold. This threshold depends on the vehicle's current roll angle and on its physical properties such as mass, centre of mass, track width and moment of inertia.

If the vehicle's roll rate exceeds the critical threshold, the rollover sensing system can predict whether the vehicle will roll over, see Figure 1. In case a complete rollover is certain the restraints control module deploys occupant restraint devices accordingly. This approach generally produces early and robust deployment decisions in rollover situations that do not involve tripping.

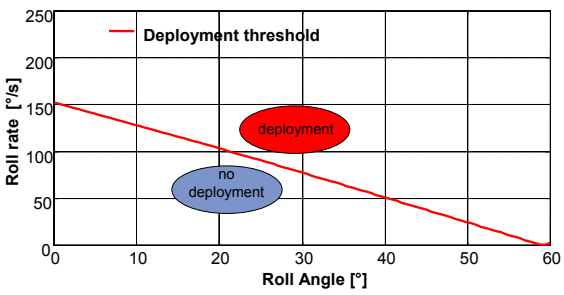

Figure 1. Example of standard rollover criterion for the deployment decision of rollover restraints

In the case of tripped rollovers, however, the rollover event is primarily induced by lateral forces. In this case a deployment decision is needed very early. This is due to the fact that the lateral forces can push the occupant's head into the deployment zone of a curtain airbag before the vehicle has built up a significant roll angle. Thus in the case of tripped rollover events, existing RoSe algorithms must be calibrated accordingly in order to produce an optimal trade-off between the requirements for early deployment and the need for high robustness against misuses. Investigations of rollover test data have shown that this conflict can effectively be resolved by incorporating information about the vehicle's driving state into the deployment decision [2].

ADVANCED ROLLOVER SENSING

Today's RoSe system analyze the roll movements of the car in order to make deployment decision. However, valuable information about a rollover risk can be derived before the vehicle has build up a significant roll angle. In the specific case of tripped rollovers the vector of the vehicle's velocity changes from longitudinal direction to lateral direction as the vehicle starts to skid, see Figure 2.

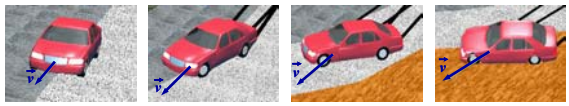

Figure 2. Change of vehicle velocity direction relative to the vehicle in a pre-roll phase

The kinetic energy thereby takes effect on the car's lateral movement, and is finally transformed into rotational energy as the wheels furrow into the soil and decelerate the car laterally. The higher the lateral velocity v_y of the car and the lateral deceleration a_y, the higher the amount energy E_{kin} which can be transformed into rotational energy E_{rot}. To differentiate how the lateral velocity indeed is inducing a roll movement, the so-called "roll effectiveness", is introduced:

$$e_{roll} = f\left(\Delta v_y, \Delta\varphi_x\right)$$

This roll effectiveness describes the relation between the decrease of lateral velocity Δv_y (due to the lateral deceleration) and the building up of a roll angle $\Delta\varphi_x$.

Taking into account that the transformation from E_{kin} to E_{rot} is caused by the lateral forces (represented by a_y) and presuming that e_{roll} determines how these lateral forces contribute to a roll movement in that situation, together with v_y (indicating how much kinetic energy is left to be transformed into rotational energy) a deployment criterion can be defined as follows:

$$a_y > a_{y,crit} = f\left(e_{roll}, v_y\right)$$

Figure 3 shows an exemplary embodiment of the Equation above corresponding to the calibration for a generic sedan. The rollover and non-rollover events are separated by the $a_{y,crit}$-surface in the

(e_{roll}, v_y, a_y)-plane. If the vehicle's lateral velocity is below the critical sliding velocity (CSV), the deployment is inhibited by an asymptotic threshold for the lateral acceleration. A similar situation occurs if the roll effectiveness is zero (e.g. during a side crash). In the case of a high lateral velocity and a high roll effectiveness, the deployment threshold converges to the static stability factor (SSF) of the vehicle.

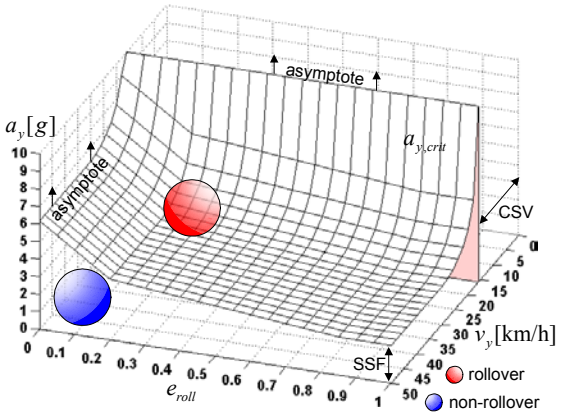

Figure 3. Illustration of an advanced rollover sensing and deployment criterion

ESTIMATION OF THE VEHICLE'S LATERAL VELOCITY

Having a rollover criterion incorporating the lateral velocity v_y leads to the need to calculate v_y during all driving situations. Based on vehicle dynamics formulas this can be achieved by using the following signals:

1. Yaw rate
2. Lateral acceleration
3. Steering angle
4. Longitudinal vehicle velocity
5. Longitudinal acceleration

All of these signals except the last one are available in vehicles equipped with a Vehicle Dynamics Control system, such as ESP. While the first three signals are provided from sensors dedicated to the ESP function, the longitudinal vehicle velocity is an estimate that the ESP system calculates by means of a model-based approach that incorporates information from all ESP sensors including the wheel speed sensors.

ROLLOVER TESTS TO VALIDATE THE SYSTEM PERFORMANCE

To validate the performance and robustness of this new approach, a realistic rollover test setup is necessary. A test setup that does not only cover the rollover phase alone, but also the pre-roll phase.

Established rollover crash tests

Today several rollover crash test setups are established for different purposes: to analyse the stability of the vehicle's structure, to analyse the biomechanical loads on the occupants and to develop and test deployment algorithms for rollover protection systems like curtain airbags. Using these tests, different aspects of real-world rollovers can be considered.

Figure 4 gives a simplified view of the motion sequences of interest. The triggering is the first crucial event. When a rollover occurs, the car can either tilt to the side only or run into one or even multiple rolls. With regard to occupant protection it is of interest how the car is damaged and how the occupants move, receive impacts and sustain injuries during the rollover.

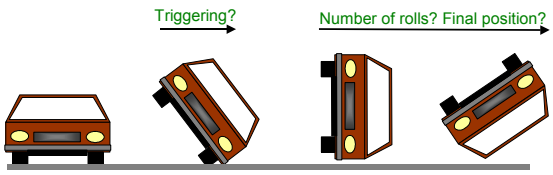

Figure 4. Points of interest to describe rollover kinematics

For the calibration of conventional rollover protection systems as well as for the evaluation of their robustness, tests are carried out in the transition zone between "roll-events" and "no-roll-events". The boundary between these two events helps to find the optimum compromise between performance and robustness.

In order to cover as many real world rollover situations as possible, several rollover crash tests are in use today (for example: Embankment rollover tests, corkscrew rollover tests, curb-trip rollover tests and sand-pit rollover tests, see Figures 5 to 8.)

The only rollover test procedure, which is regulated by law so far is the so-called "FMVSS-208 rollover test", Figure 9. In this test, a car is inclined under 23° on a sled. Test velocity is 49 kph.

Dekra and Bosch as well as other suppliers have been using all of these tests for many years [3, 4, 5].

Figure 5. Embankment rollover test

Figure 6. Corkscrew rollover test

Figure 7. Curb-trip rollover test

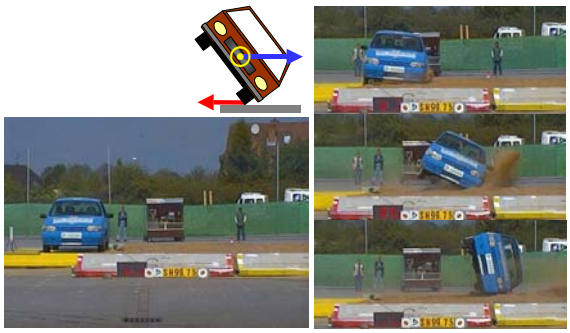

Figure 8. Sand-pit rollover test

Figure 9. FMVSS-208 rollover test

New rollover test setup and procedure

Although the above mentioned tests cover a wide range of rollover aspects, none of these tests is able to address the vehicle's skidding behaviour prior to a real-world soil-trip rollover. Since the advanced rollover sensing approach described above is dedicated to analyse the vehicle's behaviour not only during the roll-phase but already in the critical driving situation leading to the rollover, a new test setup was necessary.

The goal of Dekra and Bosch was to develop a test addressing the driving dynamics in the pre-rollover phase in a realistic and reproducible way as well as the rollover event itself. This new set up has been validated by a roll test, a non-roll test and several reproducibility tests to analyse the repeatability of the vehicle's kinematics.

<u>Test vehicle</u>

The tests presented in this paper were carried out with an SUV-type Opel Monterey RS 3.2 (see Figure 10.) with Electronic Stability Control system. The overall length of this vehicle was 4.330 mm. It was 1.835 mm wide and 1.825 mm high. The wheelbase

was 2.320 mm and the wheel track 1.410 mm (front wheels), respectively 1.462 mm (rear wheels).

Figure 10. Test vehicle Opel Monterey RS 3,2

The fuel tank of the vehicle was filled up to 10% of its volume. 196 kg of additional load (measurement equipment, etc.) was fixed in the trunk area and on the rear seats. The wheel loads of the fully equipped car (without dummies) are shown in Table 1. The total weight was 2,094 kg. The distance between the vehicle's centre of gravity (without dummies) and the front axle was 1,205 mm. All four wheels were equipped with General Tyre XP 200, Dimension 245/70 R16. The tread depth was 1.5 mm. The tyre pressure was 2.3 bar for the front wheels and 3.0 bar for the rear wheels.

The test vehicle was equipped with a yaw-, pitch- and roll-rate sensor (IMAR sensor) near to the centre of gravity, see Figure 11. Tri-axial acceleration sensors (x, y, z) were installed at the foot of the B-pillars. Additional unidirectional low-g and high-g acceleration sensors were installed at the housing of the IMAR sensor .

Table 1.
Wheel loads of the test vehicle (without dummies)

	tire left [kg]	tire right [kg]	axle [kg]
front	494	512	1,006
rear	538	550	1,088

Figure 11. IMAR sensor near the centre of gravity

The occupants of the vehicle were represented by two 50th percentile male Hybrid-III dummies. Both dummies were belted in position in the driver and passenger seat, Figure 12. Since the test was mainly dedicated to observe the vehicle's behaviour, no dummy loads have been measured. However, to indicate direct contacts of the dummy's body parts with the interior of the car, colour paintings were put at the head, shoulders, arms and upper legs.

Figure 12. Dummies for driver and passenger

Test setup and vehicle path

The test setup comprises three different phases:
A guided acceleration phase, a skidding phase and a rollover phase. In the first phase the vehicle is guided by an optically controlled steering system at a distance of 250 meters. The vehicle is guided into

straight forward direction while accelerating by its own engine to the predefined velocity. With this velocity the test vehicle enters the second phase of the test setup: the skidding area. In this area the ground is prepared to offer specific high/low-friction conditions. The low-friction conditions are achieved by using synthetic foils which had been watered, see Figure 13.

As the vehicle enters the low-friction area, the vehicle's front wheels are steered rightwards to the maximum possible steering angle as fast as possible. As a result of the steering manoeuvre the vehicle turns slightly to the right with a superimposed yaw motion. In the next step the right front wheel passes the high-friction part of the ground for a short distance. This helps to further increase the yaw motion with the vehicle hurling. At the end of the low friction area the vehicle enters the third phase of the test setup, a sand pit. The vehicle enters the sand pit with a yaw angle of approx. 40 °.

A top view of this motion sequence is given with Figure 14. Figure 15 illustrates the rollover occurring in the sand pit from a side view perspective.

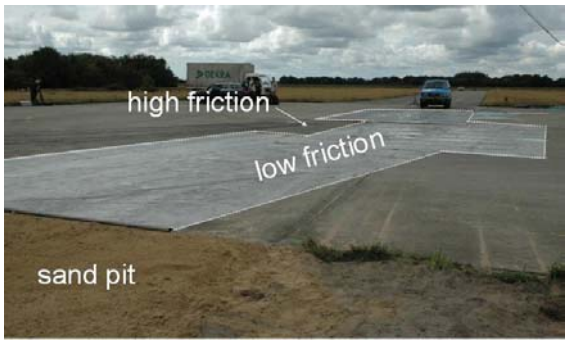

Figure 13. Test vehicle reaching the special prepared part of the test ground

With this motion path of the vehicle prior to the rollover and with the characteristics of the sand pit, the requirements for a realistic rollover crash test scenario have been met. Before the rollover, the vehicle trajectory is similar to a driving situation in a curve in which the vehicle is not following the turn line intended by the driver. After entering the soil the vehicle shows a relatively slow roll motion onto the side and roof which is typical for a rollover in soil. There was also a movement of the vehicle in forward direction when the rollover began.

Figure 14. Movement of the test vehicle on a special prepared part of the test ground into a sand pit (rollover test)

Figure 15. Rollover of the test vehicle on the sand pit

Figure 16 shows the vehicle laying on the roof in final rest position.

Figure 16. Vehicle in final position

Reproducibility aspects

To achieve a good comparability of different test runs and of different vehicles a test setup should ensure a good reproducibility. This aspect was addressed by analyzing the vehicle's trajectories in four test runs. These reproducibility tests were carried out using the same test vehicle.

Figure 17 shows the trajectories of a target point on the roof representing the vehicle's centre of gravity. The trajectories of all four tests are close together. The velocity of the test vehicle at the reference point entering the skidding area was in a range of v = 55.0 – 55.6 km/h with a side-slip angle β = 0°. At the reference line which represents the border of a sand pit, the velocity of the vehicle was in the range v = 44.5 – 48.7 km/h, and the side-slip angle in a range of β = 31° - 40°.

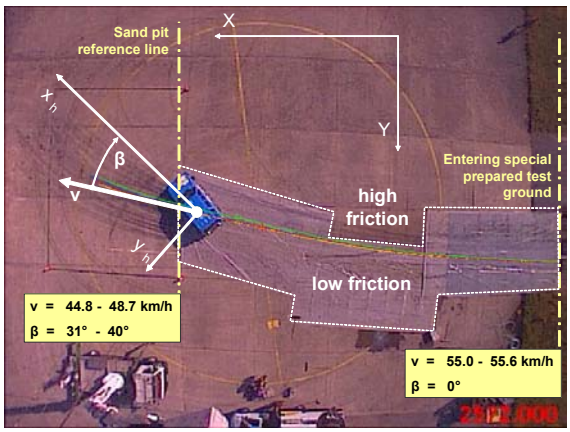

Figure 17. Reproducibility tests analyzing the vehicle's movement prior to rollover

Measurements taken at the vehicle

<u>Rollover</u>

The final rollover test was performed with the vehicle reaching the sand pit at a velocity of v = 41.8 km/h with a side-slip angle β = 39°. Figure 18 shows the signals of the roll rate, the pitch rate and the yaw rate sensor for this test with the vehicle rolled over onto the roof. These signals have been measured with the IMAR Sensor, and filter class CFC 60 was used.

The yaw rate begins to increase shortly after the vehicle enters the skidding area (defined as t = 0.0 s). As the right front wheel reaches the high-friction area (t = 0.2 s). This is due to the fact that a yaw force is induced by the high steering angle of the front wheel when entering the high-friction area. The yaw rate starts to increase strongly here and reaches its maximum of 59 °/s at t = 2.56 s as the vehicle's right front wheel digs into the sand. At this point of time the yaw rate decreases down to 25 °/s (t = 3.1 s) and increases again up to 41 °/s (t = 3.4 s). This is followed by an abrupt inversion to -30 °/s at t = 3.6 s. Finally the yaw rate increases again and comes to zero as the vehicle reaches its final position.

Both pitch rate and roll rate oscillate near zero until the sand pit is reached (at t = 2.4 s). There the pitch rate decreases down to –66 °/s (t = 3.4 s) and drops abruptly back near to zero. The roll rate decreases down to –148 °/s (t = 3.2 s) followed by a relatively smooth changeover into a steep increase to –70 °/s (t = 3.45 s). After that it takes several seconds until the roll movements of the car come to an end and the roll is zero.

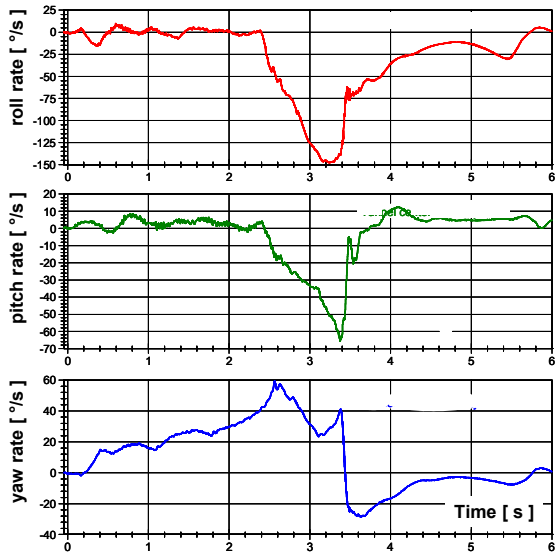

Figure 18. Time histories of roll rate, pitch rate and yaw rate for the rollover test.

The results of the integration of the signals are shown in Figure 19, which demonstrates the roll angle, the pitch angle and the yaw angle. Corresponding to the characteristics of the appropriate rates of angle velocity, the yaw angle began to increase while the vehicle was entering the special prepared test ground with the inclination of the steering angle of the front wheels to the right and reached a maximum of 90 °at t = 3.4 s. Pitch and roll angle remained at zero until the vehicle reached the sandpit (t = 2.4 s). Subsequently, the pitch angle decreased to -45 ° (t = 3.9 s) and the roll angle decreased to -171 ° (t = 6.5 s).

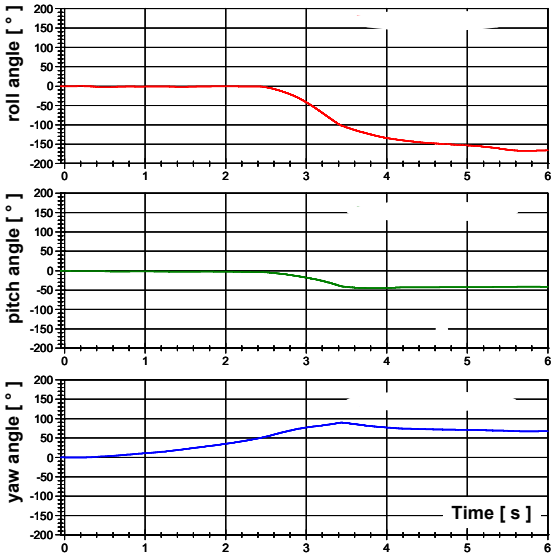

Figure 19. Time histories of roll angle, pitch angle and yaw angle for the rollover test.

No-roll event

Prior to the final rollover test and after the reproducibility tests, a dedicated no-roll test was performed using the same test setup with different friction conditions. This test was performed to find out test parameters for a non-deployment test. The starting velocity of the vehicle was 54.5 km/h. At the point where the vehicle entered the sand pit, the velocity was 42.5 km/h. While entering the sand pit the side-slip angle was $\beta = 22°$. This is 17° less than for the rollover test. Due to the lower side-slip angle the car did not come to a complete rollover.

Figure 20 shows the top view of the test vehicle's movement on the skidding area until it enters the sand pit. The no-roll event of the vehicle on the sand pit is illustrated by a side view to the scene in Figure 21.

In Figure 22 the time histories of the roll rate, the pitch rate and the yaw rate are shown as measured by the IMAR Sensor and filtered with class CFC 60.

It can be seen that the yaw moment induced by the high friction area (t=0,2s) is lower than in the roll-test. This is correlated to a higher friction coefficient at the low-friction area. So the transition of the inclined front wheel from low friction to high friction did not induce such a high increase of the yaw rate as it was the case for the final rollover test. Thereby also the yaw angle with which the vehicle enters the sand pit is affected positively. Most decisive for the roll behaviour, however, is the roll rate. It reaches a maximum of 32°/s at t=2,2s indicating that the rotational energy is not high enough to make the vehicle roll over. The vehicle reaches a maximum roll angle of approx. 20° and than falls back onto the wheels.

From this test is can be shown that a definition of roll and no-roll events can easily be achieved by changing the friction conditions, without the need to change the general test setup.

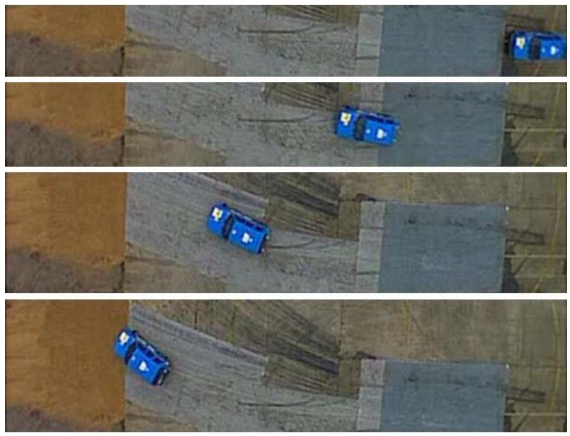

Figure 20. Movement of the test vehicle on a special prepared part of the test ground into a sand pit (no-roll event)

Figure 21. No-roll event of the test vehicle on the sand pit

The roll angle, pitch angle and yaw angle as results of an integration of the signals shown in Figure 22 are demonstrated in Figure 23.

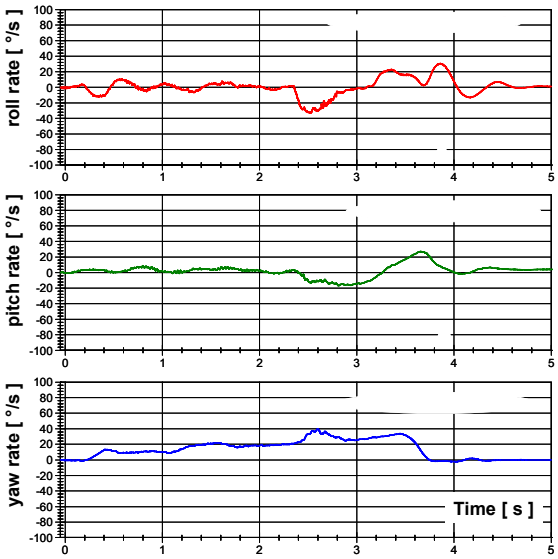

Figure 22. Time histories of roll rate, pitch rate and yaw rate for the no-roll event on the sandpit.

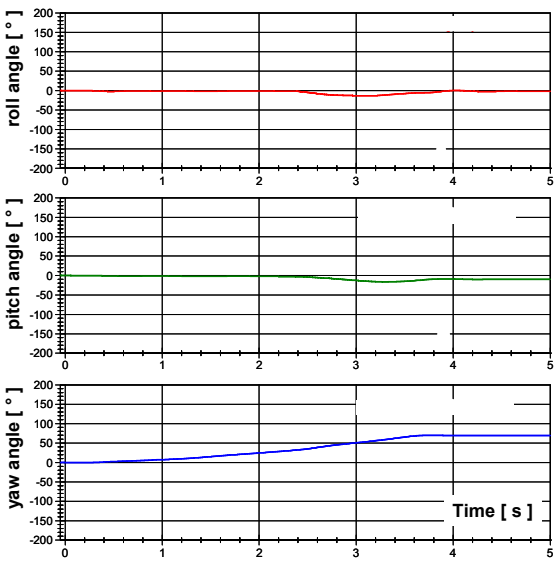

Figure 23. Time histories of roll angle, pitch angle and yaw angle for the non-roll event.

BENEFITS OF THE NEW ROLLOVER TEST SETUP

With the new rollover test setup it is possible for the first time to simulate soil trip rollover situations under a realistic circumstances. With this setup not only the rollover phase on a sandpit but also the skidding phase before the vehicle passes into the soil is covered. Thereby, advanced rollover sensing systems can be tested in a realistic and comprehensive way. The test setup is easy to accomplish and delivers reproducible results. For this reasons Bosch has added this test to list of it's final validation tests for the new Bosch advanced rollover sensing system which started in to series production in 2006.

SUMMARY

A significant improvement of occupant safety during tripped rollovers can be achieved by incorporating information about the vehicle's driving state before the rollover crash into the rollover sensing system. By estimating the vehicle's lateral velocity, important information can be gained to better judge a rollover risk and come to a reliable deployment decision on the basis of the lateral acceleration, roll rate and roll angle. This enables the advanced rollover systems to make a deployment decision for restraint devices more quickly while increasing the robustness against misuses.

To calibrate such advanced rollover sensing systems and to test their robustness a new kind of rollover test has been developed. In contrast to existing rollover tests this new test incorporates not only the roll phase of the vehicle but also the pre-roll phase. The new test setup shows a good reproducibility. The test setup offers parameters allowing for an easy pre-definition of roll- and no-roll events.

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