

An Adaptive Tire Model for Enhanced Vehicle Control Systems

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ABSTRACT

Tread depth, inflation pressure, tire temperature, and road surface condition are among the most notable factors that have a noticeable effect on the tire force and moment characteristics. They can vary significantly during the operation of a tire and can effectively modify tire (and thus vehicle) performance. This study presents details of an adaptive magic formula (MF) tire model capable of coping with changes to the tire operating condition. More specifically, extensions have been made to the magic formula expressions for tire cornering stiffness and peak grip level, to account for variations in the tire inflation pressure, load, tread-depth and temperature. As a next step, the benefits of using an adaptive tire model for vehicle control system applications is demonstrated through simulation studies for enhanced vehicle control systems using an adaptive tire model in comparison to traditional control systems based on a non-adaptive tire model with fixed model parameters. In particular, this paper investigates the improvements an adaptive tire model would bring into the following vehicle control system strategies: Electronic Stability Control (ESC) system, Brake Torque Vectoring (BTV) system, and Rear Wheel Steer (RWS) system.

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INTRODUCTION

Vehicle dynamic performance is predominantly controlled by tire dynamic characteristics through the forces and moments generated at the tire-road contact patch. Tire forces are a combination of two factors: elastic tread block deformation and sliding in the contact patch. These primary forces affecting planar vehicle motions are constrained based on the friction ellipse, as shown in Figure 1, where the tire is always subjected to a combination of cornering and braking forces. The control of the tire lateral forces benefits vehicle stability and handling characteristics. Thus, tire saturation constraints must be taken into account for a proper control system design, as this provides an indication of the maximum force that can be generated by the tire. For those control systems based on the simplified linear vehicle model, which ignores the nonlinear characteristic of the tire, the robustness subject to parameter uncertainties during vehicle driving cannot be guaranteed. Hence, the ability to reliably estimate tire forces is mainly control oriented and is pivotal for implementing and maximizing the performance of vehicle control systems, which work well only when the tire force command computed by the safety systems is within the friction limit.

Electronic stability control (ESC) systems used in current production vehicles use feedback control to track a reference yaw rate using individual braking via direct yaw control (DYC), and/or an active front steering (AFS)/active rear steering (ARS) system.

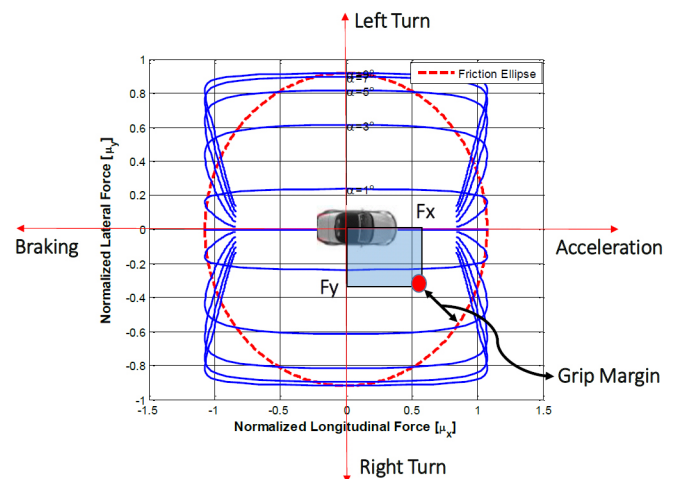


Figure 1. Tire friction ellipse

The ESC system is activated when the deviation between the reference and actual measured yaw-rate is larger than a preset dead-band. The reference yaw-rate is calculated based on a vehicle model using vehicle speed and steering wheel angle signal as inputs. The desired yaw-rate is calculated for tracking the driver's intention. The reference vehicle model in the control system is based on tire characteristics (the front and rear cornering stiffness). Hence, the cornering stiffness of the tire is an important parameter for the

controller. However, it fluctuates under varying road conditions, or under varying operating conditions of the tire, which affects the accuracy of the vehicle stability control. For example, inflation pressure increases as the contained air temperature increases with tire use. This pressure “build-up” necessarily changes tire force and moment characteristics and must be accounted for when selecting initial or “cold” inflation pressures. Tire tread depth is known to significantly change the tire cornering and braking capabilities. As the temperature changes, the modulus of elasticity will change to influence the stiffness and the coefficient of friction of the tire. For these reasons it is highly desirable to have inflation pressure, tread depth, tire temperature, and road surface condition as an input to a tire model along with the traditional operating condition inputs (normal load, slip state, camber angle, vehicle speed, etc.).

Thus, in order to account for vehicle behavior in changing operating and environmental conditions (changing tire operating and road surface conditions) a further step is required, that of adapting the tire model to changing inflation pressure, temperature, tread depth, and road surface conditions. The availability of a high fidelity tire model would facilitate the online computation of the optimized active longitudinal and lateral tire forces to achieve vehicle stability and safety without degrading driver intentions. This paper is the first step in addressing the technical challenges associated with adapting the Pacejka magic formula tire model [1] to tire inflation pressure, temperature, and tread depth simultaneously. The rationale behind the selection of temperature, inflation pressure and tread depth being the availability of these signals from tire attached sensor systems in the near future.

The purpose of this paper can be divided into two parts. The first part describes how tire temperature, inflation pressure and tread depth affect tire performance in terms of lateral force. The second part describes the modeling activities to account for such effects followed by the discussion of simulation results of a reference model-adaptive vehicle stability control to quantify the performance benefits over a controller utilizing a fixed reference model.

QUANTIFYING THE INFLUENCE OF VARIATIONS IN THE TIRE INFLATION PRESSURE, TREAD DEPTH, LOAD AND TEMPERATURE ON THE STEADY STATE LATERAL TIRE FORCE CHARACTERISTICS

In its simplest formulation, a typical tire model [1] describes the relationship between the tire force and the slip as a function of two parameters, namely, cornering stiffness and the peak friction force/grip coefficient [Figure 2], and hence these two parameters were selected as the parameters of interest for this study.

Cornering stiffness was calculated by linear regression between -1 and 1 degree slip angle. The Theil-Sen estimator, also known as Sen's slope estimator is used to achieve robust linear regression. This estimator chooses the median slope among all lines through pairs of two-dimensional sample points, thus providing more accurate results

than a simple linear regression method. The remaining Pacejka coefficients were calculated from Pacejka fitting, using a bounded nonlinear least squares fitting algorithm.

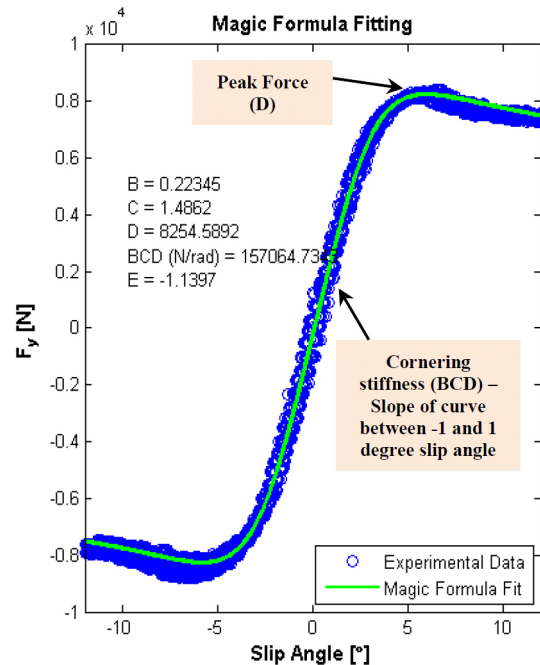


Figure 2. Tire parameters of interest

With the objective of quantifying the influence of variations in the tire inflation pressure, tread depth, normal load, and temperature on the tire cornering stiffness and the peak friction force/grip coefficient, experiments were conducted on the Flat-Trac® machine [Figure 3].



Figure 3. Flat-Trac® machine

The sensitivity study was conducted for a high performance summer tire. In addition to this, the influence of different constructions such as summer and all-season tires were also analyzed as vehicles in European countries typically have different tires mounted based on the season (summer or winter), mainly due to government mandated requirements. In the first round of tests, the influence of temperature was eliminated by keeping the slip angle sweep rate and the speed constant [Table 1].

Table 1. Variable dependency chart

	Tire Surface Temperature	Tire Bulk Temperature	Inflation Pressure	Normal Load	Speed	Tread Depth
Cornering Stiffness	X	X	✓	✓	X	✓
Peak Grip Coefficient	X	X	✓	✓	X	✓

✓: varied
X: kept constant

To evaluate the influence of the inflation pressure on the tire characteristics, four levels of pressure were analyzed: (a) 33psi, (b) 37psi, (c) 41psi, (d) 45psi.

To evaluate the influence of the tire tread depth on the tire characteristics, three levels of tread depth were analyzed: (a) full tread depth, (b) 60% of full tread depth, (c) 30% of full tread depth.

To evaluate the influence of the tire load on the tire characteristics, five levels of normal load were analyzed: (a) 33% of nominal load, (b) 67% of nominal load, (c) 100% of nominal load, (d) 133% of nominal load, (e) 167% of nominal load.

The following sub-sections present results of the sensitivity analysis study.

Influence of Inflation Pressure

Figure 4 shows the cornering stiffness-inflation pressure dependency curves. The key conclusion reached with regard to the cornering stiffness of a tire is that, an increase in the tire inflation pressure has two counteracting effects:

- A lower cornering stiffness at low vertical loads and a higher cornering stiffness at high vertical loads. These effects are clearly visible in Figure 4. The first effect is caused by the decreasing contact length as a result of the increased vertical stiffness from the increased inflation. A decrease of contact length (smaller surface area) results in a decrease of cornering stiffness. In the range of high vertical loads, this effect may also be present but it is not dominant.
- A lower inflation pressure and consequently a less stiffer carcass results in more rotation of the contact patch, this leads to lower lateral force for the same slip angle, which results in a lower cornering stiffness at high vertical loads. Conversely, a higher inflation pressure and consequently a stiffer carcass results in less rotation of the contact patch. This leads to higher lateral

force for the same slip angle, which results in a higher cornering stiffness at high vertical loads.

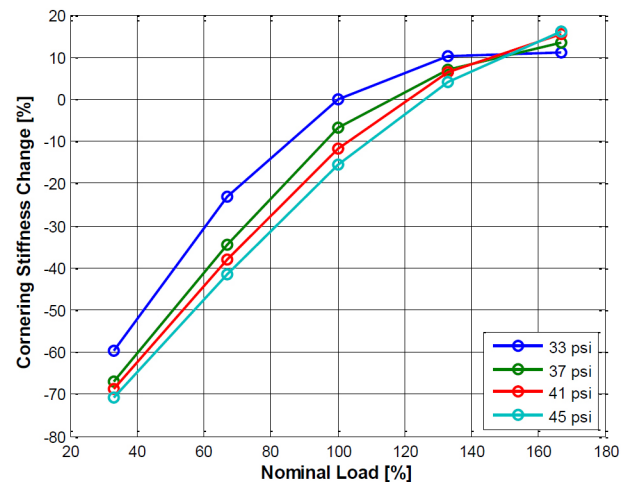


Figure 4. Influence of inflation pressure on cornering stiffness for a tire with full tread depth

Previous studies [2] have shown that the peak grip characteristics do not show a clear general relation with the tire inflation pressure. Certain tires were seen to show a minimum peak grip at low vertical loads that shifts to an optimum at high vertical loads. Other tires show an opposite behavior. Figure 5 shows the peak grip-inflation pressure dependency curves. Clearly, the influence of inflation pressure on the peak grip coefficient value doesn't seem to be very dominant.

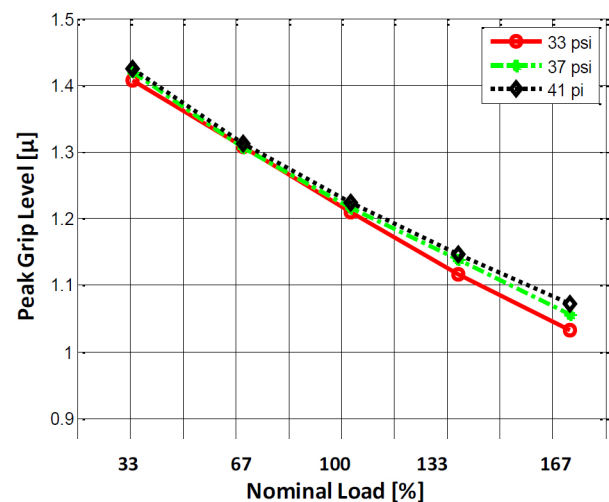


Figure 5. Influence of inflation pressure on the peak grip

Influence of Tread Depth (i.e. Tire Wear State)

In this study, worn tire was created in laboratory conditions through buffing and might not always reflect a worn tire from actual field use. As expected, a change in the tire tread depth significantly influences the cornering stiffness characteristics of the tire [Figure 6].

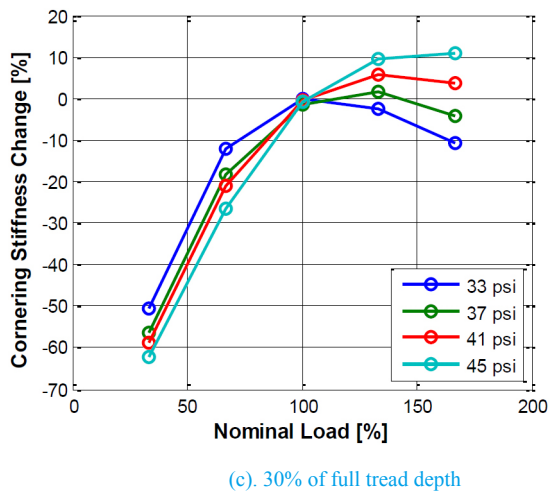
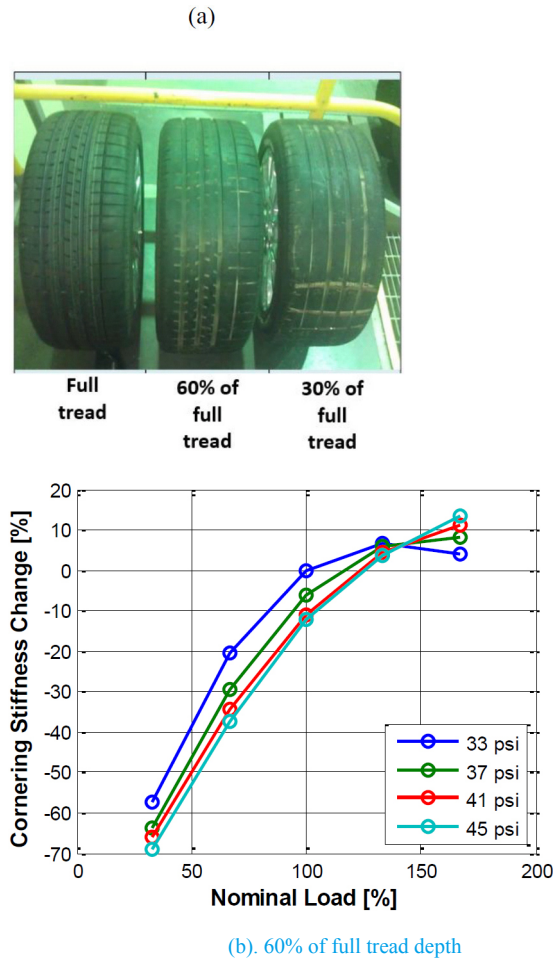


Figure 6. Cornering stiffness v/s inflation pressure - influence of tire tread depth

The key conclusions reached with regard to the tread-depth effects are summarized below.

- Lower tread-depth results in a higher cornering stiffness [Figure 7].
- At higher loads, carcass stiffness is the dominant component of cornering stiffness. Hence, even a large change in the tread depth only results in a smaller change in the cornering stiffness.

- For a tire with a lower tread depth, the cornering stiffness properties are dominated by the carcass stiffness characteristics.
- As explained previously, lowering the tire inflation pressure decreases the carcass stiffness, which explains the saturation trends seen in the CS curve [Figure 8].
- Furthermore, the saturation starts even earlier for a tire with a lower tread depth due to the dominant effect of carcass stiffness.

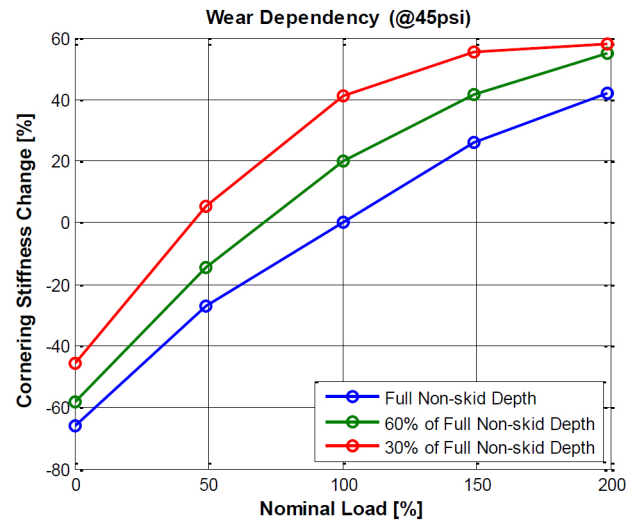


Figure 7. Tread depth dependency effects under constant inflation pressure conditions

Tread depth is seen to have a dominant effect on peak grip coefficient [Figure 9]. This could possibly be attributed to the increase in tread stiffness due to a lower tread depth.

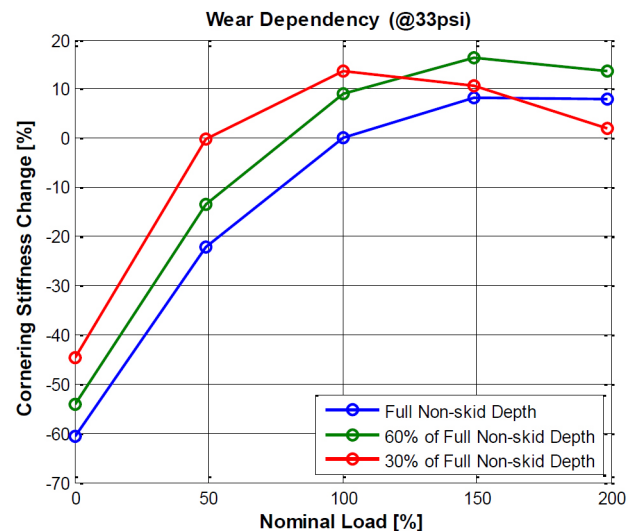


Figure 8. Tread depth dependency effects under constant inflation pressure conditions

Other factors which might influence the peak grip potential of the tire are the net-to-gross ratio of the tire and the localized contact patch pressure, both of which change as a function of the tire tread depth and these additional factors can change the trend for a different construction.

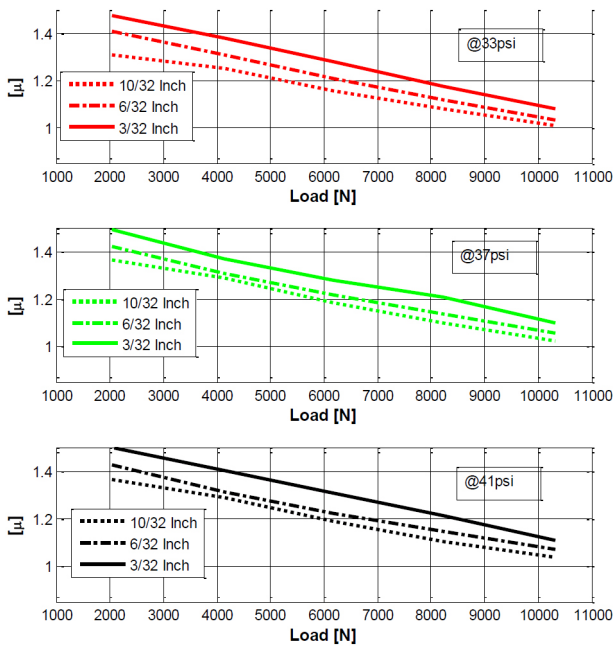


Figure 9. Peak grip (μ) - tread depth dependency at different inflation pressures

Influence of Normal load

There are two load dependent parameters affecting the tire cornering stiffness. The first load dependent parameter is the tire contact patch length (L). Typically patch length changes with tire load in an order between 1 and 2. The second load dependent parameter is the lateral elastic stiffness, which in turn is due to both the rubber tread elasticity and tire structure lateral compliance.

A final observation stemming from the results in Figure 10 is that the peak grip level decreases with an increase in the tire load. The load dependence of the grip level includes the effect of the rubber modulus. A secondary source of load dependence can be the friction induced thermal heating in the contact area leading to a reduction in the peak grip level with increasing load [Figure 11].

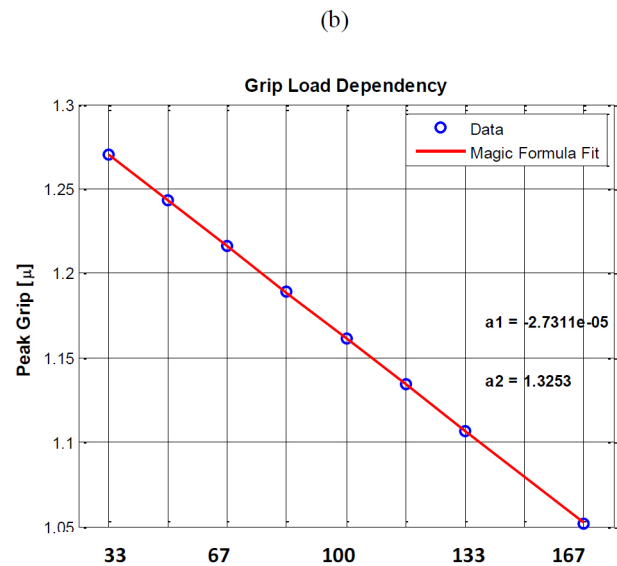
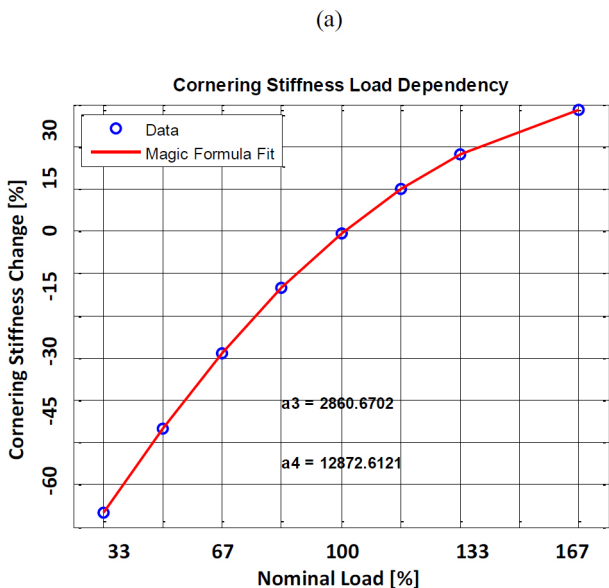


Figure 10. Influence of normal load on: (a) the tire cornering stiffness, (b) peak grip level. Magic formula parameters, 'a1', 'a2', 'a3' and 'a4' were calculated using the nonlinear least-squares (NLLS) curve fitting algorithm

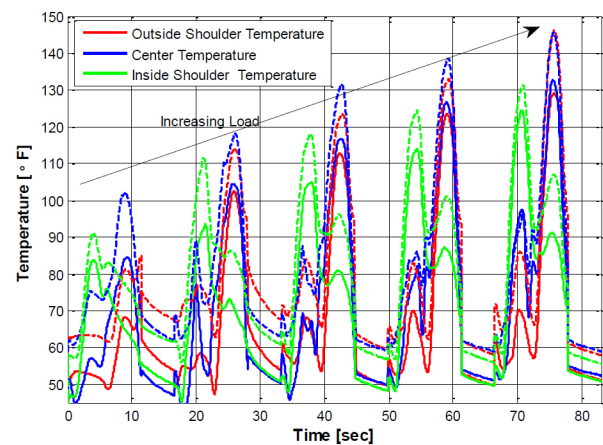


Figure 11. Load sensitivity: tire surface temperature during a load sweep test

This load dependence is not due to an intrinsic pressure dependence of the rubber friction coefficient, but a kinetic effect related to the buildup of the flash temperature [3] in rubber-road asperity contact regions during slip.

Influence of Temperature

A second set of tests were run on the Flat-Trac® machine to include the influence of temperature. The procedure consisted of running the test on new tires without a warm-up or break-in procedure. The tires were tested through 23 slip sweeps at one load and one camber condition. IR pyrometers were installed on Flat-Trac® machine allowing tire surface temperatures to be recorded throughout each test [Figure 12].

The IR pyrometers give the machine the capability to record tire shoulder and centerline surface temperatures. Tire core/bulk temperature measurements were also made in this study using a wheel mounted infrared sensor measuring the tire inner-liner/ carcass temperature. Figure 13 shows the cornering stiffness and peak grip temperature dependency curves

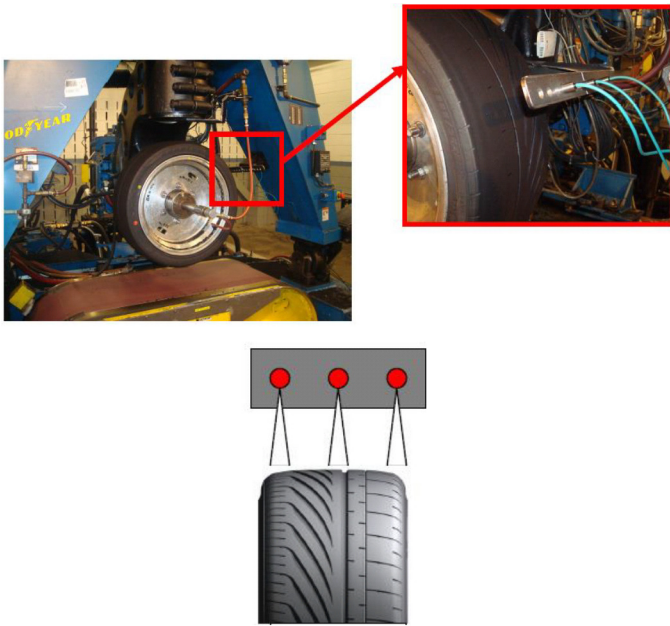
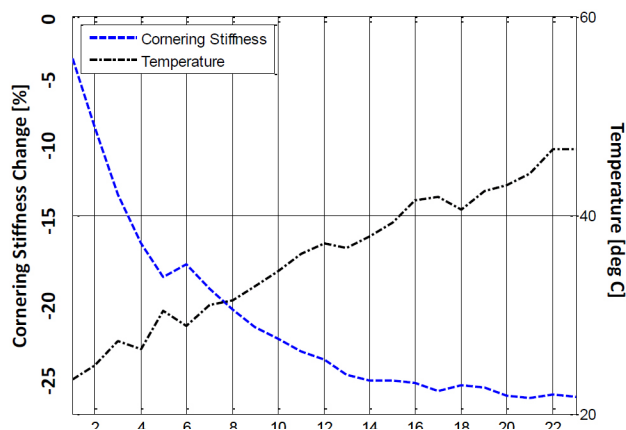


Figure 12. Tire temperature apparatus installed on the Flat-Trac® test machine

(a)



(b)

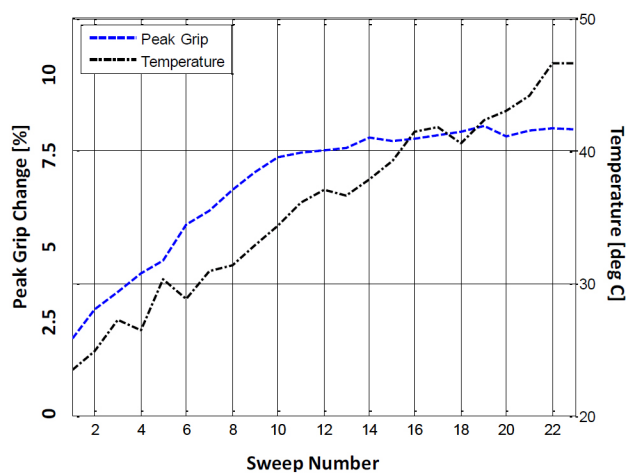


Figure 13. Influence of temperature on: (a) the tire cornering stiffness, (b) peak grip level

The influence of temperature can be mainly attributed to two main visco-elastic properties of rubber, which change with temperature; (1) the storage modulus or tread rigidity, which influences cornering stiffness. This mainly changes due to the bulk (core) temperature of the tire, (2) the coefficient of friction decides the peak lateral grip of the tire. This parameter is only influenced by the surface temperature of the tire at the road interface. Typically, the interaction forces reach their maximum values only within a narrow temperature range, while decay significantly outside of it.

Table 2 presents a summary of the sensitivity analysis, determining the influence of variations in the tire inflation pressure, tread depth, normal load, and temperature on the tire cornering stiffness and the peak grip potential.

Table 2. Summary of dependencies

	Tire Surface Temp	Tire Bulk/Core Temp	Inflation Pressure	Tread Depth	Normal Load
Cornering Stiffness (CS)	Low Dependency	High Dependency	High Dependency	High Dependency	High Dependency
Peak Grip Level (μ)	High Dependency	Low Dependency	Low Dependency	High Dependency	High Dependency

A quantifiable measure of the influence of the tire operating conditions on the cornering stiffness and the peak grip level is summarized in Table 3.

Table 3. Sensitivity analysis- summary

Tire Type		Factors Influencing Tire Characteristics		
		Pressure	Tread Depth	Temperature
Summer Tire	Cornering Stiffness	10% decrease with a 20% increase in inflation pressure	25% increase with a 60% decrease in tread depth	20-25% drop in cornering stiffness from cold to hot tire conditions
	Peak Grip	Influence doesn't seem to be very dominant	10% increase grip with a 60% decrease in	8-10 % change in grip level from cold to hot tire conditions