MOLIFE – HAZARD DETECTION IN A COOPERATIVE ASSISTANCE SYSTEM FOR MOTORCYCLES

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ABSTRACT

Vehicle-to-vehicle communication promises a large safety benefit for motorcycles. Furthermore, new motorcycles are equipped with an increasing number of vehicle dynamics sensors (e.g. wheel speed sensors, gyro sensors). These deliver information about the current driving state variables.
Hence, the *Institute of Automotive Engineering at Technische Universität Darmstadt* and *carhs.communication* are in the process of researching the fundamentals of a communication-based warning system for motorcycles. This system generates sensor-based or manually entered warning messages and sends these to other motorcyclists using wireless communication devices. In this way, riders can receive early warnings of road hazards. In order to detect hazards based on standard sensors, new methods were developed, which are presented in this paper.

An analysis of an accident database and a motorcycle rider survey revealed the following main causes for accidents that would be avoidable using a system such as that investigated here:

- Roadway damages, e.g. unevenness, ground waves, transversal ruts, pot holes
- Obstacles on the road, such as broken down vehicles behind a curve
- Excessive speed in curves, especially in irregular road conditions
- Friction steps caused by oil, gravel sand, bitumen

Driving dynamics for the above mentioned situations were analyzed. New criteria were derived and used to generate warning messages based on vehicle dynamics sensor information. In order to validate the criteria, over 500 test drives were conducted.
To detect hazards caused by individual roadway damages, a new criterion was derived based on the measurement of the vertical wheel acceleration. With this criterion, hazard detection becomes independent of hazard type and shape.
Obstacles are detected by identifying evasive maneuvers. These are distinguished from other maneuvers by means of a correlation factor, determined on the basis of a previously defined standard maneuver and the current driving state.
In a previous study, the vehicle side-slip angle velocity was found to be a criterion to detect critical driving situations during cornering. These situations are caused by friction steps or by exceeding the maximum lateral acceleration. The current study adapts this criterion for use in a communication-based warning system.
Friction steps and low friction (during straight driving) are detected by evaluating braking activity and longitudinal acceleration.

In addition to methods for hazard detection, a methodology to design an appropriate HMI was also developed and validated. To increase market acceptance, an additional comfort-oriented functionality was implemented und tested. This function is based on the same technology as the safety function.

INTRODUCTION

The accident rate of motorcycles has decreased very slowly compared to the accident rate of passenger vehicles and is still high [1]. The possibilities of passive safety systems for motorcycles are limited. Consequently, focus is placed on active safety systems. This results in an increase of vehicle dynamics sensors in motorcycles.

One type of active safety systems are communication-based systems (also known as cooperative systems). These are assumed to have a high accident avoidance potential, especially when employed as forward looking systems.

This was motivation behind developing a communication-based safety system for motorcycles that uses data from already existing vehicle dynamics sensors for further applications.

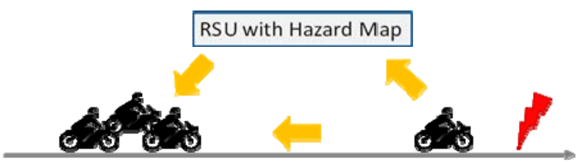

Figure 1: Schematic of the basic function of a communication-based warning system (RSU: Road Side Unit)

The basic function of a communication-based warning system is shown in Figure 1. Hazards are detected by the motorcycle sensors or the rider. Based on this, a warning message is generated and transmitted directly or via a road side unit (RSU) to other motorcycles whose riders are then warned. In order to develop such a system, research is needed in the following areas:

- Identification of hazards which lead to accidents that could be avoidable using a system such as that studied here.
- Analysis of driving behavior in hazardous situations (as the basis for generating warning messages, based on an evaluation of the information from vehicle dynamics sensors).
- Development of a methodology to find and compare appropriate warning elements (human-machine interface) for a communication-based warning system in motorcycles.
- A concept for market introduction, as a minimum degree of market penetration is required for most functions.
- Development of an additional comfort oriented functionality to increase market acceptance using the same technology.

These are the issues investigated in the "MoLife" project, a cooperation project of the *Institute of Automotive Engineering at Technische Universität Darmstadt* and *carhs.communication GmbH*. The present paper concentrates on the results of the second area mentioned above: analysis of driving behavior in hazardous situations. The findings from investigations into the other areas are briefly summarized. Details can be found in other publications of the authors.

In addition to the issues mentioned, a management system is needed for warning messages sent to and from numerous and varied vehicles. The dilemma of data security and privacy is another important point that needs to be regarded. However, these are general issues of vehicle communication and are not investigated within MoLife.

STATE OF THE ART

A large number of communication-based warning system prototypes already exist. Most of these were developed in research projects (e.g., IVHW [2], CarTalk 2000 [3], WILLWARN [4]). Such applications concentrate mainly on cars. Warning messages are generated based on an evaluation of information obtained from environmental sensors and vehicle dynamics sensors. Some systems also use the driver as a "sensor".

Existing communication-based driver assistance systems for motorcycles [5] have demonstrated the feasibility of such systems for motorcycles and have indicated a high potential to avoid accidents. These systems concentrate on the avoidance of intersection accidents. An exception is one application, which gives a warning when approaching roadworks [6]. The systems are based on the evaluation of the relative position and the interaction between motorcycles and cars or motorcycles and road side units.

HAZARD IDENTIFICATION

An analysis of the GIDAS accident database and a motorcycle rider survey were conducted. These revealed the following main causes for accidents that would be avoidable with a system such as that investigated here:

1) Roadway damage, e.g. unevenness, ground waves, transversal ruts, pot holes
2) Obstacles on the road, such as broken down vehicles behind a curve
3) Excessive speed in curves, especially in irregular road conditions
4) Friction steps caused by oil, gravel sand, bitumen

Table 1 shows the number of potentially avoidable accidents in the GIDAS database (till 2007) for all powered two-wheelers (PTWs) and for PTWs with a displacement larger than 125 cc. For the first category 6.7% and for the second category 6.0% of accidents contained in the GIDAS database would have been avoidable.

Table 1: Number of potential avoidable accidents in the GIDAS database

accident class	all (n=1411)	> 125 cc (n=729)
1)	20	9
2)	14	7
3)	23	11
4)	38	17
total	**95 (6.7%)**	**44 (6.0%)**

Because, in comparison to official statistics, accidents with certain characteristics (e.g. urban accidents with fatalities) are overrepresented in GIDAS database, a weighting of the accident data was conducted. However, the resulting accident avoidance potential is only slightly higher. A description is, therefore, omitted. A more detailed description about the hazard identification (including literature survey, analysis of the accident database and rider interviews) can be found at [7].

ANALYSIS OF DRIVING DYNAMICS FOR HAZARD DETECTION

The results of the accident database analysis and the rider interviews show that the identified hazardous situations are not negligible. Therefore, driving dynamics for the following situations are analyzed to determine criteria as a basis for generating warning messages:

- roadway damage
  - individual roadway damage
  - unevenness
- obstacles on the road
- friction steps on straight road sections
- friction steps and excessive velocity during cornering

Individual Roadway Damage

Analysis

Typical individual roadway damages are, for example, ground waves or pot holes. It is assumed that a high effort is needed to recognize the type and shape of such damage using vehicle dynamics sensors. The task, therefore, was to find a criterion, which characterizes individual roadway damage without determining its type or shape.
Cucuz [8] demonstrates that, for single roadway damages, drivers' perception depends mainly on the vertical velocity, which impacts on the driver. This indicates that the unevenness velocity (derivative of unevenness height) mainly influences the riders' perception. As the transfer characteristics of the wheel are approximately neutral in a broad frequency range $(f = 1...10 \text{ Hz})$, for this range, the unevenness velocity is approximately equal to the vertical wheel velocity $\dot{z}_W$. Therefore, a criterion KW is developed, which is based on the vertical wheel velocity $\dot{z}_W$. In the following, the determination of this criterion is described, as shown in Figure 2. For reasons of clarity, details of signal processing are omitted.

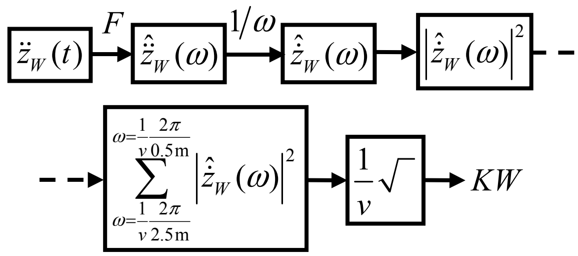

Figure 2: Determination of a criterion characterizing individual roadway damages

The vertical wheel velocity $\hat{\dot{z}}_W$ can be calculated based on the measured vertical wheel acceleration $\hat{\ddot{z}}_W$ (sampling rate: $F_S = 100\ \text{Hz}$) by multiplication by $1/\omega$, the same as an integration. Pre tests showed that typical roadway damages lead to spring-and-damper reactions with a wave length between 0.5 m and 2.5 m. With this assumption, the sum of the energy spectral density (ESD) amplitudes of the vertical wheel velocity (in this frequency range) is a measure for the excitation energy of the damage. Extracting the square root and division by longitudinal velocity v lead to the criterion KW, which is independent of the damage type and shape and also of longitudinal velocity.

<u>**Validation**</u>

Figure 3: Obstacles: low speed bump, high cleat, duct cover, high cosine wave

Seven different obstacles were constructed. To simulate a broad group of typical individual roadway damages, height h, length L and shape (steep, round) are varied in a range assumed to be typical for individual roadway damages. Figure 3 shows some obstacles, all obstacles are listed in the following:

- D1: duct cover $(h = 38\ \text{mm},\ L = 0.5\ \text{m})$
- D2: high cleat $(h = 48\ \text{mm},\ L = 0.048\ \text{m})$
- D3: low cleat $(h = 32\ \text{mm},\ L = 0.048\ \text{m})$
- D4: high cosine wave $(h = 80\ \text{mm},\ L = 1.8\ \text{m})$
- D5: low cosine wave $(h = 40\ \text{mm},\ L = 1.8\ \text{m})$
- D6: high speed bump $(h = 70\ \text{mm},\ L = 0.28\ \text{m})$
- D7: low speed bump $(h = 35\ \text{mm},\ L = 0.21\ \text{m})$

For validation, the obstacles are driven over at different speeds. The speed range is chosen according to the test rider's experience and sensor characteristics. For example, evaluations as critical maneuver or clipping of the sensor $(\ddot{z}_W > 160\ \text{m/s}^2)$ define the maximum speed.
Based on the measured vertical wheel acceleration, the criterion KW is determined as described above. Table 2 shows the determined average values of KW and its standard deviation $\sigma(KW)$.

Table 2: Determined average values and standard deviation of the criterion KW for various kinds of obstacles

Obstacle	v in km/h	$\overline{KW}$	$\sigma(KW)$
D1 (n=15)	30 … 70	0.027	0.004
D2 (n=8)	15 … 50	0.017	0.002
D3 (n=9)	15 … 50	0.012	0.002
D4 (n=15)	10 … 50	0.048	0.008
D5 (n=12)	20 … 80	0.022	0.004
D6 (n=8)	10 … 30	0.036	0.006
D7 (n=15)	20 … 60	0.016	0.002

Standard deviations account for 11% to 18% of the criterion KW. For hazard detection in a warning system, this is an acceptable range. The criterion's independence of longitudinal velocity v is, therefore, proven for the mentioned application.

In order to demonstrate that the criterion KW is a measure for the felt hazardousness of individual roadway damages, a test-subject study with 13 experienced motorcycle riders was conducted. The riders were asked to drive over the mentioned obstacles. Starting with a speed of $v = 10$ km/h , they increased their speed in steps of 10 km/h till they felt uncomfortable. After finishing this task, they were asked at which speed they wanted to be warned (when reaching such an obstacle). The results are shown in Table 3 and Figure 4.

Table 3: Warning speed for investigated obstacles, determined through a test-subject study (n=13)

Obstacle	$\tilde{v}$ in km/h	$\sigma(v)$ in km/h
D1	30	8.2
D2	41	13.8
D3	48	8.4
D4	22	11.8
D5	42	13.9
D6	22	5.9
D7	44	8.8

Based on these results, it is concluded that a higher KW value generally leads to a lower average warning speed. This indicates that the criterion is a measure for the felt hazardousness of roadway damage, independent of its type and shape. A more detailed conclusion about the dependency between v and KW cannot be made at the current state of research.

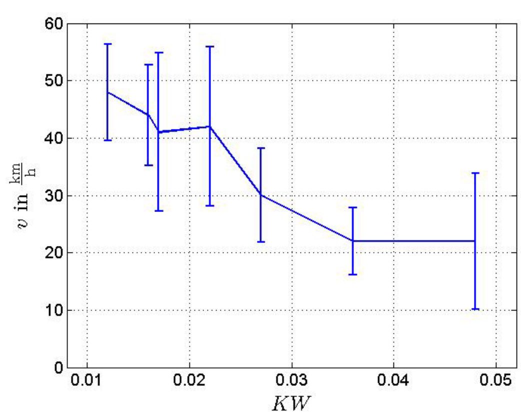

Figure 4: Dependency between v and KW (error bars for the determination of KW are not shown)

Unevenness

__Analysis__

In Germany, the longitudinal unevenness of pavement is generally characterized by the general unevenness index *Allgemeiner Unebenheitsindex* (*AUN*). It is calculated by determining the power spectral density (PSD) of unevenness height $\Phi_h(\Omega)$. The PSD can be approximated depending on waviness w and distance-related angular frequency Ω as following [9]:

$$\Phi_h(\Omega) = \Phi_h(\Omega_0)\left(\frac{\Omega}{\Omega_0}\right)^{-w}$$

The AUN is defined as PSD at the characteristic angular frequency $\Omega_0 = 1$ rad/m :

$$AUN = \Phi_h(\Omega_0)$$

The AUN increases with longitudinal unevenness. This can be a criterion for hazard detection. The determination of the AUN is generally based on a measurement of unevenness height h. Optical sensors are used. In this study, an approach is implemented, which uses sensors for a measurement of the vertical wheel acceleration $\ddot{z}_W$.

Figure 5 demonstrates this approach. For clarity reasons, details of signal processing are omitted. It is assumed that transfer characteristics of the wheel are neutral (in the frequency range $f = 1...10$ Hz). Because of this, the determined PSD is only valid for a certain bandwidth.

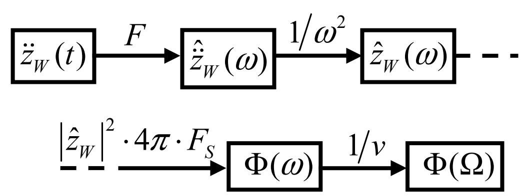

Figure 5: PSD determination based on measurement of vertical wheel acceleration

First, measured acceleration signal $\ddot{z}_W(t)$ (sampling rate: $F_S = 100$ Hz) is Fourier transformed into frequency domain and multiplied by ω^{-2}, the same as a twice integration, to obtain wheel travel $\hat{z}_W(\omega)$. Squaring and multiplication by 4π and sampling frequency F_S lead to PSD, depending on time-related angular frequency ω. Division by velocity v yields the PSD depending on distance-related angular frequency Ω (under the assumption of constant velocity). The AUN value is the PSD value at the characteristic angular frequency $\Omega_0 = 1\ 1/\mathrm{m}$ of a best-fit line.

Validation

For validation of the described method, test drives on 19 roads with known AUN values ($AUN = 1$ to $AUN = 28$) were conducted. Figure 6 shows the measured PSD for three different types of roads. The determined AUN value is the PSD value at the characteristic angular frequency $\Omega_0 = 1\ 1/\mathrm{m}$ of a best-fit line.

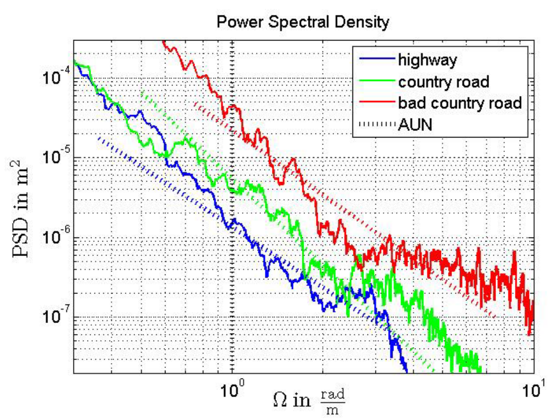

Figure 6: PSD/AUN for three different types of roads

For all test drives, the maximum error of the AUN value does not exceed 20%. It is assumed that such a rough determination of the AUN is sufficient as a basis for the generation of warning messages. Riders do not want to know the exact AUN value. They just want to be warned of bad road conditions. This leads to the conclusion that the presented method is suitable for the mentioned application.

Obstacles on the Road

Analysis

It is assumed that suddenly appearing obstacles on the road, e.g. broken car behind a curve, lead to typical driving maneuvers. One of these is an evasive maneuver. It is concluded that obstacles on the road can be recognized by detection of evasive maneuvers. These maneuvers were investigated more in detail. A literature research leaded to the following findings:

- According to Burg [10], the evasion time t_{evas} of a motorcycle is (in dependence of the lateral acceleration a_y) about 2-2.5 s (excluding stabilization phase).
- In Rauscher [11] the evasive maneuver is divided into three phases: initiation phase, evasive phase, stabilization phase. The following approximation was investigated to determine the evasion time t_{evas} (depending on lateral displacement B and lateral acceleration a_y):

  $$t_{evas} = t_1 + \sqrt{\frac{B}{a_y}} + t_3$$

  $t_1 = 0.7...0.9$ s $t_3 = 0.9...1.2$ s
- According to Spiegel [12], a roll angle of $\lambda = 20°$ is not exceeded by "normal" riders in "normal" driving situations. This is equivalent to a lateral acceleration of $a_y = g \cdot \arctan \lambda = 3,6\,\mathrm{m/s^2}$.
- In Hohm [13], it is assumed that a lateral acceleration of $a_y = 2.2\,\mathrm{m/s^2}$ is not exceeded during over-taking maneuvers of cars.

Based on these findings, a "standard evasive maneuver" with the following characteristics is defined:

- The maneuver can be described by 1.5 periods of a sine wave.
- The first and the third amplitude are smaller than the second amplitude (e.g., damped by a Hanning window).
- The evasive time is $t_{evas} = 2.75$ s . This leads to a period of $T = \frac{2.75}{1,5}\mathrm{s} \approx 1,8$ s .
- The maximum roll angle is $\lambda = 20°$. This yields a maximum roll rate of $\hat{\dot{\lambda}} \approx 80\,°/s$.

This results in the following equation describing the "standard evasive maneuver":

$$\dot{\lambda}^* = \left(0.5 + 0.5\cos\frac{t}{2.75\ \text{s}}\right) \cdot 80\frac{^\circ}{\text{s}} \cdot \sin\left(\frac{2\pi}{1.8\ \text{s}} t\right)$$

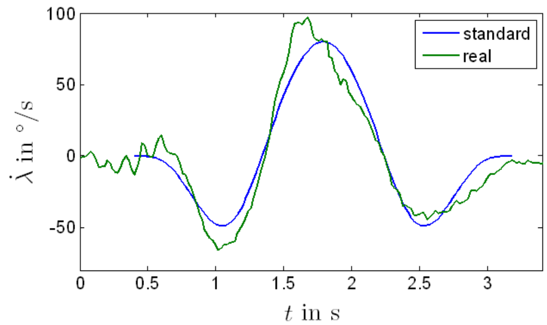

Figure 7: Roll rate of the "standard evasive maneuver" and a real evasive maneuver

Figure 7 shows the roll rate of the standard maneuver and of a real maneuver. **To detect evasive maneuvers, the course of the measured roll rate $\dot{\lambda}$ is correlated with the roll rate of the standard maneuver $\dot{\lambda}^*$. The cross correlation function $\Psi_{\dot{\lambda}\dot{\lambda}^*}(\tau)$ is determined as follows:**

$$\Psi_{\dot{\lambda}\dot{\lambda}^*}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T \dot{\lambda}(t)\dot{\lambda}^*(t+\tau)dt$$

Based on this correlation, a factor with values between 0 (no match) and 1 (exact match) is determined. This correlation factor is calculated as follows:

$$c_{evas} = \frac{\left(\max\left(\Psi_{\dot{\lambda}\dot{\lambda}^*}\right)\right)^2}{\max\left(\max\left(\Psi_{\dot{\lambda}\dot{\lambda}}\right), \max\left(\Psi_{\dot{\lambda}^*\dot{\lambda}^*}\right)\right) \cdot \max\left(\Psi_{\dot{\lambda}^*\dot{\lambda}^*}\right)}$$

To ensure reliability, the maneuver has to be completed, but only the maximum value of the cross correlation function $\max\left(\Psi_{\dot{\lambda}\dot{\lambda}^*}\right)$ is relevant. To normalize the factor, it is divided by the maximum of the auto correlation functions of the measured and the "standard" roll rate. To avoid high values of c_{evas} at low measured roll rates, in this cases it is divided by $\max\left(\Psi_{\dot{\lambda}^*\dot{\lambda}^*}\right)$ instead of $\max\left(\Psi_{\dot{\lambda}\dot{\lambda}}\right)$.

Validation

To validate the explained method, various kinds of maneuvers are conducted. These include simple driving maneuvers, evasive maneuvers and dynamically similar maneuvers (e.g. overtaking, slalom) at speeds from 30 km/h to 100 km/h. A consecutive list of the conducted maneuvers reads as follows:

- A: Straight driving (n = 25)
- B: Cornering (n = 31)
- C: Overtaking after following another vehicle (n = 13)
- D: Overtaking after following another vehicle and wobbling (n = 15)
- E: Free overtaking (without following another vehicle before) (n = 13)
- F: Slalom (n = 26)
- G: Evasive maneuver without a preceding braking (n = 36)
  - speed: $v = 30\,\text{km/h} \ldots 100\,\text{km/h}$
  - lateral offset: $B = 1\ \text{m} \ldots 2\ \text{m}$
  - lateral acceleration: $a_y = 3\,\text{m/s}^2 \ldots 8\,\text{m/s}^2$
- H: Evasive maneuver with a preceding braking (n = 18)

Table 4 gives the minimum and maximum determined values of the correlation factor c_{evas} for the conducted maneuvers. For all evasive maneuvers (n=54), the determined correlation factor is at least 0.56. For all other maneuvers (n=123), a value of 0.36 is not exceeded.

Table 4: Determined values of c_{evas}

maneuver	min(c_{evas})	max(c_{evas})
A: straight driving	0.00	0.01
B: cornering	0.01	0.09
C: overtaking	0.04	0.35
D: overtaking	0.14	**0.36**
E: free overtaking	0.05	0.33
F: slalom	0.21	0.35
G: evasive maneuver	**0.56**	0.92
H: evasive maneuver	0.75	0.92

Friction Steps on Straight Road Sections

Analysis

Maximum utilization of grip without using control systems leads to locking of the wheels (during braking) or to a high wheel slip (during accelerating). Modern motorcycles are equipped with ABS or traction control. These systems control the slip. Nevertheless, according to Weidele [14] the activity of these systems indicates the maximum utilization of grip.

In this case, the maximum friction coefficient $\mu_{\max}$ can be approximated by the quotient of wheel load G_i and longitudinal force F_x (lateral forces are neglected):

$$\mu_{\max} = \frac{\sqrt{F_x^{\,2} + F_y^{\,2}}}{G_i} = \frac{F_x}{G_i}$$

The wheel loads of the front wheel G_f and the rear wheel G_r are calculated as following, depending on wheel base l, distance center of gravity to rear/front wheel patch l_r / l_f, height of center of gravity h_c, gravity constant g, vehicle mass and vehicle longitudinal acceleration $\ddot{x}$:

$$G_{f,dyn} = \left(m \cdot g \cdot \frac{l_r}{l} \right)_{stat} - m \cdot \ddot{x} \cdot \frac{h_c}{l}$$

$$G_{r,dyn} = \left(m \cdot g \cdot \frac{l_f}{l} \right)_{stat} + m \cdot \ddot{x} \cdot \frac{h_c}{l}$$

The determination of the friction coefficient is described consecutively, for the various situations.

In cases where **ABS controls both wheels**, the braking force is transmitted to the road over both wheels. This yields:

$$\mu_{\max} = \frac{F_x}{G_f + G_r} = \frac{m \cdot \ddot{x}}{m \cdot g} = \frac{\ddot{x}}{g}$$

In situations where **ABS controls only the front wheel** and the rear wheel is not braked, the braking force is transmitted to the road over the front wheel.

This implies:

$$\mu_{\max} = \frac{F_x}{G_f} = \frac{\ddot{x}}{g \cdot \frac{l_r}{l} - \ddot{x} \cdot \frac{h_c}{l}}$$

If ABS controls only the rear wheel and the front wheel is not braked, the braking force will be transmitted to the road over the rear wheel. This results in:

$$\mu_{\max} = \frac{F_x}{G_r} = \frac{\ddot{x}}{g \cdot \frac{l_f}{l} + \ddot{x} \cdot \frac{h_c}{l}}$$

With these assumptions, the friction coefficient $\mu_{\max}$ can be determined just by using the following signals:

- activity of ABS or traction control
- longitudinal acceleration $\ddot{x}$

For the further investigations, the friction coefficient was divided in the following three classes:

critical friction: $\mu \le 0.3 = \mu_{crit}$

low friction: $0.3 < \mu \le 0.6 = \mu_{low}$

normal friction: $\mu \ge 0.6 = \mu_{norm}$

The detection of low and critical friction is based on the continuous determination of the friction coefficient (during ABS or traction control) as described above. Where the determined friction coefficient falls for at least 200 ms under the upper limit of one friction class, it is assigned to this class.

This method is demonstrated taking an example braking maneuver on a friction step from $\mu = 1.1$ to $\mu = 0.5$, shown in Figure 8. At $t = 11.45$ s, ABS starts controlling the wheel slip. The friction coefficient is determined from here on (till the end of ABS-control at $t = 12.37$ s). During that period, the determined friction coefficient falls under the upper limit of critical friction μ_{crit}, but for less than 200 ms. Hence the friction coefficient is lower than the upper limit of low friction μ_{low} for more than 200 ms, this results in an assignment of the friction step to the class of low friction.

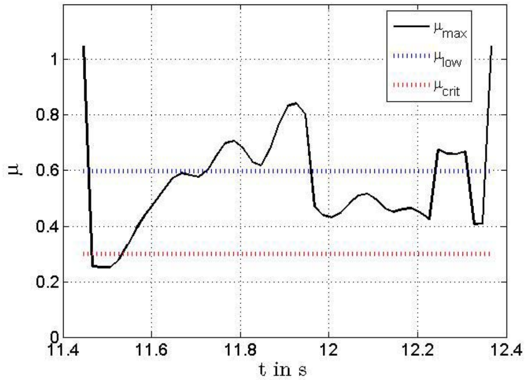

Figure 8: Determination of the friction coefficient during ABS-control at a braking maneuver $(v_0 \approx 50\ \text{km/h})$ on a friction step from $\mu = 1.1$ to $\mu = 0.5$.

Validation

For validation of the described method, braking maneuvers on roads with various known friction coefficients were conducted. The friction coefficient was determined with the described method. Consecutively, the conducted maneuvers are:

- braking on “critical” and “low” friction (μ = 0.2; 0.5)
- braking on friction steps (from μ = 1.1 to μ = 0.2; 0.5; 0.7)
- braking on “normal” friction (μ = 0.7; 1.1)

Table 5 and Table 6 show the results of the validations tests for braking maneuvers using both brakes and using only the front brake. For nearly all test runs (103 of 109), the correct friction class could be determined with the described method.

Table 5: Friction detection (both brakes)

friction coefficient (number of tests)	detection		
	normal	low	critical
μ = 1,1 (n=12)	12	0	0
μ = 0,7 (n=17)	15	2	0
μ = 0,5 (n=12)	1	11	0
μ = 0,2 (n=12)	0	2	10

Table 6: Friction detection (front brake)

friction coefficient (number of tests)	detection		
	normal	low	critical
μ = 1,1 (n=12)	12	0	0
μ = 0,7 (n=20)	19	1	0
μ = 0,5 (n=12)	0	12	0
μ = 0,2 (n=12)	0	0	12

Friction Steps and Velocity during Cornering

Analysis

Seiniger [15] investigated the potential of future vehicle stability control systems for motorcycles. Two types of accidents were mentioned. One is caused by a drop of the road friction coefficient (friction step, type 1); the other one is caused by exceeding the maximum lateral acceleration (type 2). The vehicle side-slip angle velocity $\dot{\beta}$ was found to be a criterion for detecting these critical driving situations.

On the assumption that in uncritical situations all components other than geometric side-slip velocity are negligible, the (nominal) vehicle side-slip angle velocity $\dot{\beta}_{nom}$ is described depending on caster n, wheel base l, distance center of gravity to rear wheel patch l_r and horizonted steering angle velocity $\dot{\delta}$ as follows:

$$\dot{\beta}_{nom} = \frac{l_r + n}{l}\dot{\delta}$$

In general, (actual) vehicle side-slip angle velocity $\dot{\beta}_{act}$ is determined depending on the horizonted, measured yaw rate $\dot{\psi}$, lateral acceleration a_y and longitudinal velocity v as follows:

$$\dot{\beta}_{act} = \frac{a_y}{v} - \dot{\psi}$$

Taking into account a measurement uncertainty $\dot{\beta}_{uncertain}$, this yields the following criterion for detecting unbraked cornering accidents:

$$\left| \left(\frac{a_y}{v} - \dot{\psi} \right) - \left(\frac{l_r + n}{l}\dot{\delta} \right) \right| \geq \dot{\beta}_{uncertain}$$

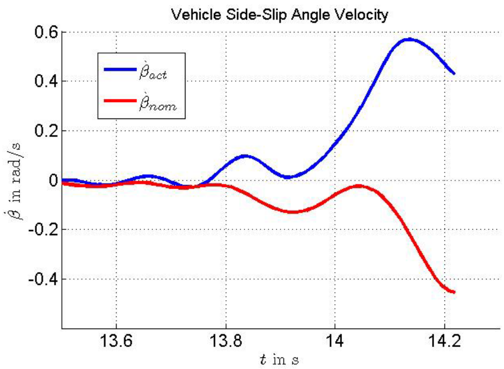

Figure 9: Vehicle side-slip angle velocity for an unbraked cornering accident caused by a friction step at 13.75 s (v = 30 km/h)

Figure 9 shows the nominal and the actual vehicle side-slip angle velocity over time t for an accident caused by a friction step. A difference between the two values can clearly be identified.

Validation

Figure 10: Safety device to avoid injuries during critical driving situations

To validate the explained detection method, both causes of critical driving situations (type 1 and type 2) are investigated on a test track with areas of low and high friction. To avoid any injury in the event that the motorcycle should fall, a safety device, shown in Figure 10, was constructed and used. Its influence on the driving behavior of the motorcycle is assumed to be negligible (additional roll moment of inertia: approx. 10%, additional yaw moment of inertia: approx. 30 %). The photo in Figure 11 shows a type 1 test.

Figure 11: Conducting a test drive (type 1) on a test track

In addition to the named critical driving situations, uncritical rides were conducted. These included maneuvers like cornering, double lane change, slalom and rides in public traffic. Table 7 shows the results of critical driving situation detection. The number of false detections is zero. All type 1 and about 65% type 2 situations were detected as critical. 35% of type 2 situation were not detected as critical. In these cases improvements of the method has to be investigated.

Table 7: Detections of critical driving situations

maneuver (number of tests)	type 1 detected	type 2 detected	no detection
cornering (n=15)	0	0	15
slalom (n=12)	0	0	12
lane change (n=4)	0	0	4
public road (120 min)	0	0	120 min
critical situation type 1 (n=22)	22	0	0
critical situation type 2 (n=17)	0	11	6

DESIGN OF HUMAN-MACHINE INTERFACE (HMI)

In order to warn the rider about hazards on his/her route, it is necessary to design a human-machine interface. It is important that this interface warns riders effectively, but also does not disturb them too much. Five various warning elements (Haptic Saddle, Auditory Warning, Warning Flashes, LED-Band, Display) and a warning strategy were implemented and analyzed through a test subject study. The analyzed elements are shown in Figure 12. In [7], this methodology is described and results of the evaluation are presented.

Figure 12: Warning Elements: Haptic Saddle, Auditory Warning, Warning Flashes, LED-Band, Display

COMFORT ORIENTED FUNCTIONALITY FOR GREATER MARKET ACCEPTANCE

The MoLife comfort-oriented feature is a simple to use voice communication application between motorcycles, called viitalk®. For this purpose, the system establishes a mobile wireless network with all equipped vehicles in range. Every rider can be identified by his/her nickname and unique ID. These functions are known from common internet instant messaging services, like Skype® or ICQ®. The users in the viitalk networks can initiate friendships with other users to become members on their buddy lists. They can talk with each other in private sessions, or they can communicate in conference calls.

The viitalk system works in the same way with an additional feature. Motorcycle riders add each other to their buddy lists and if one of them is in range the system shows his/her presence and indicates the location by showing the direction and the distance to the buddy. This could also be done in combination with a navigation function and a symbol in a map. The user can easily request a call to the buddy by pushing the call button. When the channel is established, other riders can join the session. Talking is very simple and unrestricted; there is no need to hold down a special key while speaking or to wait for others to stop speaking as in push-to-talk based systems. In contrast to mobile-phone-based systems, viitalk does not require sufficient network coverage by a provider and it does not incur additional costs, because viitalk builds up and moves the network with the group.

The communication in viitalk is based on voice over IP (VoIP) technology and is enhanced with methods to establish connections very simply.

Riders can talk to others and make arrangements, e.g. for breaks or refueling. With this communication, a group can reduce risks during overtaking or turning maneuvers. With viitalk the group sustains less misunderstanding caused by using hand signs. The biggest advantage of viitalk is the possibility for riders to simply and reliably advise their buddies (in the group) of any recognized hazardous situation. Viitalk enhances vehicle-to-vehicle communication with a direct rider-to-rider communication. For future vehicle communication systems, this enables a direct customer value, which is based on the same technology as the safety function.

CONCLUSION

Before implementing the “MoLife” project, a communication-based warning system for motorcycles that generates warning messages based on the evaluation of vehicle dynamics sensor information was not known. During the project, research gaps for the development of such a system were identified and addressed.

First, hazards which lead to accidents that can be avoided by such a system were identified. Second, an analysis of driving behavior in hazardous situations was conducted. This can be used as the basis for the generation of warning messages based on vehicle dynamics sensor information. Third, a methodology to design an appropriate HMI was developed and validated. Finally, an additional comfort-oriented functionality to increase market acceptance was implemented und tested.

OUTLOOK

Beside the technical sensors, it is possible to use the rider as a "sensor". This will offer the possibility to detect more hazards than the current system. Nevertheless, this makes the system more prone to malicious attacks. Furthermore, a much more sophisticated warning message management system is required.

Market introduction of communication-based systems is a big challenge, as a certain degree of market penetration is required in order for a system to be effective. This problem can be circumvented by employing the described system to a group of motorcycles. Riders often drive in groups. If a group is equipped with this system, it will benefit by it. Nevertheless, for the use of all functions a certain degree of market penetration is required.

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