ANTI LOCK BRAKING AND VEHICLE STABILITY CONTROL FOR MOTORCYCLES – WHY OR WHY NOT?

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ABSTRACT

In the last years there has been a decline in accident figures in Germany especially for four wheeled vehicles. At the same time, accident figures for motorcycles remained nearly constant. About 17 % of road traffic fatalities in the year 2006 were motorcyclists. 33 % of these riders were killed in single vehicle crashes. This leads to the conclusion that improving driving dynamics and driving stability of powered two wheelers would yield considerable safety gains. However, the well-known measures for cars and trucks with their proven effectiveness cannot be transferred easily to motorcycles.
Therefore studies were carried out to examine the safety potential of Anti Lock Braking Systems (ABS) and Vehicle Stability Control (VSC) for motorcycles by means of accident analysis, driving tests and economical as well as technical assessment of the systems.
With regard to ABS, test persons were assigned braking tasks (straight and in-curve) with five different brake systems with and without ABS. Stopping distances as well as stress and strain on the riders were measured for 9 test riders who completed 105 braking manoeuvres each.
Knowing the ability of ABS to avoid falls during braking in advance of a crash and taking into account the system costs, a cost benefit analysis for ABS for motorcycles was carried out for different market penetration of ABS, i.e. equipment rates, and different time horizons.
The potential of VSC for motorcycles was estimated in two steps. First the kinds of accidents that could be prevented by such a system at all have been analysed. For these accident configurations, simulations and driving tests were then performed to determine if a VSC was able to detect the critical driving situation and if it was technically possible to implement an actuator which would help to stabilise the critical situation.

INTRODUCTION

Compared with cars, the most critical vehicle factor for a motorcycle is the fact that it uses only one-track instead of two. So tilting of the motorcycle has to be avoided by steering and by the stabilizing forces of the wheels. This leads also to the seriousness of wheel locking while braking when the gyro forces and, even more important, the side forces at the front wheel vanish.
ABS therefore is one of the most promising devices to improve the safety of powered two wheelers. Besides ABS one can imagine other systems designed to stabilise driving dynamics of a motorcycle since they are well known for four wheeled vehicles.
BASt (Bundesanstalt für Straßenwesen), the Federal Highway Research Institute of Germany, therefore initiated several research projects which were carried out by Darmstadt University of Technology and University of Cologne.
The first task of the studies was to formulate requirements applicable to brake systems with which the motorcyclist can reproducibly achieve safe braking operations with short stopping distances. For that purpose ABS and combined braking systems were examined. Since ABS was identified to avoid fall events during braking manoeuvres and to reduce stopping distances also while braking in bends, a cost-benefit analysis was carried out in a second stage to clarify whether the economic benefit of ABS for motorcycles is greater than the consumed resources. In a third study the possibility to detect critical driving situations of motorcycles objectively which would be the basis

for every application of a driving stability system for motorcycles was examined. By means of studying accident figures as well as the technical possibilities for the implementation of VSC on motorcycles, possible safety gains were determined.

ANTI LOCK BRAKING SYSTEMS

Stress and Strain on motorcycle riders while braking

The technical benefit of anti-lock brake systems for the rider's safety has been shown in many research studies concerning achieved decelerations or braking distances when braking straight or in curve, and is undeniable [1, 2]. Furthermore, research was able to show that motorcycles equipped with ABS would decrease the number of accidents and the number of severely injured riders and fatalities in real-life scenarios [3].
In this research project, mental strain depending on the kind of brake system was tested. Deducted from the fact that test persons on a closed test track achieve higher decelerations with ABS and so suffer from higher acceleration forces, the working hypothesis was to test if this higher physical stress leads to higher physical strain.
Mentally the stress in real life conditions is obviously higher than in test conditions on a closed test track, but only defined test track conditions make the mental stress at different times comparable. Measuring the physical stress and strain at constant mental stress then makes it possible to deduct indications for mental strain.

Test Layout

On Griesheim Airfield, a closed test track with unevenness comparable to a German Highway [5] and a relatively high friction coefficient [4], three test scenarios have been built up:

- Full braking from 60 km/h straight,
- Full braking from 90 km/h straight,
- Full braking from 50 km/h in-curve, with 50 m radius (i.e. < 20° rolling angle)

All three took place on a wet road surface with one test motorcycle, a BMW R1150RT, see fig. 1, equipped with alternatively choosable the original combined ABS ("BMW i-ABS" first Generation, also known as FTE CoraBB) or the BMW R1100RT standard brake system with ABS ("BMW ABS II"), both disengageable, and a removable rear brake lever. With each of these 5 brake systems – standard brake without ABS, standard brake with ABS, combined brake without ABS, combined brake with ABS, combined brake with ABS and only the hand lever – 9 test persons had to absolve the test round 7 times. The sequence of brake systems had been permuted in three permutations that way, so neither a brake system had been used on the same place nor was followed by or preceding the same system a second time. For a better understanding, table 1 shows the three permutations. Each rider was allocated a specific permutation.

Table 1.
Test layout; permutation of brake systems

Permutation A	Permutation B	Permutation C
standard brake	combined brake with ABS	combined brake
combined brake	standard brake with ABS	combined brake with ABS, only hand lever
standard brake with ABS	standard brake	combined brake with ABS
combined brake with ABS	combined brake with ABS, only hand lever	standard brake
combined brake with ABS, only hand lever	combined brake	standard brake with ABS

Furthermore, the motorcycle was equipped with a pair of outriggers that catch the motorcycle at around 35° roll angle, so rider and motorcycle don't painfully touch the ground in case of a locked front wheel, see figure 1.
Beyond motorcycle test data such as wheel speeds, front and rear suspension strokes, brake and clutch lever travel, steering angle, and yaw and roll rate, human data such as the tonicities of musculus flexor digitorum (left hand) and musculus trapezius pars descendens (right side) have been recorded as well as the heart frequency. Between the tests,

Figure 1. Test motorcycle BMW R1150RT; during braking tests with integrated and hidden measurement instrumentation and outriggers to limit damage in case of a fall

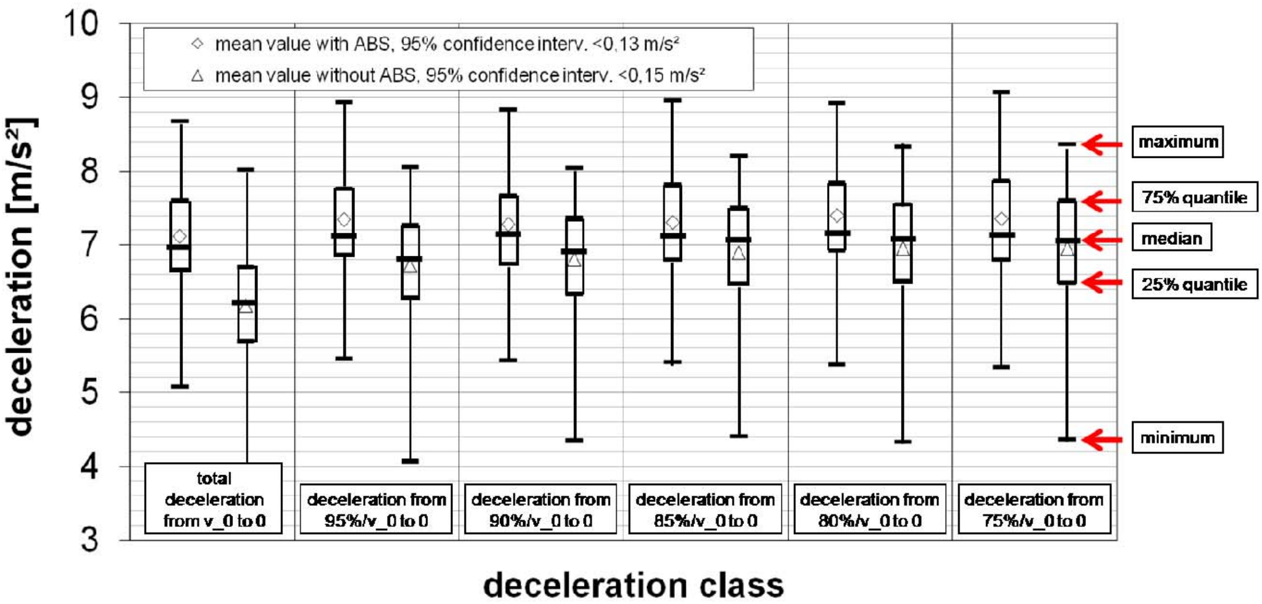

Figure 2. 90km/h straight braking with and without ABS – characteristic data)

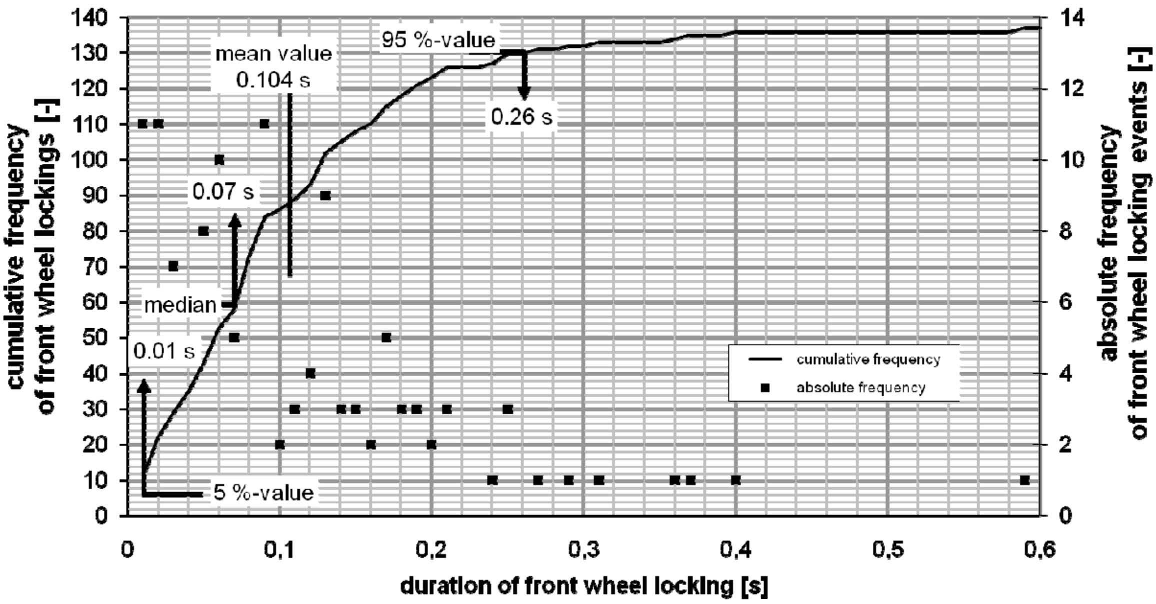

Figure 3. Absolute and cumulative frequency of front wheel locking events and front wheel locking times (100% wheel slip) without fall relevance during tests to minimize braking distance

when changing the brake system, a short mental state test [6] was carried out.

9 male test persons in the age bracket 21 years to 33 years absolved the braking tests; all of them are experienced riders with a riding experience between 18,000 km and 200,000 km.

Test results

Regarding braking distances, this research project confirms investigations which show that riders achieve shorter braking distances with ABS than without, even on a closed test track.

Figure 2 shows, where riders lose time and travel; at the very beginning of a braking manoeuvre the rider has to experience first the pressure point and then optimize the brake pressure for maximum deceleration. To complicate this manual tire slip control, the approach towards the optimum can only happen from the safe side, and the first moments of a braking manoeuvre are highly non-linear regarding wheel loads and provided tire forces [7]. Front wheel lock events have to be extremely short to be absolved without fall, see figure 3, though there is evidence for a fall after less than 0.5 s front wheel lock (figure 4).

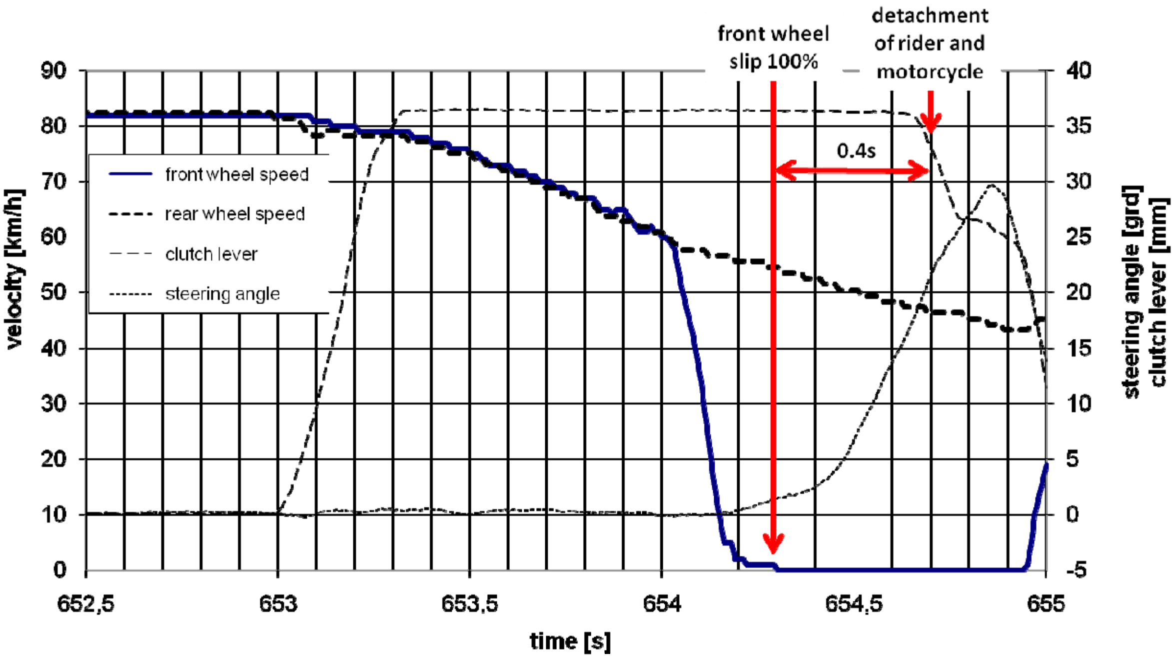

Figure 4. Fall 0.4 s after beginning front wheel locking

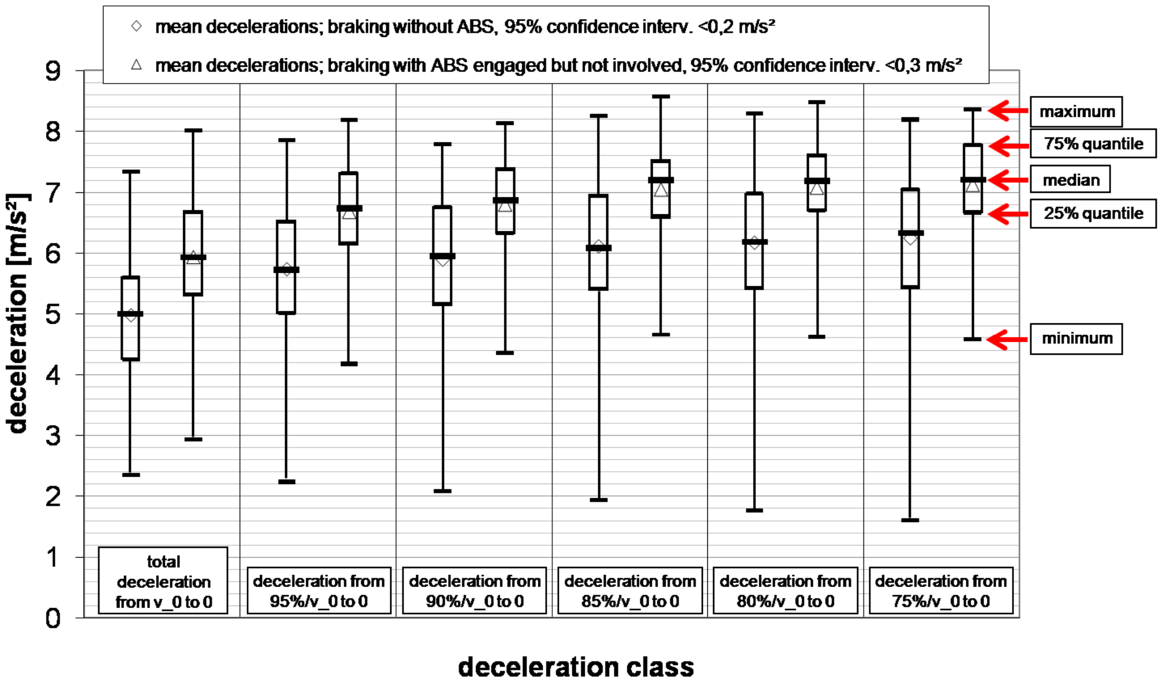

Figure 5. Time based deceleration without ABS and with ABS, but without intervening ABS control, 50km/h in-curve braking

What figure 2 shows for the straight braking at 90km/h is also valid in a weaker form for straight braking at 60km/h and – much stronger – for in-curve braking at 50km/h.

For the more challenging in-curve braking the higher achieved decelerations do not go along with using ABS; most of the braking manoeuvres happen without ABS intervention, but the decelerations achieved with engaged but not intervening ABS are significantly higher than those with disengaged ABS, see figure 5.

So just the presence of ABS makes riders achieve higher decelerations, especially during more challenging braking situations.
There is low significance between brake performance and rider experience. Only the very experienced riders (70,000 km+ riding experience), who also have experience with combined braking systems and ABS, achieve significantly higher decelerations with all kinds of brake systems; the most experienced rider (200,000 km riding experience) delivers the best brake performance, see figure 6.

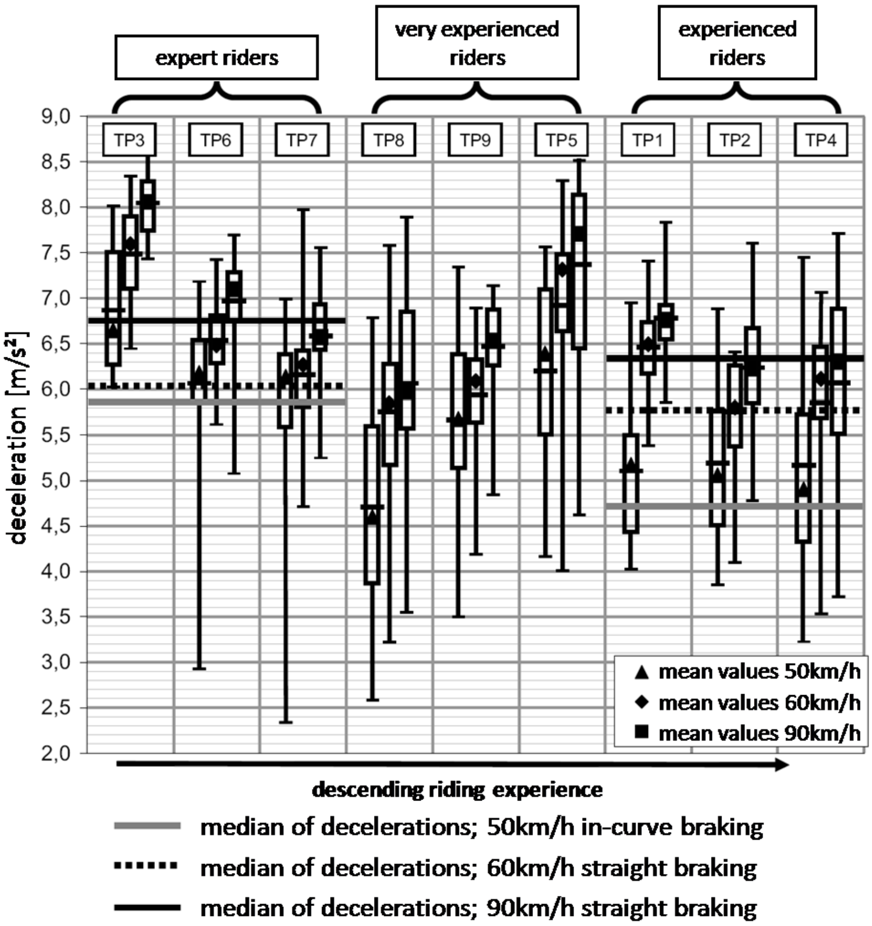

Figure 6. Decelerations of test persons, graded in descending riding experience

His in-curve braking performance is higher than the 90km/h straight braking performances of those test persons with less riding experience!
Those shorter braking distances result from higher decelerations. Higher decelerations mean higher inertia forces on the rider, and this means higher physical stress on the rider. Mental stress objectively is unchanged except for the fact that one brake system differs from another. So as a first conclusion this objectively higher physical stress should be measureable as higher physical strain, if the choice of the brake system has no influence on mental stress and so mental strain remains unchanged.
The majority of the test persons do not show any significant change in the heart rate depending on the brake system, but the other test persons show a significantly higher heart rate when doing the tests without ABS compared to the tests with ABS. Absolute heart rates can exceed 170bpm when absolving tests without ABS compared to 120bpm with ABS. Furthermore, while braking without ABS, all of the test persons show significantly higher tonicities of both musculae measuring points than during the test cycles with ABS.
There is no significance regarding combined and standard brake systems. Giving the rider just the hand lever with the combined brake system with ABS leads to no disadvantages regarding braking performance. Especially for in-curve braking, braking with the combined brake system with ABS is slightly advantageous with just the hand lever vs. both levers.
It could be shown, that the least experienced riders profit more from having ABS than the most experienced riders with regard to braking performance and especially mental strain, s. [8].

Conclusions

Anti-lock brake systems not only prevent rider and motorcycle from harm and damage by increasing active safety, but also reduce significantly mental strain while riding and braking. In case of a critical riding situation, this higher remaining mental reserve would help the rider to develop and wishfully realize alternative emergency strategies that additionally could help the rider to prevent a crash. These advantages are not expected to be neutralized by taking higher risks, as real world investigations show [9].

Outlook

Anti-lock braking systems in motorcycles today give a lot of benefit to the customer. As the press is more and more comparing ABS of different makes and its collateral effects such as brake feeling with and without intervening ABS control, ABS in-curve performance, friction step performance and last, but first in mind and benchmark, performance and feeling on uneven road surface, this will have more and more impact on ABS development. Especially uneven road behaviour and performance could be easily improved and with many positive side effects by an electronic suspension control that provides both high forces at low damping speeds for pitch control and low basic hydraulic forces for good response behaviour, like e.g. electrorheologic damping units can [10, 11].

Regarding the test results and the increasing technical safety level of motorcycles, there is no reason why regulations force motorcycle manufacturers to design two brake levers. When equipped with a combined ABS, the equipment with only the hand lever would not lead to disadvantages regarding brake performance in any way [8].

COST-BENEFIT ANALYSIS OF ABS FOR MOTORCYCLES

As the braking test showed a great safety potential is expected for ABS for motorcycles. The system is thus considered from the economic view. A cost-benefit analysis shall clarify whether the economic benefit of ABS for motorcycles is greater than the consumed resources. A break-even analysis completes the analyses. In this analysis ABS is considered from the end user view.

The considered time horizon for these analyses are the years 2015 and 2020, the area under consideration is Germany. For each of these years the accident data is forecast. At this, it is assumed that the frequency of having an accident per million registered motorcycles decreases based on the present trend. Thus, riding motorcycles gets safer. Hence, the accident data in the years 2015 and 2020 is lower than the accident data today.

Cost-benefit analysis process

In general the CBA consists of a four step process. These four basic steps can be characterized as follows:

In the first step of the procedure the relevant alternatives that will be compared within the analysis have to be defined. For the CBA two cases are introduced:

- The “with-case“, which means that a road safety technology/measure like ABS will be introduced.
- The “without-case“, which assumes that there will be no implementation of the technology/measure to be evaluated.

Within the second step the potential safety impact has to be quantified. Conceptually, the main effect of road safety technologies/measures such as ABS for motorcycles is the reduction of hazardous situations which affects the number and/or the severity of accidents. As a consequence, accident costs can be lowered.

Within the third step of the CBA process, the benefits are calculated in monetary terms by valuing the annual physical effects with standardized cost-unit rates. In addition to the monetarization of the physical benefits, the costs of the technology/measure have to be determined. The costs comprise the costs to be borne for implementation, operation and maintenance.

The result of the economic evaluation is obtained in the fourth step by comparing economic benefits with costs. For this comparison several measures can be calculated. The most common one is the benefit-cost-ratio (BCR) according to which a technology/measure is macro-economically profitable, if the calculated ratio is greater than one.

$$BCR_t = \frac{B_t}{C_t}, \text{ with} \qquad (1)$$

BCR benefit-cost ratio,
t time horizon defined,
B estimated value of benefits for t
and
C estimated value of costs for t.

The value of the ratio indicates whether the implementation of ABS is favourable from a socio-economic point of view. A BCR of more than “1“ indicates that benefits exceed the costs. Thus, the introduction of ABS would be beneficial to society. Furthermore, the value of the BCR expresses the absolute profitability of ABS which can be interpreted as the socio-economic return for every monetary unit (e.g. Euro, US-$) invested in the

implementation of ABS. For example, a BCR of "3.5" would show that 3.5 monetary units can be gained for society for every monetary unit provided for the investment evaluated. Setting absolute, monetized values of benefits and costs into relation, the BCR is a reliable indicator of efficient resource allocation.
In the cost-benefit analysis the costs and the benefits have to be determined. While the calculation of the physical benefits of ABS on basis of accident statistics and accident research is rather straightforward, the monetary valuation of accidents – that means the monetary valuation of injuries and human life – is a controversial matter. In this study the cost-of-damage approach is used to assess the value of the resource savings for the benefit categories.
The cost-of-damage approach is state of the art for cost-benefit analyses which are performed for Germany. The cost-of-damage approach is based on the total estimated amount of economic losses caused by any physical impact. Generally, the losses are quantified via the decline of gross product. For instance, the costs of an accident include the vehicle damage, medical and emergency costs and lost productivity of killed or disabled persons.
In general, there are different benefits due to accident savings which have to be assessed. But in the case of ABS for motorcycles only the safety potential is relevant. Due to the facts that a motorcycle is a narrow vehicle and that most avoidable accidents occur on rural roads with less traffic [12, 13], congestion due to the motorcycle accident is not a problem. In addition, the usage of ABS does not influence the traffic flow.

Scenarios

There are two ABS scenarios considered for each year:

- penetration rate for ABS: trend and
- penetration rate for ABS: mandatory for new motorcycles

The penetration rate is differentiated into a trend scenario and a mandatory scenario. Trend scenario means that there are no special incentives to promote ABS on the part of the politics. In opposition to that the mandatory scenario means that ABS is equipped in every new motorcycle from the year 2010 on.

Table 2.
Equipment rates and the motorcycle stock for the years 2015 and 2020 [14]

	equipment rate		motorcycles
Year	trend	mandatory	in 1,000
2015	39.7%	47.8%	4,538
2020	56.7%	69.3%	4,939

The equipment rates and the motorcycle stock for the years 2015 and 2020 can be seen in Table .
The system costs depend on the produced volume. The more systems are produced the lower are the system costs. Hence, the system costs of the mandatory scenario will be lower than the ones of the trend scenario. For the year 2015 the system costs are estimated as 120 Euro for the trend scenario and as 115 Euro for the mandatory scenario. For the year 2020 the figures are 105 Euro and 100 Euro respectively. Economies of scale and effects of learning curves are included.
It is considered that ABS influences the total number of accidents, of fatalities, of severe injuries and of slight injuries. Only accidents in which the motorcycle rider falls down before the real accident happens are considered. The fall is usually caused by locked wheels due to inappropriate braking manoeuvers which can be avoided by ABS. Additional effects due to shorter braking distances with ABS are neglected. This is due to the lack of data. Hence, both scenarios are underestimating.
In order to determine the number of avoidable accidents and casualties, the accident base for 2015 and 2020 has to be estimated (Table).

Table 3.
Estimated accident base for 2015 and 2020 [14]

			injuries	
	accidents	fatalities	severe	slight
2015	34,838	777	9,672	23,561
2020	34,487	746	9,058	23,275

Safety potential

Due to the usage of ABS, falls can be avoided. In every fifth single vehicle accident the motorcycle driver falls down [15]. Every fifth motorcycle accident is a single vehicle accident [12], thus, the share of falls in single vehicle accidents based on all accidents is 4 %. The same calculation is done for multi-vehicle accidents. Here, the share of falls is 10 % [16] while the share of multi-vehicle accidents is 80 %. Thus, the share of falls in multi-vehicle accidents based on all accidents is 8 %. Together, the share of falls based on all accidents is 12 %. The potential of ABS is to avoid 20 % of all accidents with falls [16]. Hence, due to ABS the number of accidents can be reduced by 2.4 %.
The avoided fatalities, severe and slight injuries can be differentiated into three groups:

1. ABS avoids the fall of the motorcycle but cannot avoid the crash (motorcyclist),
2. ABS can avoid the accident (motorcyclist) and
3. ABS can avoid the accident (other traffic participant).

The risk of being killed in an accident with previous fall is twice as high as for accidents without fall. ABS can avoid a fall in 85% of all cases and the share of fatalities after a fall is 22.6 % [12, 14] so that the avoidance potential due to the avoided fall is 9.59 %.
For calculating the avoidance potential of fatalities due to the avoided accident, the share of avoidable accidents (single vehicle and multi-vehicle accidents) has to be multiplied with the accordant share of fatalities in the accident category over the share of the accident category. This is done for single and for multi-vehicle accidents. All in all, the avoidance potential of fatalities due to the avoided accident is 2.26 %.
Finally, the potential in avoiding fatalities of other traffic participants has to be determined. 90 % of all fatalities due to an accident with motorcycles are motorcyclists [12].
Thus, per killed motorcyclist comes 0.11 killed other traffic participant. The share of fatalities of multi-vehicle accidents is 71 % [17]. Thus, 0.156 killed other traffic participants comes on one killed motorcyclist in multi-vehicle accidents. This figure has to be multiplied with the share of avoided fatalities in multi-vehicle accidents (1.29 %). This leads to an additional share of avoided other traffic participants due to avoided accidents of 0.2 %.
In total, 12.05 % of all fatalities can be avoided if every motorcycle is equipped with ABS.
The calculation for the avoidance potential of severe and slight injuries is similar to the one for fatalities. The results for accidents, fatalities, severe and slight injuries are displayed in Table .

Table 4.
Avoidance potential for accidents and casualties [14]

avoidance potential for			
accidents	fatalities	severe inj.	slight inj.
2.4%	12.1%	11.7%	-2.1%

In Germany, ABS for motorcycles was introduced in 1988 by BMW [7]. Today the equipment rate of the motorcycle fleet is significant. Thus, ABS avoids already accidents and, linked to this, casualties. Due to this, the accident data is underestimating – if ABS had never been introduced the accident data would be higher. The estimated accident data for 2015 and 2020 are valid for the trend scenario. For both scenarios the accident data has to be determined for the case that ABS is not available. The adjusted accident base (aab) can be determined as follows:

$$aab = \frac{estimated\ accident\ base}{1 - eq.rate * effectiveness} \quad (2)$$

The difference of the adjusted accident base and the estimated accident base is the avoidance potential of the trend scenario. The avoidance potential of the mandatory scenario is the following product:

$$potential = aab * eq.rate * effectiveness \quad (3)$$

In
Table the results are displayed.

Table 5.
avoided number of accidents and casualties in 2015 and 2020 for the trend and mandatory scenario [14]

			injuries	
	accidents	fatalities	severe	slight
2015	34,838	777	9,672	23,561
aab	35,173	816	10,143	23,364
potential trend	335	39	471	-197
potential mandatory	403	47	567	-237
2020	34,487	746	9,058	23,275
aab	34,962	801	9,701	22,999
potential trend	475	55	643	-276
potential mandatory	581	67	786	-338

Benefits

Afterwards the avoided fatalities, severe and slight injuries have to be multiplied with the accordant cost-unit rates. For fatalities the cost-unit rate is 1,190,335 Euro, for severe injuries 101,099 Euro and for slight injuries 13,923 Euro [19].
For each year and for each scenario the avoided accident numbers have to be multiplied with the accordant cost-unit rates for the casualty categories fatalities, severe and slight injuries. Afterwards the sum of the three figures is established. The safety benefits are:

- 91.4 million Euro for the year 2015 in the trend scenario,

- 110.1 million Euro for the year 2015 in the mandatory scenario,
- 126.9 million Euro for the year 2020 in the trend scenario and
- 154.9 million Euro for the year 2020 in the mandatory scenario.

Costs

The benefits have to be confronted with the costs. The costs are the product of system costs per year times equipment rate times motorcycle stock. The system costs per year are the product system costs times annuity rate. The annuity rate depends on the economic lifetime of a motorcycle, which is assumed to be 13.2 years [20], and on the discount rate, which is assumed to be 3 % [14]. The annuity rate is determined as follows:

$$AR = \frac{d * (1+d)^n}{(1+d)^n - 1} = \frac{0.03 * 1.03^{13.2}}{1.03^{13.2} - 1} = 0.0929 \quad (4)$$

In 2015, the system costs per year are 11.14 Euro in the trend scenario. The number of equipped motorcycles is 1.8 million motorcycles. Thus, the costs in 2015 trend scenario are 20.1 million Euro. In the mandatory scenario the costs are 23.2 million Euro, in 2020 the costs are 27.3 million Euro respectively 31.8 million Euro.

Benefit-cost results

The benefit-cost ratio is determined by dividing the benefits by the costs. The benefit cost ratio for the year 2015 is 4.6 in the trend scenario and 4.8 in the mandatory scenario. In 2020 the values are 4.7 respectively 4.9.
In comparison to other vehicle safety systems ABS is in the top flight.
Another possibility to assess the economical impact of ABS is the net-benefit. In this approach the costs are subtracted of the benefits. In 2015 the net-benefits are 71 million Euro in the trend scenario and 87 million Euro in the mandatory scenario. The values for 2020 are 100 million Euro and 123 million Euro respectively.

Break-even analysis

Another analysis which is done for ABS for motorcycles is the break-even analysis. In this approach the end user is in the focus. For an average motorcyclist, the market price for ABS is determined for which the costs and the benefits of ABS are the same from a user point-of-view. In this approach the lower risk of the motorcyclist of being killed, severely injured and slightly injured is considered. Afterwards the difference in the risk (with ABS versus without ABS) is multiplied with the accordant cost-unit rates which are now determined by the willingness-to-pay approach [14]. The result is a fair market price of 701 Euro for 2015 respectively 622 Euro for 2020. If the market price is below the fair market price, ABS will be worthwhile for the average user.
Another approach within the break-even analysis is to calculate the critical mileage. Therefore a market price is estimated – 400 Euro in 2015 and 300 Euro in 2020 [14]. Given this market price and the difference of risk for being killed, severely injured and slightly injured, the mileage can be determined for which the costs and benefits for the user are the same. For each mileage which is higher than the critical mileage, ABS is worthwhile. The critical mileage is 2,200 km per year in 2015 and 1,900 km per year in 2020. These mileages are below the mileage on average. ABS is worthwhile for most users.

Result

The benefit-cost analysis shows clearly that ABS for motorcycles is economically reasonable. The full potential of ABS can only be achieved by making ABS mandatory.

SAFETY POTENTIAL OF VSC FOR MOTORCYCLES

In order to assess the potential for future vehicle stability control systems (VSC), the corresponding accident types, vehicle dynamics properties and technical possibilities need to be taken into account: A technical system intended to decrease the rate of fatal accidents should address accident types that have a high risk of being fatal as well as occur often. These accident types are identified by means of an accident analysis.
To gather information on the vehicle behaviour during these accidents, real-world experiments of simulated accidents using a test motorcycle and computer simulation studies with the simulation package VI/Motorcycle are conducted. A mathematical model for the vehicle behaviour is derived from the experiments and computer simulations. The definition of critical and uncritical situations is also derived from the analysis of experimental data.
Any VSC has to fulfill two criteria: it has to be able to detect critical situations and it has to be able to prevent or mitigate them. Methods to detect the addressed critical situations are developed from the mathematical model. To check if these methods can distinguish critical from uncritical situations, they

are validated with data from the experiments and simulations (critical) and with data from various uncritical test rides.
Methods to influence motorcycle dynamics are also derived from the mathematical model and evaluated regarding physical feasibility and technical feasibility. With assessed methods for detection and prevention of critical situations, the question is answered if and how future vehicle stability control systems can help prevent accidents.

Accident analysis

The objective of the accident analysis is to find accident types that cannot be influenced by today's vehicle stability control systems ABS and TCS (Traction Control Systems). To achieve this, motorcycle experts were questioned about their own experiences with motorcycle accidents (not surprisingly, almost all experts experienced at least one accident). Because of their experience with motorcycles as well as their knowledge of physics, they are able to give a technical explanation of what happened during their accidents. This source delivers around 60 detailed descriptions.
Additionally, around 60 accidents originating from the accident database of the German Insurances Association (*Gesamtverband der Deutschen Versicherungswirtschaft*, GDV) are analyzed. The accident datasets are classified as 'preventable' (the rider reacted before the vehicle collided with the opponent or the road) and 'not preventable' (no reaction). Preventable accidents are further divided into the subgroups 'with today's technology' (ABS or TCS could have prevented the accident but were not available on the motorcycle) and 'with future technology' (unbraked accidents).
The share of those identified accidents on the total amount of motorcycle accidents then is checked with a detailed analysis of all accident datasets from the GDV database (around 900 accidents, representative for Germany). For more information on the accident analysis, refer to [20].
The high risk accident types classified as preventable by future VSC systems are unbraked cornering accidents due to a step of friction (μ-step, accident type 1) and due to exceeding maximum lateral acceleration (e.g. trying to ride at a roll angle larger than the maximum roll angle determined by the road surface, accident type 2).
Their share on Germany's high-risk motorcycle accidents is estimated to be 4 to 8%.

Test Motorcycle

The test motorcycle is a BMW R 1150 RT motorcycle (Figure 1), the motorcycle that was used for the brake tests (see chapter ANTI LOCK BRAKING SYSTEMS). To prevent damage in simulated accidents, it is equipped with a set of outriggers on both sides. The outriggers have Teflon gliders to minimize friction. In order to reduce the influence on the motorcycle inertia to a minimum, they are mounted rotatable to the motorcycle and glide on the ground permanently. If the roll angle exceeds 25°-30° (depending on the state of the Teflon gliders), the motorcycle finds support on the outriggers.
A fiber-optical gyroscope combined with acceleration sensors records the motorcycle's accelerations and angular velocities in all three axes. The accuracy of the roll rate sensor allows calculating the roll angle simply by integrating the roll rate signal. The vehicle's velocity is determined by the production ABS wheel speed sensors, the steering angle is measured by a hall sensor, and a reflex light barrier is mounted to the vehicle.

Simulated accidents

Wet epoxy surface and tarpaulins covered with glue were used to simulate unbraked cornering accidents, for details, see [21]. Both surfaces have a friction coefficient of approximately 0.2. 46 test rides in total were valid. As a variant, on seven test rides additional weight to change the vehicle's center of gravity was mounted.

Table 6.
Number of conducted tests by type and surface

Surface	Type 1 μ-step	Type 2 $a_y > a_{y,max}$
Wet epoxy	7	7
Tarpaulin with glue	28	4

The test layout is shown in Figure 7.

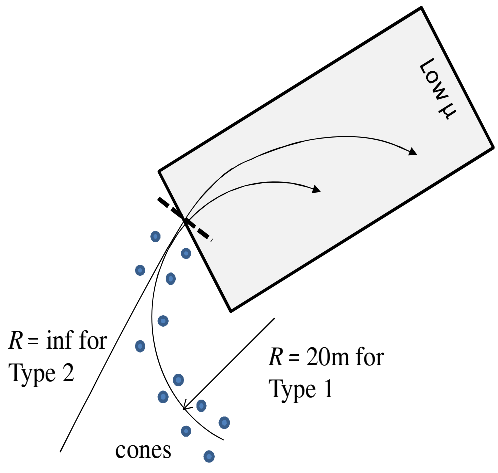

Figure 7. Test layout

For type 1, the vehicle arrives at the low-μ surface with a desired speed between 7 and 8 m/s at a desired turn radius of approximately 20 m at roll angles of 15° to 20°. Capsize of the vehicle occurs almost as soon as it has arrived on the low-μ surface. For type 2, the vehicle arrives with the same speed and a roll angle below 5°.
The objective is to increase the roll angle, once the vehicle has arrived on the low-μ surface, until the vehicle capsizes.
For both simulated accident types, the arrival of the front wheel contact patch on low-μ is detected by the vehicle-mounted light barrier and a calibrated reflector. The impact of the motorcycle on the safety bars is determined by the maximum roll acceleration. Clutch is opened before low-μ-surface.

Computer Simulation

The maximum velocities and maximum roll angles were set by the construction of the motorcycle's safety bars and the size of the low-μ surface. To gather additional data on parameter sets that could not be measured with test rides, a computer simulation software VI/Motorcycle (www.VI-Grade.com) is used. For details on the computer simulation, refer to [20].

Uncritical test rides

Based on the simulated accidents vehicle dynamics data, a criterion for recognition of critical driving situations is developed. Uncritical rides are conducted to provoke failure detection. All rides took place on the "Airfield Griesheim" test track. The test track has an unevenness of a typical German highway [5] and thus is more uneven than the epoxy test track, but all other circumstances were maintained to ensure comparability in between simulated accidents on either surface and uncritical test rides.

Vehicle behaviour in simulated accidents

As mentioned before, two types of accidents have been chosen as the most relevant for future vehicle stability control systems. Both are unbraked cornering accidents, one is caused by a drop of the road friction coefficient (μ-step), the other one is caused by exceeding the maximum lateral acceleration and thus capsizing. The feasibility of vehicle stability control systems to prevent those accident types will be evaluated. This is achieved by simulating the accident types in real-world experiments and computer simulations and developing a mathematical model from the gathered data.

The vehicle behaviour is depicted in Figure 8 for four exemplary test rides: one per surface type (epoxy or tarpaulins) and one per accident type (μ-step or exceeding maximum lateral acceleration). Type 1 accidents have a shorter duration compared to type 2 accidents. For accident type 1, the front wheel starts to slide as soon as it reaches the μ_{low}-surface. The front wheel side force decreases immediately to the value determined by the friction coefficient, the vehicle starts to capsize, see roll velocity, time t=0s. The rear wheel arrives 0.2 seconds later. At that time, the rear wheel side force also drops, the roll velocity increases. The unbalanced side forces of front and rear wheel lead to a yaw momentum and thus a yaw velocity between 0s and 0.2s. The vehicle turns to the outside of the bend. After approx. t=0.2s, the vehicle movement is inverted – it turns to the inside of the bend, until a short time later the vehicle impacts on the safety bars.
For accident type 2, the side forces drop to the sliding value both at the same time. The roll rate increases constantly. No yaw movement to the outside of the bend is observed; instead the vehicle turns to the inside just before the fall occurs (see the last 0.3 seconds). For both cases, pitch movement can be neglected.
The lateral acceleration drops to a level equal to g x μ when both wheels are sliding (after 0.2 seconds for type 1 respectively at the last 0.3 seconds for type 2). The "over-steering" yaw movement observed for the last few 0.1 seconds of both cases therefore cannot be explained by a turn. It can be explained by a slip angular velocity – the vehicle yaws but does not change its course in the same way.
[22] describes an "over-steering" yaw movement during "low sider" type accidents due to a decrease in rear wheel side force. However, the accidents described there are braked accidents – the conclusions cannot be transferred to the accident types this paper focuses on.

Detection of critical driving situations with focus on future VSC systems

With the mathematical model, the vehicle dynamics for critical situations are understood. Methods for detection and avoidance or mitigation of these accident types can be evaluated. If an accident type can be detected as well as prevented, a vehicle stability control system for this accident type is feasible.
The mathematical model of the vehicle behaviour shows that the vehicle side-slip angular velocity is unstable for critical driving situations of the type investigated here (non-braking cornering

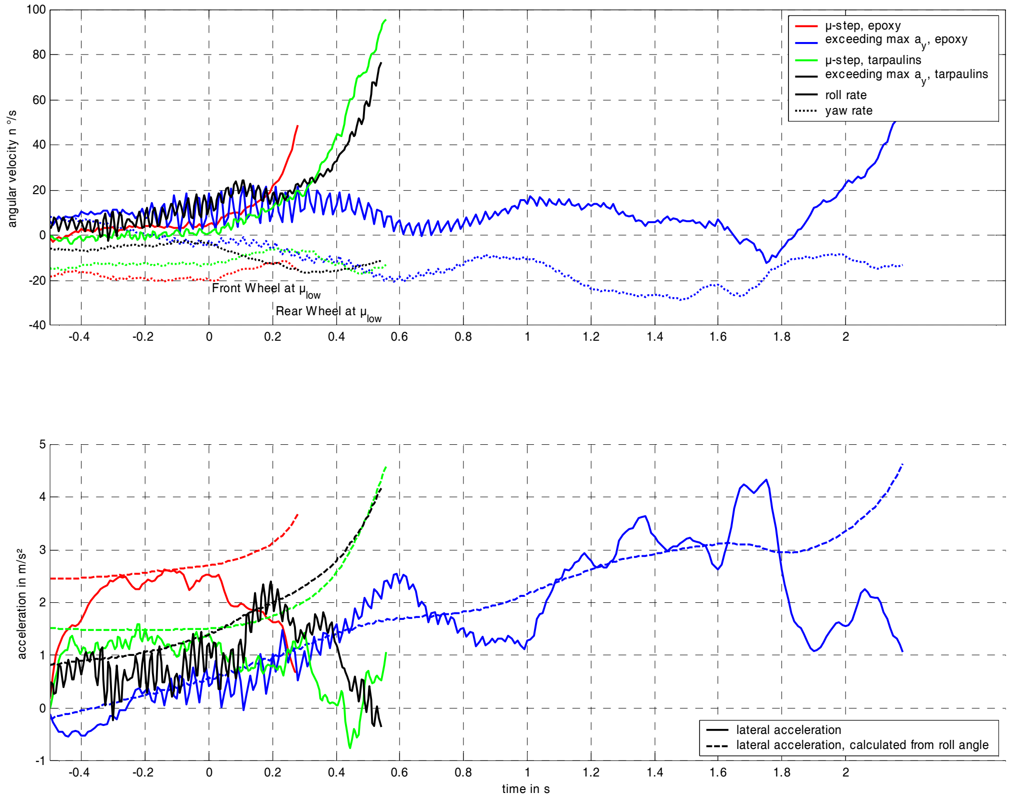

Figure 8. Vehicle behaviour during simulated accidents. All data filtered with first order low-pass filter, 10 Hz cutoff frequency. Lateral acceleration additionally smoothed. Signal vibrations are caused by engine excitation and resonance effects of the rear frame and vanish for idling engine. Pitch rate is neglected.

accidents). General motorcycle tire properties suggest the tire slip angle is always small <1° (refer to [23]), as well as the vehicle side-slip angle. The side-slip angular velocities (both tire and vehicle) are also assumed to be low.

A criterion for the detection of critical driving situations would be

$$\dot{\beta} > \dot{\beta}_{\max, stable} \qquad (5)$$

This criterion can be used to detect critical driving situations, if it fulfills the following two conditions:

- it does detect a simulated accident in all valid test rides (no false-negatives),
- it does not detect an accident in all uncritical test rides (no false-positives).

The side-slip angular velocity of the vehicle cannot be measured directly, it has to be calculated from other measurands. Using the lateral acceleration horizontal to the road plane, the vehicle side-slip angular velocity is

$$\dot{\beta} = \dot{\psi} + \frac{\ddot{y}}{\dot{x}}, \qquad (6)$$

for details on the calculation of the lateral acceleration see [21] and [20].

Figure 9 shows the time of detection for all simulated accidents as cumulative probability distribution. The time is between 0% (front wheel has reached the low-μ surface) and 100% (impact on safety bar). No false-negatives are observed. The majority of simulated accidents was detected in the

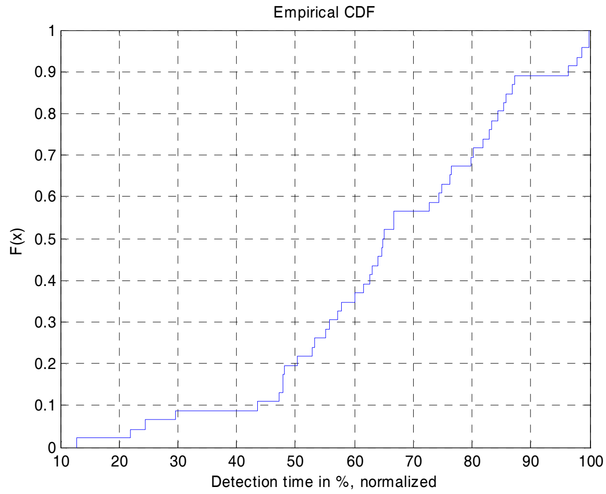

Figure 9. Results: Cumulative Distribution Function for detection of simulated accidents, time normalised with respect to critical situation duration.

last quarter of the critical driving situation duration. However, a value of 100% only means the vehicle has reached the safety bars, not the vehicle has crashed. The safety bars limit the roll angle to values of 25° to 30°. In reality, motorcycles can reach maximum roll angles of up to 55° without crashing, thus giving any control system more time to react.
The ability of the described criterion to distinguish critical and uncritical driving situations is proved, if no false-positives can be found at all. Table shows the types of uncritical test rides.
Using this experimental evidence, the criterion "side-slip rate" has proved the ability to detect critical driving situations. No side-slip rates higher than 0.15 rad/sec + estimated error have been observed for uncritical situations.
These thoughts lead to the following control objectives:

- First, the roll movement has to be stabilized.
- Second, the rear wheel side-slip angle has to be zero for the case of a sudden increase of the friction coefficient.
- Third, if a capsize is inevitable, the vehicle has to turn into the bend.

Table 7.
Description of uncritical ride tests.

	Description	Parameters
1	steady-state cornering	turn radius 9 and 14m $a_{y,0}$ from 0.1 to 0.5g
2	corner braking	turn radius 9 and 14m $a_{y,0}$ from 0.1 to 0.5g
3	swerving	
4	double lane change according to VDA	velocity from 70 to 85 km/h

Possible methods to change the movement of a motorcycle

The accidents focused by this paper involve an unstable yaw movement and an unstable roll movement. Unstable roll movement limits the duration of the accident – as soon as the vehicle hits the ground, a crash occurs. The primary focus should be on the roll stabilization.
If the vehicle capsizes and the surface friction coefficient does not change, it makes no sense to change the yaw momentum. As the motorcycle turns into the bend, the rider falls behind the vehicle. The friction coefficient of today's motorcycle clothing is higher than that of a capsized motorcycle. The motorcycle's deceleration is lower, the distance between motorcyclist and vehicle will increase during the accident.
If the friction value raises again during the tumble, e.g. if the road was slippy only in a small area, a high wheel side-slip angle on the rear wheel will almost instantly cause a high side force on that particular wheel, a dangerous "highside" type accident (which is a fast roll movement of the motorcycle away from the bend direction) would be the consequence.
In order to change the movement of a motorcycle,

- the tire side-slip angles, camber angles or longitudinal slip can be changed,
- the wheel load can be changed,
- gyroscopic effects can be utilized,
- aerodynamic effects can be used.

Roll stabilization

Unstable roll movement can be stabilized by changing the roll momentum, e.g. increasing the sum of side forces and thus the lateral acceleration or applying an additional roll torque to the motorcycle.
As long as one wheel has not reached its maximum side force (e.g. the rear wheel is still on high-μ), changing the tyre properties can increase the side force. The delay between applying a wheel side-slip angle and the resulting side force is dependent on a distance called "relaxation length", for typical tyres this value lies at approx. 0.2 to 0.5 meters [24], for camber changes the delay is negligible. From a physical point of view, stabilization seems to be possible. What needs to be taken into account is the time demand for applying the changed tyre properties. A change of side-slip angle by a rear-wheel steering system is the better choice because the ratio between angle and side force is approximately 10 times higher for side-slip angle than for camber angle. However, the absolute time lag between front wheel and rear wheel (wheel base divided by vehicle speed) is as low as 0.2 seconds for speeds as low as 7 km/h and decreases with 1/velocity. It is doubtable that this short time span is enough for detection and reaction by a technical system.
Roll momentum on a motorcycle with sliding wheels cannot be applied by changing wheel load, using gyroscopic effects or aerodynamic effects, for details, see [25].
Gyroscopic effects can stabilize the roll movement of a vehicle. This is proved by technical examples like the Ford Gyron prototypes [26]. The Ford Gyron prototype cars used a stabilizer gyro with a weight of 180 pounds. Calculations show stabilizer gyroscopes for today's motorcycles would still not be feasible due to large mass, high rotational velocity and control issues. Gyroscopic effects of

the motorcycle's wheels are far too low to stabilize the roll movement.
Aerodynamic effects are an option for capsuled motorcycles, but most probably will not work with standard motorcycles due to the bad aerodynamics.

Yaw stabilization

Side-slip angles, camber angles and longitudinal slip can change the direction of the tyre forces of a sliding wheel (which has reached its maximum side force), but the maximum value cannot be influenced – it is determined by the friction coefficient between tire and surface and the wheel load. These methods therefore can be used to change the yaw momentum to stabilize the yaw movement of the motorcycle.
The accidents that can be mitigated by this method are only a subset of the mentioned 4-8 % of all German motorcycle accidents. For more details, see [20] and [21].

CONCLUSION

Braking is one of the most difficult-to-control motorcycle manoeuvres because the rider has to control two independently operating braking circuits and the motorcycle is stabilized by side and gyro forces. ABS and combined braking systems are designed to support riders while braking. Further dynamic vehicle stability control systems for powered two wheelers besides traction control systems are not known up to now.
Several research projects therefore were carried out to determine possible safety benefits of ABS and VSC for motorcycles.
Test persons were assigned braking tasks with five different brake systems: standard and combined brake system with and without ABS in each case and ABS combined brake with single-lever operation. The stopping distances achieved as well as workload and stress variables for the rider were recorded.
The stopping distances achieved are shorter with ABS than they are without ABS. This also and primarily applies to braking when cornering. It was not possible to establish any significant difference between standard and combined brake. Operation of a combined brake with ABS and with only one brake lever did not show any disadvantage by comparison with a two-lever brake control system. In the case of braking operations without ABS, stress and strain for the rider were significantly higher than in the case with ABS.
In principle, ABS is seen to have the potential to reduce fatalities among motorcycle riders by about 10 %. A socio-economical analysis yielded benefit-cost-ratios of above 4 for motorcycle ABS indicating that this system is highly economically sensible.
ABS thus should be used on all two-wheeled vehicles wherever possible. The ABS system may be designed as a disengageable system.
To assess the technical possibilities for future vehicle stability control systems for motorcycles and the amount of accidents that could be prevented by those systems an accident analysis was carried out. Accidents while cornering without braking have been determined as potentially avoidable by future technical systems. The accidents can be caused by low friction or by raising the lateral acceleration over the possible maximum. About 4 to 8 % of all motorcycle accidents are of this type. Both accident types have been analyzed with driving experiments and computer simulation. The vehicle sideslip angle speed proved to be a robust criterion for recognizing whether a driving situation is critical.
Possibilities for technical systems to influence the critical driving situations were estimated. The roll movement of the vehicle cannot be influenced, because neither the tire side force can be increment-ted nor stabilizing gyroscopes can be built small enough. The vehicle sideslip angle speed can be influenced by braking the front or the rear wheel, thus generating a yaw moment to avoid the dangerous high-side type accidents at friction steps from low to high. The motorcycle accidents influenced by this system are only a subgroup of the mentioned 4 to 8 % of all accidents, so as a result of this study, the potential for future dynamic control systems is estimated very low. Making them mandatory can-not be recommended at present. Further research with regard to driving stability of motorcycles should rather focus on active damping devices.

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