Development of a simplified methodology for grip prediction in motorsport

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Abstract: Nowadays, knowledge of vehicle dynamic behaviour is becoming more and more ingrained, especially in applications such as motorsport where numerous linearization can be introduced into the models making studies relatively simpler compared to more complex cases. This has brought to attention a salient point that has been sought to be clarified and understood in ever greater depth over the years, namely the area of tire science. In fact, it is still extremely complicated to understand in depth how the tire behaves in the competition since it is really challenging to understand all the factors that contribute to grip generation. The aim of the following project is to create a methodology that allows the grip provided by the tire to be evaluated in a predictive manner starting from three basic inputs: road roughness conditions, tire viscoelastic properties and telemetry analysis. From the study of the different factors that contribute to the determination of grip, we are looking for a predictive tool that can provide metrics to distinguish and discriminate the performance of the tire as these basic three factors vary. The need to develop such a tool stems from the ever-increasing demand from teams to be able to understand in a predictive logic how to make the best use of the rubber element while guaranteeing a solid performance from this perspective as well. All sensitive data are normalized to preserve their secrecy.

Keywords: tire science, vehicle dynamics, grip prediction

1. Introduction

The project wants to identify a simplified methodology for predicting grip performance and its optimal temperature on the vary of three main inputs: road roughness characterization, tire viscoelastic properties and telemetry analysis. The topic is developed for motorsport applications, this introduces numerous complications and difficulties in obtaining specific types of data, thus the method is developed introducing different simplifications in order to cope with the restriction imposed. On top of that the ability to predict grip requires a deep knowledge of grip generation, however, the actual state of the art in some specific topics still lacks precise explanation regarding tire-road interaction. This makes the study more difficult and highlights the necessity of continuous development to keep pace with the scientific community. In the following figure, we present the overall workflow of the prediction method. Starting from the PSD analysis of the road surface it is possible to derive metrics that, added to the information of sliding speed coming from telemetry, contribute to the definition of the excitation frequency of the thread. By applying the Time-Temperature Superposition law, in the hypothesis of thermorheologically simple material, it is possible to shift the material curves of E_1 and E_2 , experimentally obtained with VESevo device at 1Hz, at the frequency of interest. Once this is done, applying any grip model we can join all the factors that contribute to grip generation in order to obtain the final prediction in terms of grip value and its optimal temperature. The telemetry analysis is in turn used to provide a validation of the prediction done. The project wants to analyze the lateral behaviour of the tire which is definitely more critical in competition.

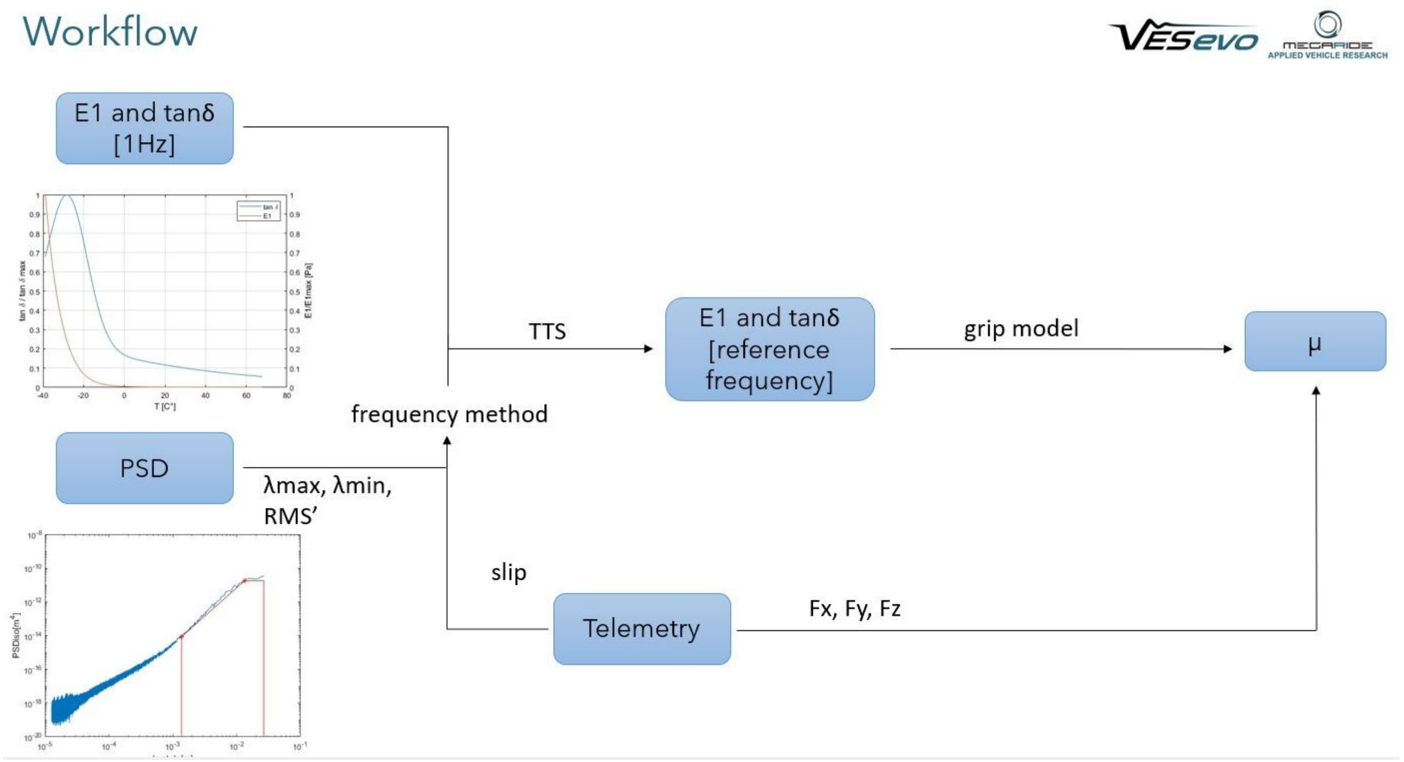

Figure 1: workflow of the prediction method

2. **Grip models**

To be able to obtain a final value of grip it is mandatory to adopt one or more grip models that, starting from the inputs mentioned provide a final value of normalized force. It is known that the overall grip is provided by two components, an adhesive contribution related to the molecular interaction of tire compound and asphalt, and a viscoelastic contribution linked to the generation of grip due to the energy dissipation of the tire that is cyclically excited by road asperities. On top of that it is known that the grip varies on the varying of temperature and sliding speed. Since the complication introduced by the motorsport application of the method makes a lot of information to be difficult to derive we need to introduce some simplification. First of all it is common practice to consider the adhesive contribution in motorsport negligible compared to the viscoelastic one which takes a higher place when high sliding speeds are considered as demonstrated by [1]. This is obviously a simplification that we will try to verify in the following sections, however, since the current adhesive models follow a law for which

$$\mu_{adh=}\frac{\tau_f}{\sigma_0}\frac{A_1}{A_0}$$

with

$$\tau_f = \tau_{f0} exp\left[-c\,\left(\log_{10}\frac{v}{v0}\right)^2\right]$$

where A_1/A_0 is the ratio of the real and ideal area of contact and c, v_0, τ_{f0} are constant proper of the phenomenon, these are almost impossible to be derived in motorsport and force us to embrace a grip modelling that only encounters the viscoelastic contribution. Thus, in a second phase, we analyze the different viscoelastic grip models proposed in literature such as the ones of Persson [2], Klüppel [3], and Popov [4]. Considering the application of the method it is easy to understand that, at least for this preliminary study the model in [4] is the one that suits better, it states that

$$\mu_{visc} = \nabla z(\lambda_{min}) \frac{E_2(T,f)}{|E_1(T,f) + jE_2(T,f)|}$$

where $\nabla z(\lambda_{min})$ is the Root Mean Square Slope of the asphalt rugosity measured at the minimum wavelength that affects the rubber behaviour, and the other contribution depends on the real and imaginary part of the complex modulus of the rubber which in turn depend on the frequency and temperature condition. The simplicity of this formulation is not to be considered as a lack of solidity of the method, indeed as discussed by Ciavarella in [5], this formulation completely agrees with the experimental evidence and represents a valid alternative to more complex models to evaluate the viscoelastic grip. As it is possible to notice from *Figure 2* the $\mathrm{RMS}'(\lambda_{min})$ and in turn $\boldsymbol{\lambda_{min}} = \frac{\boldsymbol{2\pi}}{\boldsymbol{q1}}$ play a crucial role in defining the final grip, this is one of the key points of the method. Indeed nowadays there is no unified and universally recognized method to determine the micro wavelength that affects the tire behaviour. This opens a huge question mark that needs to be deeply understood in further studies as it could provide a more solid comprehension of the phenomenon. As presented in [2] we now develop the methodology taking advantage of the previous studies that show a good correlation between models and experimental data. In particular, the micro wavelength is determined by applying a fixed scale from the macro wavelength λ_{max} of a fixed factor k the magnitude of which still needs to be properly identified by the scientific community.

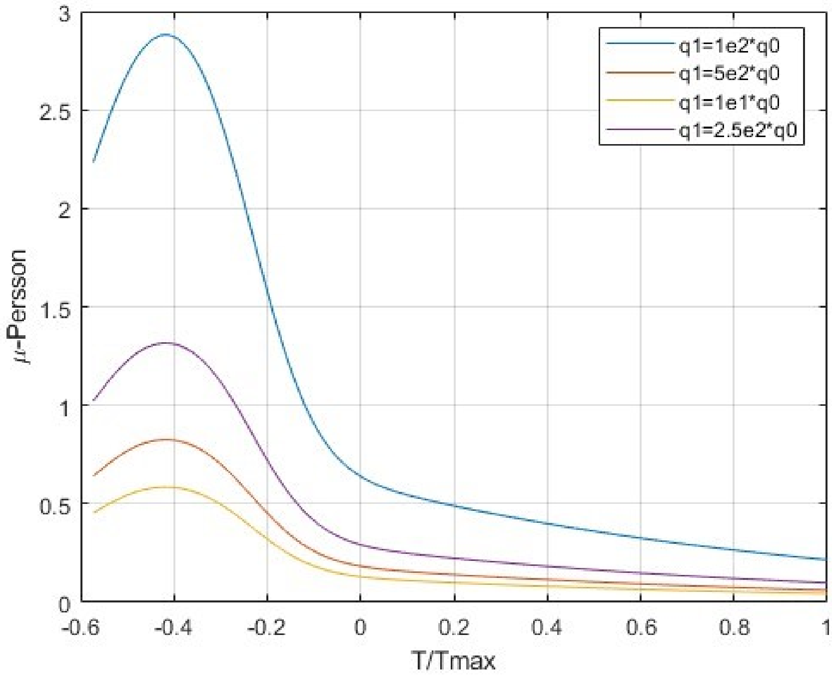

Figure 2: Popov grip on the vary of q1

3. Road roughness analysis

The analysis of the surface roughness condition is extremely important because it affects the tire behaviour both in terms of overall grip, and in terms of optimal temperature of exercise. Indeed road characterization is crucial when it comes to defining the component μ_{visc} which is directly proportional to the parameter $\nabla z(\lambda_{min}) = \mathrm{RMS}'(\lambda_{min})$ and when it is time to define the excitation frequency of the thread which is calculated through $f = v_{slide}/\lambda_{\min}$. The analysis of the surface is done by calculating the so called Power Spectral Density of the surface height signal; the PSD is calculated on the basis of [5] as

$$PSD_{2D} = \frac{\Delta x^2 \Delta y^2}{A} \left| FFT_{qxqy} \right|^2$$

for bidimensional screening of area A and pixel spacings $\Delta x, \Delta y$ and where FFT_{qxqy} is the Fourier Transform of the height signals with wavevectors q_x, q_y. Since analyzing a surface PSD is everything but easy for the human eye, under the assumption of radially symmetric bidimensional PSD we usually refer to the formulation of PSDiso which comes from the radial averaging of its bidimensional counterpart. The road surfaces in contact with the tire present a particular behaviour of the PSDiso, which identify them as self-affine surfaces which have a behaviour well represent by the following piecewise function

$$PSD_{iso}(\lambda) = \begin{cases} \left(\frac{1}{\lambda_{max}}\right)^{-2-2H} = const & if\ \lambda_{max} \le \lambda \le \lambda_0 \\ \left(\frac{1}{\lambda}\right)^{-2-2H} & if\ \lambda_{min} \le \lambda \le \lambda_{max} \\ 0 & elsewhere \end{cases}$$

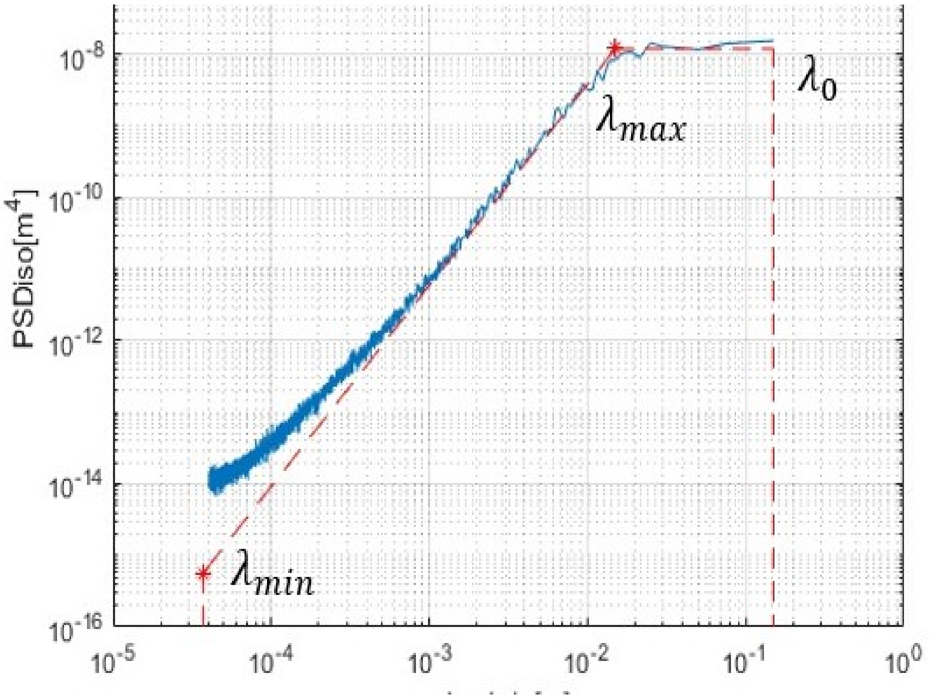

Figure 3: PSDiso of self-affine surface

In particular from these types of characterization it is possible to derive a series of parameter that describes the surface. To be mentioned are the Hurst exponent, H, the Root Means Square, the macro-wavelength $\boldsymbol{\lambda_{max}}$, but in particular, with relevant interest for this case study the micro wavelength $\boldsymbol{\lambda_{min}}$, and the Root Mean Square slope which by virtue of Parseval's theorem can be written as

$$\mathrm{RMS}' = \sqrt{\frac{1}{2\pi}\int q^2 PSD_{iso}(q)\, dq}$$

remembering the relation for which $\boldsymbol{\lambda = \frac{2\pi}{q}}$. In particular we are interested in understanding how these metrics influence the tire behaviour through the application of the prediction method. We will then apply the prediction method varying the surface characterization in order to underline some peculiar behaviour. It must be pointed out that, if almost all the previous parameters are of trivial analytical identification, the key parameter $\boldsymbol{\lambda_{min}}$ still represents an open debate in the scientific community as it was previously mentioned, since there is no unified and certainly valid method for its determination.

3. **Viscoelastic characterization**

The viscoelastic properties of the tire compound are needed in order to apply the model in [4] which combines the road characterization and the tire properties to derive a value of grip. In particular for the sake of this project we want to take advantage of the device developed by the study group of the Università Federico II di Napoli, which is able to provide the characterization of a viscoelastic material in terms of its real and imaginary part of the complex modulus such as

$$E^*(T,f) = E_1(T,f) + jE_2(T,f)$$

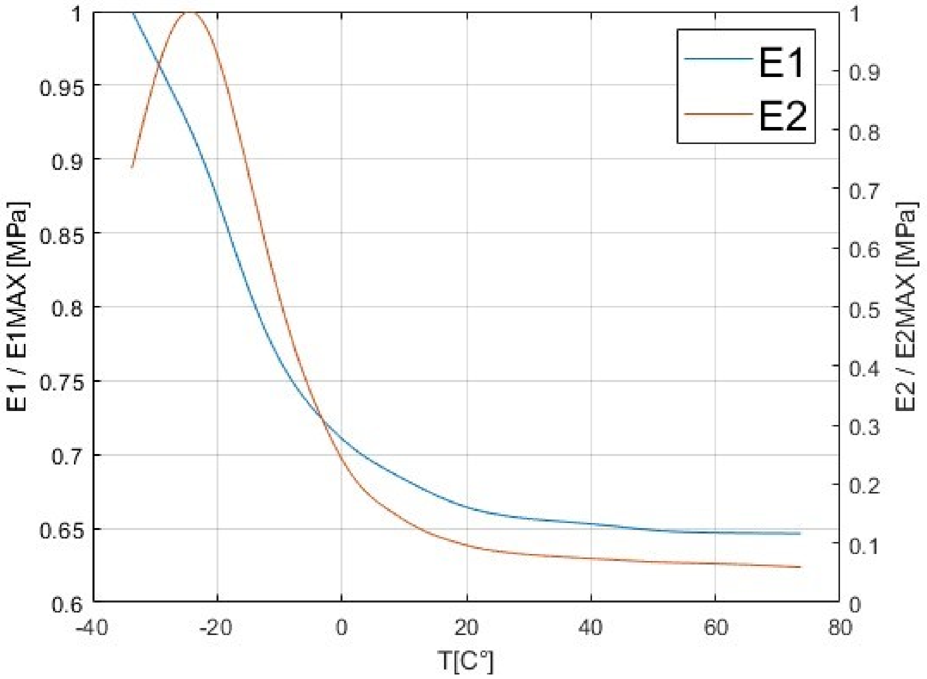

Figure 4: VESevo charachterization

which is usually function of both temperature and frequency excitation. As explained in [6] the VESevo device through the analysis of the bounce of a steel road provides to the user the curves of E_1, E_2 on the vary of the temperature at the reference frequency of 1Hz as one can see in *Figure 4*. As previously mentioned the tread of the tire is excited by the road roughness whit an excitation that is usually much higher than 1Hz, this needs to be taken into account via the so called Time-Temperature Superposition laws. With the introduction of the hypothesis of thermorheologically simple material it is possible to shift the curves of the VESevo device from the reference frequency of 1Hz to higher. To do so we have analyzed different TTS formulation, such as the William-Landel-Ferry [7] but the complications introduced by the motorsport application forces use to use an empiric formulation that replicates well the material's behaviour, since more complex one can not be applied in their complete form. In particular the shift in the temperature domain caused by an increase of the frequency excitation is derived from

$$\Delta T = k \log_{10} \frac{f}{f_0}$$

where $f_0 = 1Hz$ and f is the excitation frequency calculated as explained before.

4. Analysis of telemetry data

In a parallel analysis we focused on understanding how the tire behaves through the telemetry analysis of the track data. The first purpose is to derive an envelope curve that describes the behaviour of the tire in terms of maximum grip at each temperature of interest. To do so, we have analyzed the tire-road interaction by means of the tool and models presented in [8],[9] that allow us to describe the grip potential of the tire on the vary of the temperature. It must be underlined that also this phase is particularly delicate, indeed being able to properly determine the tire-road interaction in terms of forces from the telemetry analysis is a really complicated and subjected to uncertainty task. Once this metric is derived it is possible to perform some fitting algorithm in order to obtain a final envelope curve of maximum grip, one example of which is shown in *Figure 5* which underlines the results of the application of different treatment of the telemetry data which

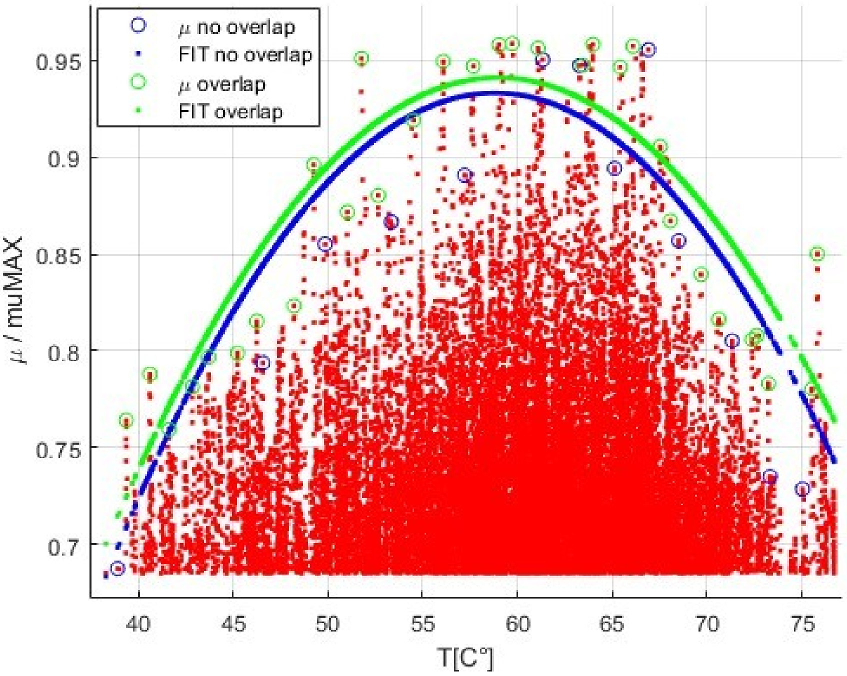

Figure 5: envelope curves as a result of different fitting approaches

are not explained in detail in this site. This analysis plays a crucial role in the study, firs of all because the prediction method should be able to replicate this trend in the most efficient way even when the initial condition varies. Secondly this curve can be used to perform some further analysis that is useful for the development of the method: indeed it is possible to use the curve as reference for the modelled grip and, using $\mathrm{RMS}'(\lambda_{min})$ as an optimization parameter which is directly proportional to μ_{visc}, it is possible to perform some optimization algorithm that reduce the error between the modelled grip [4] and the experimental data previously analyzed. As it is possible to grasp in *Figure 6*, which shows the results after the optimization process, on top one can see that the adoption of only viscoelastic grip into the modelling is not able to guarantee a precise and accurate reproduction of the experimental curve showing a non-perfect match among the curves. In further studies also the adoption of adhesive grip models such as the one in [1], which introduces an inversely proportional relationship between μ_{adh} and the Root Mean Square Slope, show that also this contribution is not enough to perfectly represent what the analysis of the experimental data shows, behavior underlined at the bottom of *Figure 6.* For this study though, we are at least interested in predicting the maximum grip and its optimal temperature of occurrence, metrics that, even considering only a viscoelastic contribution of the grip, are well grasped by the model.

5. **Results**

In this latter section we present the results of the application of the prediction method developed. In particular we show the results obtained by the treatment of data coming from the same car running on the same compound but on three different circuits thus roughness. First of all we must underline that, as it is possible to grasp from *Table 1* the circuits among which a motorsport season race are, in terms of statistical rugosity feature, very similar one to another even if we consider a larger spread of tracks: this emphasize two important aspects of the study. First of all we expect similar results in terms of maximum grip available and optimal working temperature among the different circuits. Secondly it must be kept in mind again, that all the procedure developed allows a series of simplification which added to the complexity of the topic yields to a high sensitivity of the different parameters that comes in to play when determining the grip in a predictive manner.

	Circuit A	Circuit B	Circuit C
RMS [mm]	5.4	6.2	6.7
H	0.9	0.89	0.88

Table 1: roughness characteristics of the circuit analyzed

In *Figure 6* it is possible to observe the trend of the results which come from the application of the prediction method on the vary of the road surface. If compared to what is shown through the telemetry analysis it is interesting to observe that, as a general trend the prediction is well representing the evidence coming from the track in a relative way. However, a more detailed view clearly shows a small mismatch between the prediction and telemetry points concerning Circuit B. As a general conclusion though, we can be satisfied by the results of the predictive method, because even though the punctual comparison is not perfectly respected the method is able to distinguish in the proper way the Circuit A from Circuit B and Circuit C which have similar values of roughness both for RMS and H. On top of that it must be pointed out the differences in terms of absolute values between the circuits are very close thus the error done in the prediction can be considered acceptable at least for this primary developement.

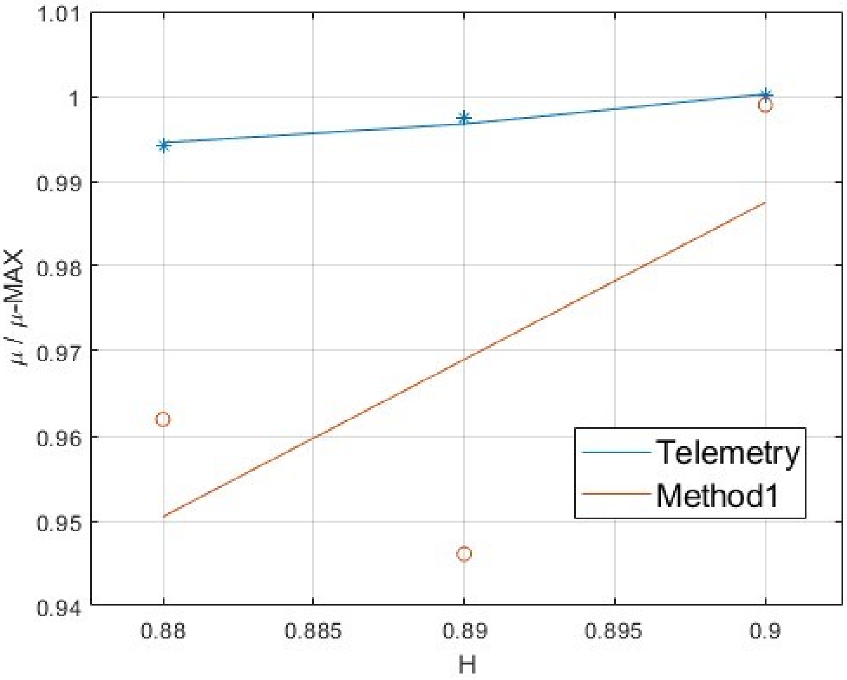

Figure 6: results of the prediction of maximum grip at different roughness conditions

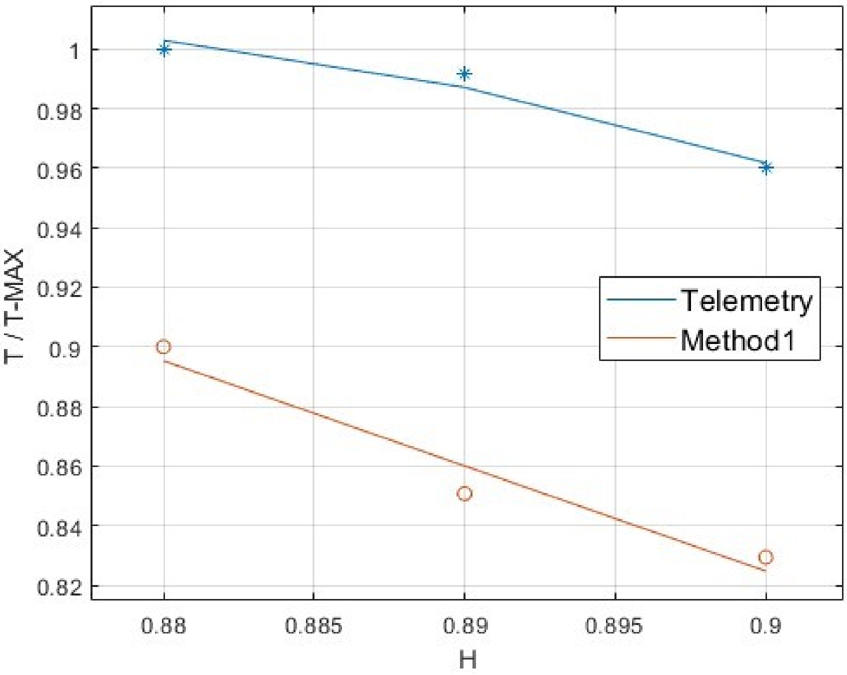

Figure 7: results of the prediction of optimal temperature at different roughness conditions

The most interesting thing to observe concerns the prediction of the optimal temperature range, which represents for the teams a greater information as it is the metric that they are interested to monitor. As one can see in *Figure 7* it is possible to notice that the results are improved as the method is very well detecting the optimal temperature for every different roughness condition. On top of all it should also be emphasized that, due to the great lack of information still present in the scientific community on all the phenomena that contribute to the generation of grip, it is still very complicate to determine in a precise a punctual manner all the values obtained.

6. **Conclusions and further developments**

The aim of this work is to identify and develop a method capable of providing a prediction of grip and its optimum temperature as the main inputs vary. After the overview on how the method has been developed, we can consider ourselves satisfied with the results obtained as the method succeeds in predicting with sufficient accuracy the sought-after trend that is represented by the experimental data. It is essential to emphasize how the work in question, despite adopting numerous simplifications in the various processes involved, manages to present reliable results in line with what was expected after the analysis performed with the track data. The simplifications introduced are either the result of the lack of precise information regarding a specific subject, as is the case with the modelling of adhesive grip or aim to make the methodology more reliable and applicable in a sector as complex as motorsport in which the lack of data plays an even more fundamental role. However, it should be borne in mind that several important issues remain to be addressed in future studies. Firstly, the study of grip models more complex than the one adopted, for instance [2] and [3] could guarantee more reliable and concrete results, not only in terms of trend but also in terms of determining the grip and its temperature optimum in absolute value. Indeed adopting a more accurate grip model that takes into account several aspects compared to the one used may yield better results because of the influence of different factors that in Popov formulation are neglected. In addition, the study seems to highlight that also an adhesive contribution to the overall grip should be considered to better represent the actual behaviour of the tire, especially for its strong effect on the value of $\mathrm{RMS}'(\lambda_{min})$ which could take a lower magnitude than the one obtained only considering the viscoelastic contribution.. Secondly, it is necessary to examine the subject of Time-Temperature shift in more detail. In fact, the use of an empirical law such as the one proposed, if on the one hand it seems to represent the behaviour of the material in a good way, on the other hand, would require more in-depth validation from an experimental point of view. This could be further confirmed by studies such as [10] where the proposal to calculate the WLF constant C1, C2 by means of viscoelastic material models is followed, which could finally bring an instrument to validate or even change the empirical law. Furthermore, the determination of the actual excitation frequency is still a debate, especially for what concerns the characteristic wavelength that affects the tire working condition. In addition, the method's ability to effectively recognize road characterization remains uncertain. While the trend of the results appears to be reliable, it is necessary to extend the study to broader cases, in which road roughness may play a more important role, in order to highlight some behaviour that it has not been seen. Lastly, it is necessary to have more data available, so that the observations made previously can be confirmed on a larger scale, which could lead to new developments with a view to more accurate prediction.

Disclaimer. The work here presented represents only a small and concise summary of what has been developed in the full project of thesis of the title " Development of a simplified methodology for grip prediction in motorsport" in which a deeper analysis is brought with additional studies and observation done to create the predictive method.

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