Tire/road interaction models

Analysis of the results provided by a grip and thermodynamics-sensitive tire/road interaction force characterization procedure

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The automotive sector is looking for the optimal solution in modeling and understanding tire behavior in experimental and simulation environments.[1,2,3] The studies and tools described here represent a new approach in tire characterization and vehicle simulation procedures, leading to the complete reproduction of the dynamic response of a tire and of its frictional and thermodynamic behavior simply by means of specific track sessions and a few laboratory measurements. This represents a bridge between a robust and widespread approach, like Pacejka's, and purely physical modeling, that satisfies predictive requests and the need for deeper knowledge about complex phenomena.

The tools

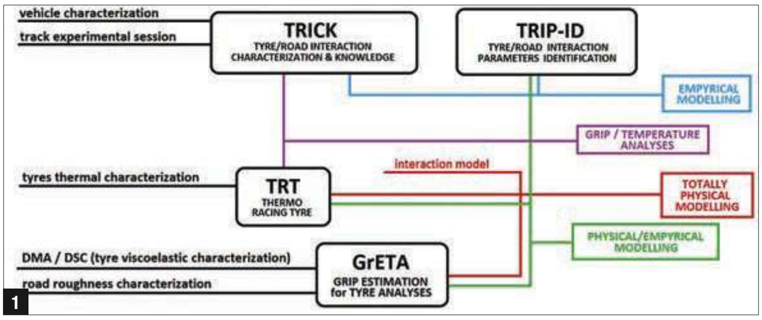
The final product is composed of the following four tools, which can cooperate to form a multitude of solutions.

TRICK (Tyre/Road Interaction Characterization & Knowledge)[4] is basically composed of a vehicle model able to process experimental signals acquired from the vehicle's CANbus and from additional instrumentation (DATRON[5]) to estimate sideslip angle, providing a sort of virtual telemetry, based on the acquired signals' time history and containing force and slip estimations useful to provide tire interaction characteristics.

Figure 1: Model integration solutions

Figure 2: G-G diagram realized both with experimental data and with results of a simulation performed with starting MF-Tyre parameters set

Figure 3: Detail of the front (left) and rear (right) tire slip angles, both from experimental data and from outputs of a simulation performed with starting MF-Tyre parameters set



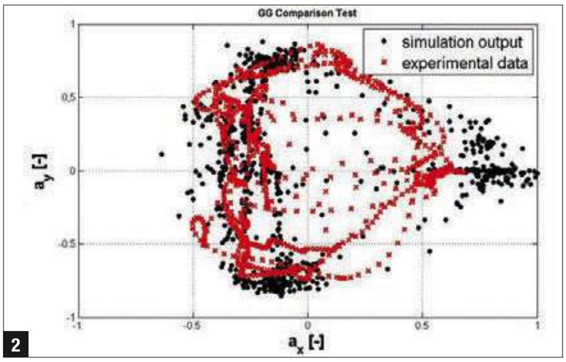
Complete and detailed studies of tires in a wide range of working conditions are commonly carried out by means of complex, bulky and expensive test benches.[6] The proposed procedure means the vehicle can be employed as a moving lab, easily applying experimental and processing techniques.

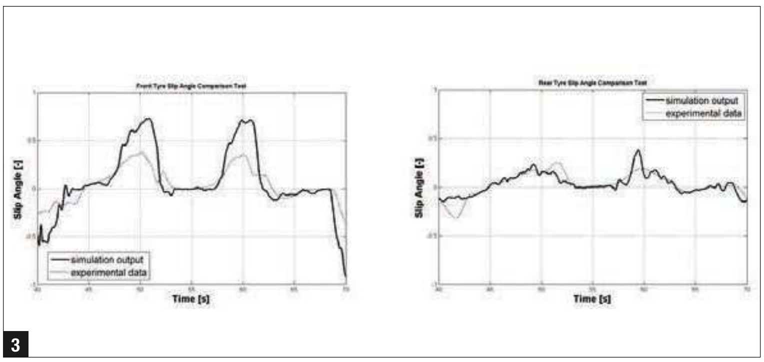
TRIP-ID (Tyre/Road Interaction Parameters Identification) provides an innovative procedure to identify the Pacejka coefficients, starting from the experimental tests carried out to measure global vehicle data during outdoor track sessions. The procedure collects and processes the data provided by TRICK, eliminating the outlier points, discriminating between the various tire wear and thermal phenomena, and taking into account the combined slip condition and the effects of vertical load and camber angle on the overall grip.

TRT (Thermo Racing Tyre)[7] is an analytical-physical thermal tire model developed with the aim of predicting temperature with a high degree of accuracy and able to simulate the high-frequency thermal dynamics characterizing high-performance systems. The model can estimate the temperature distribution of even the deepest tire layers, usually not easily measurable online, to predict the effects that fast temperature variations induce in the behavior of viscoelastic materials, and to take into account the dissipative phenomena related to tire deformations.

GrETA (Grip Estimation for Tyre Analyses)[8] is a tire/road friction physical model, developed to respond to the needs of race teams and tire manufacturers, able to provide an effective calculation of the power dissipated by road asperities indented in the tire tread, taking into account the phenomena involved with adhesive friction, expressed by means of an original formulation whose parameters are identified thanks to dedicated experimental tests.

These tools are able to describe and analyze aspects of phenomena concerned with tire/road interaction, but their cooperation can constitute an even more powerful instrument to extend the comprehension of such a complex theme.





A general overview of the developed models and procedures is shown in Figure 1, in which it is possible to observe the connections that link the models, providing different solutions for employment.

TRICK and TRIP-ID

TRICK and TRIP-ID were developed with the initial aim of increasing the confidence of car makers in adopting the Magic Formula in virtual drive modeling and vehicle dynamics models employed for predictive performance analyses. One of the main advantages of the tool is the ability to validate Pacejka coefficients provided by tire makers, or even do without their contribution, identifying coefficients after a proper vehicle characterization and a specific track session.

The weak points of the initial MF-Tyre parameter set identified by tire companies via bench procedures, and highlighted by data analysis, are as follows:

First, there is too much grip in the longitudinal and lateral interaction, due to the differences between real roads and the belts employed for testing. Next, there is a lower likelihood than in reality for the driver to be able to stabilize the vehicle after the limit of adhesion has been crossed. Finally, there is an absence of grip and stiffness variations due to thermal effects.

In Figure 2, a G-G diagram, a classic and simple instrument employed to evaluate global vehicle performance,[9] is plotted (in nondimensional form, as are all the following ones, for reasons of industrial confidentiality), comparing on a reference track lap the measured vehicle accelerations with accelerations exported as output from a commercial, highly validated vehicle simulation model employed in a virtual driving simulation environment that has been adopted for the specific MF-Tyre parameter set provided by the tire maker.

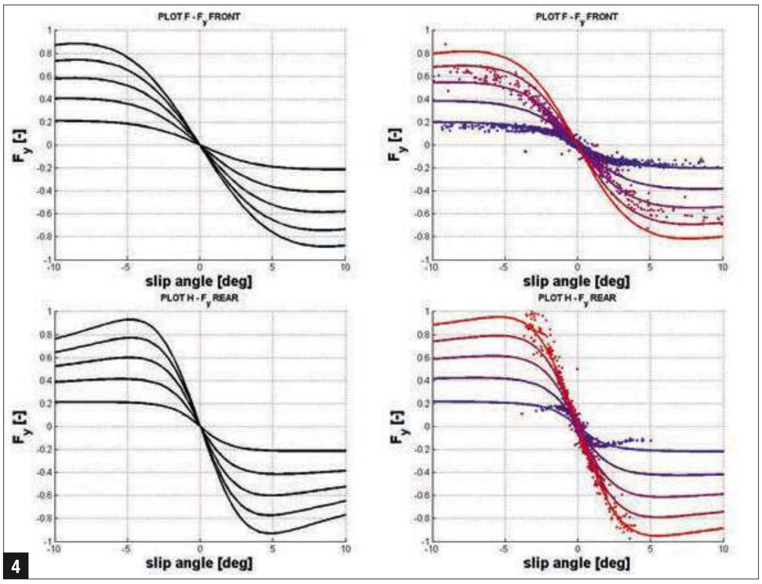


Figure 4: Plot F left: Starting set, front tire, pure lateral interaction. Plot F right: Identified final set, front tire, pure lateral interaction. Plot H left: Starting set, rear tire, pure lateral interaction. Plot H right: Identified final set, rear tire, pure lateral interaction

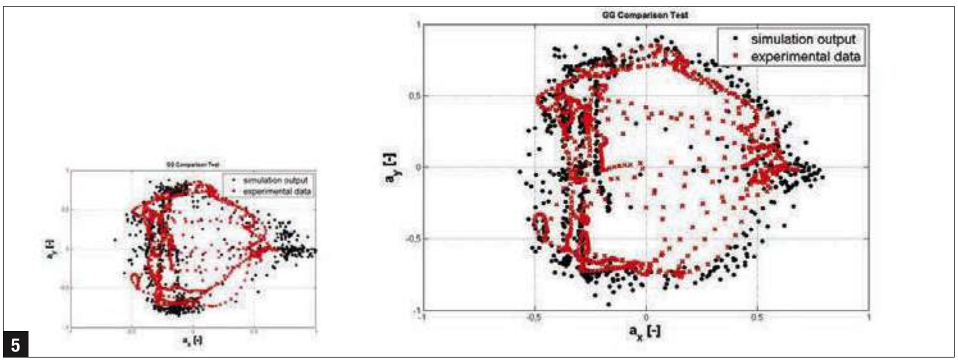


Figure 5: (Right) G-G diagram realized both with experimental data and with results of a simulation performed with the final identified MF-Tyre parameter set. (Left) Figure 2 for comparison

High grip levels reached by bench tested tires are often due to the fact that the testing countersurface is abrasive paper (or a rough material surface characterized by low macro-roughness), that is able to maximize the contact patch's effective area, providing an interface better than that on a real road.

The employment of abrasive paper and severe testing cycles causes, in addition to grip overestimation (and consequent to it), a continuous and massive heat generation at the contact interface, which increases tire temperature. As is well known, one of the main effects of temperature on tires is stiffness variation[2] (increasing temperature causes decreasing stiffness), particularly evident in the front tires, which in high-performance applications are typically narrower and less thermally inert than the rears. Figure 3 focuses on these considerations, highlighting the unsatisfactory results obtained with respect to front slip angles employing the starting tires' parameter set; the imbalances caused by poor estimation of slip angles act on the whole vehicle's tendency to understeer or oversteer.[10]

The identification of the optimal parameter set by means of the TRIP-ID procedure also enables us to solve the simulated vehicle driveability problems linked to the shape of the tires' starting set. The mentioned lower-than-reality likelihood of the driver returning the vehicle to a stable condition after the limit of adhesion has been crossed is due to two factors: an excessively peaky trend of lateral interaction curves and a too-sharp decrease of cornering force in a combined interaction at increasing values of slip ratio. The improvement that the characterized tires have represented with respect to the cited effects can be observed in Figure 4, which compares the starting set's pure lateral interaction curves (on the left, in black) with those of the optimal identified set (on the right, colored).

It can be seen that data collected during an experimental session and processed by the TRICK tool is able to provide information useful in properly modifying the starting set, obtaining an identified set that results in good agreement with the drivers' requests and with the objective data already acquired by equipping the real vehicle with measurement instruments. Figure 5 shows the results of the simulations performed with the identified tire set, comparing them with the ones relative to the starting set, shown on the left.

TRICK and TRT

TRICK and TRT can be successfully employed together, providing an

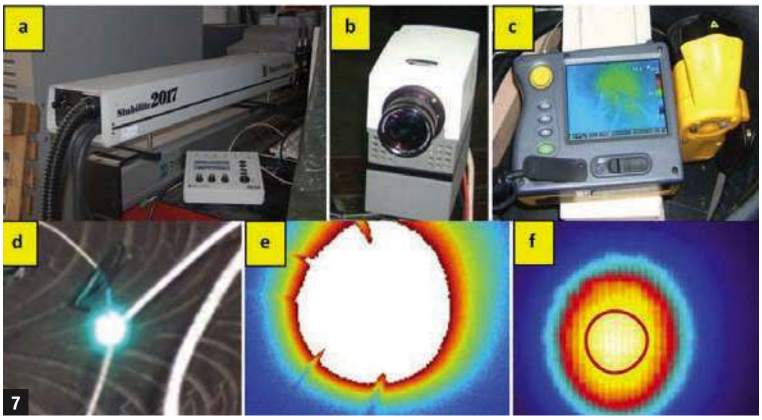


Figure 6: Detail of tire sections cut along the meridian plane

Figure 7:
(a) The Stabilite 2017 argon-krypton laser
(b) The Phoenix thermographic camera
(c) The Ti-45 thermographic camera
(d) The laser spot on the tire external surface
(e) A thermographic camera image of the laser spot on the tire external surface
(f) A thermographic camera image of the laser spot on the tire internal surface

Figure 8: Comparison of storage modulus (E') between a common passenger tire and a GT sport tire

Figure 9: Comparison of tan δ between a common passenger tire and a GT sport tire

instrument able to provide tire thermal analyses, useful to identify the range of temperature in which grip performances are maximized and enabling the optimal tires and vehicle setup to be defined.

The test procedures adopted to characterize the tires, obtaining data useful to initialize the models properly, can be schematically divided into two main subcategories – destructive and non-destructive.

To the first belongs meridian plane section analysis. This kind of test consists of the observation and measurement of the thickness of the layers constituting the meridian section. In Figure 6, it is possible to distinguish the tread layer, characterized by an evident and deep pattern, the bulk layer, in which steel cord plies are clearly observable, and the innerliner, which is very thin and impermeable.

The second component of the destructive subcategory is thermal conductivity and specific heat measurements. Tire layers need to be characterized from a thermodynamic point of view, focusing in particular on conductivity and specific heat measurements. A standard test procedure is carried out employing a Stabilite 2017 argon-krypton laser (Figure 7a) pointed at the whole tire or on specimens of each layer and emitting a beam of given power. Knowing the specimen thickness and measuring temperature of the two surfaces by means of two thermographic cameras (a Flir Phoenix, Figure 7b and a Fluke Ti-45, Figure 7c), it is possible to provide an effective estimate of the desired parameters, validated thanks to comparison with tests carried out with a COND1 device, following certified procedures.[11]

The third component is DMA viscoelastic characterization. Tests carried out on sport tires have highlighted interesting aspects, in particular comparing results with common passenger tire ones. Figure 8 shows that, as expected, sport tires are characterized by lower storage modulus values in their optimal thermal working range (35°C and over) that enable them to offer better adhesion and to adapt better to road asperities, optimizing contact area at the price of a lower wear resistance. Passenger tires are more stable and able to offer good adhesion levels even at very low temperatures, being adapted to the widest possible range of working conditions. Figure 9 shows in a clear plot the possible reason for the so-called 'feeling the grip' phenomenon. Sport tires, as distinct from passenger ones, are characterized by a clear relative maximum at about 42°C and by higher values of tan δ at the usual usage temperatures.

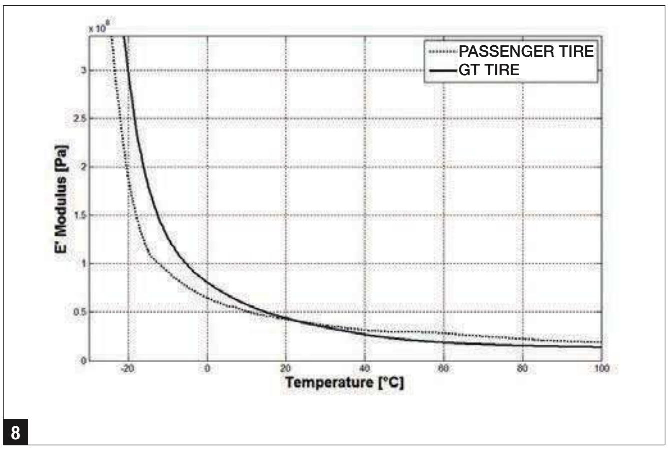
Specifying that the DMA test has been carried out at a frequency of 1Hz, notably different from common tread stress frequencies, a quick calculation, hypothesizing an average road macro-roughness wavelength λ equal to 0.01m and an average sliding speed Vs of 5m/sec, enables the real tire temperature at which the tan δ maximum can be experienced by the driver to be estimated. Applying a simplified version of the WLF equation,[8] it is possible to obtain

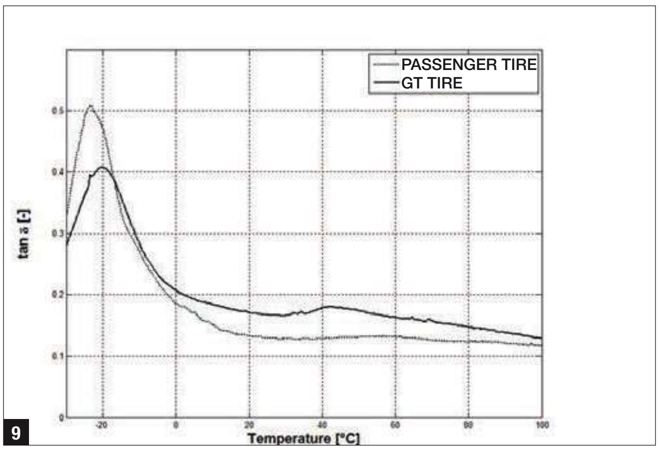
$$\Delta T = 8\,(\log_{10}(Vs\,/\,\lambda)) = 8\,(\log_{10}(5\,/\,0.01)) \approx 21.6°C$$

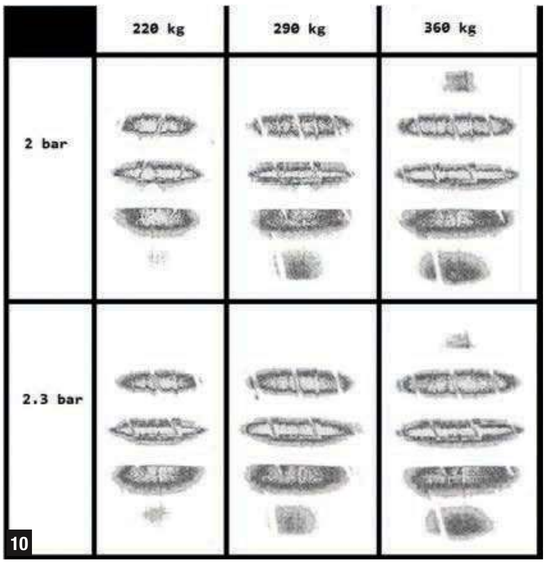
which, added to the starting 42°C, gives a temperature of 63.6°C, in accordance with the experimental value shown in the analyses already presented.

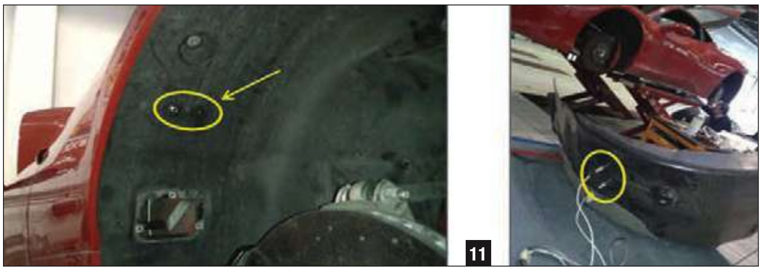
Non-destructive testing procedures

The first of these to be applied is contact patch analysis. A specific test bench[12] is used to apply a static vertical load to the tested tires, analyzing contact patch extension and pressure distribution. It is possible to interpose pressure-sensitive Prescale sheets between the tire and the flat steel countersurface, and to plan tests at different loads, inflation pressures and camber angles. In Figure 10 the results of a zero-camber testing session on a front tire are reported.









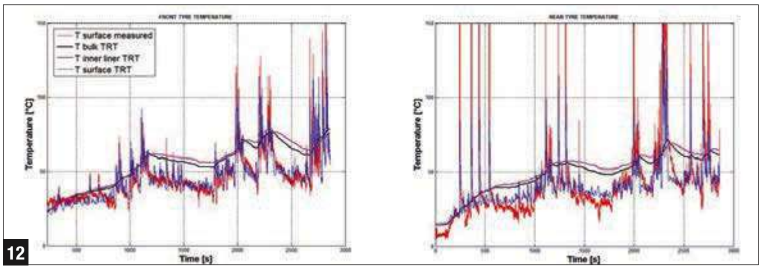


Figure 10: Scans of a GT tire contact patch under different testing conditions at zero camber angle. It is noticeable that at increasing load the contact area increases, progressively inserting shoulders in the interaction zone. At high inflation pressure the central rib is more extended, while lower pressure tends to overload the shoulders

Figure 11: Installation of infrared thermal sensors and localization inside vehicle wheelhouses

Figure 12: TRT results evaluation for front and rear tires

The second is track thermal tests. These sessions are carried out to a specifically developed procedure, with the aim of collecting tire data under various thermal conditions. In order to acquire tire temperature, the vehicle is equipped with infrared sensors installed in the wheelhouses (Figure 11) and directed on the tread surface. The signals are acquired by Dewesoft hardware. Each tire tread is interrogated by two different measurements, particularly useful for front tires, which when steering could be characterized by discontinuous temperature profiles.

After carrying out the track experimental session and acquiring data to be processed by the TRICK procedure, a 'virtual telemetry' is generated.

Speed, slip, camber and force channels are used as input for TRT, whose results are compared with the measured surface temperatures (Figure 12), delivering good correspondence with available data and, very usefully for the grip analysis discussed in the following, an estimation of tire-bulk temperature.

Common analyses concerning the relationship between the tire friction coefficient and temperature are based on the only thermal data experimentally available, i.e. the tire's external (and in a few cases, internal) temperature, measured using a great variety of techniques. A typical correlation between lateral grip and measured temperature appears like that shown in Figure 13, from which very little information can be deduced.

Thanks to the availability of the bulk temperature, it is possible to provide much more useful correlations, such as the ones shown in Figure 14, from which an optimal thermal range can be identified. The reason why the bulk temperature offers better results can be attributed to the fact that the surface temperature varies with very fast dynamics but it is not possible to modify the polymers' characteristics quickly enough to see the response of the whole tire's frictional behavior. Bulk temperature, on the other hand, can be considered to be the tread's core temperature, more resistant to fast variations and directly connected to the rubber's viscoelastic state.

As a further validation of the described procedure, it can be seen that the optimal temperature value is in good agreement with the theoretical result provided in Equation 1, confirming that the thermal model can be employed as a predictive instrument to investigate performance optimization strategies and that a proper knowledge of polymer characteristics can be a useful starting point to a better understanding of the dynamics of tire-surface interaction.

TRIP-ID, TRT and GrETA

The thermal and grip models can usefully cooperate, employing the TRT output as an input for GrETA, which can be used to introduce into the Pacejka interaction model the dependencies on temperature, tire working variables, road roughness and compound characteristics.

The advantages coming from the cooperation of these models can be summarized in the following three points, which have already been exploited (further application possibilities are clearly available).

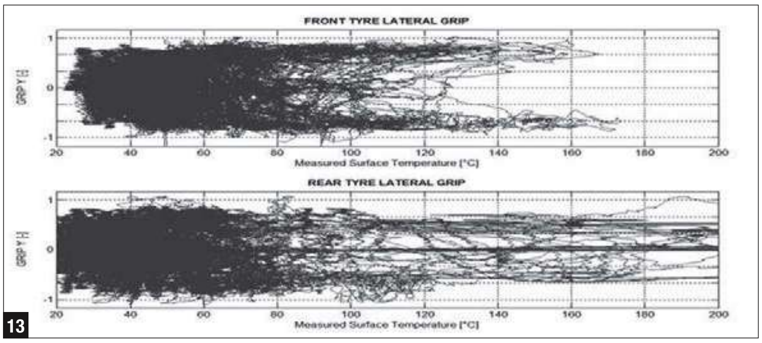
The first is the prediction of tire behavior on the various tracks of a racing championship, each characterized by different roughness (previously measured) and weather conditions.

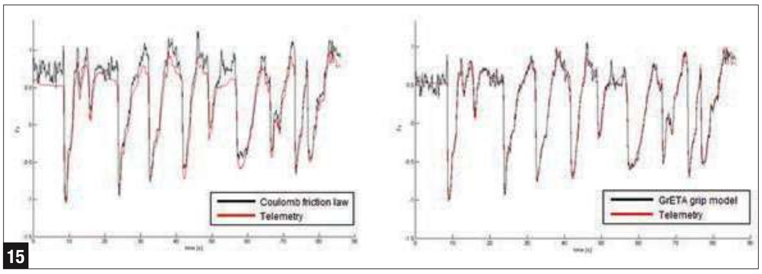
The next is a performance evaluation of the characteristics of various compounds, which enables a dialog with the tire makers to be established, directing tire construction and compound development to the achievement of a common aim.

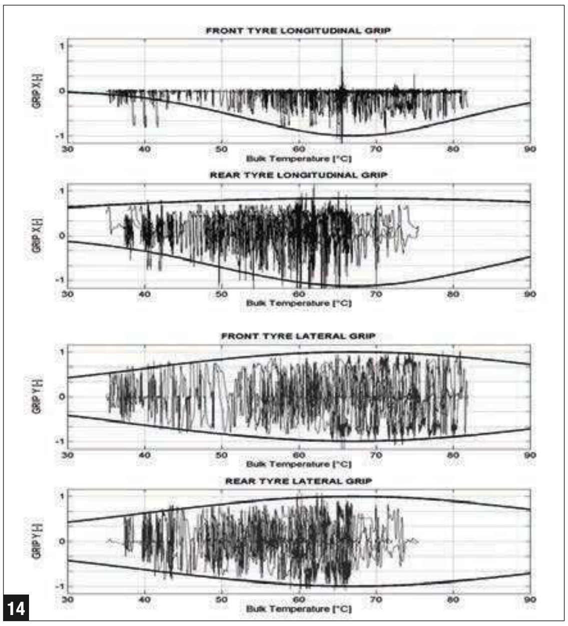
The third is the definition of an optimal vehicle setup in terms of wheel angles, load balance and tire inflation, and of driving strategies that are able to reach optimal grip/thermodynamic conditions.

Figures 15 and 16 show the differences between force data from telemetry and from the Pacejka model, whose inputs are the measured slip, load and camber. In the first case the calculated forces are reported as scaled by a Coulomb friction model, always equal to one except for the static value (which means using a standard Pacejka output, with no further processing).

In the second case the forces are processed with GrETA friction scaling factors, taking into account phenomena neglected in the first case. It can be noticed that employing the grip model produces better results, particularly with respect to longitudinal interaction in the traction phase, which is thermally stressful for high-performance tires and able to generate heat for the friction power mechanism,







which induces noticeable effects in tire/road interaction modeling.

Physical interaction model and further developments

It is clear that the Pacejka model is not the most flexible and detailed method to describe local phenomena of the tire/road interaction, but represents a very robust and intuitive solution to obtain the barely achievable aim of modeling the tire's tangential forces.

For this reason, further developments of the activities discussed in the present work will focus on the realization of a fully physical interaction model that, starting from the knowledge acquired about the topic by the vehicle dynamics research group,[13,14] will be able to interact deeply with the other models, creating an analytical and predictive instrument that can be employed in a wide range of automotive applications.

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Figure 13: Front and rear lateral grip reported as a function of measured tire surface temperature

Figure 14: Front and rear grip reported as a function of tire bulk temperature estimated by means of TRT. Bell-shape curves have been drawn to highlight the trends

Figure 15: Comparison between longitudinal tire forces modeled by MF with a Coulomb friction law and with GrETA friction model

Figure 16: Comparison between lateral tire forces modeled by MF with a Coulomb friction law and with GrETA friction model

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