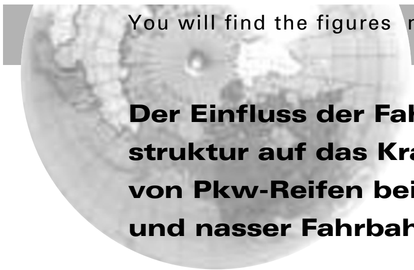

You will find the figures mentioned in this article in the German issue of ATZ 10/2001 beginning on page 950.

Der Einfluss der Fahrbahnoberflächenstruktur auf das Kraftschlussverhalten von Pkw-Reifen bei trockener und nasser Fahrbahn

The Influence of the Track Surface Structure

on the Frictional Force Behaviour of Passenger Car Tyres in Dry and Wet Track Surface Conditions

The track surface structure has a substantial influence on the frictional force behaviour of tyres. The following paper, which deals with the effect on longitudinal force/longitudinal slip curves, shows some of the research results from the "Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau" of Karlsruhe University (TH) in this field [1]. In addition to theoretical deductions, this paper presents the results of extensive tyre measurements that allow the mathematical conversion of the characteristic curves of tyres for different track surfaces.

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1 Introduction

During the development of a new passenger car, costly test drives are increasingly being replaced by simulation calculations. These calculations are aimed at achieving the optimum design of the whole vehicle, particularly the chassis, in order to improve the vehicle handling and, as a result, to increase traffic safety. The simulation models used need certain input values, such as the characteristic curves of tyres, since their accuracy is a crucial factor in the simulation result.

Such characteristic curves of tyres can be determined either by special measuring vehicles or by steady-state tyre test rigs. In the course of this determination, one continually encounters the problem of the discrepancy between measurement and reality, due either to difficulties in reproducing ambient conditions during road surface measurements or to the unrealistic track surfaces (safety walk) used in steady-state tyre test rigs. Therefore, the comparison between a test drive and a simulation often results in discrepancies if the tyre measurements for the simulation calculations were carried out on a track surface different from those used for the test drives.

In order to take such discrepancies into account in a simulation calculation, extensive research on the influence of the track surface on the frictional force behaviour of passenger car tyres was carried out, and this paper presents some of the results.

2 Characterisation of the Track Surface

When researching the influence of the track surface on the frictional force behaviour of passenger car tyres, it is important to record measurements of the track surface and to describe its specific properties by characteristic quantities. This can be acteristic coefficient of the track surface "percentage profile contact area PT". In the tyre in question, changes in the deformed volume are mainly caused by changes in the track surface's macro roughness. The corresponding characteristic coefficient of the track surface is the characteristic quantity Beta b. The change in the longitudinal force coefficient due to a change in the track surface (dry surface) is expressed by Equation 5, which weights the influences of the characteristic coefficient of the track surface concerned using the exponents $n_{PT,\mu max}$, and $n_{Beta\ b,\mu max}$.

In wet track surface conditions, the number of bindings between the tyre and the track surface is reduced by the interim medium "water". An increase in the depth of the water reduces the areas of "dry" contact and thus reduces the proportion of adhesive friction. The macro roughness of the track surface and a favourable tyre tread improve the water run-off in the tyre contact area, thus increasing the adhesive friction coefficient. As a result of very high pressure gradients at the roughness peaks, a micro roughness of the track surface ensures that the remaining water film is penetrated, thus allowing "dry" contact. As a result, an increase in the micro roughness leads to greater adhesive friction forces in wet track surface conditions.

In principle, it may be possible to describe wet track surfaces using roughness quantities according to the method used for dry track surfaces. Since micro roughness in particular is difficult to record by means of measurement technology, it seems to make more sense to describe the track surface using the characteristic quantities of skid resistance. These quantities provide direct information on the frictional force behaviour between precisely defined friction bodies and a wet track surface under fixed conditions. Therefore, these measuring procedures take both the adhesion and the hysteresis influence into account together with all secondary influencing factors.

The British pendulum test (SRT), due to the relatively slow sliding velocity (approx. 10 km/h) of the rubber test piece, allows an assessment particularly of the micro roughness and thus the microscopic sliding bearing effect of the adhesive portion. The coefficient of friction at the locked wheel (SRM), however, increasingly assesses the hysteresis influence, due to the much higher sliding velocity (80 km/h) and the increased water depth.

In wet track surface conditions, the factor $k_{\mu max}$ is composed according to Equation 6, whereas the influences of the track surface quantities concerned are weighted by means of the exponents $n_{SRT,\mu max}$ and $n_{SRM,\mu max}$.

4.3 "Most Negative Gradient" after the Maximum

The "most negative gradient" describes the course of the $\mu_U(s)$ curves after the maximum. The steeper the curve's incline after its maximum, the more distinct is the maximum. A similar statement can be made about the curvature of the curve at the maximum, which correlates very well with the "most negative gradient". In this region, it is mainly the macro roughness of the track surface that influences the decrease in friction coefficients. The higher the macro roughness of the track surface, the stronger is the increase in the hysteresis proportion for increasing mean sliding velocities in the contact area, and the smaller is the incline of the curves after the maximum

The influence of the track surface on the "most negative gradient" is indicated by the conversion factor $k_{gr.neg.Stg.}$ in Equation 7, which, in the case of a dry track surface, can be expressed by the characteristic quantity of macro roughness, Beta b, according to Equation 8. In this equation, the weighting of the influence of the characteristic quantity is also carried out via an exponent ($n_{Beta\ b,gr.neg.Stg.}$). In wet track surface conditions, in addition to a change in hysteresis friction, a change in the adhesive friction caused by the sliding bearing effect of the water film particularly influences the reduction in the coefficients of friction after the maximum. Therefore, the conversion factor $k_{gr.neg.Stg.,nass}$ is the basis, as a function of the characteristic quantity of the skid resistance SRT and SRM according to Equation 9, whereby the influences of the characteristic quantity are weighted using the exponents ($n_{SRT,gr.neg.Stg.}$ and $n_{SRM,gr.neg.Stg.}$).

5 Implementation of the Experiments

The tyre experiments for investigating the track surface influence were implemented on the internal drum tyre test bench of the "Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau" at Karlsruhe University (TH). On this test bench, the tyre, which is guided by a servo-operated wheel suspension, runs on the inside of a drum with a diameter of 3.8 m. The wheel suspension permits continuous adjustment of the slip angle, camber angle and tyre deflection, and all movements can be carried out simultaneously according to almost infinitely variable instructions. The wheel is driven and braked by a hydraulic motor, which, unlike a mechanical friction brake, can approach stable measuring points beyond the longitudinal force maximum. The housing of the whole test bench in an air-conditioned chamber allows measuring to be carried out at constant ambient temperatures, ranging from approx. – 15 °C up to + 30 °C [6].

The internal drum principle has the advantage of allowing the installation of different track surfaces. In addition to the usual "safety walk" surfaces, cassettes with asphalt or concrete fillings can be attached in segments inside the drum. Moreover, the test rig allows measurements to be carried out on wet track surfaces. In the course of this research project, measurements were carried out on six different track surfaces. A wide range of different surfaces was covered when selecting the track surfaces, including extreme track surfaces, ranging from a track surface with a very low macro roughness and high micro roughness (safety walk) to a track surface with high macro roughness and low micro roughness (washed concrete). The surfaces are shown in **Figure 5** and are numbered (as in the following diagrams) as follows:

1. Safety walk (grain size 80)
2. Asphalt 0/5 rough (grain sizes 0 mm to 5 mm)
3. Asphalt 0/5 smooth (grain sizes 0 mm to 5 mm)
4. Concrete 0/11 rough (grain sizes 0 mm to 11 mm)
5. Asphalt 0/16 (grain sizes 0 mm to 16 mm)
6. Washed concrete 0/16 (grain sizes 0 mm to 16 mm)

Track surfaces 2 and 3 differ only in their micro roughness, which is not noticeable in non-enlarged figures. Therefore, the rough and the smooth asphalt surfaces are not shown separately in Figure 5.

In summary, the different track surfaces may be classified according to **Table 2**.

6 Results

6.1 Average Track Surface Influence

The following diagrams for the average track surface influence show the effect of track surface variations on the properties of an average tyre. The term "average tyre" indicates the mean values of the tyres investigated (6 and 10 tyre types). The virtual track surface – the "average surface" – also results from the calculation of an average value. In that case, the arithmetical mean was taken for the characteristic quantities (longitudinal stiffness, friction coefficients, etc.) which had been measured on the individual track surfaces. Thus, the result yielded a certain value as a relative quantity measured on an "average" track surface.

Figure 6 shows the longitudinal stiffness values measured on different track wet track surface shows a linear dependency on the skid resistance of the track surface. The influence of the design of the tyre tread on the related longitudinal stiffness increases with growing skid resistance. This is a similar behaviour to that already seen with the rubber stiffness. Therefore, it can be concluded that the effect of the hardness of the rubber mixture on the stiffness of the tyre is similar to that of the "hardness of the tyre tread pattern".

6.3.2 Coefficients of Friction

Figure 12 shows the maximum coefficients of friction for driving and braking, in relation to the average tyre. In dry surface conditions, the slick tyre yields the greatest coefficients of friction, followed by the tyre with circumferential tread ribs and the tyre with tread bars. The tyre with a siped tread has the lowest coefficients of friction. The differences between the various tread patterns are considerably higher for finer track surfaces (Beta b high) than for rough track surfaces. The reason is that a more finely profiled tyre can cling better to a rough track surface structure, which, in turn, compensates for the differences in the contact areas resulting from the negative tread pattern percentage.

At the maximum coefficients of friction, wet track surface conditions show a reversal in the ranking between track surfaces with low and high skid resistance.

6.4 Influence of the Ambient Temperature

6.4.1 Longitudinal Stiffness

A lower temperature results in an increase in the Shore hardness of the tyre rubber. Therefore, it can be assumed that the temperature behaviour of the longitudinal stiffness results in the same dependencies as already described for the rubber stiffness. As expected, **Figure 13** shows an increase in the stiffness with decreasing ambient temperature. For the longitudinal stiffness, the deviation, in relation to the base temperature of 20 °C, is strongly dependent on the track surface. As is the case with the rubber stiffness, the deviations for track surfaces with a high profile crest density (safety walk) are clearly higher (see Section 6.2.1).

6.4.2 Frictional Force Coefficients

If the results of the measurements for rubber stiffness were transferred to the temperature measurements, the frictional force coefficients would be highest at 30 °C. However, this is the case only with driving forces. At the maximum braking forces, there is a reversal in the rankings between fine and rough track surfaces, **Figure 14**.

7 Summary

In the course of this research project, theoretical approaches were made towards converting characteristic curves of tyres determined for a specific track surface to other track surfaces. To verify the approaches and to quantify the influences, tyre measurements on six different track surfaces were carried out at the internal drum tyre test bench at Karlsruhe University (TH). The evaluation of the tyre measurements resulted in the profile crest density as the definitive characteristic quantity for describing the influence of the track surface on longitudinal stiffness in dry track surface conditions. In wet track surface conditions, the **longitudinal stiffness** is mainly determined by the maximum coefficient of friction. The algorithms determined show a very high agreement with the average stiffnesses measured.

Characteristic track surface quantities for describing changes in the coefficient of friction in dry track surface conditions are the percentage profile contact area as defined by Eichhorn as well as the characteristic quantity Beta b, which serves as a measure of the macro roughness of the track surface. However, wet track surface conditions show a very close correlation between changes in the track surface's skid resistance (expressed in a function of SRT and SRM) and the change in the friction coefficient.

In dry track surface conditions, the change in the expression of the maximum ("most negative gradient" after the maximum) can be approximately described by means of the characteristic quantity Beta b. For wet track surface conditions, a function of the skid resistance (SRT and SRM) yields sufficiently good results.

On the whole, the results show distinct differences between the real track surfaces and the safety walk predominantly used on test benches. The gradients at the beginning (stiffness) of the longitudinal force/longitudinal slip curves are on average 10 % higher on dry safety walk in comparison to dry real track surfaces. On the safety walk in dry conditions, the maximum coefficients of friction are, in most cases, approx. 5 % below the values for the real track surfaces. Even in wet conditions, the safety walk surface, due to its lower macro roughness, together with the polished washed concrete, has significantly lower coefficients of friction compared to the real asphalt and concrete surfaces. Since the safety walk showed much higher significant effects for a number of parameters than other track surfaces, it is doubtful whether tyre measurements on this type of track surface are suitable for precise simulation calculations.

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