

Influence of Tire Core and Surface Temperature on Lateral Tire Characteristics

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ABSTRACT

In investigation and development of road tires within passenger car development, temperature dependency of tire characteristics is often neglected. This research however explicitly focuses on investigation and identification of temperature dependency of tire characteristics and its interaction with other inner tire states. To this extent, a novel method using a thermographic camera for measurement of both tire core and surface temperature is used. On the basis of these measurements, the dependency of cornering stiffness, relaxation length and lateral coefficient of friction on either core or surface temperature is presented. Moreover, the effect of tire core temperature on inner pressure is investigated. By choice of appropriate operating conditions, the effects of temperature and inner pressure on tire characteristics is investigated separately. A mechanical-analytical analysis forms the basis for derivation of the relationship between material attributes and tire characteristics. Material measurements of a sample taken from the tire under investigation are performed utilizing a hydropulser test rig. The aim of this analysis is identification of rubber storage and loss moduli, i.e. material master curves. The relationship of these material attributes to tire behavior is then shown for the tire characteristics under investigation. Finally, the transferability of the presented findings regarding temperature dependency from a test rig environment to real road conditions is discussed and recommendations are made for tire and vehicle measurements.

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INTRODUCTION

Even being the only force transmitting element between vehicle and road, the physics of tires are still not fully understood. Therefore different properties affecting tire component behavior are under ongoing investigation. Though known to be one of the most important values in motorsports, the influence of tire temperature on tire characteristics is often ignored in analysis of road tires.

Especially cornering stiffness, relaxation length and maximum lateral coefficient of friction are significant tire characteristics defining to a large extent vehicle lateral dynamics. Cornering stiffness directly influences vehicle eigensteer behavior, through the understeer gradient UG , see (1).

$$UG = \frac{m(C_{Rl_R} - C_{Fl_F})}{C_F C_R l} \quad (1)$$

with vehicle mass m , wheel base l , distance of center of gravity to front respectively rear axle l_F and l_R , and front and rear axle cornering stiffness C_F and C_R . Tire cornering stiffness has a large influence on axle cornering stiffness, which can be approximated by (2).

$$C_A = \frac{1}{\frac{1}{C_{EK}} + \frac{2}{C_a}} \quad (2)$$

Where C_A is the equivalent axle cornering stiffness, which is either C_F or C_R in (1). C_{EK} is the elasto-kinematic cornering stiffness of the axle and C_a the tire cornering stiffness of each tire mounted on the axle. As usually 2 tires are mounted per axle, tire cornering stiffness has to be multiplied by 2. Tire relaxation length, in combination with cornering stiffness, defines dynamic tire behavior and therefore dynamic responsiveness of the vehicle with respect to swift steering wheel angle changes. Maximum lateral coefficient of friction $\mu_{y,max}$ determines the maximum reachable lateral acceleration $a_{y,max}$ by any vehicle, assuming a flat road surface and neglecting aerodynamic forces, see (3). For an understeered vehicle, i.e. $UG > 0$, which holds for a large share of commercially available vehicles, the lateral grip of the front axle determines maximum lateral acceleration.

$$a_{y,max} = \mu_{y,max} g \quad (3)$$

Temperature dependency of tire characteristics is investigated by FEVRIER. In this work main focus is on development of a thermomechanical tire model, accounting for both mechanical attributes of the tire and tread material as for the influence of temperature on tire characteristics. Figure 1 shows the effect of friction heating on the lateral force characteristic at two different tire loads. [1]

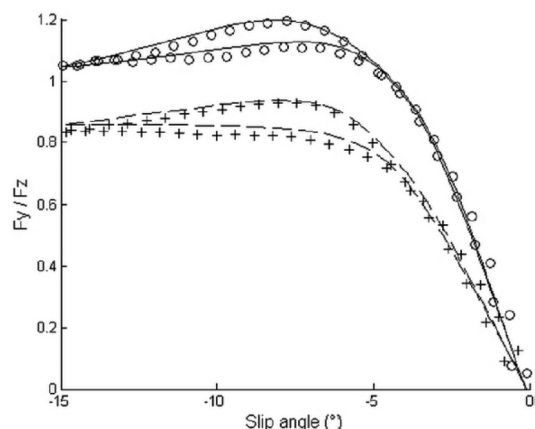


Figure 1. Quotient of lateral force to vertical force over side slip angle for $F_z = 3000\text{N}$ and $F_z = 7800\text{N}$, showing the effect of friction heating on lateral force characteristics [1]

Furthermore, research is mainly performed on material sample level. KRÖGER investigates how temperature profiles develop within a rubber material sample and how temperature affects friction forces, [2]. PERSSON derives and illustrates the role of the so-called flash temperature in the context of friction force generation. The flash temperature only exists for a very short moment in time and is caused by adhesive forces in areas where tread material has direct contact to the road surface, [3]. A relationship between analysis of kinematics of tires, material attributes and temperature dependency and full tire measurement results generally is not found. Therefore, the main focus of this paper is on the entire chain from material measurements, tire measurements and derivation of relationships between the first and the latter as well as transfer of measurement results to real road conditions.

TEST RIG FOR TIRE MEASUREMENTS

For conducting measurements in scope of this research, the tire test rig of INSTITUTE OF AUTOMOTIVE TECHNOLOGY at TECHNISCHE UNIVERSITÄT DRESDEN is used, presented in Figure 2.

The measurements are conducted on an outer drum. An inner frame carrying tire and wheel hub is mounted on the test rig, following a controllable degree of freedom about the vertical wheel axis. The piezoelectric load cell located in the measurement hub is able to measure forces and moments in the three directions in space, which in combination with measurement of slip angle and velocity, enables the conduction of a majority of tire test procedures. An overview of the characteristics of the test rig is presented in Table 1.



Figure 2. Tire test rig at Dresden University of Technology

Table 1. Tire test rig specifications

Drum diameter	2	m
Maximum speed	320	km/h
Side slip angle range	-90 to 90	°
Camber range	-10 to 45	°
Adjustment speed	30	°/s
Resonance frequency	> 300	Hz
Surface material	P120 sand paper	

Integration of a Thermographic Camera

For allowing research on the temperature dependency of lateral tire characteristics the tire test rig has been enhanced by a device for measuring specific temperature values of tires. This is realized by using a thermographic camera capturing the radiation of the tire surface in the infrared spectrum.

In order to capture radiation optimally, the camera is mounted on the lower side of the inner frame of the test rig, while viewing the tire tread in direction of the trailing edge. The configuration is schematically shown in Figure 3.

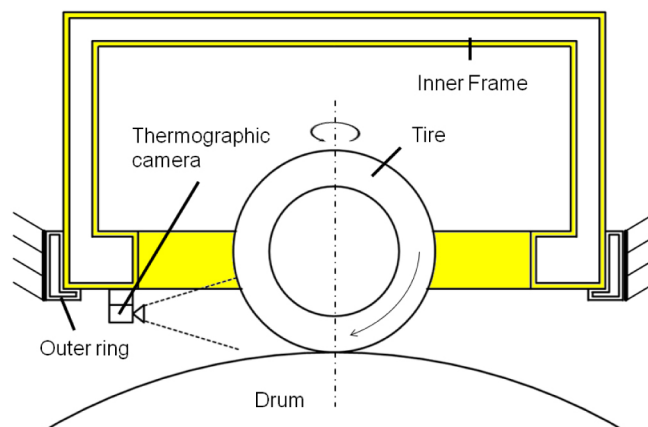


Figure 3. Integration of the thermographic camera in the tire test environment

As the thermographic camera rotates in the same direction as the inner frame and therefore the side slip angle, the same view on the tire is maintained during all lateral measurements.

For calculation of temperatures corresponding to the obtained infrared data the emittance ε is needed. Emittance compares the actual emissive power with that of a black surface at same conditions [4]. Taking this fact into account, the thermographic camera is calibrated by determination of emittance for the existent tire material. Experiments have shown that the emittance of tires generally is in the range of 0.95, which is in the same order of magnitude provided for rubber [4, 5].

A thermographic image obtained using the described set-up is shown in Figure 4. The grayscale shading represents a predefined temperature range. In this context the upper limit of the temperature scale corresponds to white and the lower limit to black.

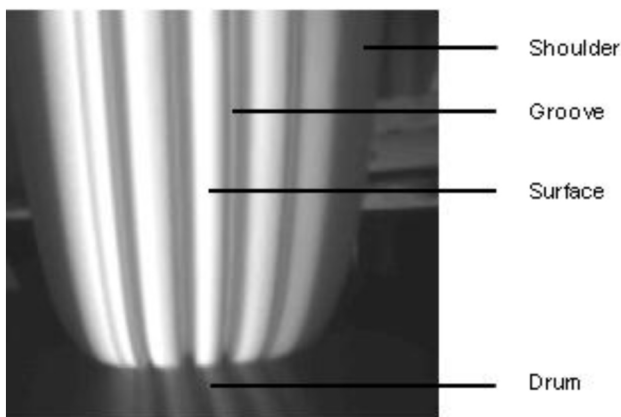


Figure 4. Infrared image of the tire tread obtained using the presented set-up (temperature range of 20 to 100°C)

The shown image allows for investigation of distribution of temperatures. At first the surface region is identified. This area corresponds to the positive profile of the tire. In the example of Figure 4 a high amount of sliding occurs in the contact patch resulting in a high surface temperature compared to the remaining tire tread. Then, the tread grooves are identified as the negative tire profile. Contrary to the tire surface the groove is not or only indirectly affected by processes in the contact patch, which results in a lower temperature in the depicted example. Furthermore, the temperature of the tire shoulder and test rig drum can be identified separately.

Thermal Image Processing Algorithm

The resolution of the shown thermographic image is 160×120 pixels. With a sampling rate of 20Hz a high quantity of measuring points are obtained. Therefore a calculation algorithm is needed for the specification of characteristic values. The temperature distribution over the tire circumference is assumed to be homogenous. Furthermore, maximum accuracy of infrared measurement is achieved by a view angle perpendicular to the

tire surface area under investigation due to directional emittance of nonconductors, [4]. For this reason the topmost row of the thermographic image is used for calculation of characteristic temperature values. An exemplary temperature profile is shown in Figure 5.

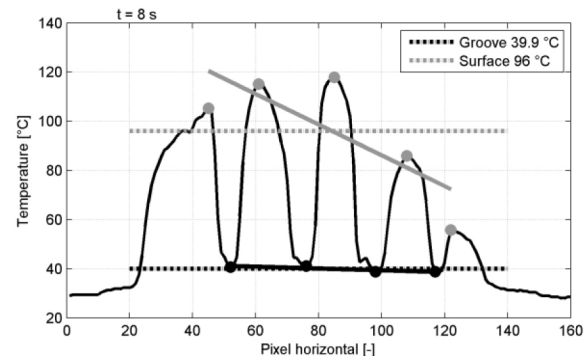


Figure 5. Exemplary temperature profile of the tire tread

Here the locations defining the previously specified groove and surface are represented through dots. The points are continuously traced as both vertical and horizontal position change as a result of temperature changes and tire deformation.

A linear fit of the determined temperature values is conducted and displayed as continuous lines. By doing so, temperature distribution on the surface can be examined in different operating conditions. Furthermore, the dashed lines show the current mean of the particular temperature which is used when referencing to temperature values.

As a generic tire core temperature cannot be derived directly from thermographic data, further effort is needed for determination of this specific temperature.

Correlation between Tire Core and Groove Temperature

For direct measurement of the core temperature, platinum resistance sensors (Pt100) are applied on the inner liner of the tire. Afterwards this temperature value is compared to the temperature data gathered by the thermographic camera. In this case it is observable that the groove temperature resembles the core temperature. Especially when the amount of sliding in the contact patch can be neglected the progress of both temperatures is similar. Furthermore when the tire is lifted after operation and both temperatures are measured, a direct correlation of the magnitudes is recognized. A comparison of the temperatures after different test maneuvers is depicted in Figure 6.

As a result of the presented correlation the groove temperature is used as a reference for the core temperature in course of this paper.

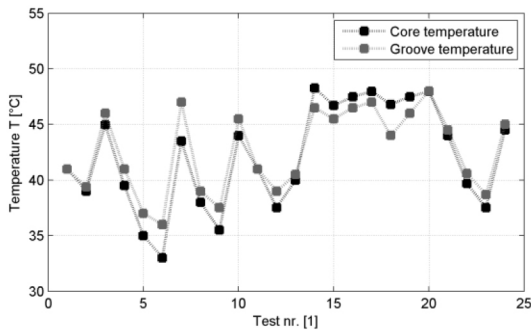


Figure 6. Comparison between tire groove and core temperature

METHODS FOR DETERMINATION OF TEMPERATURE AND PRESSURE DEPENDENCIES

In the previous chapter requirements for conducting measurements in scope of this research have been presented. During further proceedings methods for determining temperature and pressure dependencies of decisive characteristics in lateral tire dynamics are described. In this context focus is set on cornering stiffness C_{α} , relaxation length σ_{α} and maximum lateral coefficient of friction μ_{max} . Properties of the test object used in measurements are presented in Table 2.

Table 2. Test tire specifications

Manufacturer	Type	Dimension	LI/SI	Rim size
Bridgestone	Potenza RE050A	245/40 R18	93Y	8 J x 18

Cornering Stiffness and Relaxation Length

For determining the individual influence of temperature and pressure on cornering stiffness and relaxation length, common procedures are used in combination with different operating conditions, presented in Table 3. The specified pressure values correspond to the inflation pressure while the shown temperature values specify the core temperature.

Table 3. Definition of operating conditions during tire measurement procedure

Operating Conditions	$p_1 = 2,3\text{bar}$	$p_2 = 2,5\text{bar}$
$T_0 = 2^{\circ}\text{C}$	C5	
$T_1 = 35^{\circ}\text{C}$	C1	C2
$T_2 = 50^{\circ}\text{C}$	C3	C4

The definition of operating conditions is based on the behavior of the tire under real circumstances. C1 is an arbitrary initial condition, while C4 is the resulting state after heating the tire through rolling at high vertical load. By doing so viscous damping of the rubber material leads to a coupled increase of temperature and inflation pressure. Core temperature is

assumed to be equal to the inner air temperature. Therefore coupling can be defined by the ideal gas equation, presented in (4). The equation describes the relationship of the product of pressure p and volume V with the product of mass m , universal gas constant R and temperature T . [6]

$$pV = nRT \quad (4)$$

Furthermore, isochoric conditions are assumed whereas the relationship of pressure and temperature is described by (5).

$$\frac{p}{T} = \text{const.} \quad (5)$$

The assumption of isochoric conditions is verified separately. The determined relationship in comparison with an isochoric behavior is presented in Figure 7.

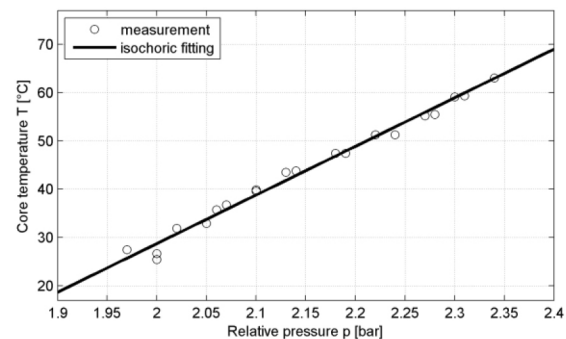


Figure 7. Relationship between pressure and temperature in comparison with isochoric behavior

In addition to the coupled operating conditions C1 and C4 temperature and pressure need to be uncoupled to determine their individual influences. In this context, operating condition C2 defines a singular increase of inflation pressure to 2.5bar. Operating condition C3 describes a singular increase of the core temperature to 50°C. In this context the core temperature is changed by either rolling and therefore heating the tire through viscous damping or by conduction of cooling intervals.

Furthermore, operating condition C5 is defined by a core temperature of 2°C and is realized for determination of the tire behavior at low temperatures. In this context the tire is cooled prior to conduction of measurements. The inflation pressure is set to 2.3bar to allow comparison of the results to operating conditions C1 and C3.

The specified operating conditions are now used in combination with procedures for obtaining cornering stiffness and relaxation length. As the friction power occurring in the procedures and heat transmission between core and environment are small the defined operating conditions are held constant during the maneuvers.

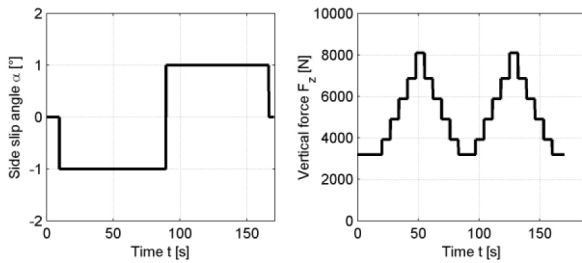


Figure 8. Slip angle and wheel load of the load step method

First the load step method is introduced. The progress of side slip angle and vertical force is depicted in Figure 8. By evaluating the defined load steps the cornering stiffness C_{am} is calculated. The characteristic is defined as mean value of single cornering stiffnesses at side slip angles of -1° and $+1^\circ$, see (6).

$$C_{am} = \frac{\frac{F_y}{\alpha}|_{\alpha=-1^\circ} + \frac{F_y}{\alpha}|_{\alpha=+1^\circ}}{2} \quad (6)$$

For measurement of relaxation length the so-called side slip angle step method is used, which is somewhat similar to the load step method presented before. In the side slip angle step method however, the slip angle is changed from 0° to -1° and $+1^\circ$ degree respectively. In this context focus is on the buildup of side force. Side slip angle and vertical force are presented in Figure 9.

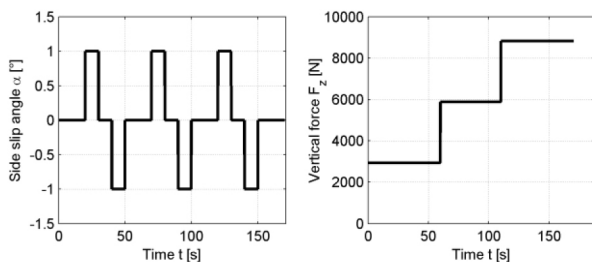


Figure 9. Slip angle and wheel load of the side slip angle step method

It is assumed that the side force buildup is characterized by a first order differential equation, according to (7).

$$T_1 * \dot{F}_y + F_y = C_\alpha \alpha \quad (7)$$

T_1 is the time constant while the corresponding gain is defined as product of cornering stiffness and current side slip angle. For determination of the relaxation length the time constant is derived from the side force buildup. Then, according to (8), the relaxation length is calculated by the product of time constant T_1 and velocity v_l [7]

$$\sigma_\alpha = T_1 * v_l \quad (8)$$

Maximum Lateral Coefficient of Friction

Unlike the methods presented previously the maximum lateral coefficient of friction is determined at high side slip angles. Moreover friction potential is mainly dependent on processes occurring in the tire surface, therefore the surface temperature is more significant than the core temperature. For determination of pressure and temperature dependency of this tire attribute, a side slip angle ramp measurement is conducted. In this procedure the tire is heated gradually with every cycle. With regard to the behavior shown in Figure 6 the inflation pressure increases accordingly. In the last test inflation pressure is decreased to its initial value allowing to distinguish between effects related to pressure and temperature changes. The side slip angle to this extent is presented in Figure 10.

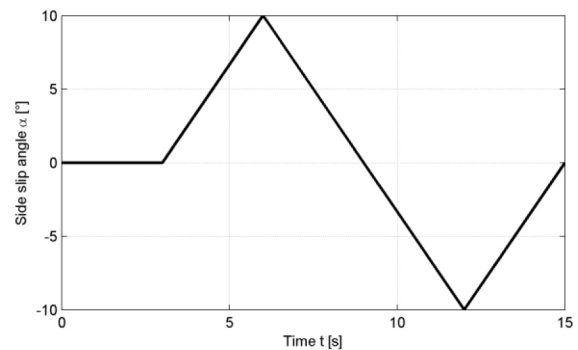


Figure 10. Side slip angle ramp

Using the presented method, determination of individual sensitivities of temperature and pressure on maximum lateral coefficient of friction is possible. However surface temperature is changed only in a limited range, due to cooling of the surface when passing through small side slip angles.

In order to be able to assess higher temperature regions the periodic side slip angle ramp is developed. In this method the tire is kept near the maximum friction potential, while changing the side slip angle in a small range. The process is stopped once surface temperature reaches a steady-state condition. The progression of the side slip angle during measurement is shown in Figure 11.

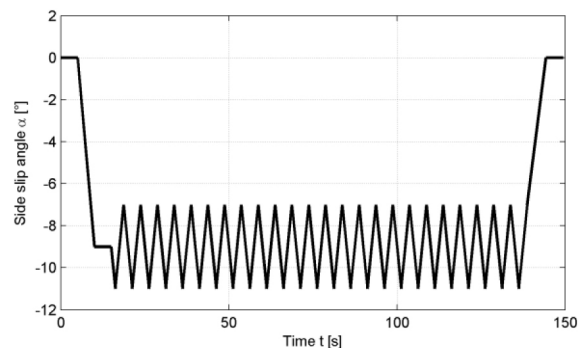


Figure 11. Periodic side slip angle ramp