White Paper: Influence of Temperature on Tire Grip

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I. Tire Heat Generation and Transfer:

It is important to first understand how heat is generated within a tire and how that heat is transferred into the surrounding environment, before discussing the two key mechanisms responsible for tire grip and their temperature dependence.

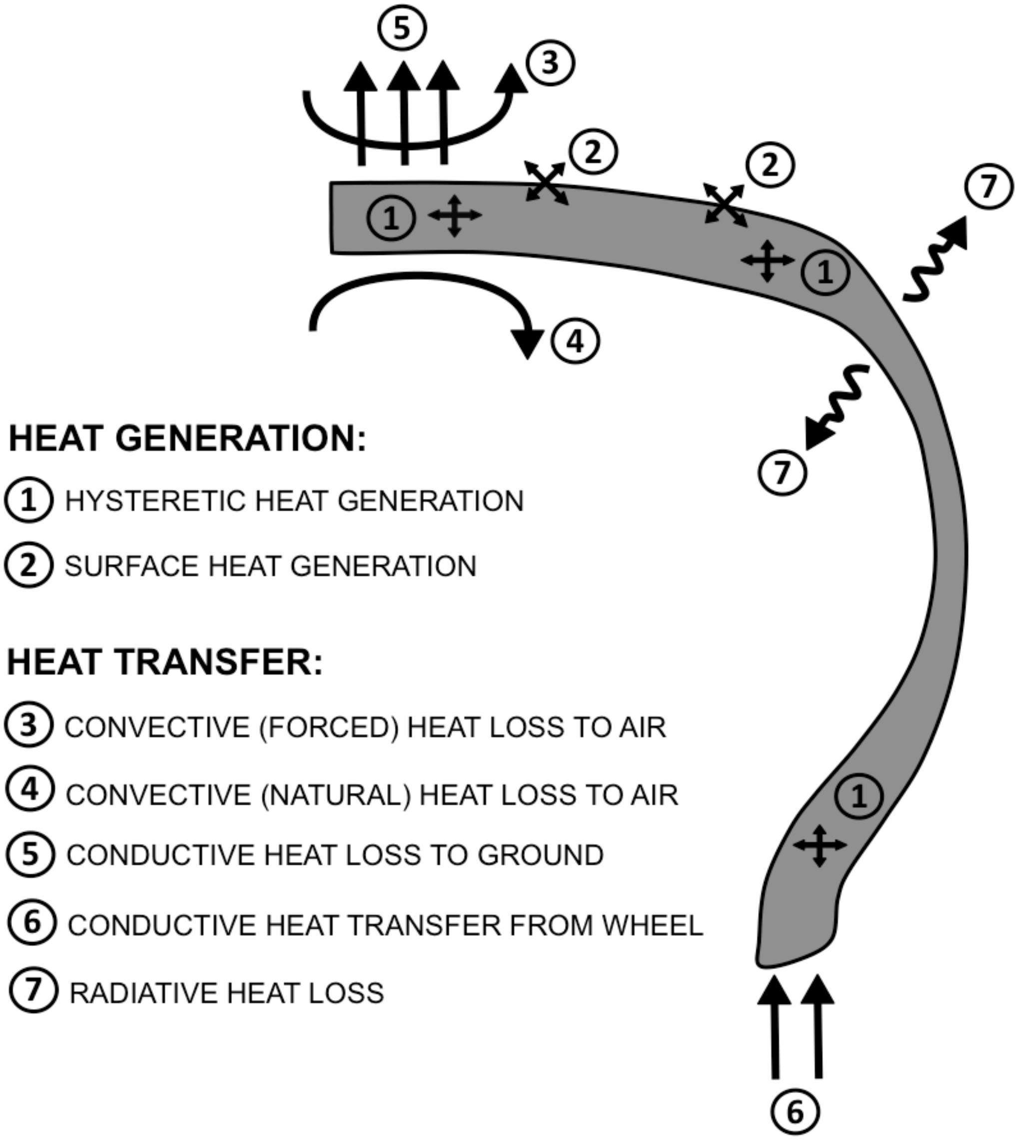


Figure 1. Cross-sectional view of tire heat generation and transfer.

A. Heat Generation

A thermal model of a tire is illustrated in Figure 1, where the two dominant modes of heat generation in a tire are:

1.) Strain energy loss (i.e., heat generation from hysteresis)

When a viscoelastic material such as tire rubber is compressed and relaxed, it stores more energy in the compression process than it releases in the relaxation process. This loss in energy is stored in the tire as heat, and is otherwise known as hysteresis loss or strain energy loss. As will be explained later, hysteresis is one of the key mechanisms responsible for producing tire grip.

A stress-strain hysteresis loop is illustrated in Figure 2, where the amount of heat generation is proportional to the area between the loop, i.e., the total strain energy loss. As a tire rotates, each tire element is cyclically stressed as it revolves through one cycle, and this cycle of stress (e.g., compression & relaxation) results in heat generation from the strain energy loss. The amount of heat generation is proportional to frequency (f = speed / tire circumference), load (downforce, banking, mass, etc.), and rolling resistance. Heat builds in a tire’s core from the accumulation of strain energy loss, as shown by the inner liner temperature distribution of race tires in Figure 3 and the cross-sectional temperature distribution of a typical passenger vehicle tire in Figure 4. The distribution and amount of heat generation in a rolling tire is non-uniform and will vary spatially, especially with pressure, load, and tire construction.

2.) Tire-road tangential interaction, (i.e., surface friction heat generation)

Heat is also generated at a tire’s surface as it slides across the roads surface, and is the product of the surface force vector and sliding velocity. With large slip angles, surface heat generation is significant in the trailing edge of the contact patch and is why the instantaneous lateral surface temperature profile represents the approximate contact patch load distribution.

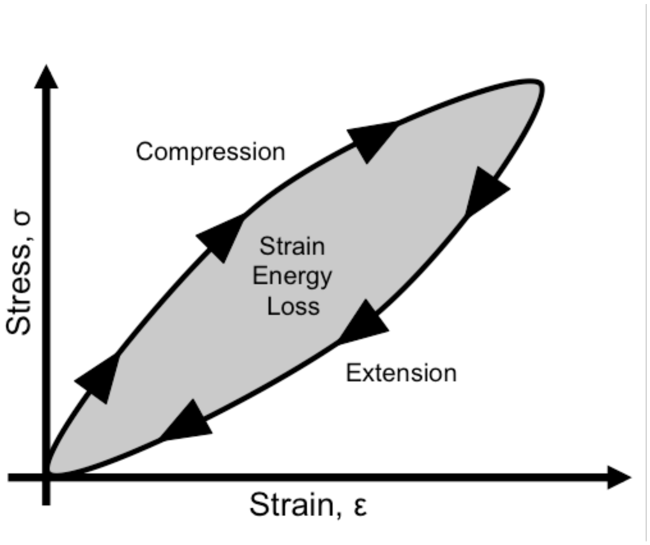


Figure 2. Rubber (viscoelastic) stress-strain hysteresis.

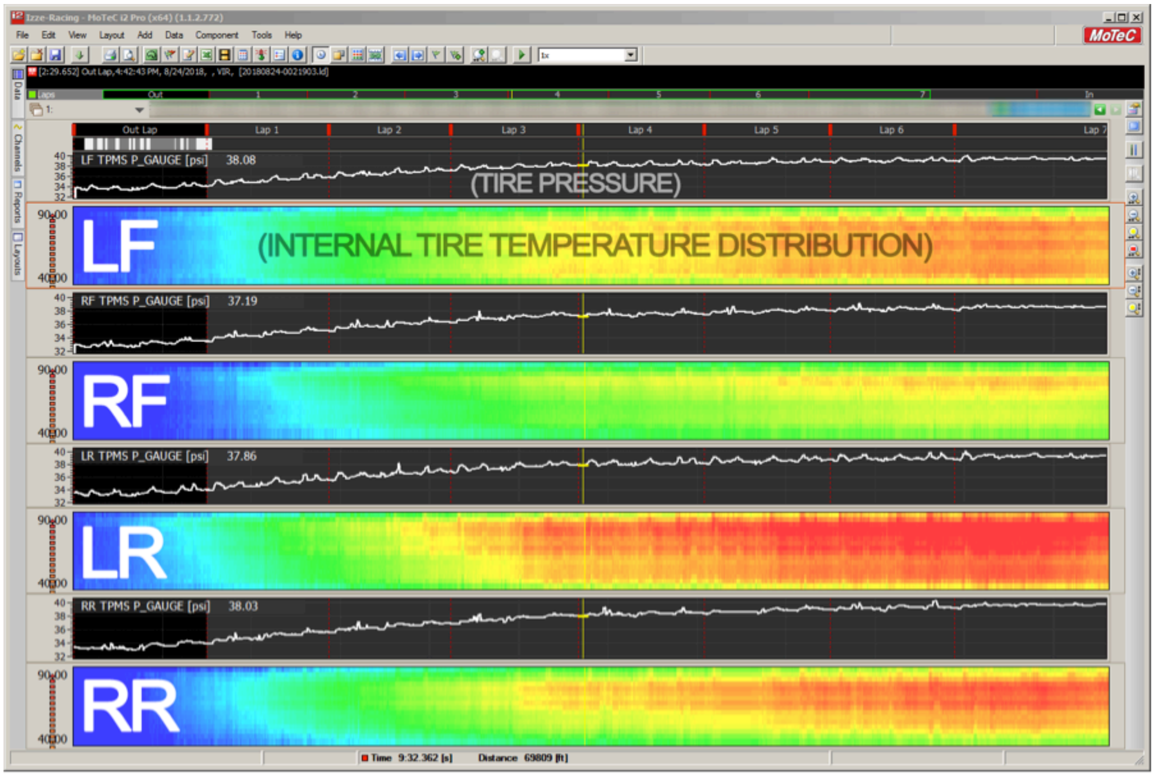


Figure 3. Race tire’s inner core tire temperature distribution.

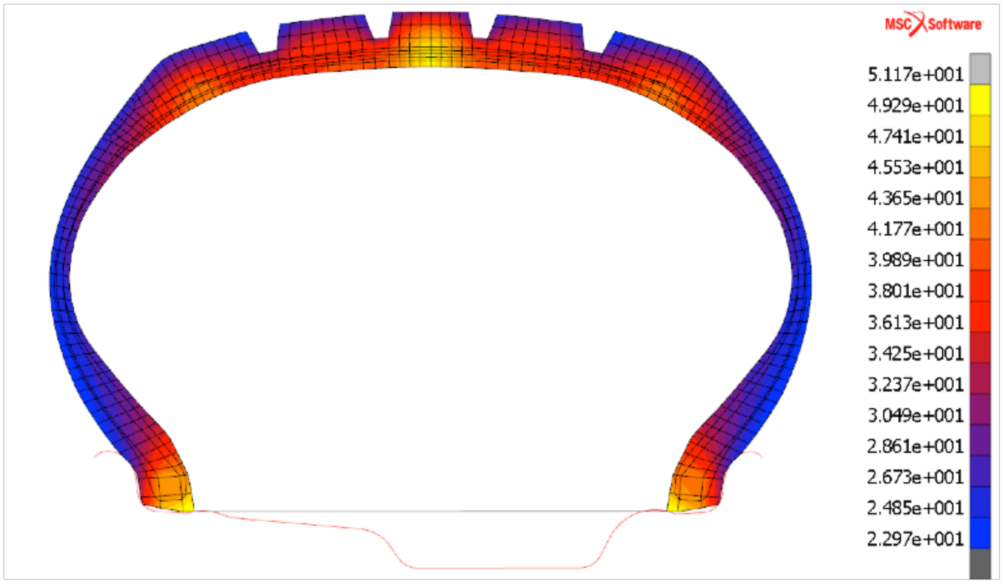


Figure 4. Representative cross-sectional tire temperature distribution [1].

B. Heat Transfer (boundary conditions)

The dominant modes of heat exchange to and from a tire are:

1.) Convective heat loss to surrounding air
2.) Conductive heat loss to road
3.) Conductive heat transfer from wheel
4.) Radiative heat loss

The majority of a race tire’s heat is lost at the tire-road and tire-air (external) interfaces. Assuming the tire is hotter than the ambient, heat is lost at the tire-road interface from conduction into the ground, and at the tire-air interface from forced convection with the ambient air. Heat losses from radiation are only significant for temperatures > 100°C and are often ignored. However, heat to and from the tire can also be managed at the wheel-tire interface; brakes feed temperature into the wheels & tires but wheels can also be used to cool & thermally manage the tire.

Given the significant heat losses at the tire-road interface and transient heat generation at the surface (surface heat generation is highly dependent on slip ratio, slip angle, and load), a race tire’s surface temperature fluctuates rapidly with dynamic loading. Conversely, the inner liner is well insulated provided the heat transfer is via natural convection, versus forced convection and conduction for the outer surface. As a result, the quasi steady state core and inner liner temperature will typically be higher than the average surface temperature and change at a much slower rate. The difference between surface and core temperature, and the infrared sensors used to acquire this data, is shown in Figure 5, showing both the outer and inner (core) temperature distributions of a race tire.

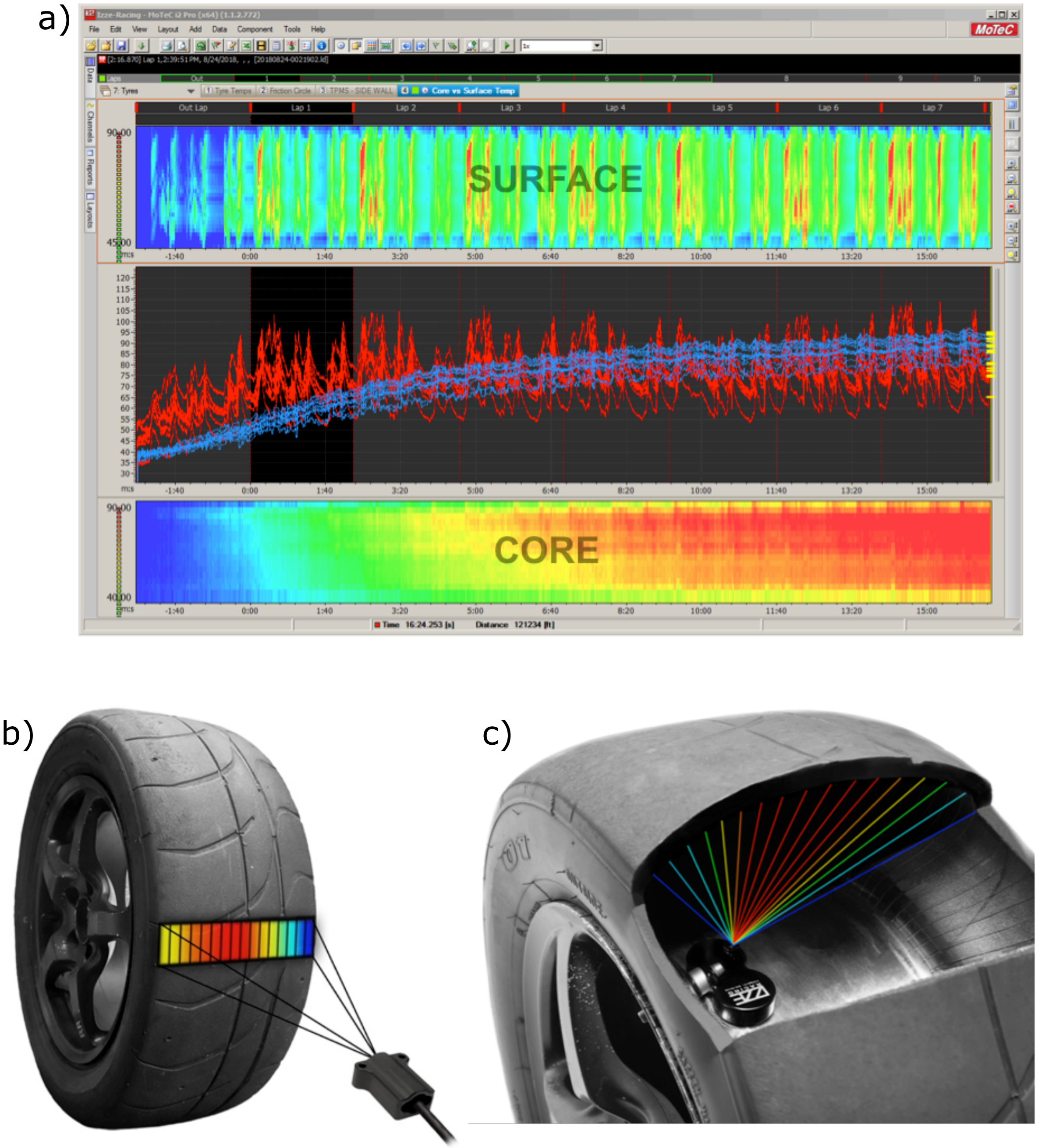


Figure 5. a) Infrared tire temperature at multiple lateral points across the width of the outside surface (top contour, red traces) and inner core (bottom contour, blue traces).
b) Izze-Racing 16-ch IR temperature sensor for tire surface
c) Izze-Racing 16-ch IR temperature & pressure sensor for tire core

II. Tire Grip: The Two Key Mechanisms

A tire's grip is generated by two key mechanisms at the contact patch: indentation and molecular adhesion. Both mechanisms are significantly temperature dependent.

A. Indentation

The indentation mechanism is from the physical indentation of road roughness topology into the tire's tread, as illustrated in Figure 6. As shown, the rubber goes through a compression-relaxation cycle as it slides across the road's surface. Compression occurs at the leading edge of the localized roughness peaks and then relaxes as the tread slides over the crest, but because of the rubbers hysteresis it does not immediately return to it's previous non-perturbed height. This asymmetrical deformation creates a force vector with an x-component (yellow) that opposes slippage and *increases in magnitude with increasing hysteresis*.

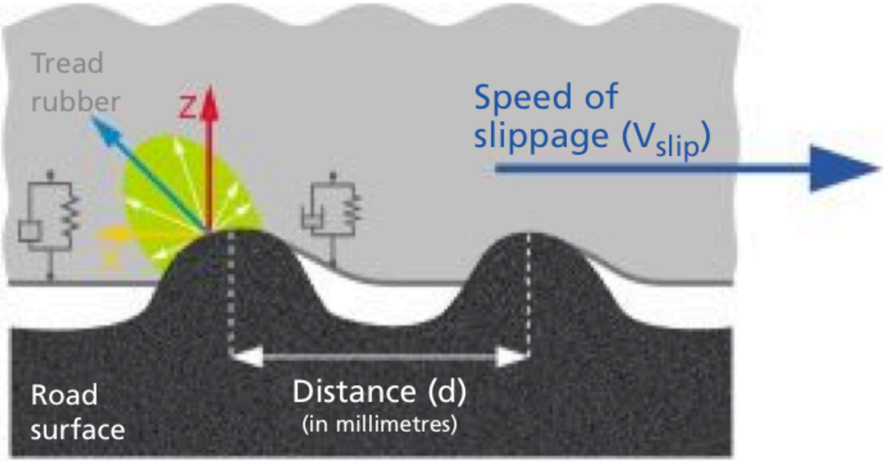


Figure 6. Indentation mechanism of grip generation at road-tire interface [2].

Accordingly, a tire's flexibility (modulus) and hysteresis are key mechanisms responsible for grip generation and is why tires – race compounds especially – are designed to operate within a narrow temperature window, Figure 7, where hysteresis & flexibility are simultaneously maximized. If a race compound is too cool, there's little hysteresis & flexibility, too hot, then hysteresis tapers off and the compound tears itself apart (blistering, accelerated rate of graining, etc.). For example, during a formation lap, heavy weaving, braking, and acceleration generate internal bulk heat from the large variations in tire load (i.e., strain energy loss from repetitive compression and relaxation cycles), whereas burnouts just before the starting grid generate surface temperature. The goal is to have the tires within their optimal window for indentation & molecular adhesion when the lights go out, which can be a window as narrow as 5°C. It should be clear that hysteresis is not just a surface phenomena but rather dependent on both the surface and core temperature-dependent properties; hence the importance of measuring both internal and external temperature distributions.

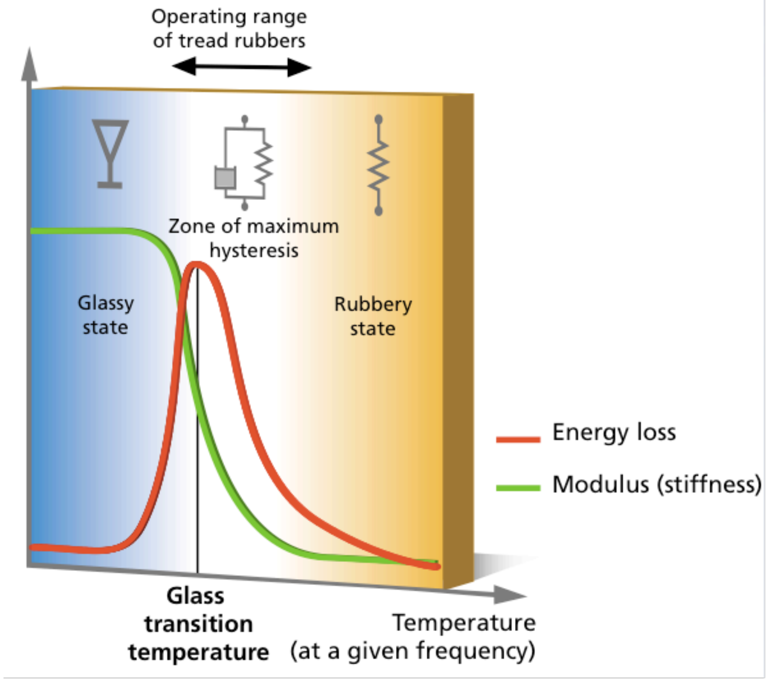


Figure 7. Hysteresis and modulus of tire rubber vs. temperature, with zone of maximum hysteresis near the glass transition temperature [2].

Grip generation from indentation is also dependent on the frequency of excitation, Figure 8, defined by the ratio of slip velocity to the macro surface roughness wavelength. Teams and tire manufactures will often scan a track's surface at specific locations to quantify a representative range of macro and micro surface roughness values and it's effect on grip (indentation, molecular adhesion), tire wear, and the optimal line.

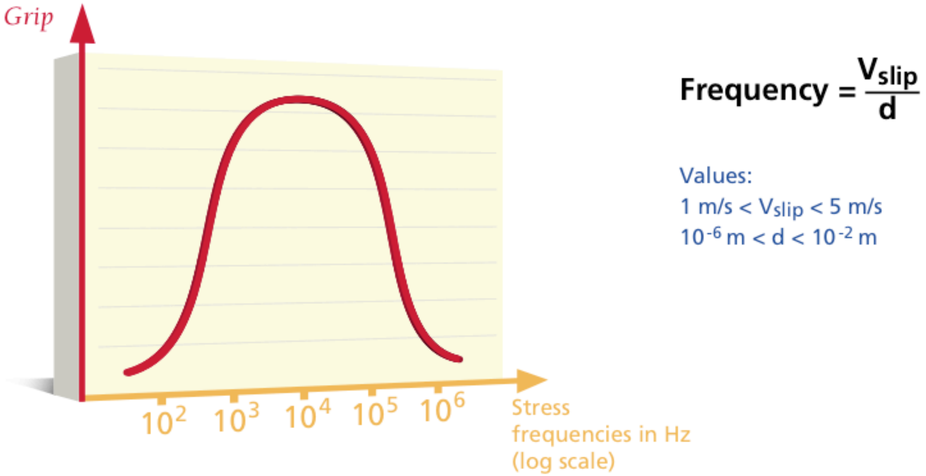


Figure 8. Influence of stress frequency on indentation grip mechanism, where Frequency = V_{slip} / d, d = macro surface roughness wavelength [2].

As previously shown in Figure 3 & 5, a tire’s core temperature builds with time from the hysteresis heat generation within the compound, the rate of which increases with speed (stress frequency) and load. However, core heat generation is also heavily dependent on tread thickness & wear because the *volume of heat generation and thermal mass decreases with decreasing tread thickness*. As shown in Figure 9, a tire’s core temperature decreases substantially with decreasing tread thickness. This temperature shift with wear can bring the tire out of its optimal temperature window (e.g., zone of maximum hysteresis) and partially explains the drop off in grip with stint duration. A less obvious effect is the influence of tread thickness on the indentation mechanism from the reduction in the diffusion of localized stress from surface roughness topology. As shown in Figure 10, a reduction in thickness cuts off the localized stress distribution from the road roughness, which reduces total hysteresis and, therefore, grip contributed by the indentation mechanism. The combined influence of temperature and tread wear on the indentation and molecular adhesion is shown in Figure 11, which estimates a 10% reduction in longitudinal and lateral grip from full to 1/3 tread thickness for this particular tire & conditions.

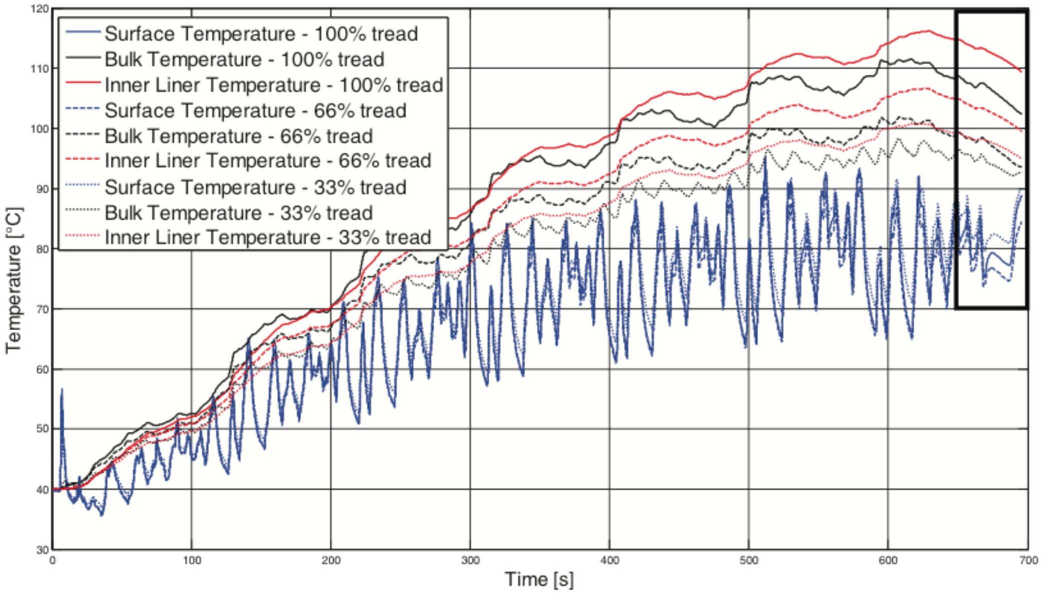


Figure 9. Surface, core, and inner liner tire temperature history for three different (100, 66, and 33%) tread thicknesses [3].

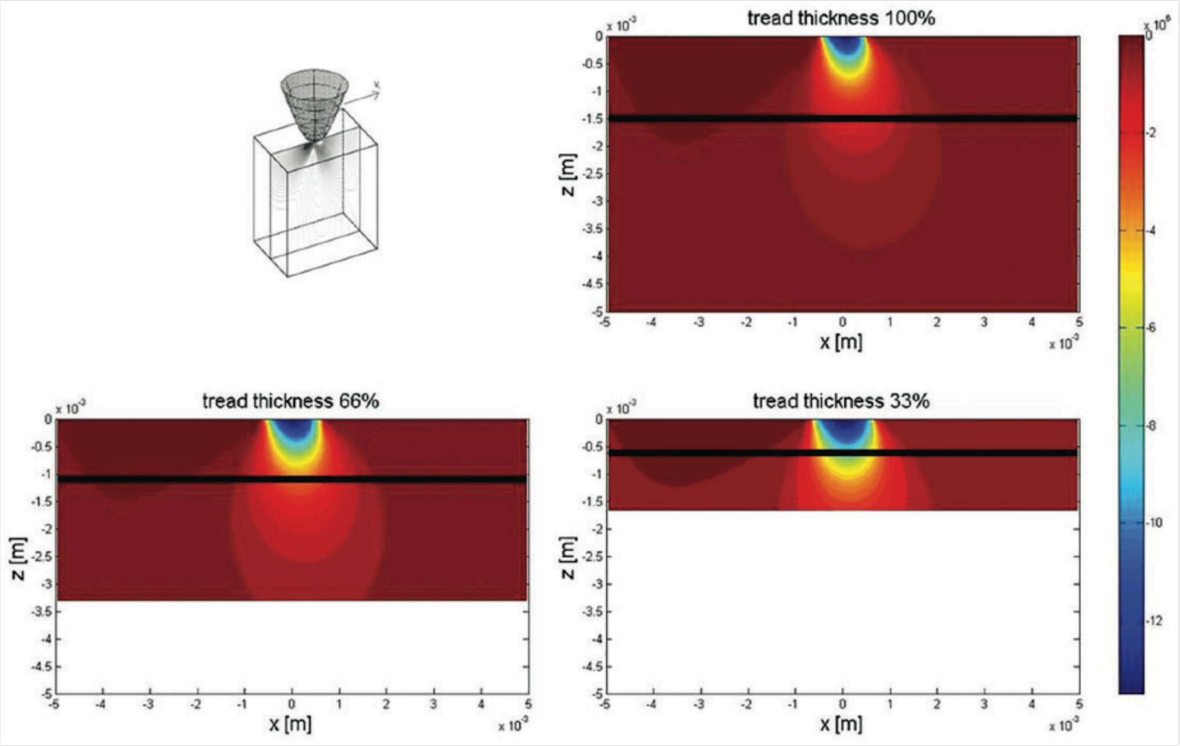


Figure 10. Simulated cross-sectional stress distribution of tire's tread for three different tread thicknesses for a single road indenter [3].

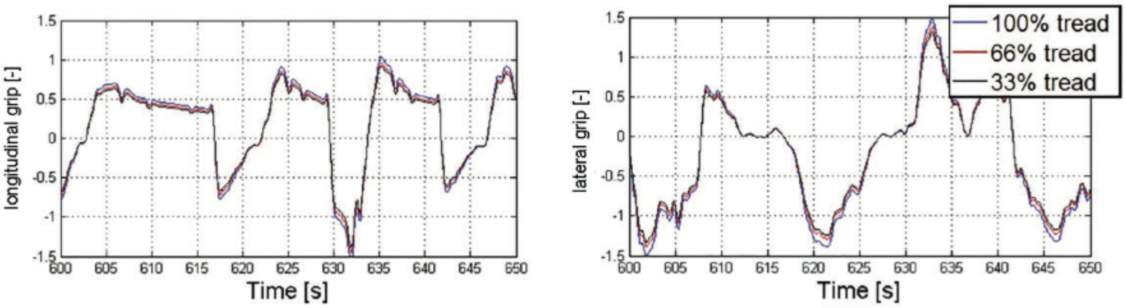
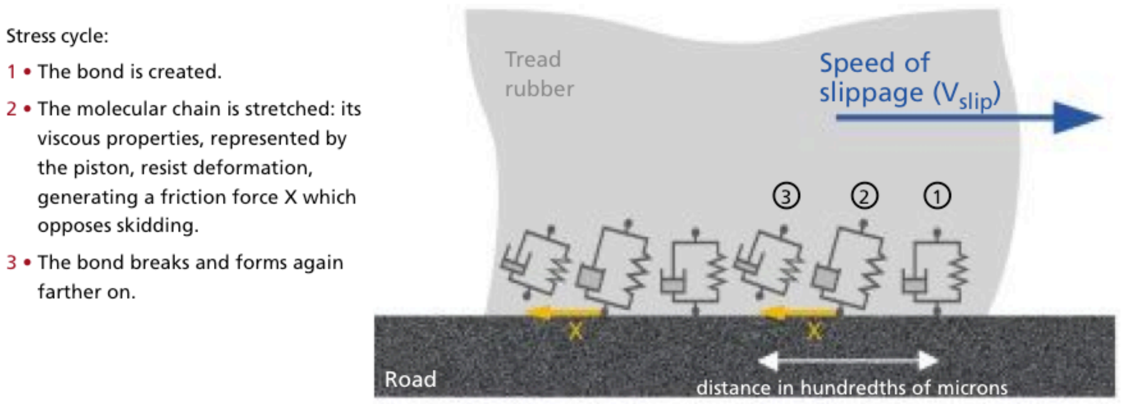


Figure 11. Simulated combined influence of temperature and tread wear on longitudinal and lateral grip [3].

B. Molecular Adhesion

Molecular adhesion is from the Van der Waals bonding at the rubber-road interface (greatly reduced in the wet); the process is illustrated in Figure 12. Bonds are continuously created at the tire-road interface, stretched (creating visco-elastic heat from friction between molecular chains), and broken. This bonding energy is multiplied by two to three orders of magnitude depending on the surface temperature and speed of slippage, as demonstrated in Figure 13. Hence, surface temperature is an important variable for maximizing molecular adhesion, as each tire compound will have an optimal temperature window.



Stress cycle:

1 • The bond is created.

2 • The molecular chain is stretched: its viscous properties, represented by the piston, resist deformation, generating a friction force X which opposes skidding.

3 • The bond breaks and forms again farther on.

Figure 12. Molecular adhesion mechanism of grip generation at road-tire interface [2].

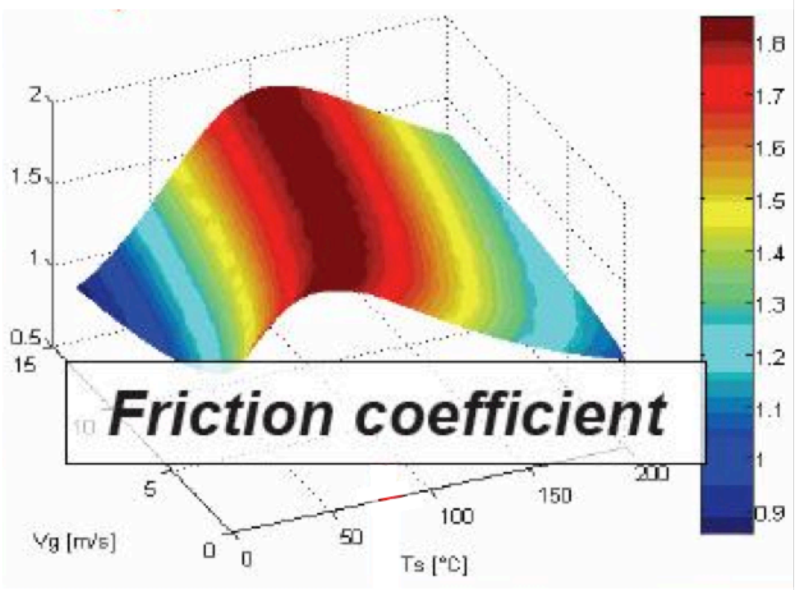


Figure 13. Molecular adhesion friction coefficient (z-axis) as a function of slip velocity (y-axis), and surface temperature (x-axis) [2].

The total contributed grip from molecular adhesion is proportional to the *effective* rubber-road surface area for adhesion, which increases with increasing pressure and decreasing modulus of elasticity (stiffness). As is the case with indentation, molecular adhesion is frequency dependent, Figure 14, where frequency is equal to the number of stress cycles per second.

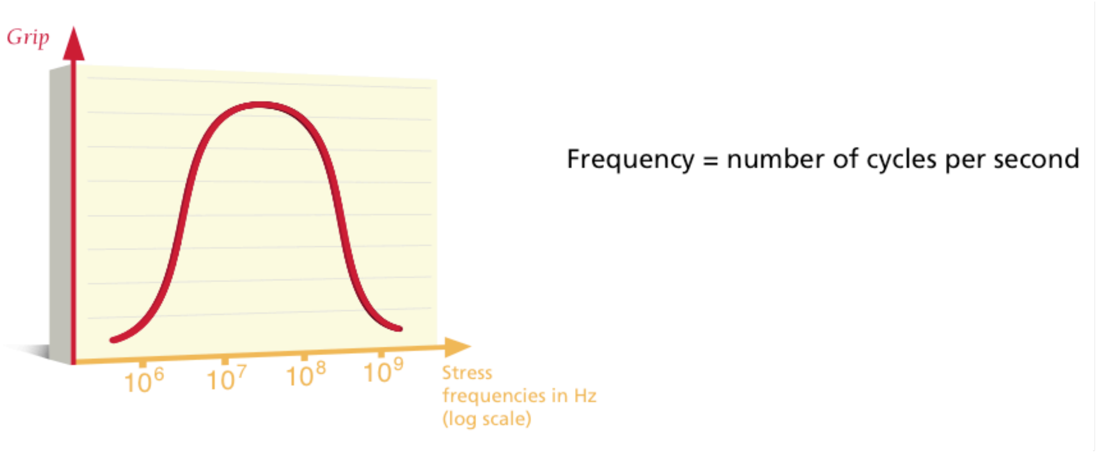


Figure 14. Influence of stress frequency on molecular adhesion grip mechanism, where Frequency = number of stress cycles per second [2].

Because surface temperature is generated from slip at the interface and quickly dissipated by convection, conduction, and diffusion, surface temperature is highly transient and therefore an excellent indicator of *dynamic loading*. Most importantly, a tire's surface temperature represents the dynamic lateral load distribution, Figure 15 & 16, i.e., contact patch size and shape, because of the slip-generated heat at the tire-road interface from molecular adhesion. This information is collected on-track using multichannel infrared temperature sensors and used to tune the chassis such that it optimizes the contact patch size, uniformity, and amount of slip. Other surface temperature tuning uses include: tire pressure, camber, toe, damper rates, spring rates, balance, temperature window of operation, and brake bias.

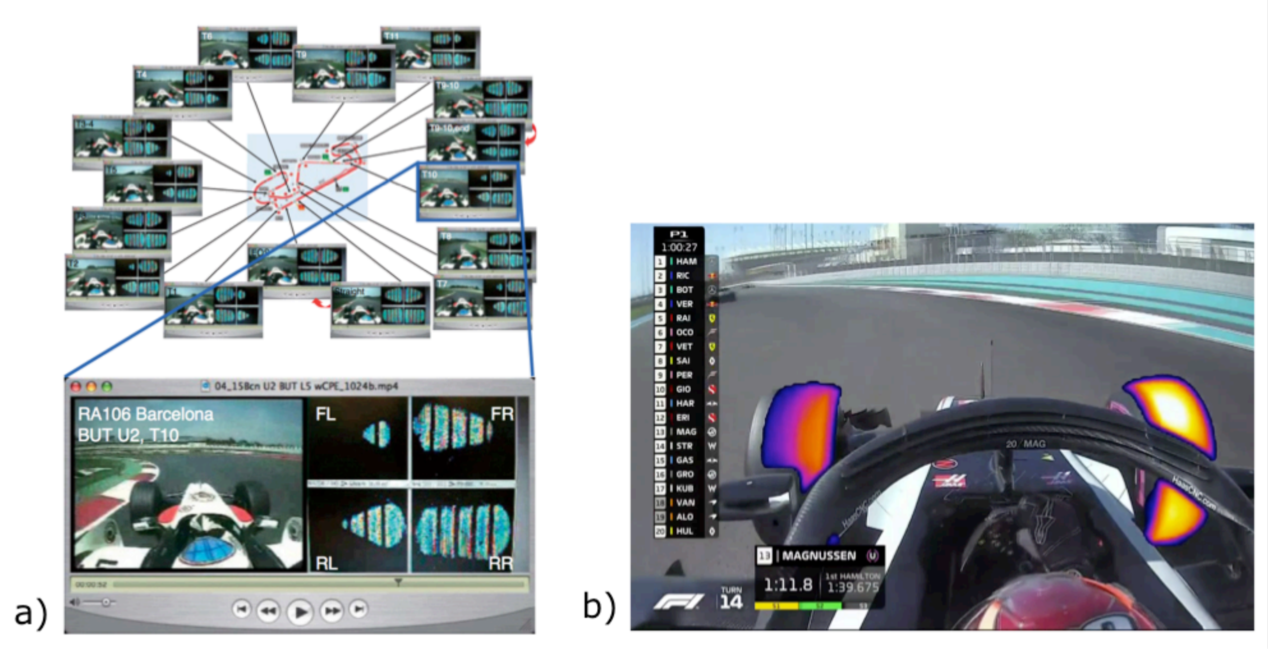


Figure 15. a) Dynamic contact patch simulation from Honda F1 shaker [4], and b) representative contact patch size from on-track lateral tire temperature distribution [5].

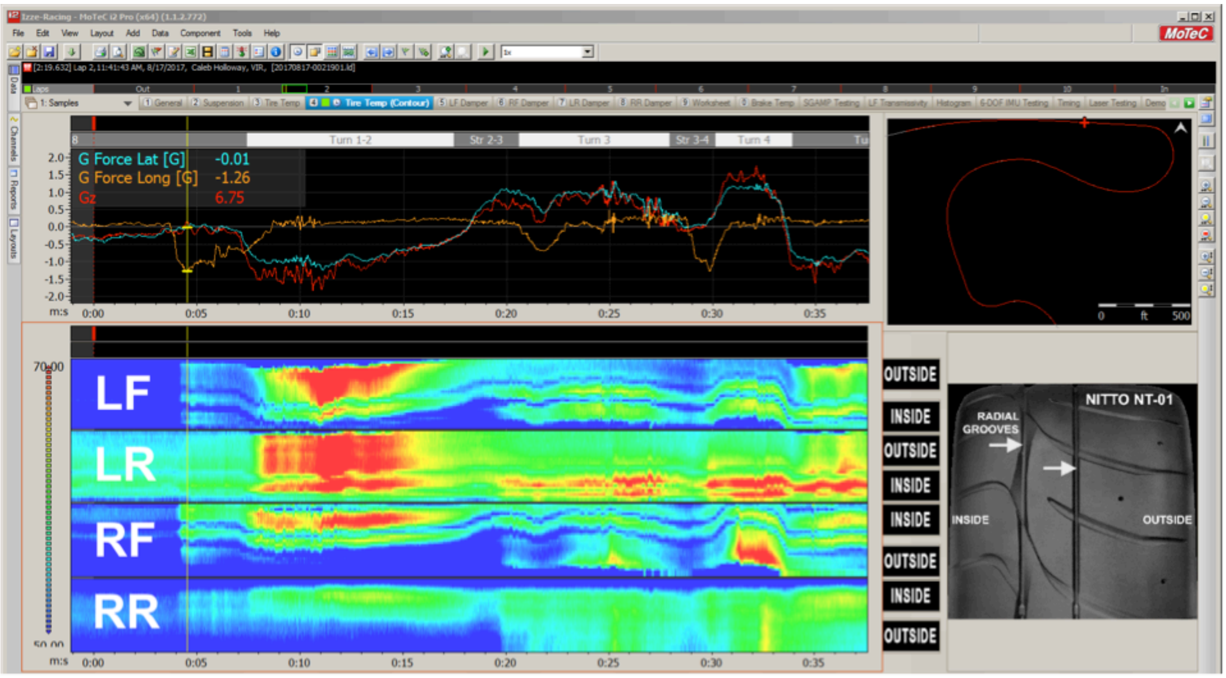


Figure 16. Tire surface temperature at VIR.

In conclusion, temperature has a significant influence on the efficiency of the two key mechanisms responsible for producing tire grip: molecular adhesion and indentation. The effectiveness of molecular adhesion is largely influenced by surface temperature whereas the effectiveness of indentation is strongly dependent on core and, to a lesser degree, surface temperature. Both mechanisms are optimized within a specific core & surface temperature range – of which any reputable motorsport tire manufacture can provide – and can be monitored in real-time using infrared temperature sensors.

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