Multiphysical analysis

A multiphysical approach to tire dynamics is vital to understanding the array of interconnected physical phenomena and their effects on tire structural characteristics

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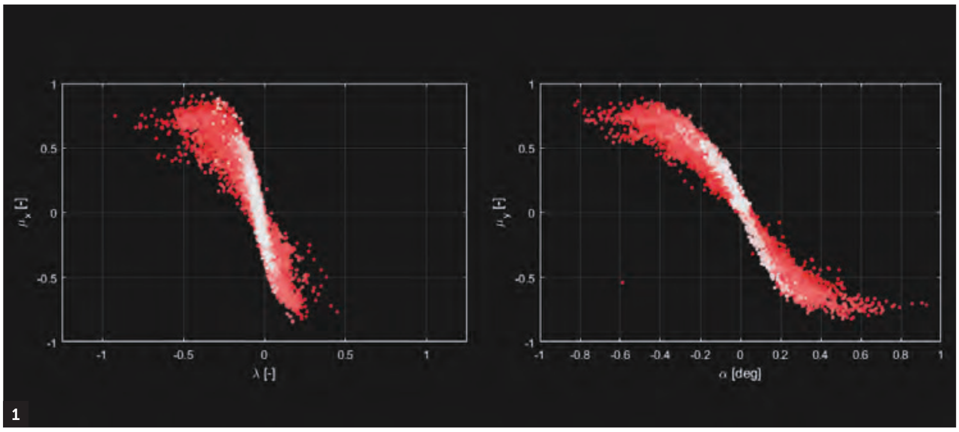


Figure 1: Tire interaction curves (longitudinal on the left and lateral on the right) as a function of tread core temperature: the color map from white to red corresponds to the tire temperature gradient from cold to hot

Figure 2: Tire tangential interactions within the TRIP-ID tool

Due to the intrinsic dependence of tire structural characteristics and compound viscoelastic behavior on a multitude of physical interconnected phenomena – including the tire inner layers' temperature, internal pressure, road roughness or tire working conditions – the only possible approach to achieving a complete understanding of the tire dynamics and its modeling is multiphysical.[1]

The experience gained through the development of physical models of tire and vehicle systems, and the recent activities conducted by the University of Naples (UniNa) research group in the field of real-time simulations, have led to the development of an innovative multiphysical tire model based on the Magic Formula interaction model,[2] which is ready to be integrated within a complete real-time vehicle simulation environment.

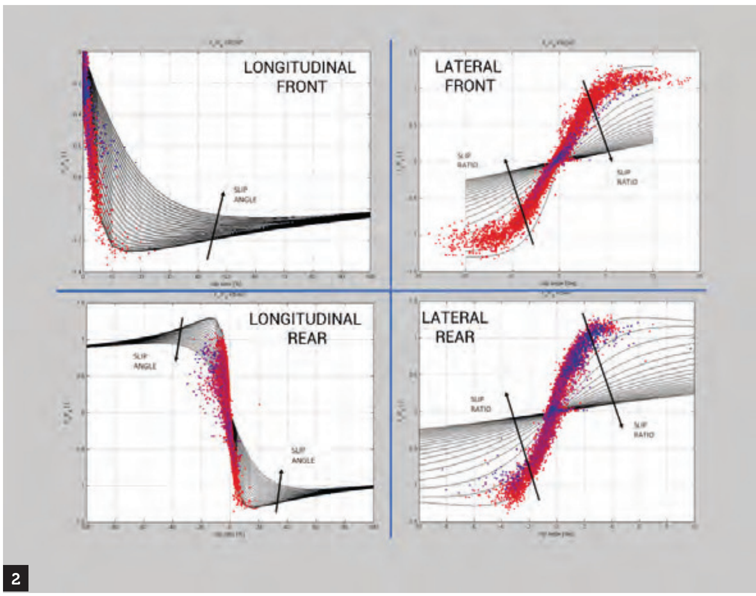
The developed MF-evo formulation has been integrated in optimum time-lap techniques to evaluate the impact of the enhanced physics of wear, temperature and friction phenomena on the entire vehicle performance, starting from diverse initial tire conditions. A further step will regard the integration of the MF-evo formulation within the full VD simulator environment with driver-in-the-loop and within the vehicle control logics to optimize safety and performance.

Research activities

The recent advances of the Vehicle Dynamic Research Group at the University of Naples covered the development of a suitable set of tools and models that are absolutely necessary to completely understand and characterize all the physical phenomena linked to the complex dynamics of tires.[1,7] It is well known that the characterization of this vehicle subsystem is difficult and delicate, because the tire forces demonstrate a complex and highly non-linear dependence on slip ratio, slip angle, camber angle, vertical load, inflation pressure, wear level, internal and external temperature distributions and, obviously, the tire structure. All the data represented in the following figures has been non-dimensionalized due to confidentiality agreements with the motorsport research partners.

As the current real-time, most effective analytic formulation, Magic Formula,[2] is able to describe the tire dynamics in a very strict range of operating conditions (fixed temperature, internal pressure, asphalt characteristics, wear level and so on), the research has been centered on the development of an innovative physically enriched MF-evo interaction model. The developed MF-evo formulation is able to take into account the pressure of the internal air, the temperatures of different tire layers, the road pavement characteristics and the compound viscoelasticity, varying the dynamic characteristics of the tire instant by instant, starting from completely different initial working conditions.

The additional physical variables are co-simulated thanks to specifically developed tire physical thermodynamic and grip models,[3,4,5,6]



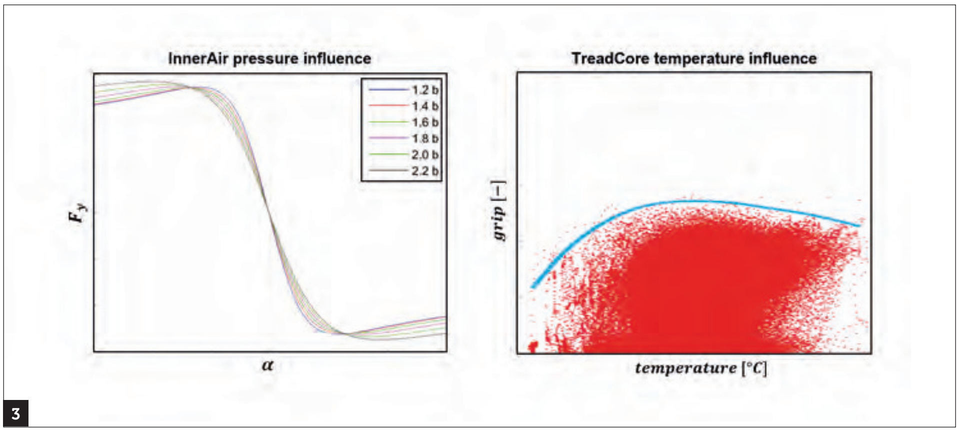


Figure 3: Internal pressure (on the left) and tread core temperature (on the right) influences on tire behavior

able to estimate in real time the tire layers' temperatures and the internal air pressure, while the road roughness characteristics and the compound viscoelasticity – considered in terms of power spectrum density, result of the elaboration obtained from the directly acquired road texture data, and viscoelastic master curve and relative WLF coefficients – describe the compound behavior at different working frequencies and temperatures.[1]

The advanced Pacejka formulation, MF-evo, therefore makes it possible to take into account the wear/temperature/friction phenomena within the tire dynamics in different working conditions, and to simulate in real time since the tire dynamic model is based on the analytic MF formulation, representing a remarkable compromise between accuracy in depicting the physical phenomena and the relatively low computational burden.

The data necessary to characterize the tires' physical behavior can be provided by bench characterizations, but they are rarely able to test tires in real working conditions as concerns road surface and the consequential thermal and frictional phenomena. For this reason, at the current stage a tire characterization suite including both the characterization procedures and the software set of tools has been developed to overcome the difficulties linked to the deeper understanding of the tire behavior and the identification of the physical quantities necessary to properly parameterize all the physical models. The developed software tools comprise an interaction forces estimator based on vehicle outdoor acquisitions (TRICK),[8] a 'smart' parameter identifier developed for Pacejka formulations (TRIP-ID),[9] a real-time physical thermal model (TRT),[3,4] and a physical grip model (GrETA).[5]

TRICK

The TRICK (tire/road interaction characterization and knowledge) tool is designed to obtain the tire/road experimental curves in real working conditions and in contact with real roads, making use of the entire vehicle system.[8] The tool is able to estimate the tire/road interaction curves directly from the track experimental data, directly acquired from the vehicle's CANbus and derived from additional instrumentation for the estimation of the vehicle side slip angle.

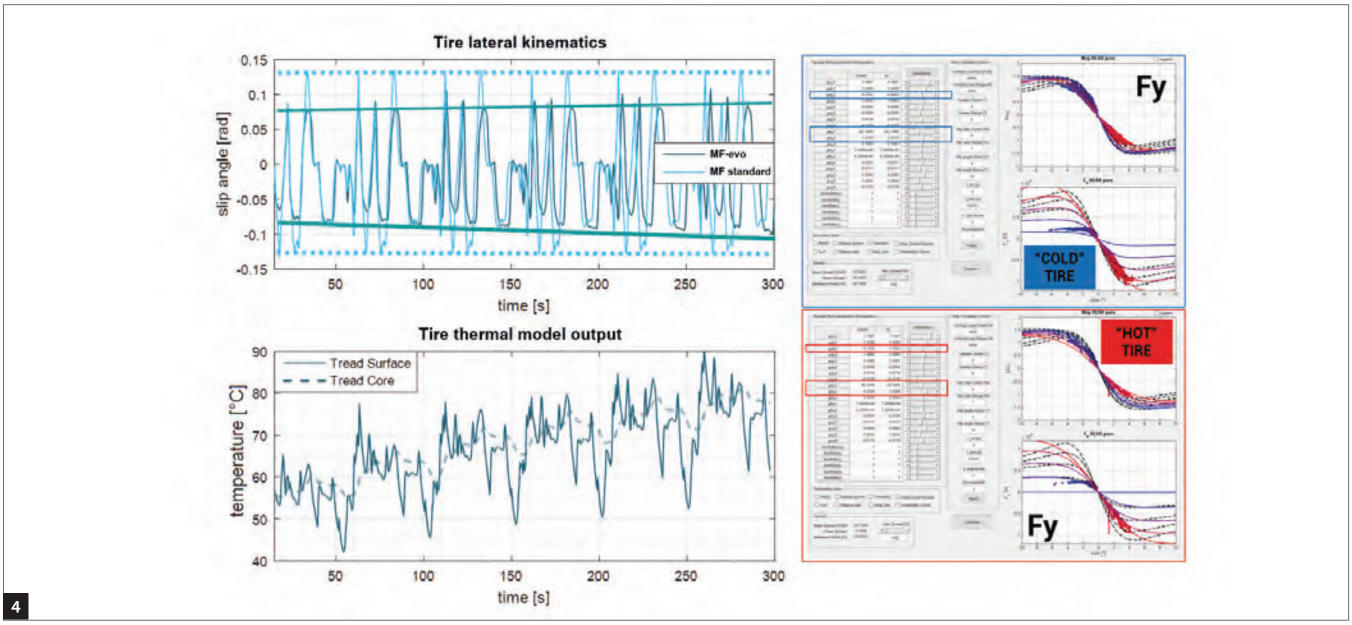


Figure 4: Comparison of the cold and hot tire kinematics within MF standard and MF-evo interaction models

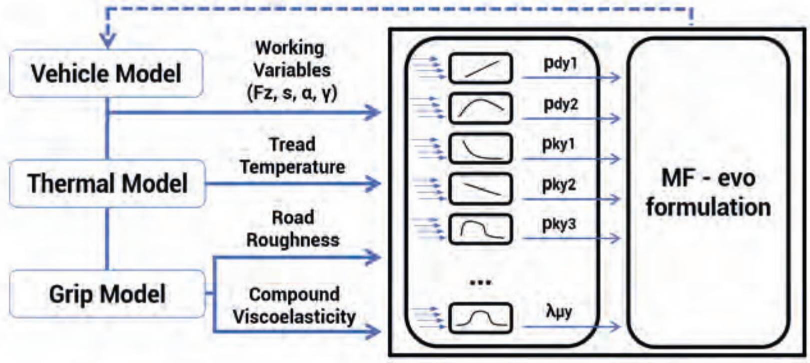


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Figure 5: Simulation scheme of the MF-evo model

The aim of the developed procedure is the determination of the tire/road interaction curves based on the data acquired during experimental sessions performed employing the whole vehicle as a sort of moving lab, taking into account physical factors commonly neglected. To achieve a suitable physical identification of the tire characteristics, it is important to work in the widest possible range of additional variables, taking into account that road roughness, temperature and wear have a great influence on the output and that they are very hard to reproduce in a laboratory. Road/track tests are more suitable for overcoming these problems, as the data refers to a tire in its usual working condition. On the other hand, it could be difficult to guarantee that the vehicle works in the neighborhood of the tire limit conditions (for example, the maximum available value of the friction coefficient).

TRIP-ID

Starting from the tire testing data, one of the greatest challenges for engineers currently involved in the vehicle dynamics field remains the identification of a correct physical parameters MF set, able to properly describe the tire's behavior. For this reason, alongside the development of physical models, it is just as important to provide instruments capable of simplifying the process of the multidimensional identification process, leading to meaningfully shorter schedules, even with the full implementation of additional physical dependences.[7]

During recent cooperation activities with tire makers, racing teams and vehicle simulation companies, it has become necessary to upgrade the original version of the TRIP-ID tool[8] to meet the needs of the identification of additional physical dependences within the MF standard tire interaction model. The additional physical channels can be provided by means of the additional sensors or physical predictive models.

In Figure 3, the pressure and tread core temperature influences on the tire cornering stiffness characteristics and on the grip modification on the same pavement surface can be easily perceived. The tire grip peak is enveloped in a limited thermal working range, strictly depending on the asphalt and compound characteristics.

Thermal and grip models

Tire data, if not already provided by the partner, is processed by TRICK, obtaining dynamic and kinematic quantities describing the tire/road interaction starting from the vehicle available dataset. Such data represents the input for the tire physical thermal model, called TRT (thermo racing tire),[3,4] parameterized thanks to a specific thermodynamic test carried out at the UniNa tire lab.

The importance of the tire thermal model's additional outputs can be easily deduced from Figure 1, where the tire tread core temperature, not available from the sensor data but provided by the TRT model, deeply modifies the tire dynamic behavior. The differences in terms of interaction curves can be easily appreciated, highlighting a stiffness decrease due to a higher tire temperature for both longitudinal and lateral tire interaction curves.

Recently the original TRT[3] has been revised to include the thermal phenomena linked not only with the tire structure but also with the entire wheel.[4] The TRT-evo model advanced structure enables inclusion of brakes, particular aero-design solutions and specific cooling/heating configurations within its interaction with both the external environment and the internal air.

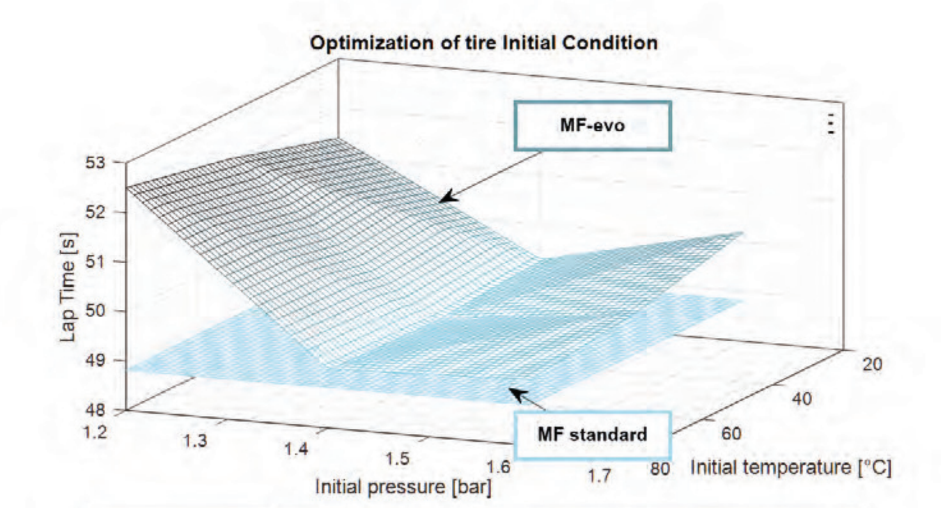
To provide the friction coefficient modification due to thermal effects, compound viscoelastic characteristics, particular pressure and velocity distribution within the contact patch and the road texture, a physical grip model, GrETA (grip estimation for tire analyses), has been developed.[5] Its aim is to provide the friction coefficient value, as a combination of two main friction contributors: a hysteretic term as a consequence of the power dissipated within the rubber compound indented by the road asperities; and an adhesive term, expressed by means of an original analytic formulation, whose formulation is identified thanks to dedicated experimental tests.

An example of the dependence of the tire structural and frictional characteristics on tire temperature distribution can be observed in Figure 4. On the right-hand side of the figure, an intermediate phase of the tire parameters' identification procedure, making use of the TRIP-ID tool, is represented for the tire in two thermodynamic conditions. On the left-hand side, the differences between the standard MF and the evolved MF interaction models are shown in terms of the tire's cornering stiffness and, consequently, of the tire's lateral kinematics toward the tread temperature. Indeed, the MF standard model, not taking into account the thermal effect, has constant tire characteristics, while the MF-evo version is able to modify the tire behavior on the basis of the thermally enriched dynamic state.

MF-evo interaction model

The simulation loop scheme of the MF-evo interaction model is represented in Figure 5, where the additional physical signals from the vehicle model and tire thermal and grip models make it possible to take into account, in real time, the variations in the micro/macro coefficients by means of pre-identified embedded analytic functions.

The advanced real-time MF-evo tire model could be suitably employed



		Initial pressure [bar]		
		1.2	1.4	1.6
Initial temperature [°C]	20	51.40	52.04	52.50
	50	49.30	49.12	49.20
	80	50.20	49.64	49.34

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in optimization procedures for vehicle performance maximization. The great advantage of making use of a dynamic tire model lies in the fact that the maximum performance conditions that can be expressed, in terms of the highest available grip level reachable within the contact patch, can be generated in a strict range of temperature and pressure levels, reachable only in a few sectors of each circuit depending on the vehicle setup adopted and on the instantaneous dynamic state of the tires. For this reason, to take into account the crucial effects related to grip/temperature relationship, tire degradation state and completely variable boundary conditions within the vehicle dynamic state, the employment of the advanced dynamic MF-evo interaction model becomes a necessity during the generation of the optimal vehicle path.

An example of a possible complex multidimensional design of experiment involving only the tire initial conditions is represented in Figure 6. Considering each vehicle's setup, track geometry and ambient conditions, it is clear the MF-evo model can represent an added-value instrument for the optimization of vehicle performance, and therefore for the minimization of the time lap.

Figure 6: MF standard versus MF-evo interaction models within the optimization algorithms of the lap

Applied vehicle research

The tire analysis and simulations branch of the UniNa Vehicle Dynamics Research Group founded a spin-off company in 2016, called MegaRide, which conducts applied vehicle research with the aim of providing a direct link with users of the developed tools, which are now engineered and ready-to-use software products.

Nowadays the expertise of the research group is focused on the development of models and procedures to be employed by vehicle manufacturers, racing teams, and road and traffic management companies seeking solutions in the fields of real-time simulations, road safety algorithms, and V2V and V2I connections. MegaRide is an official academic spin-off, providing a market channel and realizing the technological transfer of the activities carried out by the research group. The company was awarded the 2018 Tire Technology International Award for Innovation and Excellence in the Tire Technology of the Year category.

Acknowledgements

The author wishes to acknowledge the skilled and stimulating academic environment of the Industrial Engineering Department of the University of Naples Federico II and the support of several companies, motorsport teams and research institutes, all experts in their fields. **tire**

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