EFFECTIVENESS EVALUATION OF ANTILOCK BRAKE SYSTEMS (ABS) FOR MOTORCYCLES IN REAL-WORLD ACCIDENT SCENARIOS

Dr. Georg Roll
Oliver Hoffmann
Continental AG, Division Chassis & Safety
Germany
Jens König
DEKRA Automobil GmbH
Germany
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ABSTRACT

Although motorcycle ABS is meanwhile well established on the public market, detailed investigations about the relationship between crash scenarios and the effectiveness of motorcycle-ABS are rare.
Within the EC-funded SIM Project (Safety In Motion) a detailed analysis of different accident scenarios with PTWs (Powered Two Wheelers) has been performed, using the DEKRA PTW-database. The basis of this data pool is the accumulation of written expert opinions containing the accident analyses that are drawn up by skilled forensic experts throughout Germany. From this database containing 350 real-world accidents, 51 cases have been selected by imposing a reaction demand and a following braking of the motorcycle rider in order to evaluate the benefit of advanced brake control systems. The following parameters have been extracted for the evaluation:

- Collision speed and initial speed
- Distance of falling location to collision point
- Braking distance
- Median braking deceleration
- Starting point of breaking
- Reaction point/demand
- Kind of reaction
- Road surface
- Weather

With this information several real accident scenarios without ABS were analysed under the condition that an ABS system would have been installed on the motorbike. With such an approach the difference in the accident consequences with and without ABS can be observed. In addition a variation in the ABS control has been accomplished by considering different brake control systems developed by CONTI, like partial and full integral brake systems as well as systems with advanced driver-assistance functions (ADAS). As a result, a tremendous reduction in the accident consequences can be shown, for example up to 50% of the selected accidents could have been avoided by a simple 2 channel ABS.

INTRODUCTION

Within the EC-funded SIM Project (Safety In Motion) active and passive safety components are studied in PTWs (Powered Two Wheelers) to demonstrate possible improvements in accident avoidance and mitigation.
In order to evaluate the possible benefits of CONTI active safety components, especially ABS, but also integral-brake, brake-assist and advanced driver-assist systems (ADAS), several real accident cases provided by DEKRA were studied. The fundamental basis of the DEKRA accident databases is the accumulation of written expert opinions containing the accident analyses that are drawn up by skilled forensic experts at the DEKRA branches throughout Germany and totalling about 28,000 annually. The particular feature of these reports is that normally the experts are called by the police or prosecuting attorney to come to the accident scene directly after the accident happened. The DEKRA experts operate all over Germany on a 24hour/7day week basis. Consequently, the nearly 500 DEKRA accident experts have the opportunity to acquire all the information necessary for their task. The reports provide a substantial basis for accident research work. The DEKRA Accident Research department has the opportunity to select and analyse interesting cases, which normally consist of the written expert opinions, detailed accident reconstructions, sketches and photo material. The actual DEKRA PTW database comprises 350 cases from 1996 to 2007 with all kinds of other vehicles as well as single PTW accidents. About 300 parameters per accident are reviewed when using the DEKRA questionnaires. Since expert opinions are normally commissioned only

when the accident is of a really serious nature, the main focus of the PTW database is directed towards accidents resulting in severely- or fatally injured persons. These accidents happen mostly in rural areas and involve elevated driving speeds.

In each accident case, one PTW is involved. In almost all cases the reason for the accident seems to be, that a car driver couldn't estimate the speed of the PTW correctly or didn't recognise the PTW in time.
In several cases we can watch the standard situation, where a car driver intends to drive a U-turn without taking notice of a PTW approaching from behind.
As an example of this, fig. 1 shows an original crash photo and fig. 2 an according sketch of the whole accident situation, both provided by DEKRA accident database.

Figure 1. Crash photo of PTW and U-turning car (DEKRA accident database)

Another class of severe accident situations results from car drivers turning into a road without giving way to PTWs driving on this road with considerable speed.
In all these collision cases, the speed of the involved car is rather low, and the severity of the impact just depends on the speed of the PTW, which usually crashes into the car.
Normally the speed of the PTWs was not above the allowed speed limit, so that the PTW drivers behaved correctly.
On the contrary the accidents were in almost all cases caused by the erroneous behaviour of the involved car drivers, who were not able to evaluate the traffic situation properly.

Nevertheless the severe injuries and big damages result from the low medium deceleration of the PTWs, as we can learn from the accident database.

In about 43% of the studied cases, the braked PTW gets unstable (due to overbraking) and hits the ground before the collision with the car occurs.

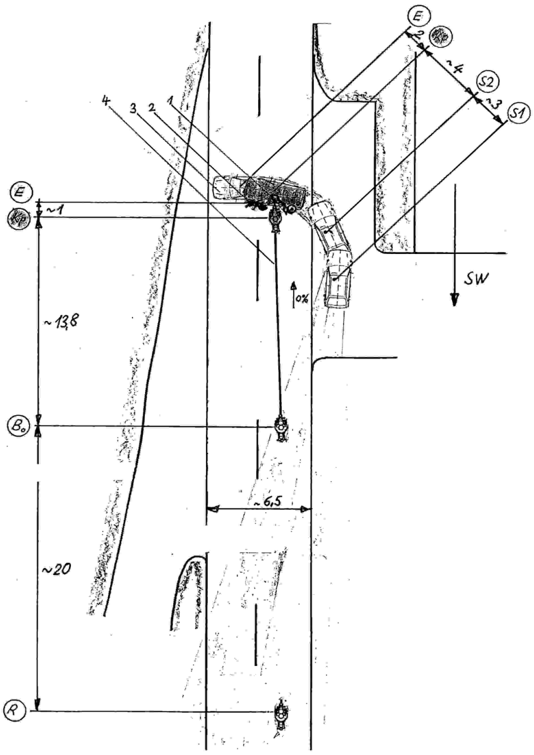

Figure 2. Sketch of the accident situation of figure 1 (DEKRA accident database)

The task of the CONTI investigation described on the following pages is to make an estimation, in which way the effects of all those real accidents could have been mitigated with the help of different electronic brake control systems.

Electronic brake-control devices for collision mitigation

First of all, even a standard ABS should reduce the effects of PTW accidents considerably, providing braking stability for the PTWs on one hand, so that falls can be avoided and the PTWs remain in a manoeuvrable state, and on the other hand increasing braking deceleration due to adjusting operating points just near the friction optimum.
Furthermore, a so-called integral brake can be very much of help in case of panic braking. A PTW driver may focus only on one brake lever during an emergency case, because he is shocked by the suddenness of the situation. It may be impossible then to manage two separate brake levers in an adequate manner simultaneously. In those cases the integral brake adjusts balanced pressure amounts to both wheels, even if the driver

applies only one brake lever.
In addition, a brake-assist function can improve the first pressure build-up time interval just after the first reaction of the PTW driver, which results in applying the brake(s) with a high pressure increase gradient. It's very important then to reach the optimal braking point in short time, in order to achieve the shortest possible braking distance. But investigations of panic-brake situations show us, that a normal driver indeed applies the brake with a high gradient but often releases it a little before the locking pressure of the wheel is reached. The brake-assist function recognises those patterns of behaviour and applies the maximum pressure to the wheels, so that the hesitation of a driver is compensated.
Another class of assist-functions is based on environmental sensors, such as infrared, radar and cameras. With the help of those sensors a critical situation may be recognised just at the beginning and valuable reaction time may be saved. Within a few ms the central computer of the assistance system can make a decision how to react properly and may warn the driver and/or get active without any driver request. In order to avoid driver irritations and due to legal restrictions, the system should not perform full braking, but can reduce gas and pre-fill the brakes in time, which may lead to a vehicle deceleration of about 0.3g. This action shows a lot of benefits. First, the vehicle speed is already slightly reduced, when the driver decides to brake. Secondly, the driver gets sooner aware of the severity of the situation, and additionally, the brakes are already pre-filled when the driver takes over, so that the first pressure increase goes much faster.

Data from DEKRA accident database

The accidents described in the DEKRA database are documented with the help of the following data, which had been evaluated by police and crash experts with the help of situation reconstruction methods, such as measuring brake traces and scratches on the road surface:

1. Distance between "obstacle in sight" (reaction demand) and the later collision location:
This is the distance between the PTW and the later collision location, when the PTW driver first recognises that a problem occurs and he is forced to react.

2. Distance between "start of braking" and the later collision location:
This is the distance between the PTW and the later collision location, when the PTW driver has already applied at least one brake, that means at this point the brake is already filled (visible brake traces on the road start at this point).
Unfortunately, from these data we do not know exactly, where and when the driver first started to apply the brake and in which way he applied it. At the first point, he was forced to make a decision and to react, and at the second point, the reaction time interval is already finished.
Between these two points, no vehicle deceleration is considered, although the driver started to apply the brake in that interval. Due to the fact, that we do not know the braking behaviour of the PTW driver exactly, this simplification is unavoidable.

3. Initial speed:
This is the speed of the PTW at the first and still at the second distance point, because no vehicle deceleration is considered in the interval between the two points.

4. Collision speed:
This is the speed with which the PTW crashes into the collision partner.

5. Falling distance:
This is the distance between the falling location and the later collision location.

6. Braking deceleration:
This is the median vehicle deceleration, which occurs between the "start of braking location" (point 2) and the collision or the fall location (if a fall happens).

As further information the road surface type (asphalt or other), weather conditions and the lighting were taken into account.

With the help of the distances and vehicle speed amounts, time diagrams can be created with corresponding time steps and time intervals.
Fig. 3 shows such a time diagram consisting of two parts, where the upper part presents the vehicle velocity and the lower part the wheel brake pressures as functions of the time.

The time step t_obstacle_in_sight corresponds with point 1, time step t_brakes_filled with point 2. Additionally the reaction time step t_reaction is shown, which defines the start of the brake application. This time step is not defined directly in the database, but can only be estimated from other database information.
Normally this time step occurs 0.3 up to 0.5s before the time step 2, where full braking is already in steady state.
For the following calculations, a medium time interval of 0.4s is assumed as time distance

between t_reaction and t_brakes_filled for all studied accident cases.

In fig. 3 three distances are defined, which in sum yield the full stopping distance s (equal to point 1). The distances are the reaction distance s_react, which the PTW passes through without any braking action of the driver, the filling distance s_fill, which the PTW passes through during driver reaction until the brake(s) are filled, and the brake distance s_brake, which the PTW passes through during full braking or sliding (in case of a fall) until the crash occurs.

Normal PTW braking without support of electronic brake components

Furthermore, fig. 3 shows as examples two typical patterns of behaviour of PTW-drivers in panic.

The first one leads to the situation the result of which is shown with the dashed signal lines. The driver first applies the front-wheel brake with high pressure increase gradient, then hesitates a little, and afterwards applies too much brake pressure, which forces the front wheel to locking. The PTW gets unstable, hits the ground and slides towards the crash partner. Although the hard brake application leads to good deceleration results in the first braking interval, the overall deceleration is rather low due to the occurring fall and the sliding.

The second braking behaviour shown in fig. 3 with the continuous signal lines is similar to the first one, but instead of overbraking the PTW, the driver being aware of the danger of wheel locking shows a more careful and hesitating braking behaviour, which leads to a clear underbraking with a bad overall deceleration result [1].

Therefore, in both cases the collision speed is rather high.

The most important problem of braking a PTW with high deceleration is the fact, that a locking front wheel leads to an unavoidable fall in almost all cases. Even if a driver is very much used to full braking and knows his PTW behaviour quite well, it won't be easy for him to find an optimal operating point abruptly in case of a panic situation. This is due to the fact that the wheel-locking pressure level varies considerably with the wheel load (violet lines P_fw_lock in fig. 3), which again is highly depending on the dynamic behaviour of the PTW. So the locking pressure is rather low at first, when the driver performs an extremely hard front-brake application, because almost all PTWs need about 300ms to get the maximum load on the front wheel. Afterwards this full amount of load is reduced regarding to a certain characteristic, which is installed by the spring and damper adjustments. After about 800ms the PTW is in steady state and the locking level remains on a constant value, presumed that the friction between tire and road surface remains constant too. But this friction is also a complex function of several parameters, which cannot be evaluated properly while acting in panic.

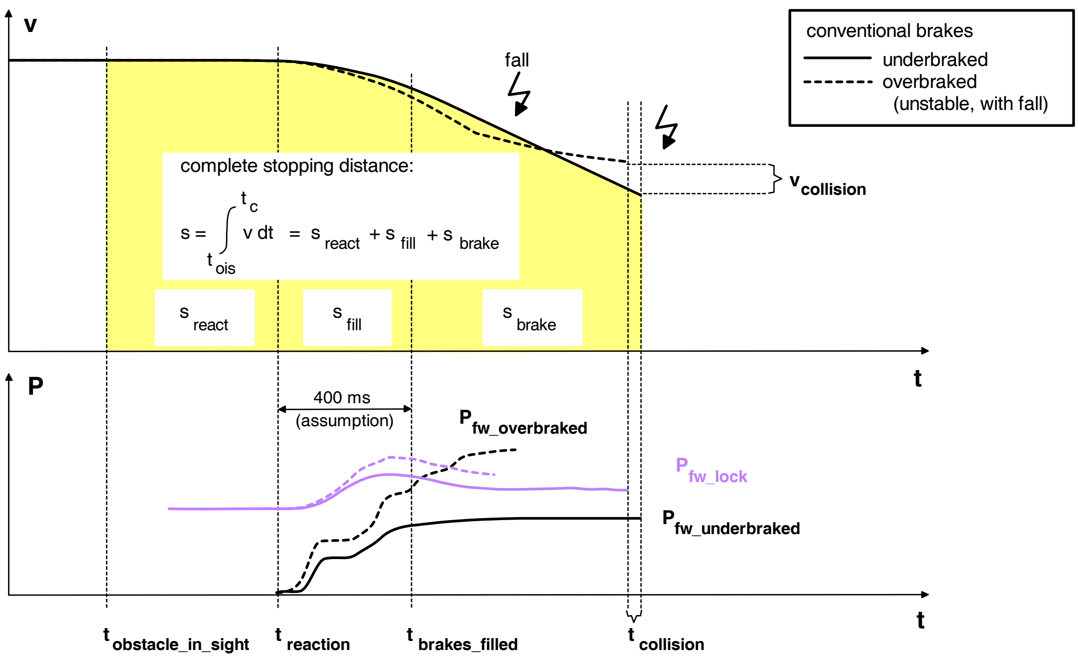

Figure 3. Time diagram of a panic-braking situation without electronic brake control

PTW braking with an ABS control device

Therefore, one of the most important advantages of ABS is that the driver may fully apply the brake levers and can absolutely rely on the optimal slip control with a highly reduced risk of getting unstable. Hesitating and careful braking is no longer necessary. ABS will always limit the wheel pressures to values just below the respective locking pressure line, which is shown in the example of fig. 4. Here, the same dangerous braking situation is presented as in fig. 3, but the braking PTW is assumed to be equipped with ABS. The two lines P_fw_lock (violet) and P_rw_lock (pink) represent the locking-pressure levels of the front and the rear wheel during the braking manoeuvre. The load of the PTW is dynamically transferred from rear to front wheel. With the help of the pressure decrease and increase patterns ABS is always trying to find the wheel-pressure optimum, which is recognised by wheel slip and acceleration observation (recognition mechanism not shown in fig. 4).
In order to demonstrate the benefits of ABS based on the DEKRA accident data, the following assumptions were made (see fig. 4):
In all cases the driver of the respective PTW is considered to behave different now, because he can rely on his electronic brake control system. So it is assumed that he will apply the brake levers harder with the result of filling at least the front brake in just 300ms (compared to the assumed 400ms without ABS).

Unfortunately, another uncertainty has now to be dealt with. Due to the two separated brake actuation levers, we do not know exactly, how the respective driver would have behaved concerning the succession of applying the brake levers.

Therefore, we have to consider three different scenarios:
1. The driver may be extremely shocked by the situation, so that he activates only the front brake. In this case, we assume that the possible vehicle deceleration is not higher than 0.8g.
2. The driver first activates only the front brake and after a short time interval applies the rear brake additionally, so that a medium deceleration of 0.9g is reached in case of highest road friction.
3. The driver is at once fully aware of his brake actuations and applies both levers in parallel. In this case the maximum deceleration is assumed to 1g.

These maximum deceleration values have now to be corrected (reduced) with the help of the road surface and weather information provided by the DEKRA database, because only a dry and warm asphalt or concrete surface enables the PTW to make use of these theoretical values.

The following reductions were considered and taken for the calculation:
1. 95% of the values in case of darkness or cloudy sky.

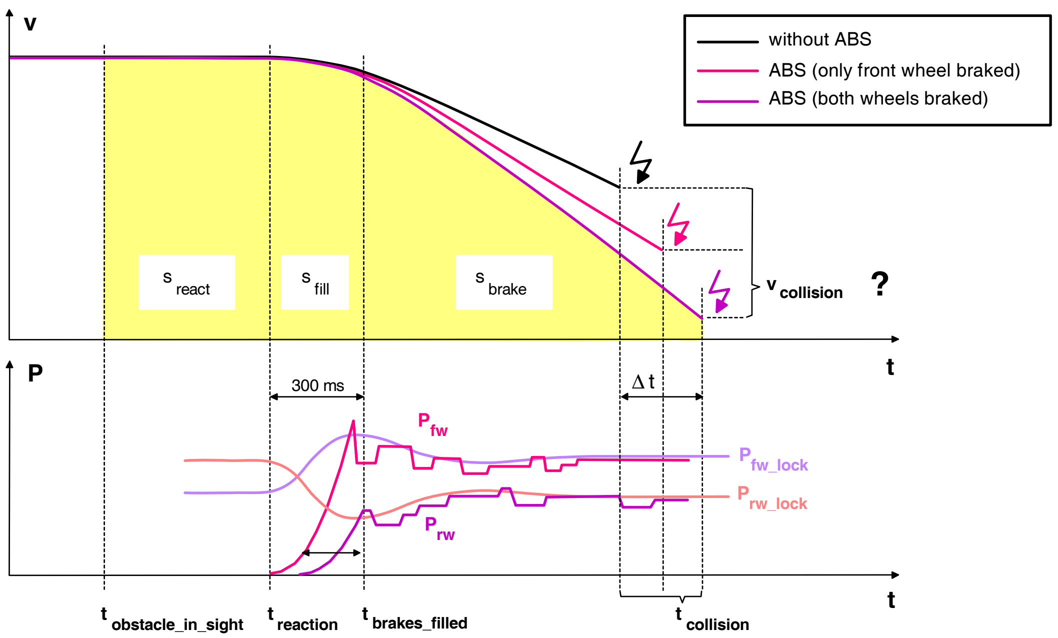

Figure 4. Time diagram of a panic-braking situation with ABS control

2. 90% of the values in case of a wet asphalt surface without heavy rain.
3. 80% of the values in case of heavy rain.
4. 90% of the result in case of slight, 75% in case of considerable and 60% in case of extreme curve braking

Because no other road surfaces and manoeuvres occur in the 51 studied cases and nothing is said about road inclinations, no other reductions had to be made.
Nevertheless it should be mentioned that the deceleration values in reality highly depend on certain technical conditions of the PTW. First of all, good brakes and tires are the most important pre-conditions for maximum braking deceleration. Other devices, like dampers and springs with well adjusted characteristics are very much of help to exploit the maximum friction between tires and road surface. Therefore, networking of electronic control devices can be helpful to make adjustments dynamically according to the respective situation.
With properly working brakes, tires and chassis components more than 10 m/s^2 of braking deceleration are possible on dry asphalt, so that the assumptions made here are in no way too optimistic.

Based on the above assumptions and considering constant circumstances, the following simple calculations can be made to get the expected collision speed and other relevant data for a PTW equipped with properly working ABS:

Available distance for full braking:

$$s\_brake_{ABS} = s\_brake + (0.1s * v\_initial)$$

The values for s_brake and v_initial are the original values from the database.
The 0.1s result from the assumption that the driver will perform a harder brake application with ABS and therefore save at least 0.1s to fill the brake. So the full braking starts 0.1s earlier.
An important remark is necessary here concerning the initial speed of full braking. Strictly speaking, in case of a fast brake application the initial speed would be a little higher than after a slow brake-pressure increase. But in the estimation, this effect can be neglected due to the fact, that without ABS the driver will normally not be able to reach an optimal braking point at all. Due to this effect, an overall time benefit of 0.1s with equal initial speed seems to be realistic when using ABS.

The needed distance for full braking with the above assumed constant deceleration is:

$$s\_brake\_needed_{ABS} = ½ * (v\_initial)^2 / a\_brake_{ABS}$$

If the needed distance $s\_brake\_needed_{ABS}$ is lower than the available distance s_brake_{ABS} no collision would have occurred. Otherwise the collision speed would have been

$$v\_collision_{ABS} = sqrt(2 * a\_brake_{ABS} * (s\_brake\_needed_{ABS} - s\_brake_{ABS}))$$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{ABS}$ compared to the situation without ABS:

$$delta\_T\_c_{ABS} = t\_collision_{ABS} - t\_collision$$

$$t\_collision_{ABS} = t\_brakes\_filled - 0.1s + 2 * s\_brake_{ABS} / (v\_initial + v\_collision_{ABS})$$

$$t\_collision = t\_brakes\_filled + 2 * s\_brake / (v\_initial + v\_collision)$$

→

$$delta\_T\_c_{ABS} = - 0.1s + 2 * s\_brake_{ABS} / (v\_initial + v\_collision_{ABS}) - 2 * s\_brake / (v\_initial + v\_collision)$$

In order to get a feeling for the effects of the ABS control, the following example should be looked at (data is based on real accident scenario of DEKRA database):

v_initial = 26 m/s
s_brake = 26 m
v_collision = 19.4 m/s

→

s_brake_{ABS} = 28.6 m
a_brake_{ABS} = 0.9g = 8.83 m/s^2
$s\_brake\_needed_{ABS}$ = 38.28 m
$v\_collision_{ABS}$ = 13 m / s
$delta\_T\_c_{ABS}$ = 0.221 s

So the collision speed would have been reduced by 6.4 m/s, and moreover the driver would have had an additional time interval of 0.221s to react with steering to avoid the obstacle, if possible.
During this time interval a crossing collision partner driving with a speed of 20 kph (5.55 m/s) moves by a distance of 1.23 m, so that it could already be out of way, when the PTW crosses the collision course. This situation is shown by the example in fig. 5.

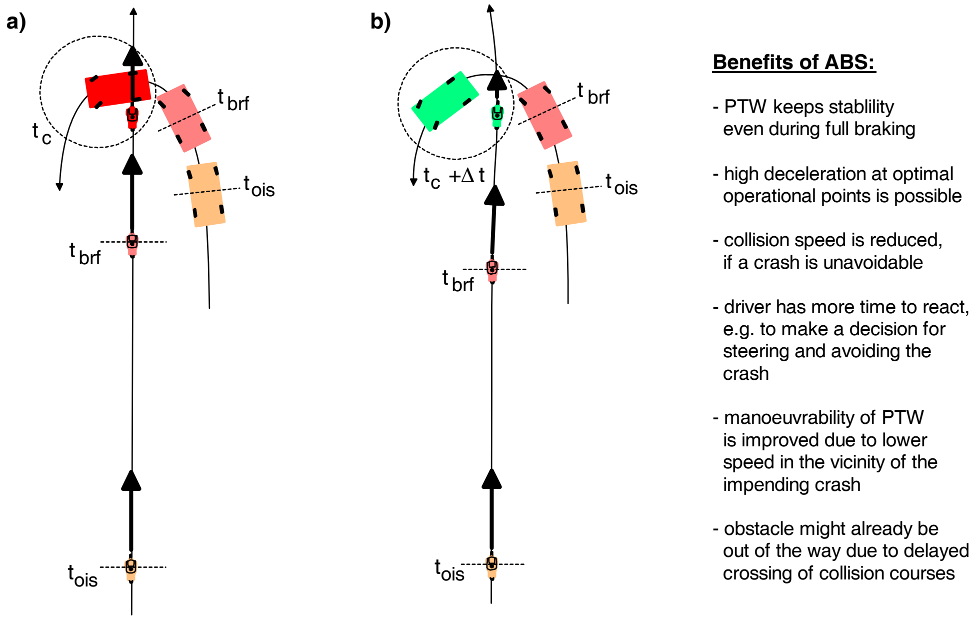

Figure 5. Sketch of a critical driving situation a) with bad, b) with high PTW deceleration

The scenario represents a typical class of severe PTW accidents. A car driver intents to make a U-turn without giving notice to a PTW, which is just going to overtake the car. The corresponding time steps are illustrated by different colours. At time step t_ois (obstacle in sight) the driver of the PTW can first recognise, what the car driver is going to do. So he is forced to react. At time step t_brf (brake filled) he already has reacted with filling the brakes. Time step t_c (collision) represents the time, when the collision actually happens.

As we see from the example, it can be very much of help for the PTW to achieve a brake deceleration, which is just a little increased. The reduced speed in the vicinity of the impending crash location increases the manoeuvrability of the PTW considerably and may enable the driver to avoid the obstacle. Furthermore, he gains an additional time interval delta_T_c $_{ABS}$ (ΔT in fig. 5) for steering action, and the obstacle might have moved already out of the way.

Therefore, it is not sure whether a collision would have happened at all with ABS, even if the theoretical calculation yields a still high collision speed. For this reason the question mark is added to the string “v_collision” in fig. 4.

The benefits resulting from ABS are listed in fig. 5.

PTW braking with ABS control, integral brake and brake-assist function

In the following step the benefits of a so-called integral brake and the brake-assist function are demonstrated (see fig. 6).

When using an integral brake, we can be sure that both wheel-brake circuits will be filled in parallel, so that we always do our calculations with the assumption that a maximum deceleration of 1g is possible on highest friction. For lower friction values, the maximum deceleration is corrected in the same way as above described for the ABS.

The added brake-assist is assumed to have the advantage of filling the brakes always with the highest possible pressure increase gradient. The result shall be a reduced fill time of 200 ms, as shown in fig. 6.

It should be mentioned here, that even shorter pressure increase time intervals are possible with electronic brake devices from CONTI. Due to the adjustment of the orifices of the wheel inlet valves, maximum pressure increase gradients are so high, that the wheel locking-pressure levels can usually be reached within 100ms. But those gradients must be set up by the brake force of the driver and cannot be applied by the ABS pump of the control device alone. For this reason the pressure increase interval is set to the more restrictive value of 200ms. This time interval can be assumed as a medium value, which can be easily achieved by the cooperation of drivers working with medium hand-force and a brake-assist function, which compensates a certain hesitating during the first brake application.

With these assumptions, the following calculation can be done in a similar manner as above:

Available distance for full braking:

$s\_brake_{INT} = s\_brake + (0.2s * v\_initial)$

The values for s_brake and v_initial are the original values from the database.
The 0.2 s result from the assumption that the brake-filling time with the original initial speed is now reached 0.2 s earlier than with the conventional braking.
Needed distance for full braking with the above assumed deceleration:

$s\_brake\_needed_{INT} = ½ * (v\_initial)^2 / a\_brake_{INT}$

If the needed distance $s\_brake\_needed_{INT}$ is lower than the available distance s_brake_{INT} no collision would have occurred. Otherwise the collision speed would have been

$v\_collision_{INT} = sqrt (2 * a\_brake_{INT} * (s\_brake\_needed_{INT} - s\_brake_{INT}))$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{INT}$ compared to the situation without ABS:

$delta\_T\_c_{INT} = t\_collision_{INT} – t\_collision$

$t\_collision_{INT} = t\_brakes\_filled – 0.2s + 2 * s\_brake_{INT} / (v\_initial + v\_collision_{INT})$

$t\_collision = t\_brakes\_filled + 2 * s\_brake / (v\_initial + v\_collision)$

→
$delta\_T\_c_{INT} = -0.2s + 2 * s\_brake_{INT} / (v\_initial + v\_collision_{INT}) – 2 * s\_brake / (v\_initial + v\_collision)$

In order to get a feeling for the effects of the integral brake and brake-assist control, the same example as above is looked at again.

$v\_initial = 26 m/s$
$s\_brake = 26 m$
$v\_collision = 19.4 m/s$

→
$s\_brake_{INT} = 31.2 m$
$a\_brake_{INT} = 1g = 9.81 m/s^2$
$s\_brake\_needed_{INT} = 34.45 m$
$v\_collision_{INT} = 7.99 m / s$
$delta\_T\_c_{INT} = 0.485 s$

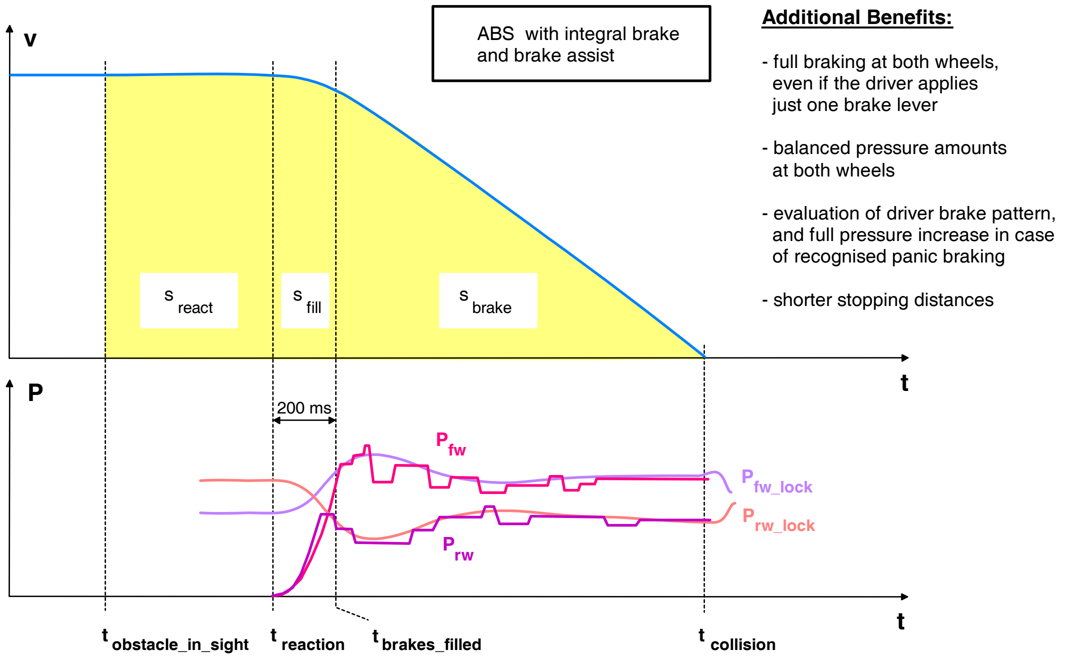

Figure 6.
Time diagram of a panic-braking situation with ABS, brake-assist and integral brake

Even now the collision speed seems to be quite high with about 8 m/s, but we have to take into consideration that it is reduced by 11.4 m/s, what can really be life-saving for the PTW driver. Moreover, the crash, if it had happened at all, would have been delayed by a time interval of 0.485 s. This gives us an idea about the chances of the PTW driver to avoid the collision.
The additional benefits of this system are listed in fig. 6.

PTW braking with ABS control, integral brake, brake-assist and automatic pre-fill function

In the following step the advantages of an advanced driver-assistance system (ADAS) are described. This system is based on environmental sensors and an algorithm for danger calculation. In case of recognising a relevant obstacle, the system is able to pre-fill the brakes actively without any driver intervention (see fig. 7). This normally leads to a maximum deceleration of about 0.3g until the driver takes over and applies the brakes himself.
It is very difficult to make an assumption, when the system could have reacted in the studied accident cases and if the driver would have been aware of the danger a little sooner due to the automatic deceleration.
In order to be able to get a result and an idea of the possibilities at all, the following assumptions were made for each DEKRA case:

- 150 ms after the obstacle occurred, the system gets active and starts filling the brakes.
- It takes another 100 ms to pre-fill the brakes with an amount of pressure, which leads to a medium deceleration of 0.3g until the brakes are filled
- The reaction time of the driver is the same as described in the studied cases.
- With the help of ABS, integral brake and brake-assist, the driver is now able to perform a full brake application in just 120 ms, because the brakes are already pre-filled.

With these assumptions, the following simplified calculation can be done in a similar manner as above:

Available distance for full braking:

$$s\_brake_{ADAS} = s\_brake + (0.28s * v\_initial)$$

Due to the pre-filling and automatic deceleration of 0.3s the initial speed is now reduced, when the driver takes over:

$$v\_initial_{ADAS} = v\_initial - (t\_brakes\_filled - t\_obstacle\_in\_sight - 0.25s) * 0.3g$$

with

$$t\_brakes\_filled - t\_obstacle\_in\_sight = (s\_obstacle\_in\_sight - s\_brake) / v\_initial$$

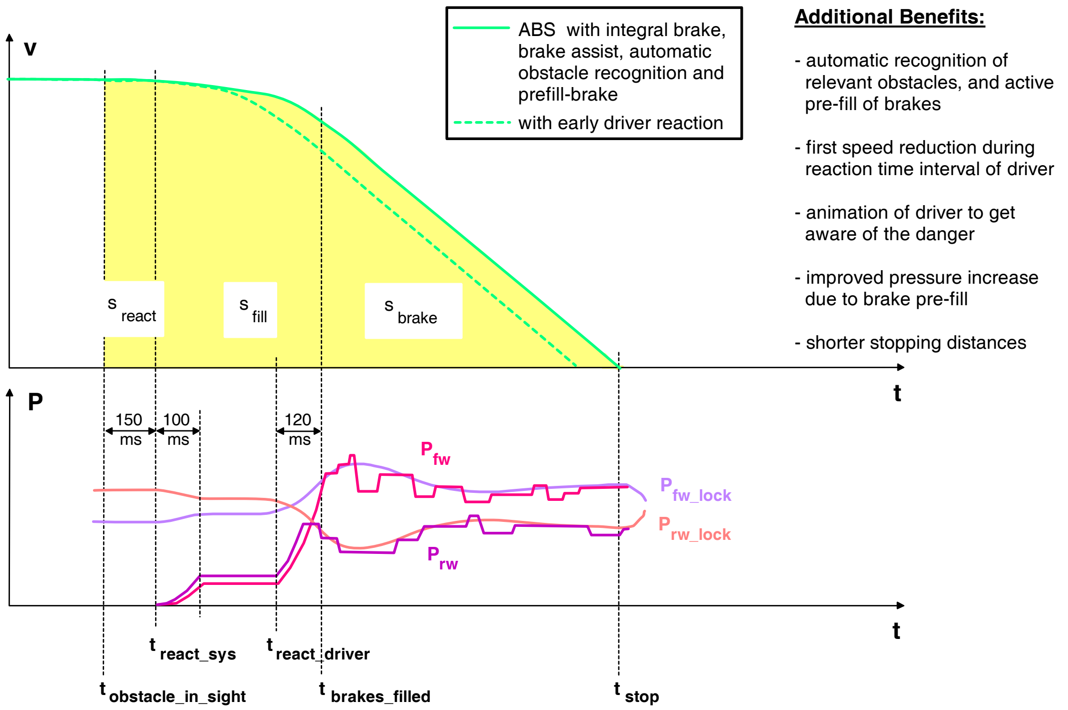

Figure 7. Time diagram of a panic-braking situation with ABS, integral brake and ADAS

The value for s_obstacle_in_sight, s_brake and v_initial are the original values from the database. The 0.28s result from the assumption that the brakes are now fully applied in 0.12s, that means 0.28s earlier than with the conventional braking.

Needed distance for full braking with the above assumed deceleration:

$$s\_brake\_needed_{ADAS} = \frac{1}{2} * (v\_initial_{ADAS})^2 \ / \ a\_brake_{ADAS}$$

If the needed distance $s\_brake\_needed_{ADAS}$ is lower than the available distance s_brake_{ADAS} no collision would have occurred. Otherwise the collision speed would have been

$$v\_collision_{ADAS} = sqrt (2 * a\_brake_{ADAS} * (s\_brake\_needed_{ADAS} - s\_brake_{ADAS}))$$

If a collision had occurred, the time step of the crash would have been delayed by $delta\_T\_c_{ADAS}$ compared to the situation without ABS:

$$delta\_T\_c_{ADAS} = t\_collision_{ADAS} - t\_collision$$

$$t\_collision_{ADAS} = t\_brakes\_filled - 0.28s + 2 * s\_brake_{ADAS} / ((v\_initial_{ADAS} + v\_collision_{ADAS})$$

$$t\_collision = t\_brakes\_filled + 2 * s\_brake / (v\_initial + v\_collision)$$

→

$$delta\_T\_c_{ADAS} = - 0.28s + 2 * s\_brake_{ADAS} / (v\_initial_{ADAS} + v\_collision_{ADAS}) - 2 * s\_brake / (v\_initial + v\_collision)$$

The effects of the system, consisting of ABS, integral brake, brake-assist control, and the driver assistance with automatic brake pre-fill, can be demonstrated with the same example as above:

v_initial = 26 m/s
s_brake = 26 m
v_collision = 19.4 m/s
s_obstacle_in_sight = 52 m

→

$v\_initial_{ADAS}$ = 23.8 m
s_brake_{ADAS} = 33.28 m

a_brake_{ADAS} = 1g = 9.81 m/s^2
$s\_brake\_needed_{ADAS}$ = 28.87 m
$v\_collision_{ADAS}$ = 0 m / s no collision, because $s\_brake\_needed_{ADAS}$ is lower than s_brake_{ADAS}

The additional benefits of this system are listed in fig. 7.
The dashed line is the vehicle speed in case of a very early driver reaction, which may occur in many cases as a result of the pre-braking done by the assistance system. The slight jerk caused by this pre-braking is felt as an indicator for an impending crash situation and can help the driver to come to a quicker decision and braking reaction.

RESULTS

Fig. 8 shows the vehicle velocities for all brake systems described above combined in one comparing time diagram.
When we take into consideration that the area below the respective velocity line is the stopping distance travelled through by the PTW during a dangerous braking manoeuvre, it is easy to imagine, what advantages can result from new electronic brake systems.

The overall result of the above estimation done for 51 DEKRA accident cases is shown in fig. 9 and fig. 10.
In fig. 9 we can see, how many of the 51 studied accidents could have been avoided or highly mitigated with the help of the respective brake system or braking behaviour of the driver.

The black frame bar marks the number of the 51 cases. The coloured bars represent the numbers of collisions, which would have been totally avoided due to the higher braking deceleration with the according brake-control system (first value on the bar). The hatched bars show the numbers of collisions, for which the collision speeds of the PTWs could have been reduced below 8m/s (second value on the bar). In these cases, the energy of the crashes would have been rather low, and moreover, due to the reduced speed and the gained reaction time before the crossing of the collision courses, we can assume, that the driver would really have had a chance to avoid the crash by steering.
In order to get a feeling of the overall effect of the collision speed reduction, fig. 10 may be looked at.
With the help of the described electronic brake control systems the medium collision speeds presented by the bar graph could be reduced considerably.

Even the system with the lowest expenditure, the 2-channel ABS, offers an impressive chance to mitigate the effects of impending crash situations. If the driver is fully aware of these facilities and

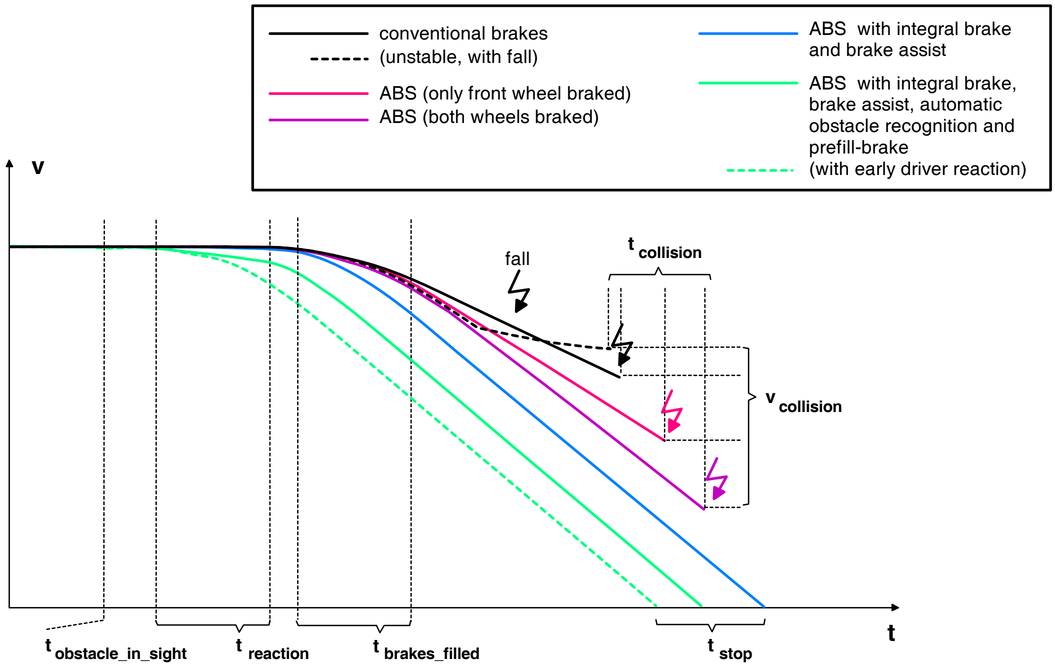

Figure 8. Time diagram of a panic-braking situation with different brake control systems

learns to rely on his anti-lock brakes, he will get used to hard and simultaneous braking with both brake levers. The potential of reducing collision speeds to about 50 or even 40% can already be life-saving and prevent the PTW driver from getting seriously injured, even if the impending crash is unavoidable.

As we know from the laws of physical science, the demolition effect caused by a collision is increased with the kinetic energy of the crash partners in a proportional manner, and the energy itself is increased with the square of the velocity. Therefore, reducing the collision speed to the half amount means reducing the demolition effect to just a quarter of the actual amount.

This means for the 2 channel ABS handled properly by simultaneous braking of both channels, that the medium demolition effects could have been reduced below 20%.

But nevertheless, the most important advantage of reducing the speed of the PTWs is yielded by the fact that the manoeuvrability and steerability of a PTW are highly improved for low velocities. Moreover, the driver gains more time to make a steering decision, because the crossing of the collision courses is delayed due to the higher PTW deceleration.

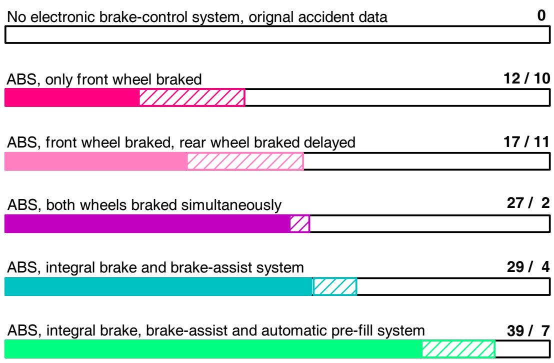

Figure 9. Numbers of accidents avoidable depending on different brake control systems

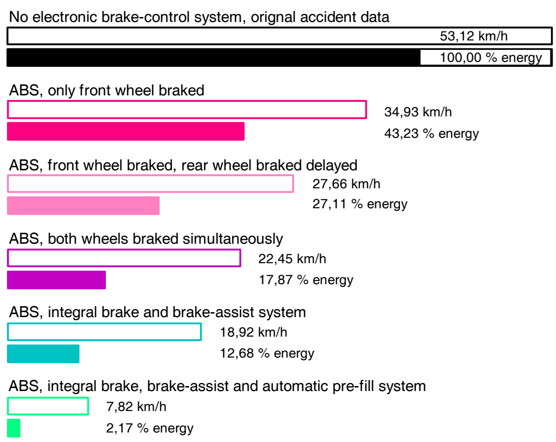

Figure 10. Medium collision speeds and percentile crash energy depending on different brake control systems

CONCLUSION

As we can see from the PTW deceleration data provided by the DEKRA database, most drivers do not use the maximum brake performance due to the fact, that they are aware of the danger of wheel overbraking. The concentration on two brake levers is certainly a big problem and seems likely to disable drivers concerning the manoeuvring decisions necessary to avoid collisions. The low medium deceleration values show us further that drivers need long time intervals to get the brakes filled and find operating points which are at least near the optimum.

The most important task of ABS is to exploit the maximum friction amounts between tires and road surface and nevertheless to provide the PTW with sufficient driving stability for the performed manoeuvre.
But the even more important effect of antilock brake control for motorcycles should be, that the system gives the driver confidence concerning braking stability even in case of hard brake application. As the above calculations show us unambiguously the best way of reducing speed in time is to have an early and hard brake activation. Saving just 100 or 200ms of brake-filling time means to reduce the whole stopping distance considerably. The driver must be sure that the brake control can be relied on, that there is no risk of wheel-locking, and he should learn to perform full-braking with ABS, simultaneously with both brake levers or at least with the front brake lever in case of a PTW equipped with integral-brake facilities.
Moreover, ADAS systems may be very much of help to make time-saving decisions automatically. Among the 51 studied DEKRA cases are only very few situations, which could not be managed by ADAS systems in a satisfying manner. These are situations which are characterized by so-called sudden cut-ins, meaning that an obstacle crosses the driving path of a PTW so abruptly, that a crash is unavoidable even in case of immediate full-braking.
At this point we see the limits of active safety systems, and that it is necessary to provide PTW drivers with passive safety as well.
In the EC-funded SIM-project, active and passive safety components for PTWs are investigated. In several test vehicles provided by Piaggio, the systems are connected via CAN-bus, so that important sensor and control-signal information can be interchanged. With the help of this networking, additional synergy effects are achieved.

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