Development of a real time Friction Estimation Procedure

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1 Introduction

Precise knowledge of the friction potential is of great importance for safe longitudinal and lateral control of a car. While today it is mostly the driver who assesses friction values and adapts his driving style accordingly, it will be necessary for future highly automated vehicles to independently obtain information on environmental conditions. Analyses of accident records show that at least 3.6 % of road deaths are due to icy road conditions. However, this number is likely to be significantly higher, since the number of accidents in Germany occurring under icy road conditions without these conditions being identified as primary causes of the accidents, is around 20 % of the total number of accidents [1].

The coefficient of friction μ is defined as the normalised resulting horizontal force which acts between tires and road:

$$\mu = \frac{\sqrt{F_X^2 + F_Y^2}}{N_Z} \tag{1}$$

F_X and F_Y act on the tire as circumferential and lateral forces and N_z is the normal or contact force. The maximum transferable friction μ_{max}, or the friction potential, is the maximum that μ can reach under the specified conditions.

The friction potential is influenced by many factors, such as the tire condition, the type of tire, or the quality of the layer between road and tire, that is to say whether the road condition is dry, moist, wet or snowy/icy. Estimating the friction potential is a challenge that numerous research projects have taken on [2–10]. Basically two approaches can be distinguished. The effect-based approach attempts to measure effects that result from different coefficients of friction on the tire. A prediction of the maximum friction coefficient is then issued based on these measurements. As an example, sensors have been developed which are integrated into the tire surface and deform depending on the current friction [11]. A disadvantage of effect-based methods is that they require a sufficient level of slip depending on the estimation method. With the cause-based approach, variables are measured that affect the friction potential. With the help of the measured parameters and an appropriate estimation procedure, the maximum friction coefficient is then estimated. Major disadvantages of this method are that additional sensors are necessary and an elaborate training of the estimation algorithm is required.

As part of a research project at the Technical University of Berlin that has been financed and given advisory support by Working Group 20 of the Research Association for Automotive Technology (FAT), a cause-based estimation procedure for estimating the maximum coefficient of friction has been developed which relies solely on information that is available without additional vehicle sensors. This information consists of data which is present in the vehicle itself, such as outside temperature, vehicle speed or rain intensity. On the other hand, the procedure draws on data provided by the surrounding infrastructure. This includes weather data from weather stations or information on road conditions obtained from road weather information systems. By combining and integrating these fields of information, the range of the maximum coefficient of friction is established using the estimation procedure developed in this project.

For the development of such estimation procedures it is first necessary to obtain detailed knowledge of the influence of the described information on the maximum coefficient of friction [12–15]. To this end, extensive measurement runs have been performed over a period of 30 months on a predefined route through urban and rural areas and the outskirts of Berlin. Here, the range of the friction coefficient was ascertained in real-world environments using test braking to establish the coefficient's position under varying conditions.

2 Measurement of the Maximum Friction Coefficient

In order to perform friction potential measurements, 32 brake points were set along a measurement course. These were positioned in town, rural areas and on highways; the driver braked on the surfaces of asphalt, concrete and cobblestones. Close proximity of the brake points to weather stations (WS) and road weather information systems (GMA)[1] was ensured. Furthermore, relevant structural features such as bridges, as well as the feasibility of brake tests in everyday traffic were taken into account. For the test runs a route in the southeast of Berlin was chosen that passes through Berlin and Brandenburg and runs further along the motorways A115 and A10. The route chosen is in proximity to the GMA Fahlhorst. Also, all the points along the route were within a distance of less than 10 km from one of the weather stations, Figure 1.

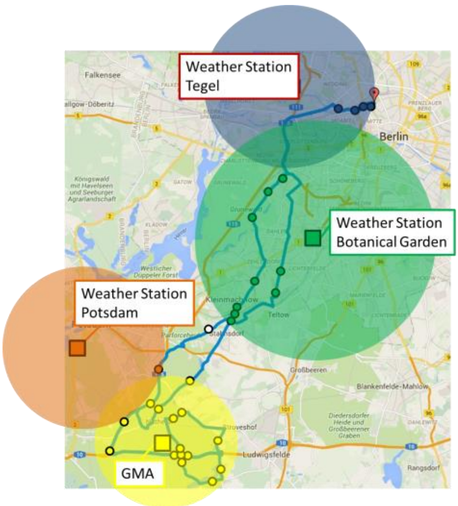

Figure 1: Measurement course with brake points, weather stations (WS) and road weather information system (GMA) (© KFZB)

At each of the 32 brake points defined for this route the driver braked once in the course of each test run. At initial speeds between 30 and 120 km/h the brake pedal was depressed in such a way that in the master cylinder a minimum pressure of 175 bar built

[1] German: Glättemeldeanlage (GMA)

up and the braking system was reliably taken to the ABS control range. This ensured that the vehicle reaches the maximum possible deceleration. This vehicle deceleration was measured by a servo-accelerometer over a period of 0.5 s, and then averaged, Figure 2. From this value the average maximum possible coefficient of friction was obtained using

$$\bar{\mu}_{\max} = \left| \frac{\bar{a}}{g} \right| \qquad (2)$$

Since the test runs were performed over a period of 30 months, a wide range of nearly all weather conditions could be taken into account. These include various rain intensities and the resulting different water heights, measurements on closed snow cover or slush, as well as different surface temperatures under dry conditions. Summer and winter tires were exchanged regularly over the whole measurement period so that results are available now for both types of tires for the weather conditions referred to above. Further tests were conducted in winter times in Sweden, where a reliable snow and ice conditions could be found.

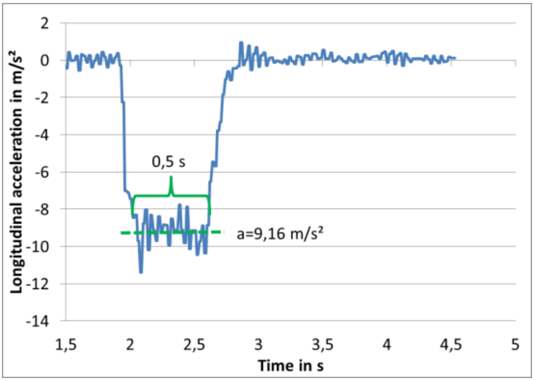

Figure 2: Time sequence of vehicle deceleration at emergency braking (© KFZB)

3 Results of Brake Tests

For the evaluation of the brake tests round about 4.000 brake measurements and the associated data sets were available. Each of these sets contains 45 parameters that describe all significant variables which affect the coefficient of friction. These are weather information, vehicle-specific data and information on road surfaces. Figure 3 shows an overview of the measurements of the maximum friction coefficients on dry roads with surfaces of asphalt, concrete and cobblestones as a function of velocity.

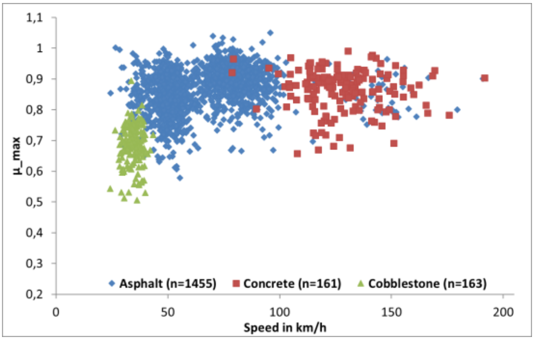

Figure 3: Maximum coefficient of friction for dry road surfaces as a function of vehicle velocity (© KFZB)

It is apparent that under dry conditions the maximum friction value is higher than $\mu = 0.5$ for all three road surfaces and all velocities. The measurements on cobblestone pavements were taken within a speed range around 40 km/h. The measured friction coefficients vary considerably for this surface and are found within a range of values from *0.53* to *0.85*. The values measured for asphalt, of which there are a lot more due to the brake point distribution, were determined at initial speeds between 30 and 190 km/h. The range of values here is *0.66* to *1.05*. The large scatter is due to the fact that along the measurement path, different varieties of asphalt were driven on. For an as much as possible exact estimation of the friction potential a small range of values is necessary. Up to now a lot of different possible parameters, which seem to influence the friction coefficient for example different asphalt surfaces, the pollen intensity, general air pollution etc. have been investigated. Obvious contexts could not be identified. For further research activities a detailed investigation of these influencing parameters in necessary.

The values measured for concrete were recorded at higher initial speeds, since this type of surface was found only on the highway part of the test section. Here the range of values for the maximum friction coefficient runs from *0.67* to *0.99*. None of the surfaces under consideration shows any significant speed dependency.

A comparison of the maximum friction coefficient for different road conditions shows, as expected, that the maximum is considerably lower for moist or wet surfaces than for dry pavement, Figure 4. A road surface is classified as moist when it is obviously no longer dry but no water is being sprayed by moving vehicles, the pores of the road surface are not closed by water, and no reflective surface has formed yet.

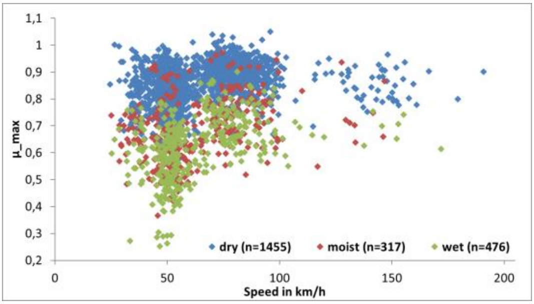

Figure 4: Maximum coefficient of friction on asphalt for different road conditions (© KFZB)

The database of maximum values of friction under different conditions, which was built up in the course of the test runs, provides a solid foundation for the development of an assessment of the friction coefficients as described below. Figure 3 and Figure 4 are examples of a variety of possible comparisons offered by this database [1].

4 Method for the Estimation of the Friction Potential

For an accurate estimate of the current coefficient of friction it is necessary to know the current status of the main influencing parameters. Among these are road surfaces or tire types. In the research project described here, the road surface was calculated on the current vehicle position and previously digitally stored road data along the measurement path. It is easy to imagine that future digital maps will provide such information. The selected type of tire was also digitally stored as information. It is conceivable that this can be done automatically in the future through corresponding coding of the tires. Communication between vehicle and tires is already standard today.

Far more challenging is an assessment of the exact road condition (dry, wet, etc.), that is to say the layer between vehicle tires and road surface. According to the requirements described at the beginning, namely that no additional measurement technology ought to be used in the vehicle other than already existing sensors, the state of this interlayer cannot be measured directly. Instead, the road condition needs to be identified with the help of other parameters. The parameters to be used here include, for example, outside temperature, rain intensity, humidity, or dew point temperature. While the outside temperature is measured directly on the vehicle and can be queried via an interface by the CAN bus, the other data has to be obtained through other means. In our project the data servers of the German Weather Service were used. The relevant information provided by weather stations along the measurement path was accessed via the Internet and transmitted directly to the vehicle via mobile communication. Additional information, such as road surface temperatures or the dew point data, was delivered by the road weather information system.

Based on this data the state of the layer between tires and road was estimated using logistic regression. This is a method of statistical analysis for dichotomous[2] distributions. For a property, there are exactly two distinct states, for example yes/no, on/off, 0/1, wet/not wet. Using this method, it is possible to describe the relationship between individual weather factors and corresponding road conditions. Based on this description, the probability of a certain state of the interlayer between tire and road can then be calculated.

To determine the road condition by means of logistic regression, the possible surfaces are defined as: dry, moist, wet or icy/snowy. Based on the database obtained in the test runs, the road conditions presented above were determined for every weather parameter and at each brake point. This results, for example, in the following distribution for the relationship between relative humidity and the state dry, Figure 5 (blue dots). Based on this distribution, the functional equation of the logistic regression is optimised. The equation has the following form:

$$P(y(x)) = \frac{c}{1 + ae^{-bx}} \tag{3}$$

where P is the probability of occurrence of a particular road condition y, dry in the example shown, which in turn depends on the value of x, here the relative humidity. The free parameters a, b, and c are optimised such that the squared error between P and y is minimised. Figure 5 shows an optimised curve of the regression line (red). According to [17], the conditional variance for the function curve can be calculated, which indicates the predictive uncertainty. Its range is between 0 and 0.25. If this value is normalised and the reciprocal formed, the result is a functional assessment of the quality G of the calculated probability (orange), with

$$G(y(x)) = \frac{1}{4P(1-P)} \tag{4}$$

The same procedure is applied for all states of road conditions and for all parameters considered, so that a total yield of 25 optimised regression functions and their corresponding quality function results from five different states and five different inputs. In order to obtain an assessment of the probability of occurrence of a certain road condition

[2] Dichotomous (Greek): split into two parts

as a function of the input variables, all the individual probabilities are calculated and weighted by their respective associated quality:

$$\overline{P}_{k,j} = \frac{\sum_{i=1}^{n} P_{k,j}\left(y_j(x_i)\right)\cdot G_{k,j}\left(y_j(x_i)\right)}{\sum_{i=1}^{n} G_{k,j}\left(y_j(x_i)\right)} \tag{5}$$

n is the number of input variables taken into account, x_i corresponds to each input variable, y_j is the road condition and k is the number of the respective brake point.

The state y_j with the highest probability calculated is the estimated road condition. The greater $P_{k,j}$, the more reliable is the estimate of the road condition. Overall, the method of logistic regression is characterised by great clarity of the structural process and ease of identification. The impact of changes in the input variables can be traced and read directly.

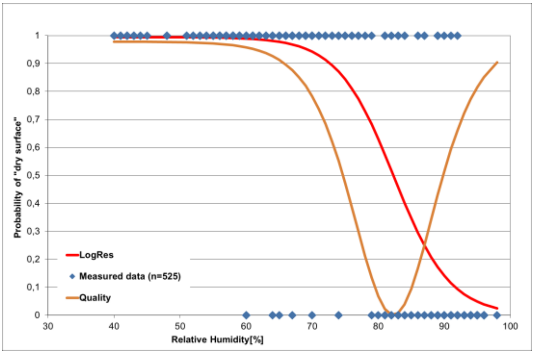

Figure 5: Logistic regression of the relationship between humidity and road condition dry (© KFZB)

The final structure of the estimation algorithm was defined in several optimisation steps. The target was to find out with which structure the best results could be achieved. One main result of this optimisation was that much better results arise, when different types of interlayer are identified in different steps. That means, that in the first level of the algorithm it is only distinguished between “dry” and “other” interlayers. For this first level the single logit function described above, were adapted and optimised. Based on the “other”-cases from the first level in the second level the algorithm distinguishes between “moist” and “other” interlayers. In the third level the algorithm differs between wet and snowy/icy. Additionally, a switch is integrated. Whenever the outside temperature is above 4°C the algorithm decides to wet, if it is below -2°C it decides for snowy/icy. That means the method of logistic regression in the third level is used for conditions between -2 and +4°C only.

Example	Parameter	Maximum friction coefficient between
-	No restrictions	0.04 ... 1.05
↓ Snow/Ice	Road conditions	0.04 ... 0.52
↓ Asphalt	Road surface	0.16 ... 0.52
↓ Winter tires	Type of tire	0.16 ... 0.52
↓ < 50 km/h	Velocity	0.19 ... 0.36

Figure 6: Flowchart for the prediction of the upper and lower limit of maximum friction coefficient (© KFZB)

Based on the estimated road condition, the actual friction potential is predicted as a next step. For this procedure the database obtained from the test drives is used. Depending on the detected road condition, a lower and an upper limit of the coefficient of friction can be established using data on the road surface, the type of tires, and the driving speed. The assessment is refined through increasing awareness of the different key parameters, Figure 6. Hence, for a drive in snowy conditions on asphalt with winter tires at a speed slower than 50 km/h, the maximum coefficient of friction is between 0.19 to 0.36. With a remaining uncertainty of the coefficient of 0.17, a fairly precise real-time prediction is possible.

5 Results of the Real Time Friction Potential Estimation

For the development of the estimation procedure a total of 2,676 records were used. These were all data, which were measured in Berlin, independently whether or not for all data sets all data were available. That means that also data sets were considered where no information from the GMA were available. To evaluate the method for determining road conditions, the logistic regression curves were initially created and optimised with 80 % of the data from the established database; subsequently, the quality of the process was checked with the remaining 20 %. This quality check corroborates the validity of the method developed for determining the maximum coefficient of friction.

In about 96 % of the cases the measured maximum friction value was within the estimated limits of the friction coefficient, which show an average difference of 0.33. In the remaining casesof 4 %, where the measured maximum friction coefficient was outside the estimation range, the maximum deviation was 0.16.

A deeper look in the cases where the measured friction value was outside the estimated range showed, that most of the fear estimations occurred in transitional situation. For example, if rain has just started or was just over. Additionally, in situations of snow slush it is still difficult to estimate the correct interlayer. In some cases, the estimation algorithm calculated a wet surface instead of snow slush which lead to significant higher friction limits.

6 Summary and Outlook

The evaluation of the results of the estimate of the friction coefficient clearly shows that for dry, moist, wet and snowy/icy road surface a reliable prediction of the maximum of this coefficient is possible without additional sensors. The developed estimation procedure shows a high degree of correct predictions. The acceptance of false predictions should be considered for the specific application case.

Still challenging is to reduce the range of the estimation limits. Here a better understanding for the influencing parameters of the maximum friction coefficient is needed. Detailed analysis of the data sets of single braking points should help to understand under which circumstances the friction coefficient changes.

The evaluation of the estimation algorithm showed, that it provides satisfactory results even if some information (like the GMA) are not available.

For the future it is imaginable that numerical weather simulation models, which give detailed weather information and which also consider local effects of the vegetation can improve the friction estimation a lot. First research results of the FU Berlin showed promising results.

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