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Application of tire multi-physical modeling methodologies for the preliminary definition of a racing motorcycle setup

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Abstract:

Optimizing the performance of racing motorcycles is a central goal for competition teams. The necessity to ensure driver stability and a good level of grip in the widest possible range of riding conditions makes it necessary for tires to work in the right temperature window, capable of ensuring the highest interaction force between tire and road. Specifically, the internal temperature of the tire is a parameter that can be difficult to measure and control but has a significant impact on motorcycle performance and, also, on driver stability. Deepening knowledge of internal tire temperature in racing motorcycles can improve performance optimization on the track and finding the right motorcycle setup. In this work, a physical thermal model is adopted for an activity concerning the development of a moto-student vehicle, to predict the racing motorcycle setup allowing the tire to work in a thermal window that optimizes grip and maximizes tire life. More in detail, a focus has been placed on the effects of the motorcycle’s wheelbase and pivot height variations on internal tire temperatures. Indeed, the stability and handling of the vehicle are highly dependent on the geometric properties of the chassis. Several values of such quantities have been tested in a properly implemented vehicle model developed in the “VI-BikeRealTime” environment, validated by outdoor tests, able to provide forces acting on the tires, slip indices, and speeds, needed by the thermal model as inputs. Through the analysis of the internal temperatures calculated by the model, reached by the various layers of the tire, it has been possible to investigate which of the simulated conditions cause a too-fast thermal activation of the tire and which of them can avoid overheating and underheating phenomena. Lately, this research has delved into the correlation between motorcycle riders’ paths and temperature fluctuations with the aim of comprehending how minor alterations in routine maneuvers may influence tire energy activation, particularly in the context of racing and qualifying conditions.

Keywords: Automotive engineering, Motorcycle Thermal Model, Multi-physical Modeling, Motorcycle Setup Optimization, Tire Characterization

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Introduction

Racing teams that are in competition strive to maximize the performance of their motorcycles. The fundamental need to ensure rider stability and secure excellent grip across a wide spectrum of riding conditions necessitates that motorcycle tires function within an optimal temperature range [8]. This temperature window is essential for attaining the highest possible interaction force between the tire and the road surface, a parameter that profoundly influences the vehicle's stability and handling characteristics [10]. This need for tire optimization becomes particularly pronounced in the context of motorcycle racing, where high roll angles and rapid speeds amplify the tire's significance as the sole point of contact with the road [3].

The tire's capacity to deliver optimal performance hinges on its complex structure and viscoelastic characteristics, which are, in turn, significantly governed by the temperatures experienced by various layers within the tire [7]. However, accurately measuring and controlling the internal temperature of a tire presents a formidable challenge. Despite these difficulties, it remains abundantly clear that tire temperature profoundly impacts motorcycle performance and rider stability on the track.

To address this critical challenge, our research harnesses a motorcycle-specific adaptation of the physical thermal model thermoRIDE [6]. This model has proven its mettle by faithfully replicating the thermal dynamics of motorcycle tires across diverse operational conditions. Notably, it empowers us with a granular and comprehensive temperature distribution map within the tire's inner rubber layers.

In the current study, we harness this cutting-edge thermal model to guide the development of a racing motorcycle prototype. Our goal is to predict the optimal setup for a racing motorcycle that will enable the tire to function at its optimum temperature, ensuring improved traction and longevity.

Our current area of focus is the analysis of how the fork angle and swingarm length of a motorcycle impact the distribution of temperature in the tire. These key chassis components play a significant role in determining the motorcycle's overall stability and handling capabilities.[15]. Additionally, we will explore how various driving patterns can affect the activation velocity of the tires' energy. Understanding the preferred driving style is crucial for the driver to prepare for a qualifying lap or the start of the race. To conduct this research, we employ a meticulously calibrated vehicle model within the "VI-BikeRealTime" simulation environment. This model yields crucial inputs such as the forces acting on the tires, slip indices, and speeds, all of which are essential for the thermal model's operation.

Ensuring the reliability and consistency of our results, we also embark on the task of identifying the thermal diffusivity of each layer within the tire. This endeavor is realized through a procedure grounded in experimentation and validation [1].

Furthermore, we delve into the complexities of the contact patches between the tire and the road. These contact conditions prove to be dynamic and multifaceted, shifting with variations in load, pressure, and camber conditions. Employing a combination of indoor testing and validated procedures, we scrutinize the contact patch extension. Our aim is to unravel the intricate relationship between these conditions and the inner tire temperatures. By carefully analyzing the internal temperatures across various layers of the tire, we aim to pinpoint the conditions that lead to rapid thermal activation, as well as those that prevent overheating or underheating phenomena.

This research endeavor unfolds in the backdrop of a broader understanding - that the optimization of tire performance and the thermal conditions of these critical components hold the key to unlocking the full potential of racing motorcycles. Our work contributes to this understanding by shedding light on the intricate interplay between motorcycle performance, tire temperatures, and vehicle setup. The insights we generate hold immense value for racing teams striving to achieve the perfect balance between tire performance and rider stability in the demanding and dynamic world of motorcycle racing. In the pursuit of this balance, we embrace the challenge of translating scientific knowledge into practical racing solutions, with the ultimate goal of enhancing performance on the track.

1 Materials and Methods

1.1 Motorcycle dimensions

The model utilized in this context is exemplified by the motorcycle prototype that took part in the international Motostudent competition. To be more specific, the focus of our analysis was on a Pre-Moto3 motorcycle prototype. This model was designed to

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accommodate modifications in the fundamental dimensions of the motorcycle. Within this framework, it's possible to adjust critical components such as the positions of the steering joint, pivot, and stiffness for both suspensions. These alterations are undertaken with the primary objective of identifying and achieving the optimal configuration for the prototype. The general layout of this motorcycle prototype encompasses various key elements that play a crucial role in its performance and handling characteristics. These elements include the steering joint, pivot, and ride height, along with other essential design features and specifications. The chosen solution for the front suspension is the conventional upside-down telescopic design, whereas, for the rear suspension, a progressive-to-frame solution has been selected. The model encompasses the utilization of geometric dimensions, including the relative length and position of fundamental points such as the "steer joint" and "pivot," as well as the inertial properties such as weight, inertial matrices, and coordinates of the centroids of the vehicle to be simulated. The geometric dimensions were determined through prior analytical calculations, while the inertial properties were acquired using the CAD system. The geometric characteristics of the motorcycle are summarized in the following Table 1:

Table 1. Motorcycle Geometric Features

Geometric Feature	Value
$Wheelbase$	$1290 \pm 77mm$
$Offset$	$30mm$
$SwingarmLength$	$513 \pm 7mm$
$ForkAngle$	22 ± 2
$MotrocycleMass$	$110kg$

1.2 Testing and simulations

In essence, the primary objective revolves around the meticulous analysis and refinement of the motorcycle prototype. The overarching goal is the improvement of design, performance, and overall functionality, particularly during open-loop maneuvers. This undertaking is fueled by the imperative need to identify and understand the paramount factors that wield a significant thermal influence on motorcycle tires' performance, especially during intricate maneuvers like slaloms. To achieve this, the team embarked on a comprehensive and systematic series of simulations [14], methodically adjusting the parameters thoughtfully illustrated in Figure 1.

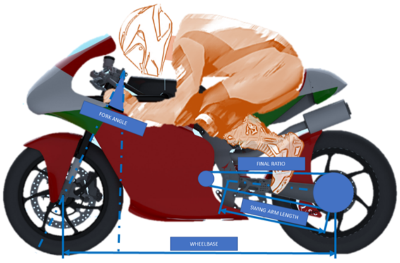

Figure 1. Fundamental Dimensions Considered during the Vehicle Performance Analysis.

Moreover, the inquiry extended beyond the mechanical aspects. The team ventured into the realm of the rider's driving style, conducting a meticulous exploration of the various trajectories adopted to successfully navigate the challenging slalom course. The rider's techniques and choices in maneuvering the motorcycle through this course offered invaluable insights into the interplay between human and vehicle.

The conducted analyses have been divided into three steps. Specifically, variations of one parameter at a time were individually considered. The test groups considered are as follows:

1. TEST I: Variation in the rider's driving style. Trajectories taken by the rider during the slalom were altered;
2. TEST II: Variation in the length of the motorcycle's swingarm;
3. TEST III: Variation in the fork angle.

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For each of these tests, the telemetry channels most related to the temperatures developed by the tires were considered so as to better understand as the mechanical parameter of the bike or riding style changed what was happening to the temperatures developed by the tires themself. More in detail, since the grip is closely related to the temperatures that develop in the inner layers of the tire, these analyses were done using a physical-analytical thermal model called the "thermoRIDE" model.

2 thermoRIDE Model

The thermoRIDE model is a physical-analytical tire model designed to comprehensively study and analyze the complex interactions between a tire, its external environment, and the inner wheel chamber as can be seen in Figure 2 [6].

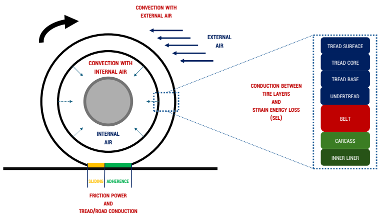

Figure 2. thermoRIDE Model Scheme.

This model is capable of simulating the temperature distribution in the tire layers and of relating this distribution to the heat exchange mechanisms. thermoRIDE model considers several critical heat-related phenomena, including heat generation and exchange processes within the tire structure and with the external environment [5]:

- ***Heat Generation Mechanisms***
  - *Friction Power:* Arising from the tire-road tangential interaction;
  - *Strain Energy Loss:* Resulting from cyclic deformations during tire rolling.
- ***Heat Exchange Processes***
  - *Tire-Road Thermal Conduction:* heat conduction between the tire tread and the road pavement;
  - *Internal Thermal Conduction:* heat conduction between different points within the tire structure due to temperature gradients;
  - *Tire-External Air Thermal Convection:* convection phenomena occurring at the tread surface with external air;
  - *Tire-Inner Air Thermal Convection:* convection phenomena occurring between the inner liner layer and the inner air.

This model is designed to assist in optimizing the motorcycle's performance by providing guidance on how to properly carry out the motorcycle setup in order to improve the tire behavior. Additionally, it offers valuable insights to help prevent potentially dangerous situations such as overheating or problems caused by tires that are too cold.

2.1 Mathematical Model

The mathematical foundation of the presented model relies on Fourier's diffusion equation, applied to a three-dimensional domain. This equation describes the energy within the system, accounting for gains and losses. Fourier's law of heat conduction, a fundamental principle in thermodynamics, states that heat transfer is proportional to the temperature gradient and the thermal conductivity of the material [11]. Mathematically, this relationship is expressed as:

$$\vec{q} = -k\nabla T \tag{1}$$

Where:

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- $\vec{q}$: Local heat flux density (W/m²)
- k: Material's conductivity (W·m/K)
- ∇T: Temperature gradient (K/m)

It is possible to derive a parabolic partial differential equation from Fourier's law, suitable for numerical integration in transient thermal conditions [13]. To achieve that, an infinitesimal volume element $dV = dxdydz$ is considered.

Since the change in the internal energy of a closed system is equal to the amount of heat supplied to the system, minus the amount of work done by the system on its surroundings, and the control volume is considered not deformable, the internal energy dU of the infinitesimal volume dV is given by the following expression:

$$dU = \rho \cdot dV \cdot c_v \cdot T \tag{2}$$

Here, ρ represents density, c_v denotes specific heat at constant volume, and T signifies temperature.

Since the volume dV is not able to do any work ($dL = 0$), the change in the internal energy dU is linked only to the amount of heat dQ added to the system. The term dQ encompasses two distinct contributions:

- *Heat exchanged through the outer surface of the volume dV:*
$$dQ_{EX} = -dt \cdot \oint dS \cdot \vec{q} \cdot \hat{n} \cdot dS = -dt \cdot \nabla \cdot (k\,\nabla T) \cdot dV \tag{3}$$
- *Heat generated within the volume dV:*
$$dQ_G = \dot{q}_G \cdot dV \cdot dt \tag{4}$$

Here, $\dot{q}_G$ represents the rate of heat generation per unit volume and unit time (in W/m$^3 \cdot$ s), and $\hat{n}$ denotes the normal unit vector to the faces of the volume element.

By combining equations 2, 3, and 4, the energy balance equation for the infinitesimal volume dV is derived:

$$\rho\, dV\, c_v\, dT = \dot{q}_G\, dV\, dt + dt\, \nabla \cdot (k\,\nabla T)\, dV \tag{5}$$

Equation 5, divided on both sides by the quantity $\rho \cdot dV \cdot c_v \cdot dt$, defines the Fourier heat equation:

$$\frac{\partial T}{\partial t} = \frac{\dot{q}_G}{\rho c_v} + \frac{\nabla \cdot (k \nabla T)}{\rho c_v} \tag{6}$$

Equation 6 enables the determination of the three-dimensional temperature distribution $T(x, y, z, t)$, contingent upon the specification of boundary conditions. It governs the temporal variation of temperature concerning a specific thermal gradient and elucidates how temperature evolves due to generative effects and heat transport phenomena.

The complexity of the phenomena to model and the degree of accuracy required for the applications towards which it is intended has made it necessary to take into account the dependence of the thermodynamic quantities and in particular of the thermal conductivity on the temperature. Furthermore, the non-homogeneity of the tire has also made it important to consider the variation of the above parameters along the thickness. Therefore, the Fourier equation takes the following state-space formulation:

$$\frac{\partial T}{\partial t} = \frac{\dot{q_G}}{\rho c_v} + \frac{1}{\rho c_v} \left(\frac{\partial^2 k(z,T)T}{\partial x^2} + \frac{\partial^2 k(z,T)T}{\partial y^2} + \frac{\partial^2 k(z,T)T}{\partial z^2} \right) \tag{7}$$

To solve Equation 7 by means of a numerical method and obtain the evolution of the temperature field over time, it is important to make an appropriate tire model, and correctly model the thermal phenomena introduced above.

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2.2 Tire Structural Model

The tire is considered parallelepiped-shaped and it is discretized by means of a grid, whose nodes represent the points in which the temperature will be determined instant by instant thanks to the written Fourier Equation 7 [5]. The discretization of the tire, which caters to its unique attributes such as dimensions, diffusivity, and inertia, can substantially vary. This variability is aimed at accurately representing the transient and steady-state thermal dynamics while upholding real-time requirements across diverse tire operational conditions.

The default tire structure encompasses six layers along the radial direction:

- *Tread Surface:* the outermost part that is in contact with the road and external air;
- *Tread Core:* positioned just below the surface, directly tied to grip and also to tire stiffness;
- *Tread Base:* the deepest tread layer, whose temperature affects mostly the tire stiffness rather than the grip level;
- *Belt:* situated beneath the tread base and made of a series of wire cloths arranged with small angles, this layer is significantly linked to the strain energy loss phenomenon;
- *Body Plies:* layer composed by a series of mutually parallel cords of very durable and at the same time flexible material, surrounded by the vulcanized rubber compound; it is another important contributor to the SEL, because of the energy dissipated by the friction among different plies and within the plies;
- *Inner Liner:* last layer of the tire which is in contact with the inner air, not significantly influencing SEL, stiffness, or grip.

For what concerns the lateral discretization of the tire, the standard one is illustrated in Figure 3 on the right. However, for motorcycle tires, the discretization along the y direction can be customized with up to 16 ribs (Figure 3 showcases the default 5-rib configuration). This customization is contingent upon the availability of pre-initialized boundary conditions maps specific to the analyzed tire [6].

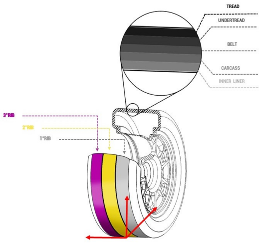

Figure 3. thermoRIDE Tire Mesh Scheme.

2.3 Heat Exchange and Heat Generation Mechanisms

The writing of the balance equations for each generic node requires the modeling of the heat exchange and heat generation mechanisms. In order to achieve that, there is a need to model the mechanisms of heat exchange and heat generation introduced at the beginning of the chapter.

2.3.1 Friction Power

Friction power (FP), is a heat generation mechanism connected with the thermal power produced at the tyre-road interface because of the tangential stresses that, in the sliding zone of the contact patch, work by dissipating heat [9]. In the balance equations writing, FP can be associated directly with the nodes involved in the contact with the ground. FP is calculated based on global force and sliding velocity values assumed to be equal throughout the contact patch:

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$$FP = \frac{F_x {v_x}^s + F_y {v_y}^s}{A_{CP}} \tag{8}$$

where F_x and F_y are the longitudinal and lateral interaction forces; ${v_x}^s$ and ${v_y}^s$ are the longitudinal and lateral sliding velocities; A_{CP} is the contact patch area. Part of this thermal power is transferred to the tire, the remaining to the asphalt.

2.3.2 Strain Energy Loss

The energy dissipated by the tire as a result of cyclic deformations is called strain energy loss (SEL) [2]. This dissipation is due to a superposition of several phenomena: intra-plies friction, friction inside plies, and nonlinear viscoelastic behavior of all rubbery components. The cyclic deformations to which the system is subject occur with a frequency corresponding to the tire's rotational speed. During the rolling, indeed, portions of the tire, entering continuously in the contact area, are submitted to deformations which cause energy loss and then heat dissipation. The empirical SEL formulation is a function of the following parameters and it deeply depends on the tire characteristics [4]:

$$SEL = f(\overline{F}, \omega, \gamma, {p_{in}}^{air}) \tag{9}$$

where $\overline{F}$ is the average interaction force at the contact patch in $[N]$, ω is is the wheel rotation frequency $[rad/s]$, γ is the wheel alignment camber angle $[rad]$ and, finally, ${p_{in}}^{air}$ represents the inflation pressure in the wheel chamber $[N/m^2]$.

2.3.3 Heat Exchange with the Road

Thermal conduction between the tire's tread and the asphalt is modeled using Newton's formula, which employs an appropriate heat exchange coefficient. The heat exchange term (Q_C) for the i-th node is computed as follows:

$$Q_c = H_c(T_r - T_i)\Delta X \Delta Y \tag{10}$$

The terms of this expression can be described as follows:

- H_c is the equivalent conduction coefficient in $[\frac{W}{m^2K}]$
- T_r is the track temperature in Kelvin;
- T_i is the temperature of the generic node in Kelvin;

This heat exchange mechanism strongly concerns the tread surface layer.

2.3.4 Heat Exchange with the Outside/Inside Air

The intricate process of heat transfer between a surface and a fluid in motion at varying temperatures is elucidated by natural and forced convection equations. In detail, to describe the tire heat exchange with the external air it's necessary to consider the mechanism of forced convection, occurring when there is relative motion between the car and the air, and the mechanism of natural convection linked to situations of absent motion.

Supposing the tire invested by the air similarly to a cylinder invested transversely from an air flux, the convection heat transfer can be modeled by Newton's law of cooling formulation [12]:

$$Q_{conv} = h_c(T_{air} - T_i)\Delta X \Delta Y \tag{11}$$

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where T_{air} is the air temperature at the boundary tire layer in Kelvin and h_c is the convection coefficient. The determination of this last coefficient, both for forced and natural convection, is based on the classical approach of the dimensionless analysis.

Finally, it can be noted that the radiation heat transfer is neglected.

2.4 Contact Patch Evaluation

In order to model the thermal exchanges involving the tire, it is crucial, as observable from the above formulas, to have information about the size and shape of the contact zone between the tire itself and the road. The size and the shape of the contact areas are obtained by means of specifically developed test procedures, based on the use of a scanner and a special tool developed in Matlab. In these tests, the tires are scanned in different working conditions. In detail, tests are executed in different static conditions varying the vertical load F_z, the internal pressure ${p_{in}}^{air}$, and the wheel alignment configuration in terms of camber angle γ. In particular, because very high wheel alignment angle angles are reached for motorcycles, in order to have robust information related to contact patches, it has been necessary to develop a special mechanical arm that, integrated into the hydraulic press required to bring in the desired loads, allows very high angles of inclination to be reached for all load and pressure conditions.

An example of the obtained contact patch related to a vertical load of 1800N, an inflation pressure of 2.7 bar, and an inclination angle of 40 degrees, is shown in the following Figure 4:

(a) 3D Tire Mesh.

(b) Contact Patch.

Figure 4. Example of Measured Tire Contact Patch.

At this point, for each contact patch, a set of four values is measured that allows to characterize each footprint. After checking the physical consistency with respect to the limit settings identified with the experimental tests, these values just computed go as input to a tool that generates a map of the contact footprints according to the working conditions chosen from time to time.

Finally, however, it should be noted that the instantaneous dynamic contact patch extension and shape can be quite different because of particular transient conditions of wheel loading, the centrifugal effect on the rolling tire, and viscoelastic tire intrinsic characteristics. To implement the contact patch dynamic characteristics an MBD/FEA tyre model able to fit both static and dynamic experimental data can constitute a valid instrument.

2.5 Tyre Thermal Characterization

The thermoRIDE model, developed to accurately reproduce the tire thermal dynamics in all the vehicle working conditions, needs a proper thermal characterization of all the tire layers of interest. With this aim, an appropriate non-destructive procedure, allowing to obtain the thermal diffusivity of the different layers, has been originally proposed by C. Allouis et al. [1]. In this procedure, the tire tread surface is heated in a small spot employing a laser beam collimated with a lens, while the temperatures reached on an area located around the heated point (tread) and on the corresponding inner surface (inner liner) are acquired using two thermal cameras. Using the above instrumentation, the tire radial and circumferential temperature gradients are acquired. Then, these are employed in a model, known as "Thermo Racing Tyre Laboratory" model (TRTLab), to obtain the thermal diffusivity of the tire layers based on the use of Fourier's equation of diffusion applied to a three-dimensional domain. The heat generation term of the Fourier law, in this case, is related to the laser thermal flux at the tread surface nodes. This heat generation term is assigned only to the tread nodes located within the laser spot area and the entire heating flux power is subdivided into singular nodes in relation to the laser spot area portion. The TRTLab Model is able to simulate the trend of the surface temperature and the inner temperature. So, knowing the data

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about these temperatures deriving from the experimental procedure explained above, a reverse engineering process is carried out by modifying the values of density, specific heat, and thermal conductivity until the simulated curves overlap with those acquired. When this happens the values of these quantities found for each layer are assumed as the physical parameters of the tire.

For the rear tires of the motorcycle under consideration, the TRTLab model provided the following results for what concerns the thermal conductivity and the specific heat coefficient (Figure 5):

(a) Thermal Conductivity.

(b) Specific Heat Coefficient.

Figure 5. Rear Tire Thermal Properties.

The solid blue curve relates to the thermodynamic properties of the tread, the dashed blue curve to those of the inner liner, and the orange curve refers to the belt in which metal wires are present. From these curves, it can be seen that for this tire, the type of compound from which the tread is made conducts more heat than that from which the inner liner is made. Instead, these two compounds have very similar values of specific heat. As for the belt, it has completely different values because of the different material it is made of and, of course, it conducts heat much more than the rubber.

2.6 Model Input/Output

The input data needed by the thermoRIDE consists of the telemetry channels, obtained using the "VI-BikeRealTime" environment, shown in Table 2. Instead, as for the output temperatures, they are summarized in the following Table 3.

Table 2. Model Input

Quantity	Description
F_z	Vertical interaction force
F_x	Longitudinal interaction force
F_y	Lateral interaction force
v_x	Wheel hub longitudinal velocity
v_y	Wheel hub lateral velocity
s_r	Slip ratio
s_a	Slip angle
ω	Wheel angular velocity
γ	Inclination angle
T_{Air}	Ambient air temperature
T_{Track}	Road pavement temperature

Table 3. Model Output

Quantity	Description
$T_{\text{TreadSurf}}$	Tread surface temperature
$T_{\text{TreadCore}}$	Tread core temperature
$T_{\text{TreadBase}}$	Tread base temperature
$T_{\text{InnerLiner}}$	Inner liner temperature
T_{InnerAir}	Internal air temperature
p_{InnerAir}	Internal air pressure

3 Results

This section presents the results of simulations done with the thermal model in order to understand the influence of certain changes in vehicle setup and driver's driving style as they affect temperatures. In particular, there is a focus on tread temperatures, which are the ones that most influence grip. The results are all related to slalom maneuvers performed in the VI-BikeRealTime virtual environment. The aim of this preliminary analysis is to examine the prospect of utilizing the thermoRIDE to improve the performance of racing motorcycles. It is worth noting that this is an exploratory study to determine the model's reaction to various factors linked to the motorcycle setup or the rider's driving style. Hence, it is advisable to avoid giving excessive importance to the precise temperature readings and instead concentrate on the qualitative patterns and fluctuations when executing even a very basic maneuver as the slalom. In addition, it is specified that all results presented refer to the rear tire but, for this type of maneuver, similar considerations apply to the front tire.

In Figure 6a, the thermoRIDE simulation results for two different trajectories followed by the virtual driver are shown. The trajectories were generated by changing in the VI-BikeRealTime virtual environment the radius of curvature with which the slalom is approached by the rider. These two different paths both refer to setups having a fork angle of 19.8° and a swingarm length of 506 mm. First of all, it can be seen, in both cases, that for the slalom maneuver under exam, the temperature of the middle layer of the tread is the one that increases the most. This is related to the fact that no thermal blankets were used, so the tread surface starts from a low temperature and this does not rise much because this layer is most affected by the effect of convection with the outside air. In contrast, the tread core, not being subject to convection, retains some of the heat from friction power and also some of the heat from the inner layers. Finally, for this type of maneuver, the SEL generated is not much so the base tread (innermost layer of the tread), feeling less of the effects of friction power and having little heat coming from the tire carcass gets less warm.

Clear differences can be highlighted by comparing the results of the two different trajectories. Specifically, the first one (path A), referred to by the continuous curves, is a narrower trajectory while the second one (path B) is more outward as can be seen in Figure 6b. As can be seen from Table 4 and in Figure 6c the innermost trajectory generates higher longitudinal forces, thus higher longitudinal friction powers. Instead, the lateral forces are only slightly higher in the case of the wider trajectory as shown in Figure 6d. So, Path A generates more friction power and raises tread temperatures higher than Path B. In addition, the narrower trajectory is traveled at a slightly higher speed and, therefore, there is somewhat higher SEL generation.

Table 4. Average Rear Forces and Longitudinal Velocities for Different Paths

Path [m]	**Average Longitudinal Force (N)**	**Average Lateral Force (N)**	**Average Longitudinal Velocity (m/s)**
$PathI$	437.1	299.6	11.56
$PathII$	395.8	336.3	10.32

(a) thermoRIDE Results for Two Different Trajectories.

(b) Comparison of Trajectories.

(c) Longitudinal Force Comparison.

(d) Lateral Force Comparison.

Figure 6. thermoRIDE Results Analysis for Two Different Trajectories.

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The analysis of temperature variations in the tread layers following setup changes are shown in Figure 7a and Figure 8a with their respective zooms in Figure 7b and 8b. More in detail, Figure 7a compares the temperatures for two different fork angle inclination values, 19.8° and 24.8°, when the swingarm length is set at 506mm; while Figure 8a shows the variation in temperature due to changes in swingarm length, 506 mm and 526 mm, when the fork angle is set at 19.8°. In the first case, it can be seen that the model is sensitive even to a simple setup change such as the one under consideration and for a very trivial maneuver such as the slalom. In particular, from the zoom on the right, it is possible to note that when the fork angle value is higher there is a slight rise in all three tread layer temperatures. The clearest is observable for the tread core. Figures 8a and 8b demonstrate that extending the swingarm length leads to a decrease in tread temperatures across the board, with a more pronounced effect than previously observed. By implementing these adjustments and utilizing thermoRIDE to analyze their impact, there is the opportunity to acquire valuable intelligence on how to optimize tire thermal regulation.

(a) thermoRIDE Results for Two Different Fork Angles.

(b) Zoom of thermoRIDE Results for Two Different Fork Angles.

Figure 7. thermoRIDE Results Analysis for Two Different Fork Angle Values.

(a) thermoRIDE Results for Two Different Swingarm Lengths.

(b) Zoom of thermoRIDE Results for Two Different Swingarm Lengths.

Figure 8. thermoRIDE Results Analysis for Two Different Swingarm Lengths.

Conclusion

In this study, we conducted simulations using a physical-analytical thermal model to investigate the effects of various changes in vehicle setup and driver's driving style on tire temperatures, with a specific focus on tread temperatures, which significantly influence grip. The simulations were performed during slalom maneuvers within the VI-BikeRealTime virtual environment. The primary objective of this preliminary analysis was to assess the potential utility of the thermal model in enhancing the performance of racing motorcycles. It is important to emphasize that this study serves as an exploratory investigation, aiming to understand the model's responses to different factors related to motorcycle setup and rider behavior.

Valuable preliminary insights were gained from the simulations conducted, revealing how the thermal model can optimize racing motorcycle performance. The results indicated that different trajectories impact tire thermal histories. This information, provided by thermoRIDE, can be highly beneficial in assisting drivers to warm up their tires prior to a qualifying session or race. Additionally, the model can be important to carefully approach curves on certain circuits to avoid overheating that may lead to thermal degradation, causing faster wear and reduced performance during the race.

Even though the effect of modifications in fork angle geometry and swingarm length on thermal model simulation outcomes might not be as considerable as the impact on trajectories, it is still detectable. The thermal model is very responsive to even the tiniest adjustments in maneuvers like the slalom, which is crucial to grasp how to handle the correct configuration and where to concentrate on enhancing motorcycle design. In the subsequent phase of our research, we intend to perform more complicated and extended maneuvers beyond the slaloms talked about in this article to fully comprehend the effect of these modifications and observe more noticeable temperature changes.

In addition, similar analyses will be conducted not only using simulations in the virtual environment but also using telemetry acquired on the track appropriately. Finally, another focus point will be a more accurate definition of the SEL formulation for this type of application.

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