

# Tire Temperature Analysis for Formula car

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**Abstract**—Our project focuses on understanding that how different tire compounds (soft, medium, hard) behave at different temperatures. Since the tire plays a important role in the handling of the vehicle, grip with the surface & acceleration. Our goal is to make simulation which can generate graphs to show temperature effects on tire. Using the tire data & a friction-temperature model, the model generates 3 key graphs for each tire compound: temperature vs coefficient of friction, lateral force vs slip angle & linear speed vs time at different temperatures. The simulation shows that each compound reacts in a different way - Soft tires give better grip at moderate temperatures while hard compound gives better grip at high temperatures. This directly affects the manoeuvring and handling of the vehicle. Over all our model helps the formula car teams to make better decisions during the races. This model supports improved performance in sharp corners, straights & sudden manoeuvres.

**Index Terms**—Formula car, Tire Model, Gaussian Curve, Temperature Dependent, Coefficient of friction, Slip Angle, Tire Dynamics, Vehicle Simulation, Longitudinal Dynamics, Lateral Force, Race Car Engineering, Tire Compounds, MATLAB Simulation, Performance Analysis.

## I. INTRODUCTION

Tires are the most important components in the performance of any ground vehicle, particularly in high performance cars, like formula style cars. The tire is the only contact between the road and the vehicle, hence the tires determine that how the car will accelerate, brake & corner. It doesn't matter that how advance the powertrain, aerodynamics or the transmission is, it all comes down to the tire's ability to generate forces. Hence getting a detailed understanding of the tire's behaviour in different condition sis essential for engineering reliable race cars. Formula car teams often rely on the data obtained from the manufactures, limited test tracking &

assumptions while taking decisions about the tire selection. But the tire behaviour is very non linear and is influenced by many variables like load, slip angle, slip ratio and most importantly the temperature of tire. Tire temperature affects the viscoelasticity of rubber which affects it's stiffness, hysteresis, deformation & it's ability to generate grip. Even a small change in temperature directly affects the compound.

Real-world testing of temperature effects is difficult for teams due to limitations like, cost of tires, weather changes, and the need for specialized instruments. As a result of this, many teams enter competition without totally understanding how each and every compound behaves or behaves at different temperature ranges. This lack of insight can lead to very poor performance in corners, straights, and initial pickups where a consistent tire behaviour is a very important factor.

To overcome this challenge, our project develops a computational simulation framework that models the behaviour of Formula car tire compound under different temperature conditions. Real tire data is integrated with a mathematically based temperature-dependent friction model, where a Gaussian formulation captures the sensitivity of friction to the operating temperature. Additionally, simplified Pacejka-based lateral and longitudinal force equations are used to compute slip-angle-dependent lateral force ( $F_y$ ) and slip-ratio-dependent longitudinal force ( $F_x$ ). These models are used to simulate vehicles acceleration dynamics as the temperature changes.

The study mainly focuses on three most commonly used tire compounds that are Soft, Medium, and Hard and evaluates their performance at four main critical temperatures: 25°C, 50°C, 75°C, and 100°C. For each type compound, the simulation generates three main performance visualization:

1. Coefficient of friction vs. temperature, showing the thermally driven grip behaviour.

2. Lateral force vs. slip angle, illustrating how cornering capability shifts with temperature.
3. Vehicle acceleration response vs. time, demonstrating real-world performance impact.

The results show clear distinctions among compounds. Soft tires provides a strong grip at low temperature but tend to lose stability as the temperature increases. Medium compounds has balanced performance across the entire range of compounds, while Hard tires shows us predictable behaviour as the temperature increases, making them ideal for endurance event. These insights are very valuable to us for choosing the optimal tire based on event type, track length, ambient atmospheric conditions, and driving strategy.

By combining all, theoretical modelling, real-world data, and simulation, our project gives a practical tool that Formula car teams can use to make informed, data driven decision. This model helps us to reduce the need for extensive physical testing of tyres and allows teams to understand tire characteristics even before the car is fully operationally working. Finally, the main aim of our study is to have more accurate vehicle setup, improved race-day consistency, and a more deeper understanding of tire mechanics amongst engineers.

## II. METHODOLOGY

The methodology of this study has five major phases: (1) data acquisition and preprocessing, (2) development of a temperature dependent friction model (3) implementation of lateral and longitudinal tire force models (4) vehicle acceleration simulation (5) generation of graphical outputs for analysis. The steps are designed to accurately to represent tire behaviour for Soft, Medium, and Hard compound across different tyre temperature conditions.

### 2.1 Data Acquisition and Preprocessing

Tire data has been obtained from a Formula car slick tire dataset in CSV format. The dataset has includes load, tread radius, reference temperature, friction coefficient, and Pacejka coefficients for different compounds. For this study:

- Row 1 corresponds to the Soft compound
- Row2 corresponds to the medium compound
- Row 3 corresponds to the Hard compound

The dataset was imported into MATLAB using:

```
Tire Data = readtable ('FormulaCar_Slick_Tires.csv',
'VariableNamingRule', 'preserve');
```

Important parameters such as normal load (Fz), effective rolling radius (Re), friction coefficient ( $\mu_0$ ), and Pacejka coefficients (B, C) were extracted for each and every simulation we performed.

### 2.2 Temperature-Dependent Friction Modeling

Tire friction changes significantly with temperature because of rubber viscoelasticity. To model this behaviour, a Gaussian temperature sensitivity model has been implemented successfully:

$$\mu(T) = \mu_0(1 + 0.3\exp(-\frac{(T - T_{opt})^2}{2\sigma^2}))$$

Where:

- $\mu_0$  is the base friction coefficient
- T is the tire temperature
- $T_{opt}$  is the compound's reference (optimal) temperature
- $\sigma$  is spread factor (set to 25°C)

This model shows a smooth representation of how the increase in grip near the optimal temperature and decreases when underheated or overheated. Friction curves were evaluated over a temperature range of 20°C to 120°C for all compounds.

### 2.3 Lateral Tire Force Model (Slip Angle Analysis)

Lateral force (Fy) was modelled using a simplified Pacejka "Magic Formula" representation:

$$F_y = D \cdot \sin(C \cdot \arctan(B\alpha))$$

Where:

- $\alpha$  is the slip angle (converted from degrees to radians)
- B is stiffness factor
- C is shape factor
- $D = \mu(T) \cdot F_z$  is peak lateral force
- $F_z$  is the vertical load on the tire

Slip angle values from 0° to 20° has been tested at temperatures 25°C, 50°C, 75°C, and 100°C. This helped us in comparing of cornering performance across different compounds and temperatures.

### 2.4 Longitudinal Tire Force Model (Slip Ratio & Traction)

Longitudinal force ( $F_x$ ) was evaluated using a similar Pacejka-type expression:

$$F_x = D \cdot \sin(C_{long} \cdot \arctan(B_{long} \cdot s))$$

Where:

- $s$  is the slip ratio
- $B_{long}, C_{long}$  are default longitudinal coefficients
- $D = \mu(T) \cdot F_z$  is the temperature-adjusted peak force

Slip ratio was calculated using:

$$s = \frac{R_e \omega - V}{\max(V, R_e \omega) + \epsilon}$$

with  $\epsilon = 10^{-3}$ .

This model shows traction behaviour and is used in the acceleration simulation.

### 2.5 Vehicle Acceleration Simulation

To evaluate real-world performance implications, we implemented a simplified longitudinal vehicle dynamics model. The simulation does calculation of vehicle speed over a 20-second window using a time interval of 0.01 seconds.

At each time step:

1. The speed of the wheel is increased from 0 to its maximum value
2. Slip ratio is computed
3. Longitudinal tire force  $F_x$  is calculated
4. Aerodynamic drag is applied using:

$$F_{drag} = \frac{1}{2} \rho C_d A_f V^2$$

5. Net force is used to compute acceleration:

$$a = \frac{F_x - F_{drag}}{m}$$

6. Vehicle velocity is integrated w.r.t time.

The final velocity is converted from m/s to km/h to make it more readable.

### 2.6 Visualization and Output Generation

For each of the compound, this simulation generates three graphical outputs as:

1. Coefficient of friction vs. temperature
2. Lateral force vs. slip angle
3. Vehicle speed vs. time

Here we have used MATLAB's tabbed UI (uitabgroup) to display these graphs cleanly, that

ensures easy comparison across Soft, Medium, and Hard compounds.

Additionally, numerical summaries ( $\mu$  values and peak forces) are printed in command window for our reference.

### 2.7 Summary of Methodology

This methodology provides a very structured, physics-based simulation framework that combines:

- Real tire data
- Temperature-sensitive friction modelling
- Simplified but accurate Pacejka force equations
- Aerodynamic and vehicle dynamic calculations
- Graphical analysis tools

Together, all these components allows a comprehensive evaluation of how different tire compounds behave under different varying thermal conditions.

## III. RESULTS

The results in this study are presented across these three major categories for each tire compound: (1) the variation of friction coefficient with temperature (2) the lateral force response to slip angle and (3) the change in vehicle's acceleration behaviour at differently varying thermal conditions. All the given simulations are performed for Soft, Medium, and Hard compounds at four representative temperatures: 25°C, 50°C, 75°C, and 100°C. The key findings are summarized below.

### 3.1 Friction Coefficient vs Temperature

The curve generated in the Gaussian friction model show a very clear thermal behaviour change for each compound:

Soft Compound

- It exhibits the highest friction coefficient at lower temperatures (25–50°C).
- $\mu$  increases sharply as it approaches the reference temperature, indicating strong sensitivity to temperature.
- Beyond approximately 75°C, the friction coefficient begins to decline, showing that the soft compound overheats easily, leading to reduced grip.

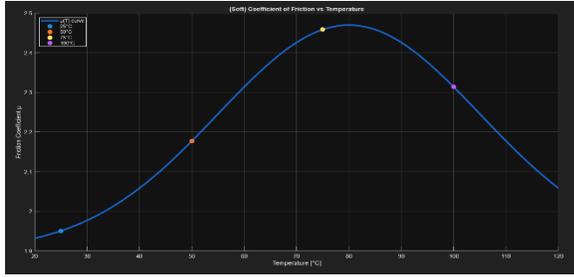


Figure 1. Soft Compound - Friction Coefficient vs Temperature

Medium Compound

- It displays a balanced and stable friction profile across the temperature range.
- $\mu$  rises smoothly towards the optimal temperature and declines gradually at high temperatures.
- This compound demonstrates the least sensitivity to temperature variations, making it suitable for consistently changing track conditions.

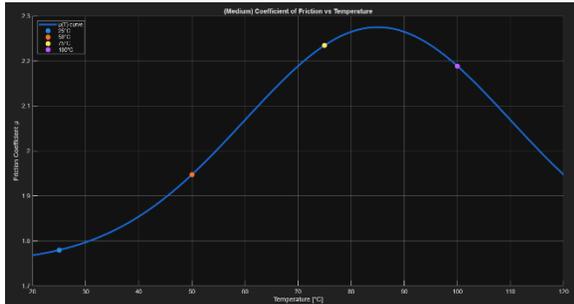


Figure 2. Medium Compound - Friction Coefficient vs Temperature

Hard Compound

- Shows lower friction values at low temperatures (25–50°C).
- $\mu$  increases steadily and peaks at higher temperature regions, indicating that the Hard compound performs best when heated.
- At 100°C, it maintains relatively stable friction, demonstrating its suitability for endurance events where tires heat up very significantly.

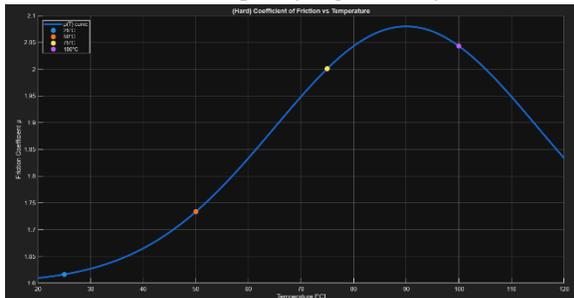


Figure 3. Hard Compound - Friction Coefficient vs Temperature

Overall, the results confirm that the temperature has a major influence on the tire’s grip, and each compound reaches peak performance at different thermal levels as seen above.

3.2 Slip Angle vs Lateral Force

The slip angle simulations has further highlighted the performance differences between compounds.

Soft Compound

- It produces the highest peak lateral force at 25°C and 50°C.
- Shows a very rapid saturation:  $F_y$  reaches its peak quickly at small slip angles (6–8°).
- The performance decreases significantly at 100°C, matching the  $\mu(T)$  decline.

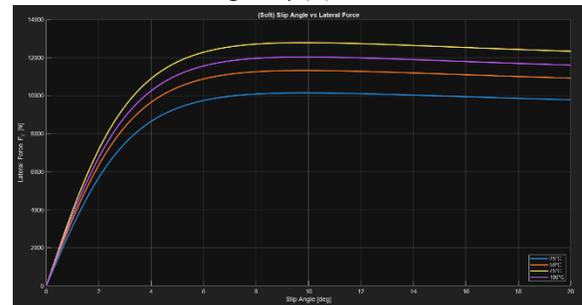


Figure 4. Soft Compound - Slip Angle vs Lateral Force

Medium Compound

- It generates moderately high lateral forces when compared to soft, with consistent peak values across all temperatures.
- The  $F_y$ – $\alpha$  curve remains smooth, with a controlled saturation behaviour.
- It exhibits a predictable cornering performance, confirming its stiffness between above two.

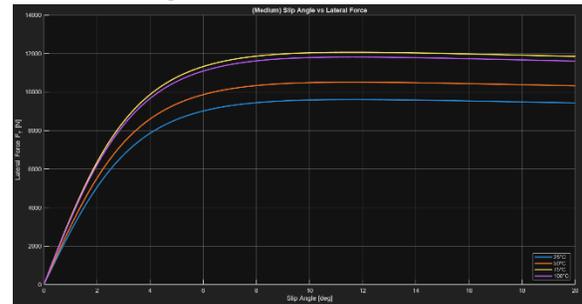


Figure 5. Medium Compound - Slip Angle vs Lateral Force

Hard Compound

- Delivers lower forces at lower temperatures due to reduced  $\mu$ .
- However at 75°C and 100°C, its peak  $F_y$  increases considerably.

- The slip angle for peak  $F_y$  is higher, showing us the greater stiffness and slower saturation, characteristic of harder rubber compounds.

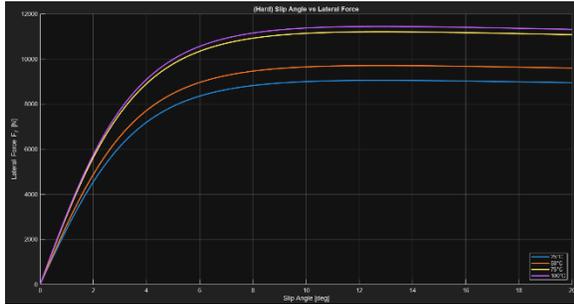


Figure 6. Hard Compound - Slip Angle vs Lateral Force

These results clearly shows that the soft compound offers the maximum cornering grip, the medium compound provides balanced handling, and the hard compound performs best under high-temperature conditions amongst the all above .

### 3.3 Vehicle Acceleration vs Time

The longitudinal dynamics simulations shows us how the temperature and compound affects the straight-line acceleration.

#### Soft Compound

- Achieves the highest acceleration at 25°C and 50°C due to high  $\mu$ .
- However, at 100°C, acceleration reduces quite considerably as overheating reduces the available traction.
- Results show that soft tires provide a excellent early run acceleration but are not ideal under sustained thermal load.

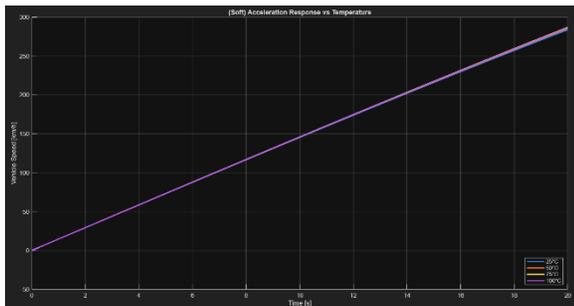


Figure 7. Soft Compound - Vehicle Acceleration vs Time

#### Medium Compound

- It provides stable and consistent acceleration curves across all the temperature range.
- Although it is not the fastest at low temperatures, but it maintains performance without a sharp drop off at higher temperatures.

- This makes the medium compound the most reliable for variable environmental conditions.

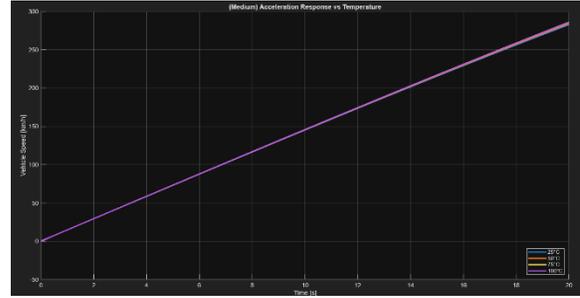


Figure 8. Medium Compound - Vehicle Acceleration vs Time

#### Hard Compound

- It accelerates slower at low temperatures due to poor grip.
- At 75°C and 100°C, acceleration increases significantly as the compound reaches its intended operational range.
- Hard tires outperform soft tires at high temperatures, especially in longer acceleration runs.

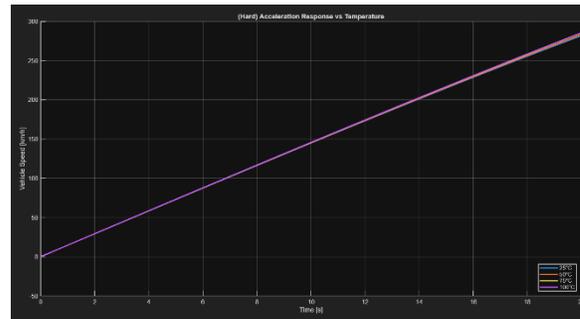


Figure 9. Hard Compound - Vehicle Acceleration vs Time

### 3.4 Comparative Summary

Across all simulations:

- Soft tires performs the best when cool, so offering strong grip and fast acceleration but are very prone to overheating.
- Medium tires offer consistent, predictable performance, making them optimal for average or mixed conditions.
- Hard tires require high temperature to unlock performance, they excel in endurance and high-load conditions.

These results of our simulations perfectly aligns well with real-world expectations in motorsports and validate our accuracy of the temperature-based modelling approach.

## IV. CONCLUSION

This study has successfully developed a comprehensive simulation framework to analyse the performance of Formula car's tire compounds—Soft, Medium, and Hard under differently varying temperature condition. With integrating real tire data with a Gaussian-based temperature friction model and simplified Pacejka's formulations for lateral and longitudinal force generation, this project provides a clear insight on how tire's thermal behaviour influences the grip, cornering forces, and the vehicle acceleration.

The results clearly demonstrates that temperature has a very large effect on tire's performance, and each compound reacts differently to thermal variation. The Soft compound gives us the highest grip and largest lateral forces at low to moderate temperatures but it experiences a very noticeable loss on performance when overheated like in case of 100°C. The Medium compound has shown a stable, balanced behaviour across all tested temperatures, which makes it the most consistent and flexible option. The Hard compound shows poor performance at low temperatures but it significantly improves at high temperatures, aligning with its design for the long endurance and has sustained heat loads.

The lateral force analysis showed the nonlinear nature of slip-angle behaviour and confirms the relationship between the peak grip and compound softness. Similarly, the acceleration simulations also showed us variation in friction due to temperature directly affects vehicle's traction and straight line performance. These results are consistent with real-world observations in motorsport and validate the effectiveness of the adopted mathematical models.

Overall, the developed simulation tool provides the Formula Student teams with a valuable decision making resource for them. It helps teams to understand tire behaviour even before physical testing, also helps to optimize tire selection for different event, and improve the overall vehicle's performance. By giving a clear comparison across compounds and temperatures, our model aids in designing a better setup strategies for race events.

The study reinforces that a properly modelled tire is a very essential for the accurate vehicle performance predictions, and that temperature must be considered

as a critical parameter in tire and vehicle dynamics analysis.

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