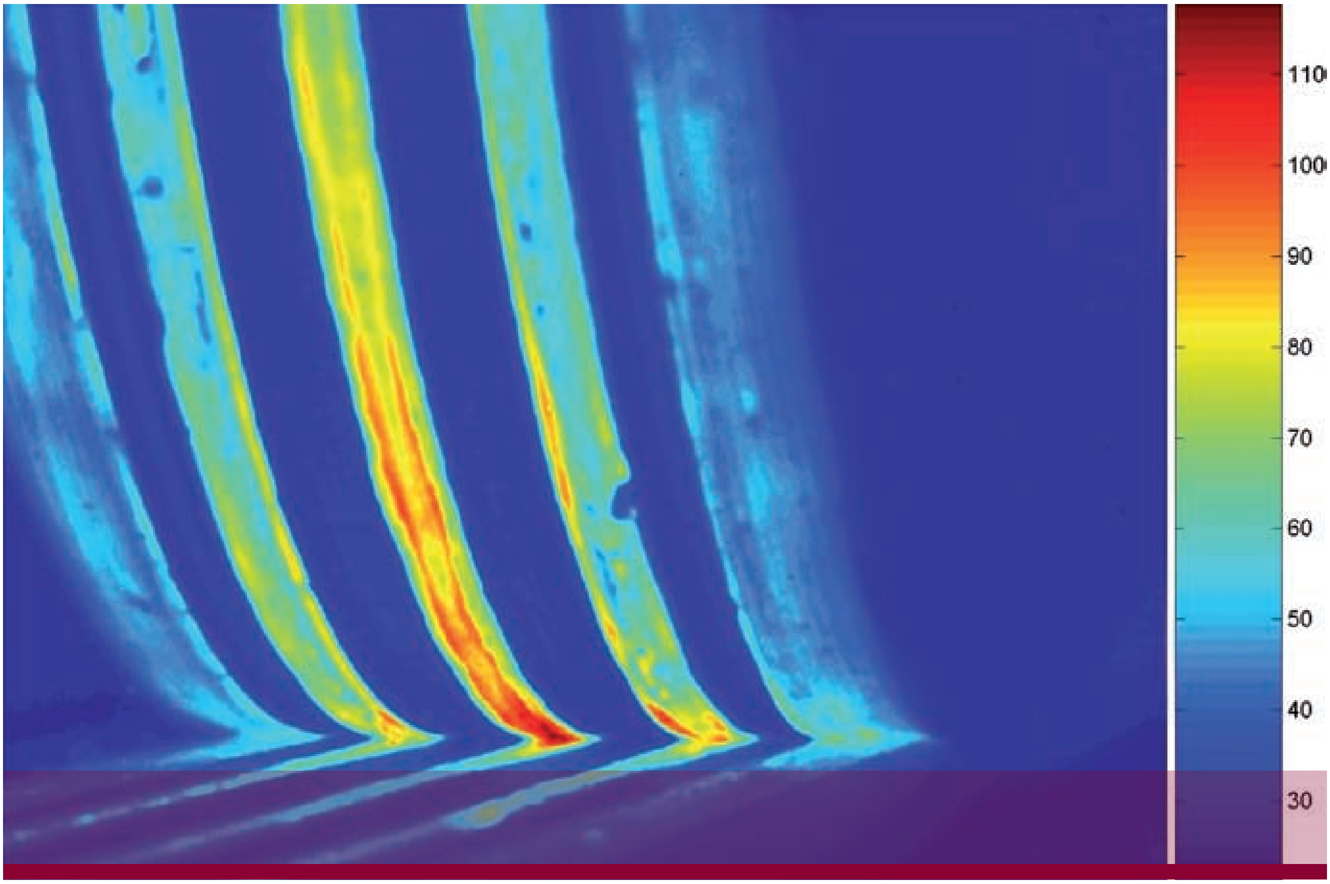

Thermal and Mechanical Tyre Modelling for Handling Simulation

TaMeTirE is a new thermo-mechanical tyre model for handling simulation developed by Michelin. Its main benefit compared to mathematical fit models is its capability to extrapolate tyre force and moment to the actual driving conditions of the vehicle by taking both speed and tyre temperature effects into account and showing their significant influence on the lateral force in pure cornering conditions. TaMeTirE can accurately predict the lateral force especially when the tyre is at the limit of friction.

1 Introduction

The ability to predict tyre characteristics that are relevant to the actual driving conditions for the tyre and the vehicle combined remains an important means of improving tyre models for handling and vehicle dynamics. Many test results show how tyre force and moment characteristics are dependent on the test conditions under which they are obtained [1]. This is mainly due to thermal effects and thermo-dependent elastic and viscous properties of the rubber compound. The current state of the art for tyre modelling is based on mathematical formulas that are fitted to indoor test machine measurements. These can represent the tyre characteristics for a wide variety of tyre types and sizes, but the forces and moments they describe are only representative of indoor measurement conditions that the model is based on, and the quality of the model prediction is completely linked to the measurement protocol. Recently, new developments regarding the measurement protocol have been carried out to bring the tyre's thermal states as close as possible to the situations encountered on a track by the vehicle's tyre [2]. However, because indoor tests cannot cover all the actual driving conditions, such an approach that disregards the influence of thermal effects remains limited to a few vehicle manoeuvres. The aim is to develop a tyre force and moment model that takes thermal effects into account for vehicle dynamic simulation tools and for any vehicle manoeuvres. The mechanical and thermal tyre model TaMeTirE calculates the longitudinal and lateral force as well as the self-aligning torque in a combined slip angle and slip ratio, at different loads, inflation pressures, camber angles, travelling speeds and road and ambient temperatures. First the modelling approach and the equations are presented. This is followed by an analysis of data from flat-track measurements and simulation results in pure cornering conditions for a Michelin Primacy (225/55 R16) tyre.

2 Thermal and Mechanical Tyre Model Development

The complex non-uniform and non-linear deformations of the tyre structure have a significant effect on the tyre force generation. In cornering conditions, the sidewalls, belt and tread deformations lead to a non-uniform contact patch shape and load distribution, **Figure 1**. An accurate modelling of the mechanical behaviour of the tyre can be addressed with Finite Element approaches. Such models are used to gain an understanding of tyre design and tyre mechanics. However, for full vehicle dynamics simulation, tyre modelling simplifications are necessary in order to keep the model as simple and as fast as possible. Basically, the TaMeTirE model is based on three models: one for the tyre mechanics, one for the compound characteristics (shear modulus and friction) and one for the tyre temperatures, **Figure 2**.

2.1 Mechanical Model

The mechanical model is based on the well-known "brush element" approach [3-13]. The total force is the sum of the tread elementary shear forces in the adherent and sliding areas of the contact patch (CP). Moreover, the total lateral force causes a CP displacement as well as belt bending and casing twisting, thus modifying the tread shear force generation. The following stiffnesses are introduced:

K_T	sidewall twisting stiffness
$1/S_2$	belt bending stiffness
K_X, K_Y	tread stiffness in the longitudinal and lateral directions.

In cornering conditions, **Figure 3**, the self-aligning torque M_Z leads to a sidewall twisting mechanism that reduces the effective slip angle δ' of the CP, Eq. (1):

$$\delta' = \delta + \delta_0 + \frac{M_Z}{K_T} \qquad \text{Eq. (1)}$$

In addition, the lateral force induces an in-plane belt deflection (that is bending in the X-Y plane) that reduces the shear deformation of the tread. This deflection is approximated by a quadratic formula,

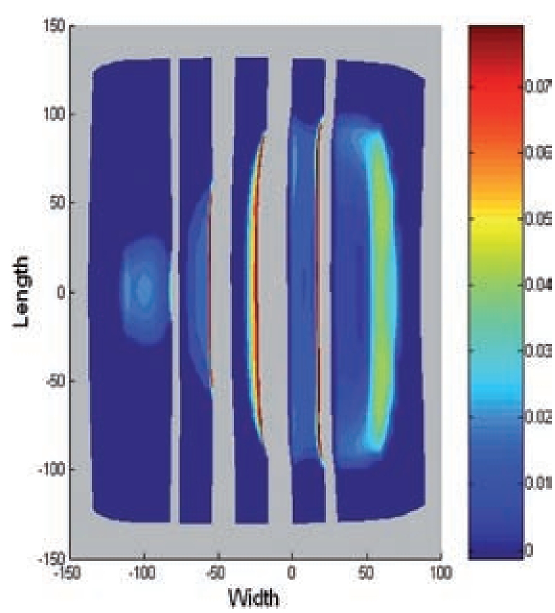

Figure 1: Tyre contact patch and pressure distribution in cornering condition from Finite Element simulations

The Authors

Dr.-Ing.
Pierre Février
is technical manager for tyre modelling and traction research at Michelin in Clermont-Ferrand (France).

Ing. Gérard Fandard
is tyre performance expert at Michelin in Clermont-Ferrand (France).

in which the curvature ρ of the belt at the CP centre is given by Eq. (2):

$$\rho = S_2 Fy \qquad \text{Eq. (2)}$$

The CP width *Ly* and length *Lx* are functions of the load and inflation pressure. The pressure distribution along the CP is given by a polynomial equation. At small loads or high inflation pressures, the pressure distribution along the CP is parabolic. In contrast, at high loads or low inflation pressures, the pressure distribution is more uniform. The tyre force derivation is detailed in [14]. The force distribution is calculated along the CP according to a one-dimensional brush element approach (that is one rib). The effect of the non-uniform CP shape is introduced by modifying the rib boundary conditions. For calculation time efficiency, it is convenient to consider that there is a unique point *b* in the contact patch that corresponds to the transition between adherent and sliding conditions. When the shear force is balanced by the friction force, the contact remains sliding until the exit of the contact patch. The longitudinal and lateral forces are given by Eq. (3) to Eq. (5):

$$F_X = \int_{-Ly/2}^{Ly/2}\int_{b}^{a} K_X (X_K - X_N) dS + \int_{-Ly/2}^{Ly/2}\int_{-a}^{b} \frac{r_K \tau}{\sqrt{(r_K \tau)^2 + (1+\tau)^2 \beta^2}} \mu(p,Vg,T) p \, dS \qquad \text{Eq. (3)}$$

$$F_Y = \int_{-Ly/2}^{Ly/2}\int_{b}^{a} K_Y (Y_K - Y_N) dS + \int_{-Ly/2}^{Ly/2} \frac{\int_{-a}^{b} (1+\tau)\beta}{\sqrt{(r_K \tau)^2 + (1+\tau)^2 \beta^2}} \mu(p,Vg,T) p \, dS \qquad \text{Eq. (4)}$$

$$\beta = \delta' - \frac{1}{2} S_2 F_Y (a+K_N), \quad r_K = \frac{K_X}{K_Y}, \quad a = Lx/2 \qquad \text{Eq. (5)}$$

The first term of Eq. (3) and Eq. (4) is the total force in the adherent area of the CP. This force contribution is governed by the tread stiffness and CP dimensions. The second term of Eq. (3) and Eq. (4) is the total friction force in the sliding area.

2.2 Rubber Shear Modulus Model and Friction Model

Tread rubber characteristics play an important role in the tyre force generation, as they govern the tread stiffness, the friction properties and the heat generation. The energy loss and modulus vary not only from one compound to another but depend also on the stress frequency and the temperature for a given compound. The tread rigidity is directly related to the rubber compound shear modulus *G*, Figure 2. As the rubber becomes softer when its bulk temperature *Ti* increases, the tread rigidity will depend on the tyre warm-up. As pointed out in [1], higher cornering stiffness is obtained at a lower tread temperature. Accordingly, the influence of the ambient and road temperatures on the cornering stiffness is significant, as well as the operating condition history of the tyre. As far as friction is concerned, two stress mechanisms are involved in the relative slippage between the rubber compound and the road surface. The first mechanism is the frequency excitation of the material by the road texture. The rubber is distorted when it slips over the rough spots on the road, thus leading to a loss of energy, the so-called indentation mechanism. The second mechanism is molecular adhesion, which

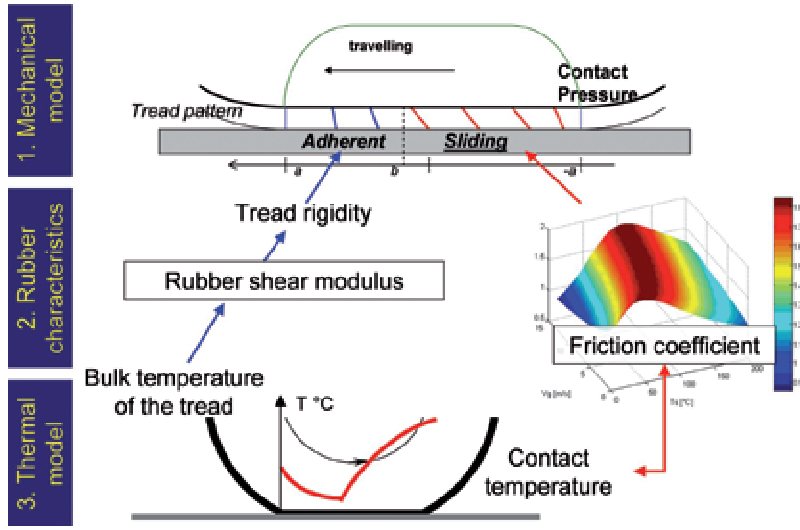

Figure 2: TaMeTirE modelling approach: 1. Mechanical model based on the "brush element" approach. 2. Rubber compound characteristics (shear modulus; friction coefficient evolution with the contact temperature and sliding speed). 3. Thermal models for the contact temperature as well as for the surface and internal temperatures of the tread over a period of wheel rotation

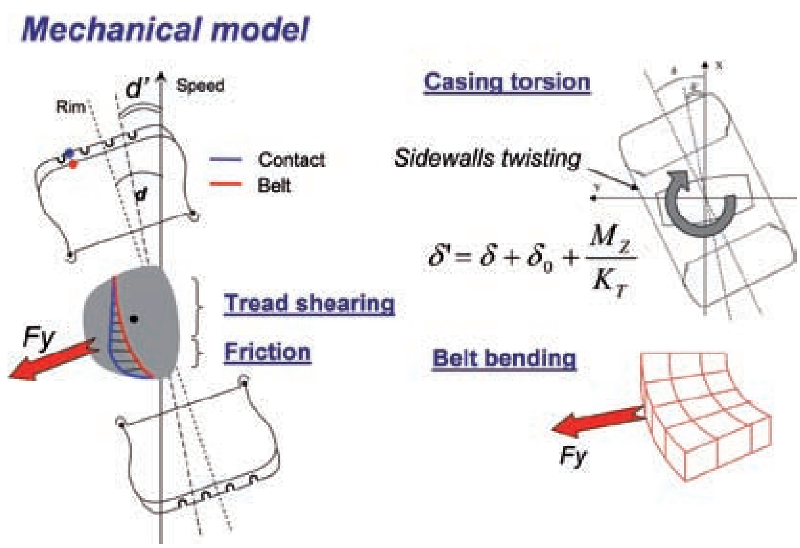

Figure 3: Tyre structure deformations in cornering conditions: sidewall twisting due to the self-aligning torque and belt bending due to the lateral force

comes into play at a scale of one hundredth of a micron, and which is amplified by slippage. In both cases, the viscoelastic properties of the rubber, and particularly its hysteresis at a high frequency, play an important role. As a result, the friction properties of a tread material sliding on a road surface are a function of the contact pressure, the sliding speed and the contact temperature, Figure 2. Generally speaking, for a given sliding speed V_g , the friction curve $\mu(T)$ shows a peak value that can be significantly greater than the friction at a very low or very high temperature. With increasing sliding speed, the peak value of the $\mu(T)$ curve is shifted towards a higher temperature. Finally, as pointed out in [15], the friction coefficient μ tends to decrease with increasing contact pressure.

2.3 Thermal Models

The friction force is coupled to the contact temperature evolution along the CP, Figure 2. The contact temperature is estimated according to the theory of two uniform semi-infinite media in a perfect thermal contact. In the sliding area of the CP, the dissipation of energy due to friction leads to a rise in the contact temperature. The dissipation is modelled by a heat flux at the interface between the rubber and the road surface, Eq. (6):

$$\varphi = \mu p V_g \qquad \text{Eq. (6)}$$

In addition, the surface and internal temperatures Ts and Ti of the tread are calculated from the one-dimensional thermal equation in the tread thickness, averaged over the tyre width and over a period of rotation, **Figure 4**. The heat transfer at the tyre surface is governed by conduction to the track, as well as by convection to the air and heating due to friction. Compression and shearing in the contact patch are responsible for an additional heating in the core of the tread due to the rubber hysteresis at the tyre rolling frequency [16].

3 Application to a Passenger Car Tyre

Measurements on a flat-track machine were carried out for a Michelin Primacy passenger car tyre (size 225/55 R16). The test protocol consisted of several sequences: cornering stiffness at three inflation pressure and slip angle sweeps between -15°, 15° at different loads and travelling speeds (40 km/h, 80 km/h and 160 km/h). The surface temperature was measured at the top of the tyre using an infrared thermal camera.

3.1 Tyre Stiffness Prediction

The cornering stiffness (Dz), self-aligning torque stiffness (Gz), camber force stiffness (Hz) and self-aligning torque stiffness due to camber (Jz) at the three inflation pressures are shown, **Figure 5**. Both measurement data and simulations are depicted. The cornering stiffness Dz is one of the main tyre characteristics governing vehicle dynamics at a small lateral acceleration. At a small load, Dz is mainly governed by the CP dimensions and the tread stiffness. The influence of the casing parameters S2 and KT is negligible. When either the load increases or the inflation pressure decreases, the contact patch becomes longer and wider, thus leading to an increase in Dz. At a higher load, the influence of the casing is more and more important. The belt compliance S2 tends to reduce the tread shear force, while sidewall twisting leads to a reduction in the effective slip angle of the CP. Therefore, Dz is found to decrease at a very high load. Moreover, the casing and es-

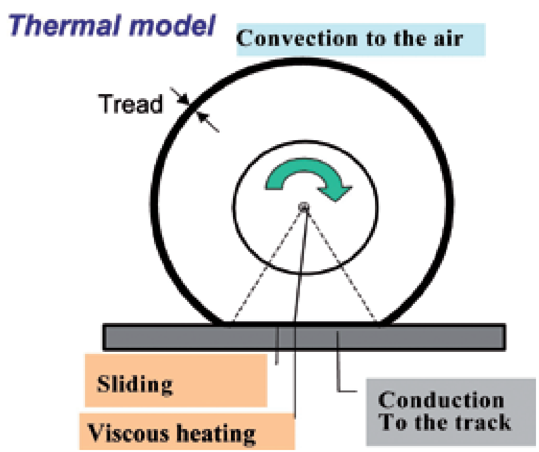

Figure 4: Thermal modelling of the tyre tread temperature over a period of wheel rotation

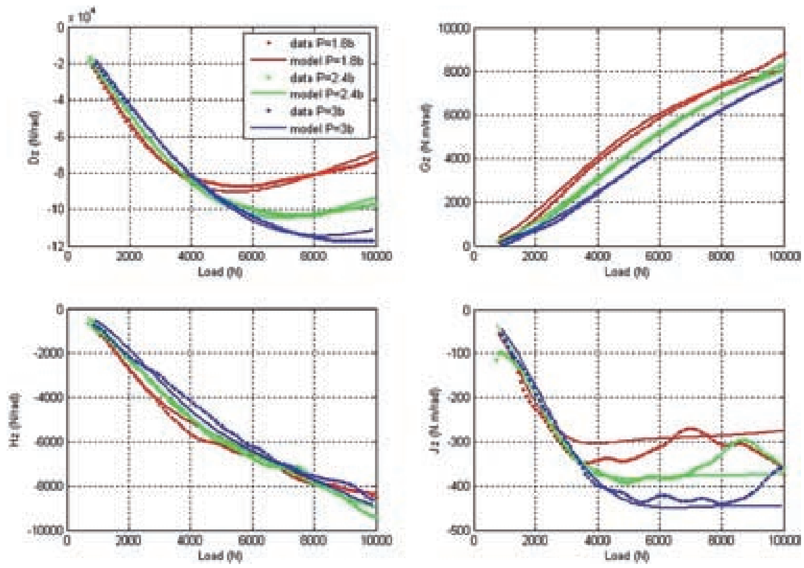

Figure 5: Tyre stiffness evolution with load at three inflation pressures (1.8 b, 2.4 b and 3.0 b): cornering stiffness (Dz), self-aligning torque stiffness (Gz), camber force stiffness (Hz) and self-aligning torque due to camber (Jz). The dots correspond to the measurement data and the lines to the TaMeTirE simulations

pecially the sidewalls become stiffer at a higher inflation pressure, so that Dz increases with the inflation pressure at a high load. It is worth noting that the model can predict Dz as well as the other tyre stiffnesses Gz, Hz and Jz with a very good accuracy.

3.2 Influence of the Tyre Temperature

Measurement data and model predictions of the lateral force at high slip angles are shown in **Figure 6**. The results correspond to slip angle sweeps from 0° to -15° (ramp-up) and from -15° to 0° (ramp-down), at 3000 N and 7800 N tyre loads respectively. At a high slip angle, the lateral force is mainly governed by the friction force. A significant tyre surface temperature is built up due to the friction heat flux. Because of the thermal inertia of the rubber, the surface temperature during the ramp-down is higher than during the ramp-up. Accordingly, the results show a loss of about 10 % of the maximum lateral grip between the ramp-up and the ramp-down. The TaMeTirE model can predict the influence of the temperature on the lateral grip evolution at the different loads with a good accuracy. It is worth noting that the influence of the load on the lateral grip is also mainly due to thermal effects. Indeed, at a high load, the CP is longer. The heating of the rubber due to friction is therefore more important. This leads to a lower lateral grip at a load of 7800 N than at 3000 N, Figure 6.

3.3 Influence of the Travelling Speed

The measurement data and the simulations show a decrease in lateral grip when the travelling speed increases, **Figure 7** and **Figure 8**. Between 40 km/h and 160 km/h, the loss of lateral grip can be higher than 10 %. As the travelling speed increases, the sliding speed inside the CP increases in the same proportion. Furthermore, as one of the main mechanisms governing friction is the frequency excitation of the material by the road texture, the primary effect of the sliding speed on the grip is to change the frequency excitation of the rubber. The second effect, which is at least as important as the frequency, is the friction reduction due to higher contact temperatures. Indeed, the friction heat flux increases with the sliding speed, Eq. 6.

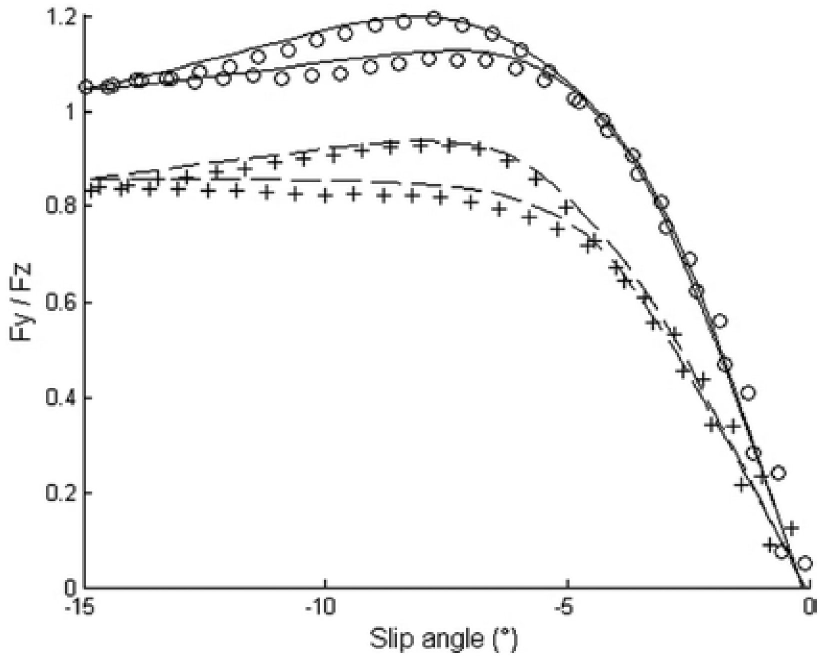

Figure 6: Influence of the thermal effects on the lateral grip (Fy/Fz) during a slip angle sweep at 3000 N and 7800 N tyre load respectively. Symbols: measurement data; lines: model predictions. The circle and solid line corresponds to the 3000 N tyre load. Crosses and dashed line corresponds to the 7800 N tyre load

4 Conclusion

TaMeTirE, the new physical tyre model, has been developed to improve tyre force and moment predictions. The model calculates the longitudinal and lateral forces in combined conditions according to a one-dimensional brush-element approach. The forces are coupled to the tyre temperatures by introducing the rubber compound properties of the tread. The shear modulus decreases with increasing internal temperature and the friction is governed by the contact temperature, sliding speed and contact pressure. An analytical thermal model based on the theory of two semi-infinite media in perfect contact is used for the contact temperature. In addition, the average surface and internal temperatures of the tread over a period of wheel rotation are calculated from the one-dimensional thermal equation in the tread thickness. The non-linear thermal and mechanical equations are derived assuming a single transition point between the adherent and the sliding area of the contact patch. This enables fast calculations of tyre forces and moments to be performed for vehicle dynamic simulation with a capability for real-time simulation. Measurements on a flat-track machine show the strong influence of the thermal effects and travelling speed on the lateral force. The variations in the lateral grip can be higher than 10 %. Such evolutions are complex and depend on the rubber operating conditions in the contact patch: the contact temperature, the sliding speed and the contact pressure. These depend on the tyre design parameters, such as the tread and casing stiffnesses and on the CP dimensions. They also depend on the tyre operating condition history, which governs the tyre temperatures. The main benefit of TaMeTirE is its ability to predict the tyre force and moment in accordance with the actual driving conditions of the vehicle. As temperature and speed effects are taken into account, tyre simulations can be carried out for a wide range of vehicle manoeuvres. Vehicle simulations can be improved especially for manoeuvres with high lateral acceleration, such as safety manoeuvres and fast lap times in which the evolution of the tyre surface temperature is significant. At small accelerations, the vehicle dynamics are mainly governed by the tyre stiffness Dz, Gz, Hz, Jz. These

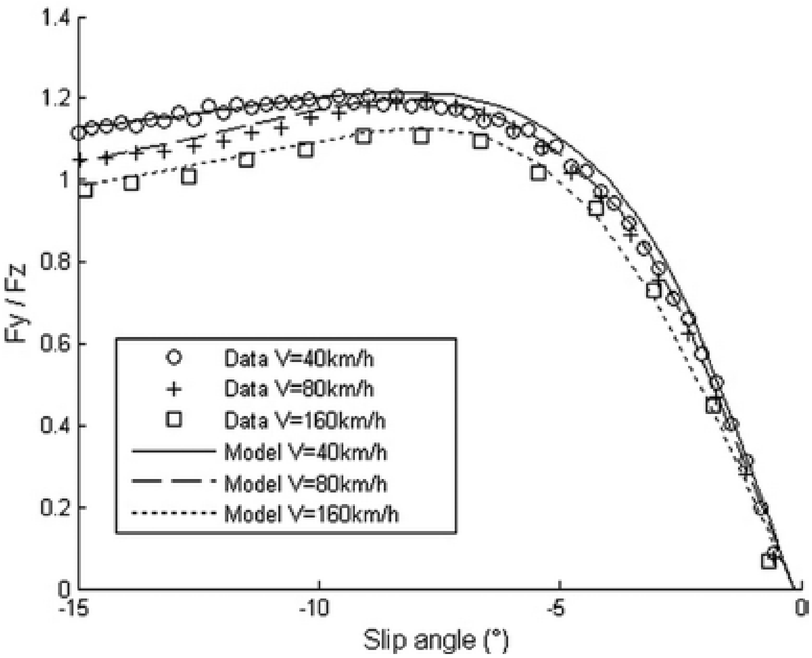

Figure 7: Influence of the travelling speed on the lateral grip (Fy/Fz) at a 3000 N tyre load; symbols: measurement data; lines: model predictions

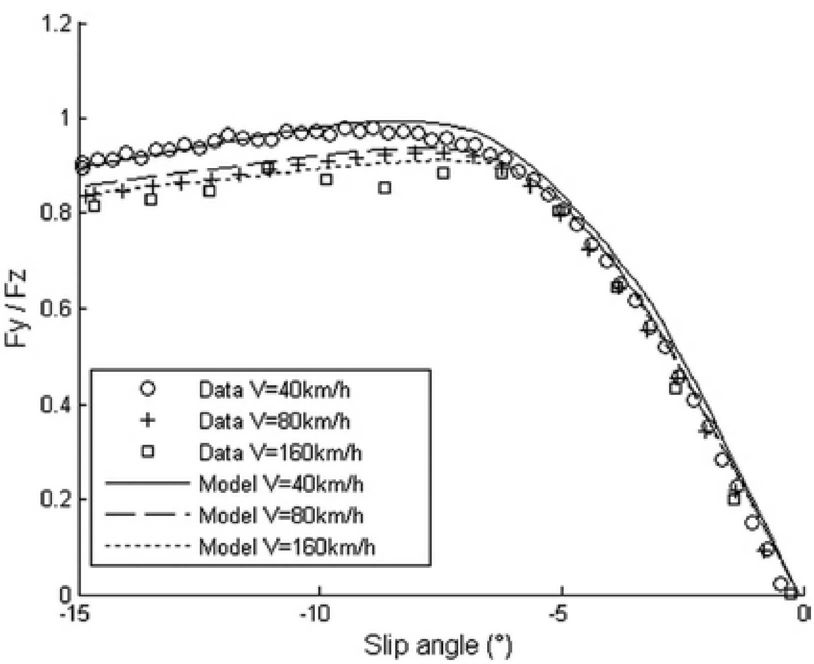

Figure 8: Influence of the travelling speed on the lateral grip (Fy/Fz) at 7800 N tyre load; symbols: measurement data; lines: model predictions

characteristics depend on the tread stiffness and, accordingly, on the internal temperature of the tread. Therefore, the use of TaMeTirE should also improve vehicle simulations in the range of low lateral accelerations. The TaMeTirE coefficients can be obtained from specific tyre measurements on a flat-track machine. Mechanical, friction and thermal parameters are derived from the tyre force and moment characteristics and from the tyre temperature measurements. The approach is currently under validation for a wide range of tyre types and sizes.

References

[1] Février, P.; Fandard, G.: Thermal and mechanical tyre force and moment modelling, Tyre.Wheel. Tech, TÜV Süd Automotive Gmbh Congress, Munich, December 5th-6th 2006

[2] Buisson, J.: Michelin indoor characterization for handling applied mathematical formulae, 15. Aachener Kolloquium Fahrzeug- und Motorentechnik, Aachen, October 9th-11th 2006

[3] Clark, S. K.: Mechanics of Pneumatic Tyres, U.S. Department of Commerce, National Bureau of Standards, November 1971

[4] Sakai, H.: Theoretical and experimental studies on the dynamic properties of tyres. Part I: Review of theories of rubber friction. International Journal of Vehicle Design, Vol. 2, No. 1, 1981

[5] Dixon, J.C.: Tyre Suspension and Handling, 2nd edition, SAE Inc 1996

[6] Hallum C.: Understanding Race Tyres, Motorsports Engineering Conference Proceedings, Vol. 1: Vehicle Design and Safety, SAE 1998

[7] Lacombe J.: Tyre model for simulations of vehicle motion on high and low friction road surfaces, Proceedings of the 2000 Winter Simulation Conference 2000

[8] Miyashita, N.; Kawazura, T.; Kabe, K.: Analytical model of mu-S curve using generalized skewed-parabola, JSAE Review 24 (2003), pp. 87-92

[9] Pauwelussen, J. P.: The local contact between tyre and road under steady state combined slips, Vehicle System Dynamics, Vol. 41, 2004

[10] Gäfvert, M.; Svendenius, J.: A novel semi-empirical tyre model for combined slips, Vehicle System Dynamics, Vol. 43, 2005

[11] Velenis, E.; Tsiotras, P.; Canudas-de-wit, C.; Sorine, M.: Dynamic tyre friction models for combined longitudinal and lateral vehicle motion, Vehicle System Dynamics, Vol. 43, 2005

[12] Holtschulze, J.; Goertz, H.; Hüsemann, T.: A simplified tyre model for intelligent tyres, Vehicle System dynamics, Vol. 43, 2005

[13] Miyashita, N.; Kabe, K.: A new analytical tyre model for cornering simulation. Part II: Cornering force and self-aligning torque, Tyre Science and Technology, Vol. 34, April-June 2006

[14] Février, P.; Fandard, G.: A new thermal and mechanical tyre model for handling simulation, 11th International VDI congress, Tyres-Chassis-Road, Hanover, October 23rd and 24th 2007

[15] Guo, K.; Zhuang, Y.; Lu, D.; Chen, S. K.; Lin, W.: A study on speed-dependent tyre-road friction and its effect on the force and the moment, Vehicle System Dynamics, Vol. 43, 2005

[16] Février,P.; Le Maitre, O.: Tyre temperature modelling: application to race tyres, proceedings VDI 13th International Congress numerical analysis and simulation in vehicle engineering, Würzburg, September 27th-28th 2006