PERSPECTIVES FOR MOTORCYCLE STABILITY CONTROL SYSTEMS

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ABSTRACT

Motorcycle accident figures did not decrease significantly over the last fifteen years, but as the total number of road fatalities decreases, the share of motorcycle fatalities raises and puts motorcycle accident issues in the focus of decision makers. This paper describes the enormous potential of technical measures to help save motorcyclists' lives. It summarizes safety research carried out by the Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) in the last 25 years, including especially the authors' own work in the last five years, and the state of the art in motorcycle control systems. The conclusion is the encouragement of further investigation in motorcycle control systems and mandatory Anti-Lock Brake System (ABS) application on motorcycles, thus making the powered two-wheeler a safer urban transportation system.

Motorcycles are statically unstable. During riding, they are stabilized mainly by two mechanisms. Both stabilizing effects require a possible increase in side force (on the front wheel). They do not work with sliding wheels, which happens on slippery surface. In the event of a locking front wheel, the motorcycle becomes kinematically unstable. A coupled yawing and rolling motion is induced that lets the motorcycle tumble in fractions of seconds.

This instability can be treated by ABS. Recent studies on the impact of ABS on motorcycle accident numbers in Germany show a possible reduction of motorcycle fatalities by at least 10 %. A benefit-cost-analysis reveals a cost-benefit ratio of about 4 for the case of mandatory ABS. However today's systems are not fully qualified for cornering, because they do not take the roll angle into account. Wheel slip control while cornering induces oscillations of steering torque. The vehicle does not capsize as it would without ABS, but the course can be disturbed. One possible control strategy that avoids steering torque oscillations is to switch the brake force distribution during cornering so that the rear wheel is overbraked. Another countermeasure is the adjustment of the steering axis by means of a technical device. The actuator technologies required for these approaches are already available. Recent advances in signal processing and sensor technology have been made so evolution of these systems is expected for the next decade.

In a research project carried out for BASt, a method for the detection of motorcycle critical driving situations has been developed. This method evaluates the vehicle slip angular velocity, utilizing the fact that motorcycles do have almost no slip angle during uncritical driving situations. Roll angle stabilization of a motorcycle with sliding wheels is not possible with today's technology. But with the detection method, in the case of a motorcycle accident (or a near-accident), an automatic warning message to surrounding vehicles can be generated.

Active stabilization of Motorcycles is not possible and will very likely never be possible in the future. Therefore further development, evolution and optimization of ABS and Traction Control System (TCS) are required. Also, the general application of today's ABS systems on motorcycles should highly be encouraged.

1 INTRODUCTION

In its white paper „European Transport Policy for 2010“, the European Commission defines the goal to reduce the traffic fatalities rate in Europe by 50 % in the time period 2001 to 2010. Some (but not all) member states are on course for that goal, regarding the total traffic fatalities rate. Motorcyclist fatalities, however, do not decrease with the same reduction rate, and as a conclusion, the share of motorcyclists on all traffic fatalities increases. Thus, motorcycle accident figures will more and more get into the focus of policymakers.

In this paper, the authors will show how active safety of powered two-wheelers contributes to motorcycle accident reductions and give an overview on measures, state of the art and what can be expected in the future.

One key contributor to the reduction of total traffic fatalities over the last decade are vehicle stability control systems, one of the most known being the Bosch Electronic Stability Control (ESC), see [1], [2]. However, the most sophisticated system available for powered two-wheelers is an Antilock Brake System. Presently it is not designed to work during strong cornering. An Antilock Brake System that allows braking at high lateral accelerations could contribute to lowering the accident rates. The technical foundations for such a system have been laid in research projects carried out on behalf of BASt by the Technical University Darmstadt (Technische Universität Darmstadt, TU Darmstadt) [3]. In a more holistic study, driver behavior during braking [4] and the requirements for future motorcycle brake systems [5] have been investigated, and the potential for vehicle control systems beyond ABS has been assessed [6]. Concluding from this research work, an improvement of Antilock Brake Systems can be achieved and in combination with driver behavior improvements a substantial impact on accident figures can be expected. Research also shows that further control systems comparable to ESC are not feasible on motorcycles.

2 SPECIFIC MOTORCYCLE STABILITY ISSUES

The different and complex driving dynamics of motorcycles in comparison to four-wheeled vehicles are certainly the main issue in designing vehicle stability control systems for motorcycles. Motorcycles are inherently unstable vehicles, their stabilization depends on two mechanisms: if the velocity is high enough, the motorcycles' wheels act as gyroscopes, and for lower velocities, the rider stabilizes the vehicle by handle bar movement. Both mechanisms depend on sufficient friction between the tires and the road. If the friction potential is exceeded, motorcycles can become irreversibly unstable, and also instantaneous loss of gyroscopic effect due to wheel locks can lead to a fall. In contrast to four-wheeled vehicles, motorcycles can become unstable if the front wheel locks even if the gyroscopic effects would still be there. The reason for this is a kinematic instability with growing vehicle slip angles.

A full description of motorcycle dynamics is given in several sources [7], [3]. At this place, only the mentioned driving stability and braking stability issues are discussed. They are important to understand the expected impact of control systems on accident figures.

2.1 Driving Stability

The most obvious difference between four- and two-wheeled vehicles is the banking while cornering. The equilibrium bank or roll angle λ depends mainly on the lateral acceleration. The roll angle as defined in Figure 1 is given as

$$\lambda = \arctan\frac{F_F}{G} = \arctan\frac{\ddot{y}}{g} = \arctan\frac{v^2}{R \cdot g}$$

with the centrifugal force F_F, the weight force G, lateral acceleration $\ddot{y}$, gravity g, cornering radius R and velocity v.

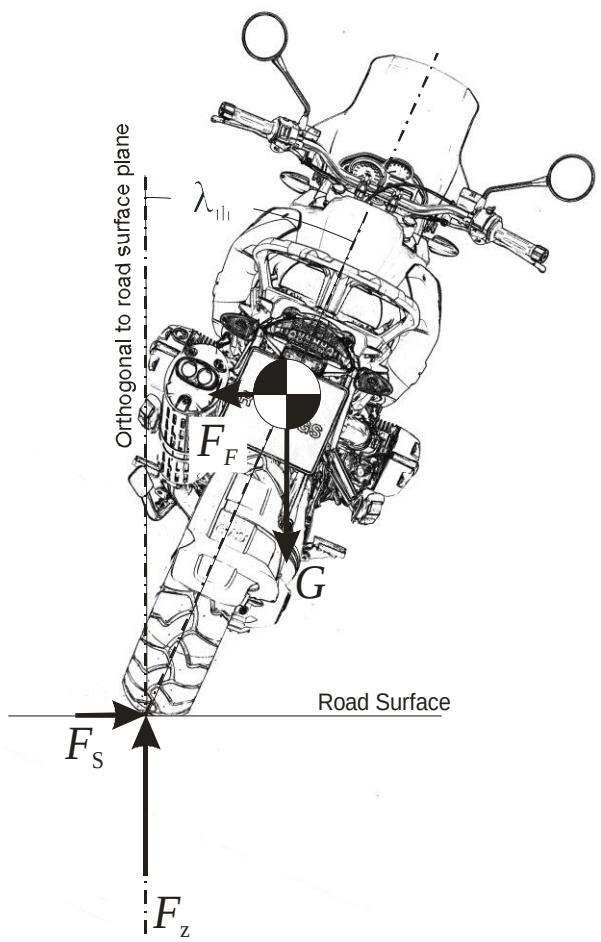

Figure 1: Definition of Roll Angle

The equilibrium for the roll angle is unstable. Small perturbations generate a roll momentum that would either cause a capsize motion or a flip-over of the vehicle.

The bank angular velocity can be controlled by handle bar actuation: whenever the handle bars are turned into the bend, the lateral acceleration is increased and thus the vehicle is lifted, and the other way around.

For velocities above approximately 30 km/h, the gyroscopic coupling mainly of the front wheel connects handlebar movement and bank angular movement in a stabilizing way. Below this velocity, the rider needs to turn the handle bars in order to stabilize the vehicle. Both mechanisms depend on an increase of the vehicle lateral acceleration, and that can only work if there is sufficient friction between road and tire. Stabilization is not present in any case of exceeding the possible friction, which happens e.g. on slippery roads, and also if the accelerating or braking forces are too high. The gyroscopic coupling also vanishes when the front wheel stops turning, e.g. if the brake force is too high and the wheel locks.

2.2 Braking Stability

The brake systems of four-wheeled vehicles are commonly designed to lock the front wheels first. In the case of locked front wheels, the vehicle side-slip angular motion is stabilized by the rear wheels that generate side forces that compensate the side-slip angle [5], [6].

As mentioned, the gyroscopic stabilization of a two-wheeled vehicle vanishes whenever the front wheel locks, so this mechanism cannot be used on two-wheelers. Moreover, the capsize that occurs because of a locked front wheel generates a camber side force on the rear wheel. The sum of the side forces on the rear wheel does not stabilize (and for higher roll angles destabilizes) the side-slip angular movement. Both movements combine to a sudden fall of the motorcycle that can take as little time as 0.2 seconds from upright position and an accident is almost inevitable [5]. During cornering these times will be significantly shorter[1].

As a conclusion, motorcycles become unstable when the front wheel locks because of hard braking, and they become unstable when the road friction is exceeded (e.g. slippery roads).

3 STATE OF THE ART AND BENEFIT OF MOTORCYCLE CONTROL SYSTEMS

3.1 Accident Situation

Motorcycle accident figures (for Germany) stayed almost constant since the mid-nineties. Each year, between 800 and 1.000 fatalities and approximately 30.000 severe injuries occur.

Three facts are significant in comparison with the total accident situation:

1. Wrong brake actuation is a contributor to at least 10% of all motorcycle accidents [8]
2. Motorcyclists brake weaker while cornering [5]
3. Driving accidents (meaning a loss of control occurred prior to the accident) account for about 60% of motorcycle fatalities, but only for 41% of all fatalities (see Table 1) [9]

Table 1: Share of driving accidents on all accidents, figures for Germany 2007.

	Slightly injured[2]	Severely injured	Fatalities
All powered two-wheelers	36,8%	52,5%	60%
Motorcycles (>125 cm³ engine displacement)	40,1%	57,7%	60%
All traffic participants	16,2%	31%	41%

Motorcycle operation itself seems to be a problem in some driving situations. Obviously, braking while going straight ahead (with wrong brake actuation) and while cornering (with weak braking and/or brake steer torque effect, see section 5) are fields where active safety systems can contribute in accident figure reductions. The system of choice for these situations is the Antilock Brake System.

The fact that driving accidents are significantly higher for motorcycles can not only be explained by brake accidents. To address all kinds of driving accidents, traction control, improved ABS that works during cornering and also stability control would be needed.

[1] See e.g. the explanations in 3, S. 149, Figure 106

[2] Official German definition: Accident participants that had to stay in hospital at least for one night are severely injured. Those who were treated at the scene or could leave earlier are slightly injured.

3.2 Motorcycle Control Systems State of the Art and Limitations

Antilock brake systems do help preventing wheel locks, but they are not yet designed to work during strong cornering. This is expected for future Antilock Brake Systems in the new decade that will make use of new sensor technologies.

Motorcycle Antilock Brake Systems are commercially available since 1988. Key milestones were ([10])

- Pure wheel acceleration controllers, two independent channels, one for each wheel (BMW ABS1, ABS2, etc. ([11]).
- Hydraulic integral ABS (Honda Single- and Dual-CBS-ABS) that controls both wheel brakes to ensure a reasonable brake force distribution. These systems have a full hydraulic connection between brake lever and wheel brake.
- Electronic integral ABS (Continental MIB, Bosch ABS-M8). These systems can apply brake pressure on at least one wheel independently from driver input, but still have a hydraulic connection between brake lever and wheel brake.
- Brake-by-wire-system (Honda eCBS [12]), no hydraulic connection between brake lever and wheel brake (under normal operation conditions).

None of the existing systems has a lateral acceleration or bank angle sensor, and thus no system available on the market today can adapt to cornering. No system today is suited for full cornering, because the brake force oscillation on the front wheel that is generated by ABS control induces potentially dangerous steering torque oscillations. Figure 2 shows an ABS control cycle during cornering.

The front wheel slip rises at t = 0 s, a roll angle of approximately λ = 20° and a velocity of approximately v = 65 km/h. Note that the wheel velocity does not become zero, the ABS controller releases the brakes and allows the front wheel to accelerate again.

At the time the front wheel slip rises, friction potential is over-exceeded and the front wheel builds up a significant side-slip angle. In case of sliding wheels, the brake force is about 10% smaller than the maximum brake force, so at the time the wheel starts to lock, the brake force also decreases significantly.

The sum of all components of the steering torque is close to zero, as the braking situation is almost steady-state, but steering torque has a part that is directly connected to brake force (see also section 5). This part decreases proportionally with brake force, but the rider does not adapt his steering torque fast enough and turns the handlebars out of the bend. The same thing happens after the control cycle in the opposite direction, but obviously the rider tried to adapt his steering torque. An effect on roll and yaw rates can clearly be observed, and if this had happened in real traffic, a departure of the lane could have been the consequence.

This example shows that present ABS do not deliver optimal support for the driver while braking in bends.

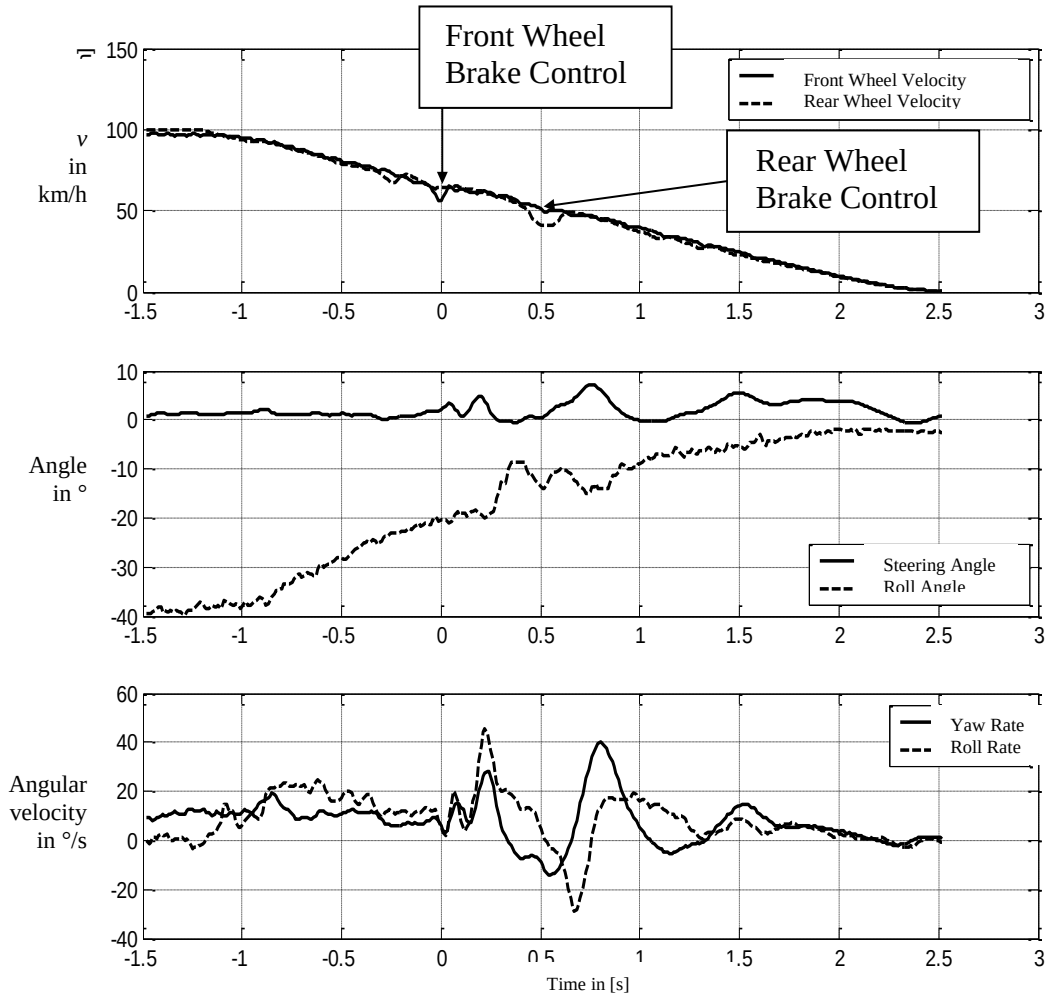

Figure 2: Example of a corner braking situation from [13], S. 378.

Although corner braking is a challenge for vehicle and component manufacturers, the necessary scientific foundations have been laid out already in the mid-nineties by WEIDELE [3]. Their implementation and evolution requires mass production roll angle sensors to adopt to the cornering situation. These sensors are available from 2010 on e.g. in the BMW S1000RR [14].

The mentioned S1000RR control system however uses its roll angle sensors up to now only for traction control, another control system that helps preventing accidents, with the first generation being available on the 1993 Honda Pan-European and the second generation on the BMW R-Series in 2006.

3.3 Estimated Effect of Today's ABS on Future Accident Figures

Braking poses stress on motorcyclists and leads to mental strain. In a research project carried out on behalf of BASt, the mental strain was investigated on a closed test track [15]. Test riders had to brake with different brake systems on the same motorcycle (Standard brake system = independently operated front and rear wheel brakes, Standard brake system with ABS functionality, combined brake system, combined brake system with ABS functionality, combined brake system with only the hand lever) in three different situations (going straight ahead, braking from 90 and 60 km/h and cornering, braking from 50 km/h). The strain was measured indirectly using mainly the heart rate of the test persons.

Results show that braking distances are shorter with ABS, mostly because the brake force is built up faster (straight ahead) or because the brake deceleration is higher (cornering). The rider's strain is higher without ABS. These results clearly show the positive effect of ABS, even on a closed test track.

Other authors estimate ABS on all motorcycles could lower the motorcycle road traffic fatalities by at least 10% [8]. A cost-benefit-study of carried out on behalf of BASt reveals a benefit-cost-ratio of more than four (taking into account the system costs, the effect of ABS on accident figures and the development of accident figures over the next decade) [16].

Taking into account all these results, the mandatory application of ABS on all powered two-wheelers is strongly encouraged. From a society point of view, the benefits are not neglectable, and technical issues can definitely be solved.

4 CONCEPTS BEYOND ABS AND TCS

Another question that arises from motorcycle driving dynamic issues is whether any systems beyond ABS and TCS are feasible. These current control systems control the longitudinal forces on each wheel but have no direct effect on wheel side forces. Future systems that would resemble the ESC for passenger cars or stabilize the roll motion are not feasible for reasons that are shown in this chapter. However, future systems could act as a kind of electronic co-pilot comparable to the aviation state of the art [17].

4.1 Detection of Critical Driving Situations

Critical driving situations are defined by the fact that friction demand due to lateral acceleration is higher than the friction potential. These situations happen in real life e.g. because of wet, slippery or icy road conditions, because of bad road construction (see [18]), because of leafs on the road during autumn or because of sand on the road. In all these situations, the horizontal forces that can be generated by the tires are limited to the product of the friction coefficient and wheel load. Relevant accident situations that derive from the defined situations are mainly cornering accidents without and with braking or accelerating – the latter situations are being dealt with by ABS and TCS. Thus, focus for research are situations without braking or accelerating.

Main requirements for the feasibility of a control system that addresses cornering accidents without longitudinal acceleration are the detection of those situations and methods to stabilize the motorcycle in those situations.

In a research project carried out on behalf of BASt, these accident situations were simulated and analyzed [19]. Cornering accidents without braking are detectable using the vehicle side-slip angle. The side-slip angle of a motorcycle is close to zero in normal driving but rises with a high dynamic in critical driving situations. The side-slip angular velocity criterion developed from the analysis proved to be adequate in critical driving situations (detection of all situations) as well as in uncritical driving situations (no false detection).

Data on the said critical driving situations and also on uncritical driving situations like swerving etc. was gained with a test motorcycle equipped with outriggers and measurement devices as shown in figures Figure 4 and Figure 5.

Figure 3: Test motorcycle equipped with outriggers

Figure 4: Test motorcycle during experiments on slippery surface

Motorcycle tire side-slip and vehicle side-slip angles cannot be measured directly (with the exception of an optical system like the DATRON CORREVIT that still is influenced by the roll angle and needs complex correction methods). A method to determine the actual vehicle side-slip angular velocity $\dot{\beta}$ is the calculation using vehicle velocity $\dot{x}$, vehicle yaw rate $\dot{\psi}$ and vehicle lateral acceleration a_y. These three quantities are connected as follows with the motorcycle treated as a rigid body:

$$\dot{\beta} = \dot{\psi} - \frac{a_y}{\dot{x}}$$

The assumption of a rigid body is not true for a motorcycle. Turning the motorcycle handle bars tilts the line connecting the wheels out of the symmetry plane. This effect has to be taken into account if the measurement unit is placed in the vehicle's symmetry plane. A correction can be done with the handle-bar angular velocity. This is explained in detail in [6].

More complexity derives from the motorcycle roll angle. The lateral acceleration has to be measured with respect to the road plane. For this correction, at least two orthogonal acceleration sensors have to be combined, the roll angle has to be measured and also an assumption of the height of the vehicle's roll axis with respect to the road plane is needed to correctly incorporate the roll angular velocities and accelerations into the correction.

For regular driving situations, the roll axis height will approximately be zero. When the friction coefficient approaches zero, the roll axis approaches the vehicle's center of gravity, and calculating the lateral acceleration with the assumption of a roll axis in the road plane leads to an error.

A reference value for the vehicle side-slip angular velocity $\dot{\beta}$ could be given by measuring the lateral acceleration and roll movement of the vehicle, calculating a friction demand from these quantities and using the tire side-force functions to define the tire side-slip angles. However, it is not possible to robustly use this method because of two main facts: Even if the tire side-slip angles as function of the side-force demand are known, it is not possible to distinguish between the rider's intention to lower the side forces to zero (to achieve a high roll acceleration) or low road friction values. The other fact is that the calculation of the friction demand is very sensitive to axis deviations of the roll angle sensor that can easily occur because of slight pitching motions of the vehicle and other errors.

Driving experiments of critical and uncritical driving situations show a robust detection of critical driving situations using the assumption that $\dot{\beta}$ is almost zero in uncritical driving situations – of course with the exception of the so-called geometric side-slip angle (and also some noise due to sensor errors).

The reference value then is

$$\dot{\beta}_{ref} = -\dot{\delta}_{eff} \cdot \left[\frac{l_r}{l} + \frac{c}{l} \right]$$

with the wheel base l, the distance rear wheel to center of gravity l_r , the front wheel caster c and the steering angular velocity with respect to the road plane $\dot{\delta}$.

Figure 5 shows an example of this calculation method. Extensive testing proves the feasibility of this concept to distinguish between critical and uncritical driving situations.

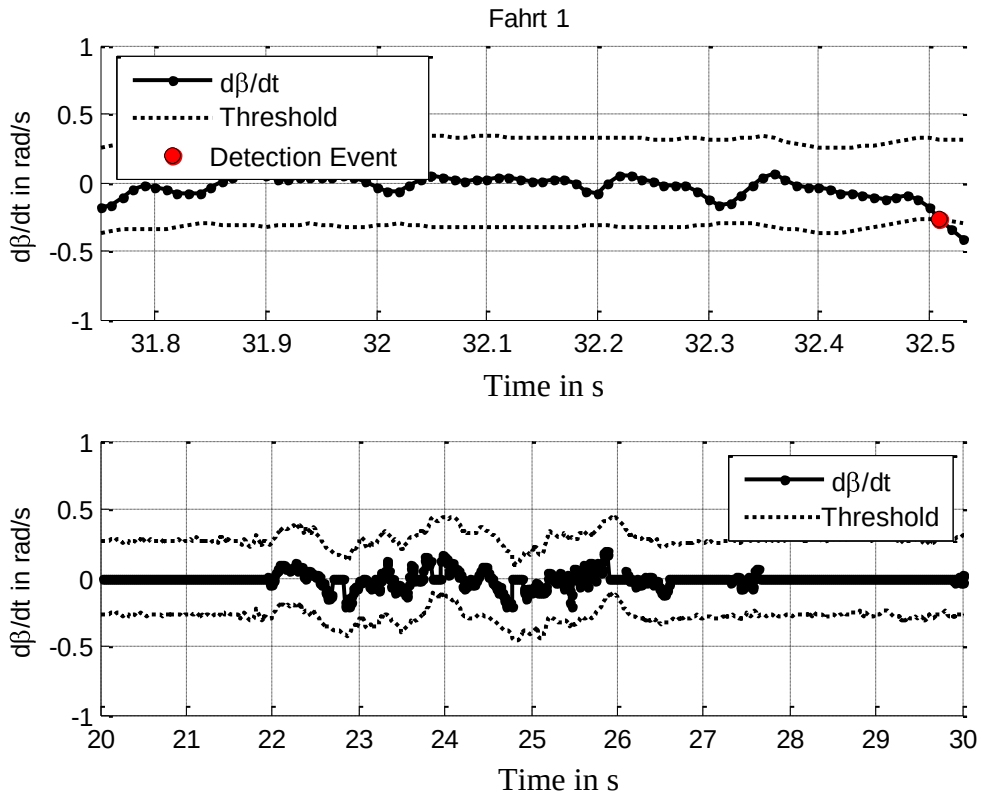

Figure 5: Example of vehicle side-slip angular velocity in critical (upper) and uncritical (lower) driving situations, also showing the boundaries that are made up by reference value and error estimations. Detection occurs for the critical driving situation (upper), but not for the uncritical driving situation (lower).

4.2 Stabilization of a Motorcycle

Goal of any driving dynamics control is to prevent or at least mitigate a critical situation. The roll instability tilts the motorcycle in a very short time and thus limits the time that is available for a control cycle. Primary goal must therefore be the stabilization of the roll angle. If this goal is achieved, the secondary goal has to be the stabilization of the yaw movement of the vehicle and the prevention of the dangerous high-side type accident where the vehicle tilts over to the "high side".

A simplified form of the roll equation for steady-state cornering is

$$\begin{aligned}\Theta_{Roll} \cdot \ddot{\lambda} &= h_{CG} \cdot m \cdot (\sin\lambda \cdot g - \cos\lambda \cdot \ddot{y}) + M_{Gyro} \\ &= h_{CG} \cdot m \cdot g \cdot \sin\lambda - \cos\lambda \cdot \sum F_S + M_{Gyro}\end{aligned}$$

with the roll moment of inertia Θ_{Roll}, the height of the center of gravity h_{CG}, lateral acceleration $\ddot{y}$, tire side forces F_s and the gyroscopic moments M_{Gyro}.

Roll stabilization is achieved when the sum of roll moments is positive with respect to an upright movement (in theory already a sum of 0 leads to a stabilization, but in real situations the motorcycle will still capsize because of the roll angular velocity), either because the side forces generated by the tires or gyroscopic coupling compensate the vehicle's weight moment. Since the wheel side forces in that specific situations cannot be increased, stabilization is only possible by applying gyroscopic moments, however this method puts technical requirements on the gyroscopic devices that are not feasible today.

Another option could be the control of the normal forces of the wheels. The side forces of sliding wheels are directly connected to the wheel load via the friction coefficient:

$$F_s = \mu \cdot F_z$$

Active suspension could admit control of the wheel load of a specific wheel by lifting the vehicle body. For the time the body is accelerated upwards, the wheel load will be increased, and the other way around. For motorcycles, this control method will also raise the friction demand, so the positive effect on side forces is over-compensated. Stabilization cannot be achieved. More details on this topic can be found in [6].

For yaw stabilization the difference of side forces between front and rear wheel needs to be controlled. The reduction of side-forces is possible e.g. by control of the wheel slip. A simplified form of the yaw equation is

$$\Theta_{Yaw} \cdot \ddot{\psi} = F_{s,rear} \cdot l_{rear} - F_{s,front} \cdot l_{front}$$

Control of the yaw movement of the motorcycle is technically feasible. This can help to prevent high-side type accidents. The effect on accident figures however is estimated relatively low.

To sum up, roll angle stabilization of a motorcycle with sliding wheels is not possible with today's technology. However, with the detection method using $\dot{\beta}$ as criterion, in the case of a motorcycle accident (or a near-accident), an automatic warning message to surrounding vehicles could be generated, or this information could be used for on-board passive safety systems like airbags etc., or could also help to improve ABS and TCS with regard to corner braking.

5 POSSIBLE EVOLUTION OF TODAYS SYSTEMS

While today's TCS as on the BMW S1000RR already feature a roll angle sensor and are thus fully cornering-approved, this does not hold true for brake systems currently in the market. As

described in section 3 and also in the following chapter, efficient corner braking is a complex and demanding task that often leads to (near-) accidents. Therefore, a fully cornering-approved brake system in combination with a behavioral change in activating the brakes in curves could change the structure of motorcycle accidents completely rather than just decrease a specific accident type. The analysis of rider behavior patterns and intuitive interaction with new safety concepts and a safe reproduction of relevant critical situations with test persons in the loop are key issues for the testing of new systems, which is not addressed in this section.

5.1 Theoretical Potential of Ideal Corner Braking and Brake Steer Torque Problems during Real Corner Braking

In comparison to straight braking, corner braking under ideal conditions (even road, constant friction potential, ideal brake force distribution, and ideal steering control through the rider) offers a great theoretical potential for shortening stopping distances, illustrated in Figure 6.

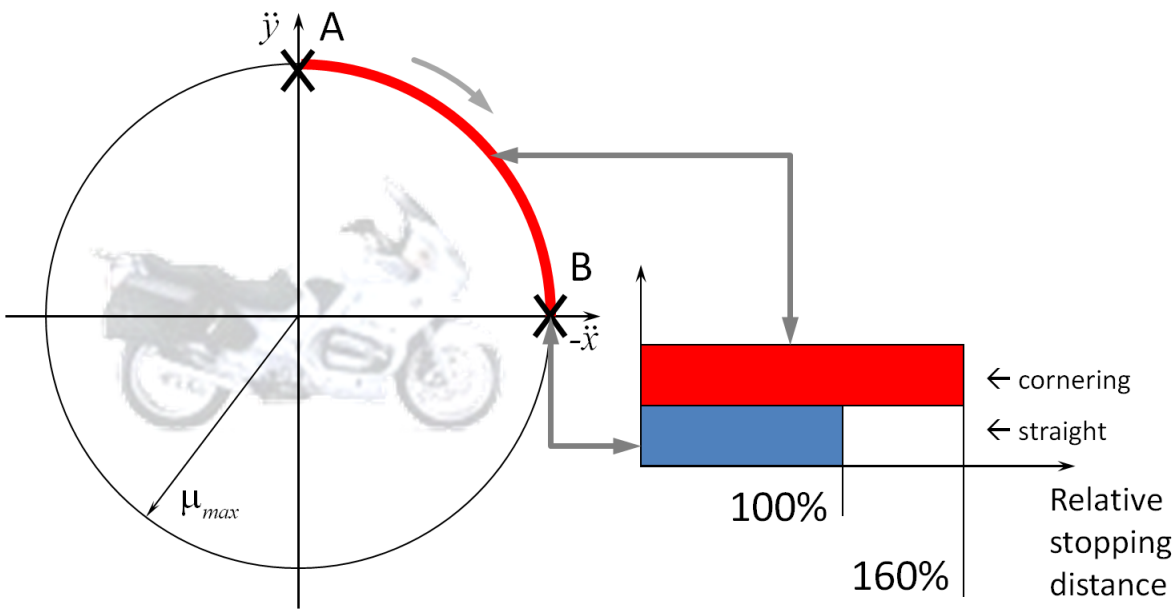

Figure 6: Kamm Friction Circle: $\ddot{x}, \ddot{y}$ =longitudinal and lateral accelerations, respectively. μ_{max} = max. friction potential tire/road. Bar Graph: Comparison of stopping distances (const. radius turn / straight) for a touring motorcycle from an initial velocity of 30 m/s to a stop (model calculation).

Beginning at steady state cornering conditions with 99 % of the overall friction potential used to generate the necessary side forces (high roll angle, point A), the friction potential for braking increases rapidly with decreasing velocity, side forces and roll angle (moving from point A to B on the Kamm Friction Circle). Thus the total braking distance in the above extreme example is just 60 % longer than in straight braking (being in point B all the time).

A great deal of this potential can be accessed by trained riders under controlled conditions, as can be seen in Grand Prix Racing. However, the smallest irregularity can immediately lead to a crash. Unexpected hazardous situations in real traffic can cause the rider to fall in some sort of shock condition, leading to partly unreasonable reactions. Especially the coordination of

conventional brakes under difficult conditions demands too much of the rider's control capabilities (see also quotes[3] from [20]).

Current Combined Brake Systems (CBS) and especially ABS could already be of great help, if the riders would brake hard enough. However, knowing the risk of falling with an over-braked front wheel, most riders do not dare to do so, as was revealed by a naturalistic driving study conducted for BASt in the 1990s ([4]).

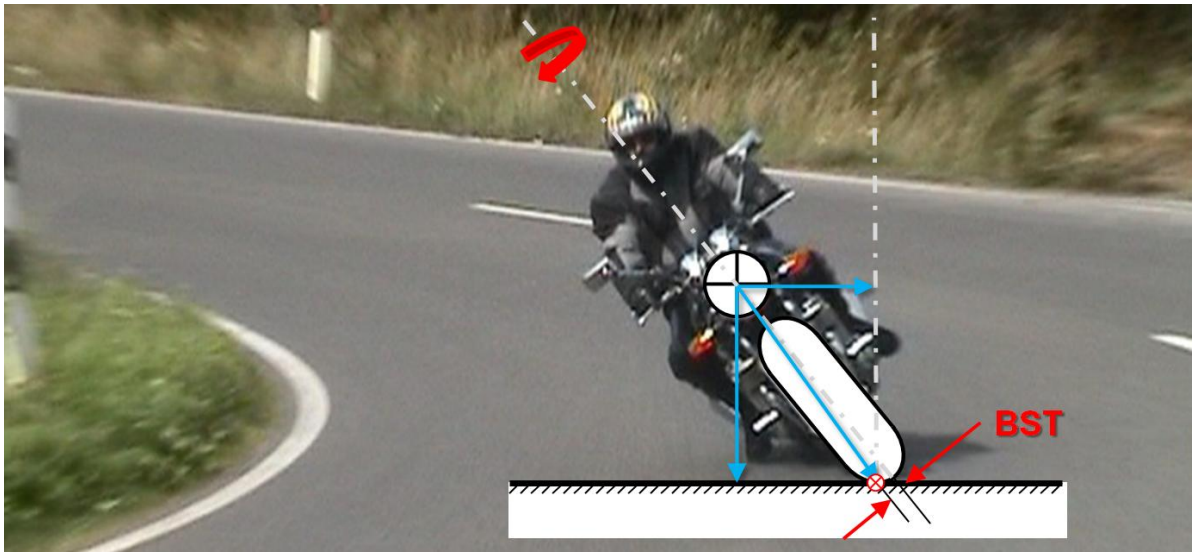

Figure 7: Generation of Brake Steer Torque (BST) through lateral offset between tire contact patch and steering axis in cornering conditions. [Picture: Wolfgang Stern, German Safety Tour Rider Training, ifz Motorcycle Conference, Cologne 2006].

An additional disturbing effect that makes corner braking difficult for the rider is the so called brake steer torque (BST, Figure 7). Due to the tire geometry, the tire contact patches move out of plane with the steering axis. If a brake force is applied, especially at the front wheel, the roll angle dependant contact patch offset to the steering axis generates a BST, that wants to turn the handle bars to the inside of the bend. As described in section 2, this leads to an upward roll movement of the bike, if the rider does not compensate the BST. Given a hazardous situation and high brake force gradients that can also arise from ABS activation, the BST gradient is so high, that the rider is not able to do so (see also Figure 2). Moreover, under shock, the upward roll movement of the bike might confuse the rider. The tendency of the motorcycle to leave its trajectory tangentially often leads to an even stronger application of the brakes, which in turn amplifies the negative side effect (see also quotes[4] from [20]).

In order to take these cornering specific challenges into account, a roll angle sensor is essential for future safety systems.

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[3] 12.1 Findings (page 417): "The typical motorcycle accident allows the motorcyclist just less than two seconds to complete all collision avoidance action." – "Motorcycle riders […] showed significant collision avoidance problems. Most riders would over-brake and skid the rear wheel, and under-brake the front wheel greatly, reducing collision avoidance deceleration. The ability to counter-steer and swerve was essentially absent."

[4] 7.18 Motorcycle Rider Loss of Control (page 150 ff.): "Also, those riders involved in "running wide on a turn loss of control" gave the same impressions of having no plan or strategy for traffic hazards. In those cases where the rider entered a curve at excess speed, the ability to brake effectively was always absent. Also it appeared that most of these riders would lean adversely (they would straighten up rather than lean into the turn) and thereby reduce ground clearance and cornering ability, and many of the collision contact conditions confirmed this impression."

5.2 Approaches to Brake Steer Torque Optimized Corner Braking

The BST that needs to be compensated by the rider can be written as:

BST_{rider} = *(Brake Force) * (Offset between Steering Axis and Tire Contact Patch)*
– Steering Damper Torque
– Active Counter Steer Torque

This equation shows four different means to approach the BST problem:

1) Reducing the Brake Force (→ "Corner Adaptive Brake Force Distribution")
2) Reducing the Offset between Steering Axis and Tire Contact Patch (→ "BST Avoidance Mechanism", BSTAM)
3) Adapting the Steering Damper Characteristics (→ "Advanced (Semi-Active) Steering Damper Control")
4) Providing an Active Counter Steer Torque (→ "Electronic Co-Pilot")

Reducing the Brake Force

Given the fact, that the contribution to the BST effect is much bigger at the front wheel than at the rear, and that the friction-optimal Brake Force Distribution (BFD) becomes anyway more rear wheel oriented under large roll angles (Figure 8), an over-braking of the rear wheel will relieve the front wheel to a certain degree from brake forces and thus reduce the BST effect in partial braking conditions.

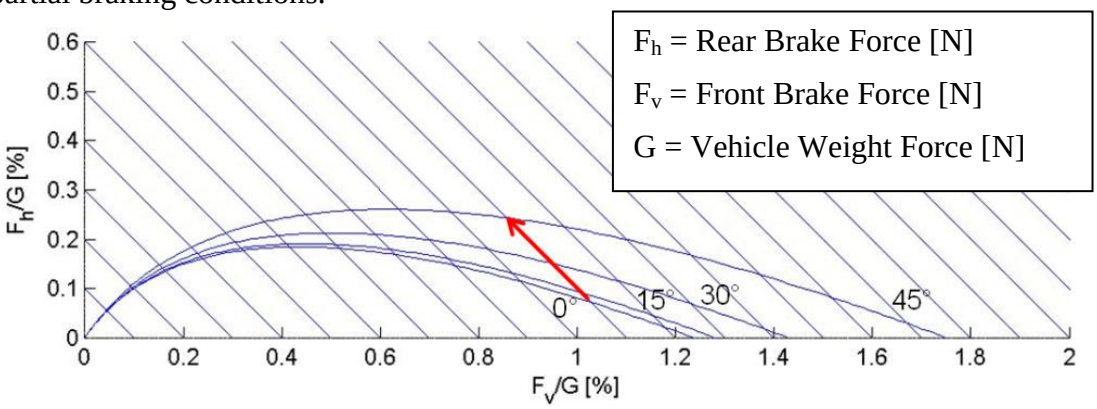

Figure 8: Friction-optimal Brake Force Distribution (BFD) at different roll angles (Model calculation for a sports touring bike equipped with measurement devices): Under cornering conditions, the center of gravity is lower than straight. Since the wheel base remains almost constant, the BFD becomes more rear wheel oriented.

In order to assess the technical effectiveness of such a system, preliminary experiments have been carried out at TU Darmstadt. A series BMW F800S motorcycle (with ABS) has been equipped with measurement devices (among others: steering torque, steering angle, brake pressures, and roll angle sensors) as well as manually adjustable brake lever stops for front and rear brake (Figure 9).

Figure 9: BMW F800S test bike equipped with measurement devices and manually adjustable brake lever stops during corner braking experiments.

The maximum deceleration for rear braking has been experimentally determined to be approximately 0.4 g before the ABS of the test motorcycle is activated. Consequently, this marks the absolute maximum of brake force, that could be shifted from front to rear by means of a corner adaptive BFD. To estimate the benefit for the rider, the front brake lever stop has been adjusted to a point, that allows for the same deceleration in a predefined cornering situation (R = 70 m, v_o = 60 km/h, max. brake pressure ~ 8 bar). However, in preliminary tests (with only two test riders) this seems to be the threshold value to recognize a disturbing BST effect from a subjective rider point of view. (On a scale from 0 to 10, “don’t feel anything” to “out of control” it was ranked between 1 and 2).

Moreover, there is a trade-off between the benefit in BST mitigation and rear wheel stability. On real surfaces an over-braked rear wheel has a strong tendency to wheel lock and thus ABS activation. With conventional ABS this leads to a perpetual alternation between a sliding and rolling rear wheel, causing a harmless and – under controlled boundary conditions – easy to control jerking movement of the bike, which might greatly disturb the rider in real traffic, especially in panic braking. Therefore, the overall positive impact of a Corner Adaptive BFD on the BST effect is estimated to be rather low, from today’s point of view.

However small the potential of such a solution may seem, it is easily accessible by adding a roll angle sensor to current CBS/ABS that offer the possibility to freely transfer brake load from front to rear and vice versa, especially when its ABS control is rather smooth.

Reducing the Offset between Steering Axis and Tire Contact Patch

The second approach allows a variety of opportunities to deal with the BST effect, ranging from mitigation to full compensation and even over-compensation. The principle of function of the so called BST Avoidance Mechanism (BSTAM) is shown in Figure 10.

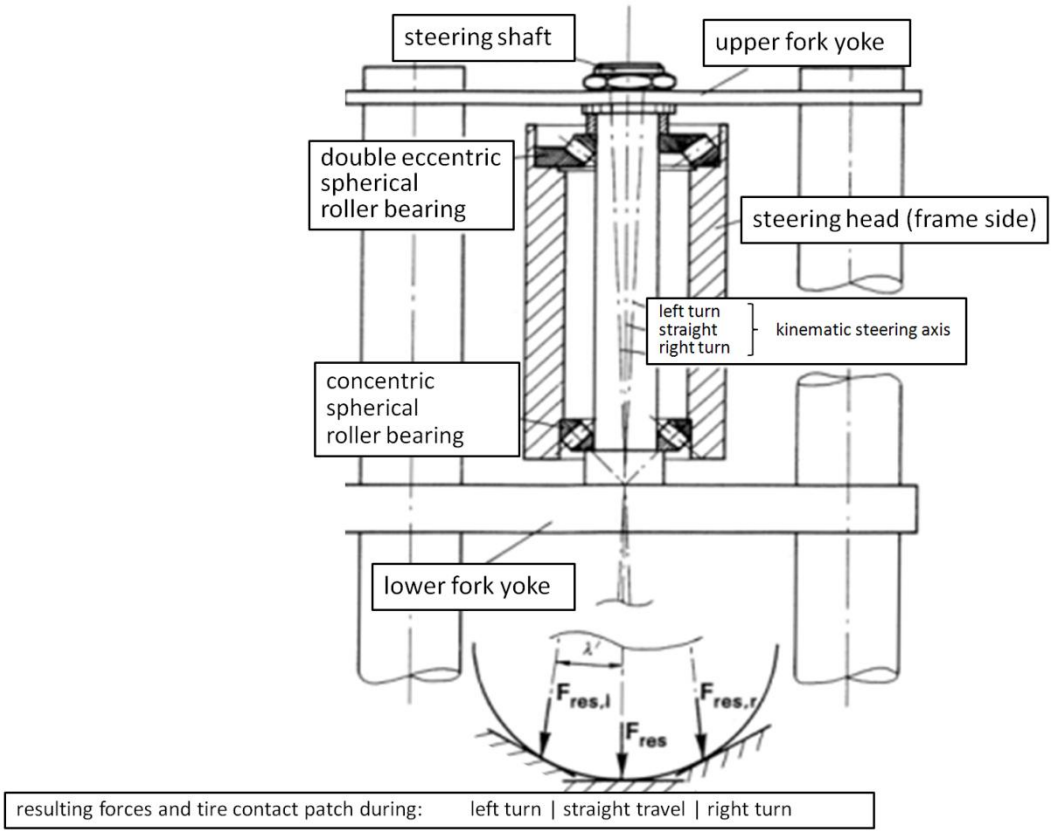

Figure 10: Principle of function of a Brake Steer Torque Avoidance Mechanism (BSTAM) [Picture: 3].

For a full BST compensation the steering axis is moved sideways in such a manner, that it is always in plane with the front wheel tire contact patch by means of a double eccentric layout of the upper spherical roller bearing in the steering head.

A prototype motorcycle equipped with a BSTAM is currently being developed at TU Darmstadt in cooperation with an industry partner in order to investigate its function under various conditions with a rider in the loop.

Adapting the Steering Damper Characteristics

Semi active steering damper control with speed and acceleration dependant damping is already available on the market (e.g. the Honda Electronic Steering Damper (HESD) system in the current CBR-Models). Based on multi sensor information (e.g. brake actuation, roll angle, and others), such systems could be upgraded to selectively react on BST relevant corner braking situations as well. However, damping forces can only be applied when the steering is turned. The function of such a system is therefore limited to BST (gradient) mitigation.

Providing an Active Counter Steer Torque

A fourth solution features an actuator to apply an additional steering toque. Based on a multi sensor layout that – to a certain degree – allows a prediction of the expected disturbing BST, this system allows even more degrees of freedom, than the BSTAM presented before.

Both systems could be the basis for further future safety systems, such as autonomous corner braking or a correction of the current trajectory before a crash, e.g. in order to prepare for

airbag inflation. However, such “Co-Pilot” functions require thorough safety concepts regarding the intuitive interaction with the rider.

6 CONCLUSIONS AND RECOMMENDATIONS

Motorcycling is dangerous compared to driving a four-wheeled vehicle, but on the other hand, it has advantages, not only in terms of resource and energy consumption, and can be one of the future urban mobility solutions. As a consequence, it is highly needed to further improve motorcycle safety systems.

A giant leap towards safer motorcycles is the application of ABS. Even today’s systems that are still improvable would be socio-economically sensible with a benefit-cost-ratio of more than four. The impact on accident figures is estimated to be at least a 10% reduction. Concluding from these results, all motorcycles should be equipped with ABS.

Further systems like active stabilization of Motorcycles are not possible and will very likely never be in the future. Therefore further development, evolution and optimization of ABS and TCS are required as a basis for other advanced safety systems.

It was shown that improvements especially addressing corner braking are possible and could be realized with available technology. However, research is needed to find out how the interaction between drivers and advanced safety systems can be achieved best.

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