Development of a friction prediction system

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ABSTRACT

In recent years driving stability and driver assistance systems have become more and more common in modern cars. Along with this development there is a growing demand for a system predicting the actual friction potential in the tyre contact patch. Within the European research project VERT (Vehicle Road Tyre Interaction) a big number of friction measurements were carried out to define the main influencing parameters of the tyre-road-friction-process. With the help of empirical and physical models it was possible to describe the effect of these main influencing parameters on friction values.

The aim of the research work in this project is to implement these models in driving simulations as well as to consider the feasibility to implement them into real cars. This paper presents the possibilities of developing a friction prediction model suitable for implementation in a moving vehicle.
INTRODUCTION

The interaction between tyre and road is decisive for the safety and driving dynamics of a vehicle since all forces necessary for the longitudinal, lateral and vertical dynamics of a vehicle are transferred via the tyre contact patch, except for the forces active during coast-down.

The European research project VERT, financed by the EU, aims at recording and valuing the factors influencing the friction between tyre and road. Moreover it aims at describing the effect of these factors on the behaviour of the vehicle with the help of empirical and physical models. Part of the project is to study the basics of friction and to examine possibilities leading towards a friction prediction system in a running vehicle. This system should be able to yield information regarding presently available and future friction potentials.

DETERMINATION OF INFLUENCING FACTORS

For friction prediction, it is first of all necessary to define and record the influencing factors of tyre, vehicle and friction, \textbf{figure 1}, and to value them with the help of diagrams presenting longitudinal friction over slip resp. lateral friction over side slip angle.

\textbf{Parameters}

\textbf{Vehicle}
- Speed
- Toe, camber
- Wheel load ...

\textbf{Tyre}
- Type
- Tread depth
- Temperature
- Pressure ...

\textbf{Lubricant}
- Type
- Depth
- Temperature ...

\textbf{Road}
- Pavement
- Micro-/macro-geometry
- Drainage capacity ...

\textbf{Effects}

\textbf{Vehicle}
- Forces
- Slip
- Noise ...

\textbf{Tyre}
- Stress, strain
- Deformations
- Vibrations ...

\textbf{Lubricant}
- Compression
- Drainage ...

\textbf{Road}
- Stress ...

\textbf{Fig.1:} Parameters of Tyre – Road – Friction [2]
Within the VERT project about 3000 measurements have been carried out and have led to the definition of the following influencing factors as of „maximum relevance“:

- speed of vehicle
- wheel load
- tyre tread depth
- water film thickness
- microtexture of road
- macrotexture of road

In order to assess the influencing factors of the vehicle resp. the road and their effect on the friction, fzd uses the tyre measuring trailer PETRA, figure 2.

With the help of a rim force transducer this trailer is able to measure forces and torque acting on the measuring tyre up to a speed of 80 km/h. Toe and camber angle as well as wheel load can be varied within ranges common in average cars. Furthermore it is possible to fix stable operation points up to 90% brake slip.
CHARACTERISATION OF PAVEMENT TEXTURE

The characterisation of the road macrotexture (within the wavelength range of $0,5\text{mm} < \lambda < 50\text{mm}$) and the calculation of the MPD-value (Mean Profile Depth) can be realised in different ways: The most common method is based on the principle of laser-triangulation. A sensor detects the distance between a laser spot on the pavement and a PSD (Position Sensitive Device) [2]. The measuring speed depends on the sampling rate, the accuracy in x-direction and the spot-diameter. This type of sensor is suitable for use in a moving vehicle.

A stationary system to characterise the macrotexture of a pavement is based on the principle of topometrical measurements, **figure 3** [3].

A light source projects an array of stripes onto a surface. A picture of the surface is taken by a CCD-camera. This picture includes the three-dimensional pavement information which has to be calculated by a special data-processing software. After that the data can be used to calculate the MPD-value or the drainage capacity of the pavement. The accuracy of the system in vertical direction is about $\Delta z = 0,005\text{mm}$ and in horizontal direction $\Delta x = 0,2\text{mm}$.

A direct texture value, comparable to the MPD-value, does not yet exist for the microtexture of a pavement. To describe the sharpness of the road surface aggregates, an ASTM-tyre is used to measure the skidding friction coefficient in longitudinal direction at a speed of 20 km/h on wet road (BFC$_{20}$ value = Brake Friction Coefficient).
Middle Smooth Macrotexture
MPD = 0.75

Smooth Macrotexture
MPD = 0.6

Fig. 3: Topometrical Description of Road Surface
DETERMINATION OF WATER DEPTH

To determine the water depth in front of the measuring tyre in measurements with PETRA, a sensor developed by the IKFF of Stuttgart University and already tested in the PROMETHEUS project [4], is implemented. This sensor uses the different absorption characteristics of water depending on the wave length of the light source. As can be seen in figure 4 the degree of transmission of water has its local maximum at about $\lambda=1080\text{nm}$. This local maximum results in a minimal absorption of the ray of light while passing through the water layer. Therefore this wavelength is used as the point of reference. The measuring wave length to define water depths between 1 and 10 mm is at $\lambda=1190\text{nm}$. In order to reach greater accuracy in the range of water depths smaller than 1 mm, the wave length at $\lambda=1190 \text{ nm}$ is used as point of reference.

The area-integral measurement of water depth demands knowledge about the road macrotexture in order to carry out a texture related auto-calibration of the measuring...
signal. Here it must be differentiated whether there actually is a water layer above the road aggregates or whether the aggregates are only moist. The accuracy reached by this method lies within a measuring range of 1 to 10 mm at \( \Delta WT < 0.5 \text{mm} \).

**DEFINITION OF FRICTION VALUES**

Side force - slip angle and friction - slip-curves were used for the evaluation of the effects of individual influencing factors on friction value. The friction measurements within the VERT-project were carried out by the respective partners on defined testing tracks. Therefore it was possible to use a considerable number of different textures and to vary the influencing factors, *figure 5*. The measurements were carried out by Pirelli, Nokia/Helsinki University of Technology HUT, Centre d’Etudes Techniques de l’Equipment de Lyon CETE, Swedish National Road and Transport Research Institute VTI, Transport Research Laboratory Civil Engineering TRL and the Automotive Department of Darmstadt University of Technology *fzd*.

![Friction Measurements](image)

*Fig. 5*  Influence of Macrotexture on Maximum Friction in Longitudinal Direction
In correspondence to the results of [5] and [6], a significant influence of the road macrotexture on the maximum friction value in longitudinal direction on wet road (3mm water depth) could be observed. A comparison between the measurements at a medium profile depth of 0.58mm and those at 1.96mm shows that the friction values increase up to 70% with rougher macrotexture on wet road. Here obviously the roughness of the pavement and therefore the drainage capacity have a significant influence. Also the sharpness of the road aggregates must be taken into consideration, even though the influence under the chosen circumstances (2mm profile depth and 80 km/h speed) should be minimal. The friction values on dry surface are nearly at the same level.

The influence of the microtexture on the maximum friction value in longitudinal direction is shown in figure 6.

**Fig. 6:** Influence of Microtexture on Maximum Friction in Longitudinal Direction

The sharpness of the pavement is described by the BFC20 value. On a wet road with a water thickness of 3mm at a speed of 20km/h and a chosen tyre with a tread depth of
4mm there is no significant influence of the microtexture on the friction value. Also the influence of the macrotexture at that low speed is minimal. In contrast to the wet condition the effect of the microtexture on a dry pavement is considerable. The maximum friction values in longitudinal direction increase up to 25%.

The free parameter in all these measurements is the speed of the car respectively the speed of the tyre. Transferred to a car this is also the factor that a driver can choose deliberately while driving. The other influencing factors (e.g. water depth, wheel load...) effect the vehicle-driver-system from the outside.

The combination of the individual influencing factors results in different speed ranges within which a strong decrease of the maximum friction value can be recognised. Subsequently, this speed is called „critical speed“. In figure 7, the influence of the tyre tread depth on the maximum friction value in longitudinal direction can be clearly perceived. The critical speed for the tyre at a water depth of 3mm increases from 40 km/h for a worn tyre with a profile depth of 2mm up to 90 km/h for a new tyre.

**Fig. 7:** Friction Measurements (CETE) – Influence of Wheel Load and Tyre Tread Depth
Another influencing parameter shown here is the wheel load. An increase in wheel load from 2000N to 5000N at this water depth results in an increase of the friction value of up to 20%. This can be attributed to the improved water displacement in the tyre contact patch and to a reduction of the hydrodynamic forces in vertical direction. On dry road the effects turn around: an increase in profile depth and wheel load results in a decrease of the maximum friction value. This is due to the inhomogeneous pressure distribution and to shear stresses in the tyre contact patch caused by flat spot. These come about because a rotational symmetric body is forced onto an even surface [7].

MODEL DEVELOPMENT

The next step is the quantification of the effects of the main influencing factors on the friction value between tyre and road. Since the partly contrary effects of the parameter changes in dependence on the road condition build up a multi-dimensional map, it is useful to employ statistic calculation software. In this case the software tool SPSS was used. This tool allows examinations related to variance analysis with which the effects of the influencing factors were tested and examined for reciprocal effects. This led to first models for the description of influences. Moreover correlation analyses for the evaluation of the significance level were carried out to define the main influencing factors on the friction value. But in order to achieve this aim, first the possible products and their values must be defined through analysis of longitudinal friction-slip and lateral friction-slip angle-diagrams.

The actual semi-empirical model for use in a car takes into consideration the influence of microtexture BFC20, macrotexture MPD, wheel load $F_z$, tyre tread depth TD, water depth WD and speed $v$ on the maximum friction value in longitudinal direction,
\[ \mu_{\text{max, long}} = K1 + K2 \cdot v \cdot F_z + K3 \cdot v - K4 \cdot v \cdot v - K5 \cdot WD \cdot v - K6 \cdot WD + K7 \cdot WD \cdot MPD + K8 \cdot TD - K9 \cdot TD \cdot MPD - K10 \cdot MPD \cdot v + K11 \cdot MPD \cdot v \cdot v + K12 \cdot MPD \cdot MPD \cdot v - K13 \cdot MPD \cdot MPD \cdot v \cdot v - K14 \cdot BFC20 / v - K15 \cdot F_z + K16 \cdot F_z \cdot F_z \]

**K** = Constant value

**Equation 1:** Semi-empirical Model of Maximum Friction in Longitudinal Direction

A comparison of measured and calculated friction values is shown in **figure 8**: The measurements have been carried out by CETE on a wet asphalt pavement with a water thickness of 3 mm, a BFC\textsubscript{20} value of 0.58 and a MPD value of 0.58 mm. The tyre tread depth varies from 2 up to 8 mm.

![Influence of Tyre Tread Depth](image)

**Fig. 8:** Comparison of Measured and Calculated Friction Values depending on the Speed

Looking at the 2 mm tyre at low speeds the calculated friction value is lower than the measured one. But at speeds higher than 50 km/h both curves fit very well. The model results and the measured values of the 4 mm tyre are very similar in the whole speed range.
range. Regarding the 8mm tyre the model calculates extremely high values at low speeds and extremely low values at high speeds. A reason for this can possibly be found in the consideration of the microtexture at low speeds. Maybe there has to be more emphasis on the effect of the BFC\textsubscript{20} value. Another reason may lie in the measured values especially at higher speed. At a friction level of 0.2 the model shows a constant value. This is due to the lack of data at very low friction conditions.

Regarding all validated measurements in longitudinal direction the model fits in a wide range, figure 9. But at very low friction values there is still a need for measured data.

![Fig9](image_url) : Actual Friction Prediction Model for Use in a Vehicle

**TRANSFER OF THE MODEL INTO THE VEHICLE**

The future implementation of a friction prediction system will result in a transfer of information about the present friction potential to driving dynamics and driver assistance systems. And moreover it will result in a warning to the driver in case a
dangerous situation approaches that is due to friction demand exceeding friction potential. This warning should reach the driver in different ways depending on the necessary reaction on the driver’s side. It can be given via optical-acoustical signs or via haptic, for example by moving the accelerator against the foot force of the driver [8] [9].

To receive information about the present friction potential in longitudinal and lateral direction, the influencing factors considered in the model have to be measured by suitable sensor systems.

The further steps planned by the author are based on the following considerations [10]:

The measurement of the water depth is carried out with the help of an absorption sensor already employed for friction measurements with PETRA. This sensor is attached in front of the right front wheel, **figure 10**. The water depth in front of the left front wheel is assumed as equal to that of the right front wheel.

![Testing Vehicle](image)

**Fig. 10:** Testing Vehicle
In order to comply with the StVZO (road safety laws) when driving on public roads, and due to its sensitivity towards sunlight and spray fog, the water depth sensor must be protected during driving.

The speed of the test vehicle is captured via a Correvit sensor.

Since the scanning of the road texture with the help of a laser sensor is very limited on wet roads, the testing vehicle is not equipped with a texture sensor. Yet, in order to offer the model some information about the road surface, a data bank has been established which the friction prediction model can access, figure 11. This data bank stores information about the texture (MPD and BFC\textsubscript{20} value) as well as information about the track.

![Diagram](image_url)

**Fig.11:** System – Interaction

Now, in order to make available the necessary information to the friction prediction system, two conditions must be fulfilled: the system must know the car’s present
location and which road shall be used next. These two conditions are fulfilled through the use of a GPS in connection with a navigation system.

The road data is captured in advance with the help of a laser profilometer and the measuring trailer PETRA and transferred to the texture data bank.

The curve data (entrance and exit radius) of the testing track has been determined with the help of a map of the road office (Amt für Straßen und Verkehrswesen Darmstadt) as well as with the help of a special testing device. The lateral acceleration calculated from the square speed of the vehicle divided by the curve radius can be compared with the lateral acceleration potential calculated by the friction prediction model. Later on this information can be used to warn the driver or to inform a driving stability system.

In order to achieve a comparison of the calculated deceleration potential and the actual deceleration of the vehicle, acceleration sensors are implemented close to the centre of gravity of the car. To adapt the friction prediction model to the testing vehicle, the calculated fully developed mean deceleration is compared with that measured in the vehicle. At this point in time only the stationary wheel loads are taken into consideration.

CONCLUSION AND OUTLOOK

The actual friction prediction model for use in a moving vehicle is able to calculate the maximum friction value in longitudinal direction in a wide range. A model for the maximum value in lateral direction is being developed. The model is validated for summer conditions, but it still has to be validated for textures with a MPD > 1,2mm and speeds higher than 100km/h.

A system which can deliver information about the friction potential will certainly be found in future vehicles. It could help to prevent accidents that are due to excessive use of tyre-road-friction and it could also help to mitigate consequences if accidents should occur.
Traffic telematics could play a decisive role to provide information about road roughness and water depth along the track. This could be realised by stationary systems beside the road or by using car-car-communication (“floating car system”).

The first approaches to a friction prediction model implemented in a car must be extended by more data of roads with different micro- and macrotexture. Moreover factors related to driving dynamics, as for example wheel positions and dynamical wheel load, must be taken into consideration in the calculation of the friction potential and its use.

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