

A Detailed Thermo-Mechanical Tire Model for Advanced Handling Applications

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ABSTRACT

Currently used tire models have shown a certain lack of accuracy in some advanced handling applications. This lack of accuracy is believed to be partly due to thermal effects. In reality, the tire rubber temperature is not constant during the normal operating conditions and it's really well known that the tire friction coefficient strongly depends on the temperature level.

The temperature generation, propagation and evolution are the result of a dynamic energy equilibrium between phenomena of different natures. Various mechanisms create a non-uniform temperature distribution in various parts of the tire structure: heat is generated in zones with large cyclic deformations due to the energy dissipated from the rubber strains and in the sliding part of the contact patch due to friction. The rubber cools down because the heat energy transferred to the air (internally and externally) and to the asphalt in the stick zone of the contact patch. The presented thermodynamic tire model allows for the simulation of all these local thermal phenomena and the thermal energy equilibrium is described by the Fourier diffusion equation solved with a finite volume approach.

Furthermore the described thermal model is coupled with the structural MBD tire model 'CDTire/3D' and with an enhanced magic formula (MF) formulation. The coupling strategy naturally incorporates the structural tire model, while in the case of the MF model some empirical adaptations are needed. Both tire models' behavior is influenced by the local calculated temperature, e.g. by modifying the local friction of the tread/asphalt contact. One result the model clearly shows is the variation of the road holding performance as a consequence of the temperature evolution. The capabilities of the overall model are demonstrated and validated in some illustrative scenarios by using measured data from motorsport applications.

CITATION: Calabrese, F., Baecker, M., Galbally, C., and Gallrein, A., "A Detailed Thermo-Mechanical Tire Model for Advanced Handling Applications," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(2):2015, doi:10.4271/2015-01-0655.

INTRODUCTION

The tire plays an essential role in car performance, handling, road holding and driving comfort. In the past many different tire models have been developed [1] to estimate forces and moments transmitted from the tire to the hub of the vehicle. For all these tire models the effect of the temperature on the tire behavior has not or only rarely been taken into account. But the effect of the temperature on the tire behavior is manifold.

Most adults may have experience driving a car with winter tires in late spring when the temperature is well over 20 °C. In such a situation one can really feel that the car tends to "swim" laterally on the highway or that the traction in curves become worse. The reason for this phenomenon can mainly be found in the softening of the tread block stiffness but also in the fact that the friction coefficient of the tread rubber leaves its optimum. So from this simple application case one can derive two main effects of the temperature on the tire:

- The structural stiffness's (storage module) of the rubber compound is strongly temperature dependent, as well as the loss module.
- The friction between rubber and road is temperature dependent.

There is a third and also important temperature effect on the tire and that is the influence of the filler gas temperature to the tire inflation pressure. This can be observed if one looks at a tire in a strong winter which has been filled last in summer. If one decreases the temperature of the inner air from 20 °C to 0 °C, the inflation pressure reduces approximately by 6 percent.

In the vehicle development processes, the temperature dependency of the tire behavior has not been considered very deeply in the past, while the effect on the inflation pressure may be covered by a temperature measurement of the filler gas, the local bulk or tread temperature cannot be measured with a reasonable effort. To get access to these temperatures a detailed thermo-dynamical tire model is needed to estimate the temperature creation and propagation in the tire.

Various authors [2] [3] [4] [5] faced with this problem, they all agree in the physics description of the phenomena: the temperature evolution can be assumed as the result of the energy equilibrium between the air, the asphalt and the tire systems. The main terms of energy generation are friction and rubber dissipations, the main cooling terms are due to the external air and asphalt interaction. In [3] [4] the finite difference approach is fully described. In [2] [5] the authors propose an approach to couple the thermal model with semi-empirics tire models.

In this paper a full thermo-dynamical tire model will be introduced. The main purposes and unique contributions of the current study respect to previous ones are:

- The thermal model is designed like a module, in order to make possible to combine the thermal model with different mechanical tire models which can be vary in resolution, accuracy and physicality. This aspect seems to be not taken into account from [2] [3] [4] [5] because there is not a real separation between thermal and mechanical effect. By discerning these two parts results possible to use the same thermal module with a semi-empirical, physical or FEM tire model as well. In this article two cases are discussed: in some application where a low computational cost is more important than the accuracy, a Pacejka MF can be used. In some other application, where the extrapolation, prediction and accuracy are fundamental requirements, the thermal model can be coupled with a full 3D physical model [6] [7].
- The overall thermal tire model which will be introduced is a fully 3D finite volume based model with a fine resolution (which can be varied) in thickness, circumferential and lateral dimension. Respect to the finite difference one the finite volume approach is fully-stable and conservative.
- A new approach to interface the MF with the thermal module is analyzed. Respect to [2] it will be shown how the MF has to be expanded with a 'contact patch model'. In this case also effect like lateral force, internal pressure, and contact patch shape will be considered in the energy distribution.
- The friction-grip dependency will be modeled in accord with the WLF law [6]
- The coupling with a fully 3d structural tire model [7] is described. In this case the structural energy dissipation and the material property are modeled in a detailed physical way respect to the first approach.

After introducing and discussing the thermal model and the interfacing to different mechanical tire models, some application examples will be shown and discussed. For these examples the authors are focusing to the coupling with a temperature enhanced MF tire model. The discussed applications are mainly handling-like applications. At the end, a validation of the overall model will be shown using measured data from [Formula 1](#).

IMPORTANCE OF THE THERMAL EFFECT ON TIRES AND THE MECHANISM OF TEMPERATURE GENERATION

Tires have a very complex composite structure made of different layers such as carcass, bandage and steel cords kept together with the filled rubber. The rubber compound has a prominent role for the tread behavior. Indeed due to its viscoelasticity properties the rubber is capable of dissipating energy in order to create friction and absorb impact.

Usually the heat generation due to the rubber strains is the most important source for temperature creation. At the same time as temperature arises, also the rubber loss and storage modulus decrease. (See [figure 1](#))

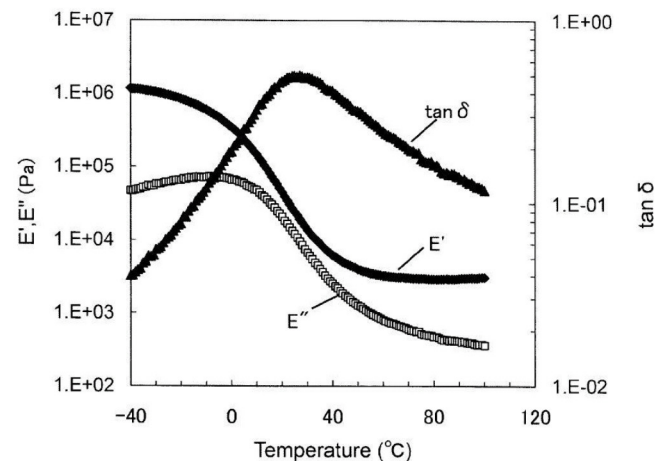


Figure 1. Viscoelastic property of the rubber, storage, loss modulus and tan delta.

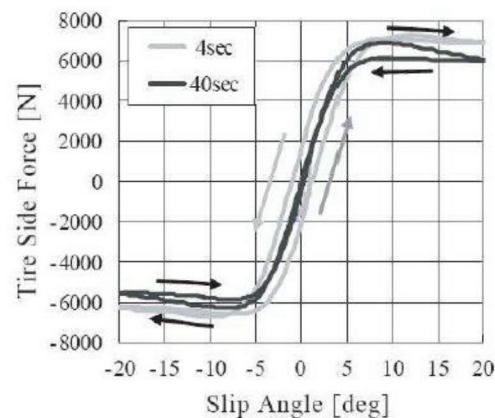


Figure 2. Lateral force during a side slip angle variation for different time length of the experiment. [2]

The rubber-asphalt interaction mechanisms are influenced as result of these phenomena because the rubber penetration into the asphalt asperities depends on the rubber compliance. Therefore the resulting friction coefficient is very sensitive to the temperature variation. This effect can be seen really clearly during a sweep angle experiment (See [figure 2, 3](#)). In the following figures the temperature-force correlation during this kind of standard test is shown [2]. If the test is performed over a relatively long time (dark gray line in [figure 2](#)) the temperature can also reach variations from 60 °C up to 80 °C respect to the initial temperature (See [figure 3](#)). In this case it is

possible to observe that the peak of the force characteristic curve changes when the temperature rises. Obviously these phenomena have an impact on the tire performance given that the friction is not always at its optimal level but changes with the temperature.

If the test is performed in a relatively short time (gray line) the heat has not enough time to penetrate into the tread and warm up the tire, so in this case the temperature results are quite constant during the experiment, but the measurement is not suitable for parameter identification purposes because of the presence of the relaxation length effect in the slip stiffness.

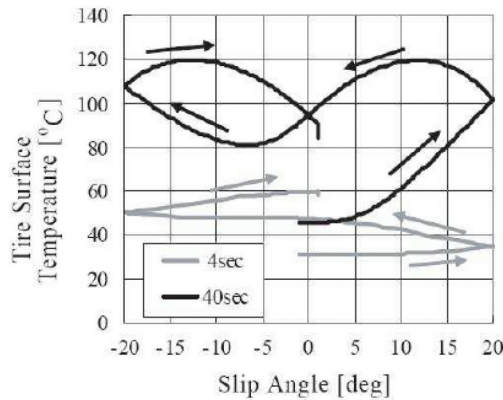


Figure 3. Temperature during a side slip angle variation for different time length of the experiment. [2]

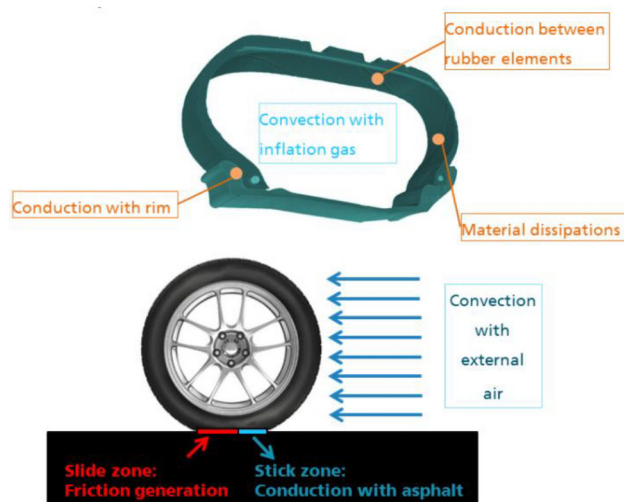


Figure 4. Description of the various heat phenomena.

Furthermore because of temperature creation and propagation there are also some secondary effects like the internal pressure and rolling resistance change. However in this article only the friction and inflation pressure dependency will be analyzed.

The phenomena responsible for the temperature variation of the rubber are basically the following [2] [3] [4] [5]:

- Energy dissipated by the rubber strains
- Convection with the external air
- Friction in the sliding zone of the contact patch

- Conduction with the asphalt through the contact patch
- Propagation through the tire volume

All this phenomena and their mathematical and physical description will be analyzed in the next paragraph.

MODEL EQUATION DESCRIPTION

The heat conduction phenomena can be described by the Fourier diffusion equation (1). The equation can be integrated on the discretized volume of the tire (figure 6) using the so-called finite volume approach and applying the Navier-Stokes theorem (2)

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q}_g = \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

$$\int_V (\nabla \cdot k \nabla T + \dot{q}_g) dV = \oint_{s_i} k \frac{\partial T}{\partial n} ds_i + \int_V \dot{q}_g \cdot dV = \int_V \rho \cdot c_p \dot{T} \cdot dV \quad (2)$$

Where the following terms can be called as:

$$q_{tot} = \oint_{s_i} k \frac{\partial T}{\partial n} ds_i : \text{Global thermal flux}$$

$$E_g = \int_V \dot{q}_g \cdot dV : \text{Energy generated inside the finite volume}$$

$$E_{st} = \int_V \rho \cdot c_p \dot{T} \cdot dV : \text{Energy variation inside the material}$$

The equation (2) obtained after the integration represents the energy equilibrium of a single finite volume element: In this equation the sum of the thermal fluxes q_{tot} that enter in the element through the surfaces with the internal energy generation E_g gives the variation of internal energy of the thermal cell E_{st} for an infinitesimal instant of time.

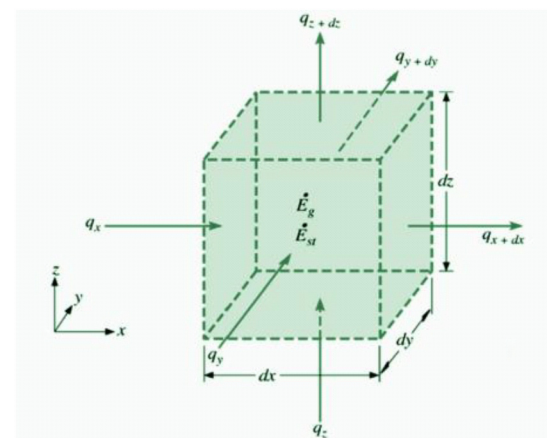


Figure 5. Representation of the thermal energy equilibrium of a single finite volume element.

The finite volume approach has the advantage over finite differences in that it allows using volume elements of arbitrary shape. This aspect is important because it allows having a non-uniform discretization without error in the energy balance calculation of the domain.

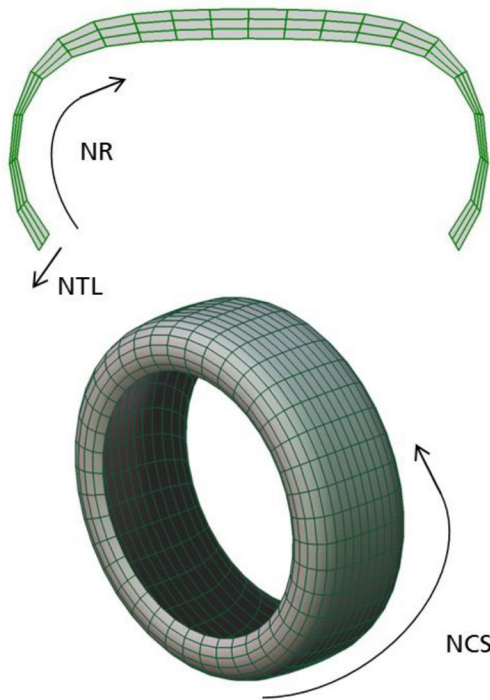


Figure 6. Example of discretization. NR, NTL, NCS are the three integer number that define how fine is the discretization along the thickness, the section and the circumferential direction.

The full volume of the tire is discretized along the circumferential, sectional and thickness direction. Such a fine discretization is necessary in order to also describe asymmetric scenarios of generation and propagation (e.g. large camber or full sliding condition during braking) and the various material properties along the thickness direction.

All the possible thermal phenomena in the tire thermodynamics can be included as flux generation at the boundary of the single thermal cell without changing the form of the [equation \(2\)](#). The basic form of each flux is represented as follow:

- Friction power density: it can be described as the product of the tangential force multiplied for the sliding velocity.

$$\vec{q}_{fp-i} = \tau_i \cdot v_s \quad (3)$$

- Road Conduction: it depends on the difference in temperature between road and asphalt and on the thermal resistance. The thermal resistance depends on rubber-asphalt conductivities.

$$\vec{q}_{rc} = R_{asphalt-rubber} (T_{road} - T_{rubber}) \quad (4)$$

- Convection with the external gas: It depends on the difference of temperature between air and tire and on the convection coefficient. The convection coefficient H is calculated by

using the Nusselt number (Nu). For this calculation the basic assumption is that the tire has the shape of a cylinder. The convection coefficient will be a function of the tire geometry, the relative velocity between tire and external air and of the air conductivity

$$\vec{q}_{ig} = H_{fc} (T_{ext-air} - T_{rubber}) \quad (5)$$

- Heat generated by the rubber strains: It can be locally described as integral on the volume of the stress that multiplies the rubber strains. During the normal operational condition it will depend on the amplitude and frequency of the global forces Fx, Fy, Fz applied at the contact patch.

$$\dot{q}_{g-i} = \int_V \sigma \frac{\partial \varepsilon}{\partial t} dV \quad (6)$$

Furthermore in order to describe in a correct way the diffusion phenomena into the material also a local description of the material property is possible because of the fine discretization along the thickness. Each finite volume element can have a different conductivity depending on the material. A thermal element will have the same number of thermal resistances as the number of paths of heat flow. In general the paths of heat flow are six, given that an element has six faces. As summarized in the [figure 7](#) the thermal resistance of an element relative to a certain path flow in the diffusion phenomena is equal to:

$$R = \frac{L}{k \cdot A} \quad (7)$$

Where:

L: distance between the two centroids of two adjacent elements relative to a certain path of heat flow

A: Cross-sectional area relative to the path of heat flow between two adjacent elements

k: Thermal conductivity

If two element have different conductivity properties along a certain path flow the thermal resistance can be calculated as:

$$R_{tot} = \sum R_i \quad (8)$$

In the [figure 7](#) the representation of the thermal resistance calculation for the mono dimensional case of an infinite wall is represented. This concept has been expanded for the 3-dimensional case for each single finite volume element of the model.