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Tire and Brake Interaction – A New Test Rig to Study Wheel Locking

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Abstract

The paper investigates the dynamics of the tire and brake during hard braking or wheel locking, from the view point of a brake manufacturer. A new test rig, named BRAD (BRembo Automotive Dynamometer) is presented which measures the forces acting both at the brake and at the tire-ground interface. Lateral forces are not measured. In the test rig, the ground is represented by a drum. The features of the test rig are presented. The measurement accuracy is declared. The first result is that, near wheel locking, a substantial part of the braking power is generated by the tire and not by the brake. The test rig quantifies such a partitioning of brake power, which is important for current and future electric motorsport activities. Some 30% of the braking power is due to tire during hard braking. The second result is that, due to such important braking power at the tire, the tire is heated up, which increases considerably the maximum friction. This implies that brakes interact with tires near wheel locking. The new test rig enables to study such an interaction.

Introduction

For the design of vehicle brake system, we need to study not only the brake, but specifically the brake and the tire. This implies the accurate measurement of forces and moments applied both at the brake and at the wheel (tire). This is a relatively complex and never attempted task, according to the knowledge of the Authors.

The focus of the research is the interaction of brake and tire at high longitudinal slip. Precisely, we study primarily the *actual brake (calliper, pads and so on) and the actual tire* that work together. Lateral force at the tire contact patch is not measured.
The normal dynos used for brake development could not be used. We had to use an actual suspension system to reproduce indoor the brake and tire interaction at high longitudinal slip. The problem was to measure the relevant acting forces (both external and internal) in a setup which is very close to an actual application, namely a suspension system. This requirement was the main challenge of the research.

At the Politecnico di Milano, a new test rig has been developed for monitoring all of the relevant forces and moments that act during braking, both at the brake and at the wheel.

The history of laboratory and on-road force-and-moment tire testing was not mentioned because the connection with the topic of the paper is relatively loose.

In the literature, a number of dynamometers (‘dynos’) have been presented to study either brake performance or tire-ground interaction [1-22]. A limited number of dynos have been conceived for studying the ultimate brake force that the brake may provide to the tire and that the tire may apply to the ground [7,9]. Unfortunately, in [7] the tire-road friction coefficient is replaced by magnetic powder clutch. In [9] the performance of the ABS system was studied without focusing in-depth on the forces acting at the brake and at tire.

In the well-known literature focusing on vehicle dynamics [28-38], the topic of wheel locking is addressed without reference to brake and tire interaction.

In the current and future motorsport activities involving electric vehicles, the actual energy that can be stored into batteries has to be precisely estimated. The BRAD enables studies on the quantification of the energy that may flow back to batteries.

The dynamometer that has been developed (BRAD) can measure all of the relevant forces that act when the wheel is locking during a hard braking maneuver. The scientific presentation of the test rig as a measurement instrument can be found in [39].

The paper is organized as follows. At first the new dynamometer (BRAD) is presented. Then, the power dissipated at the tire, during a braking maneuver, is studied. Finally, the role of tire during hard braking is addressed for further studies.

BRAD test rig

General overview of BRAD

BRAD belongs to the broad class of chassis dynamometers [4]. We focus here on the sub-class of brake dynamometers, which can be divided into two families. The first family is typically composed by a motor, by a rotor with proper inertia, and by a brake. In the second family, a pneumatic wheel, rotating with the brake to be tested, rolls on a drum (with properly calibrated inertia), which is launched at a certain initial speed by a motor. BRAD belongs to the second family of dynamometers.

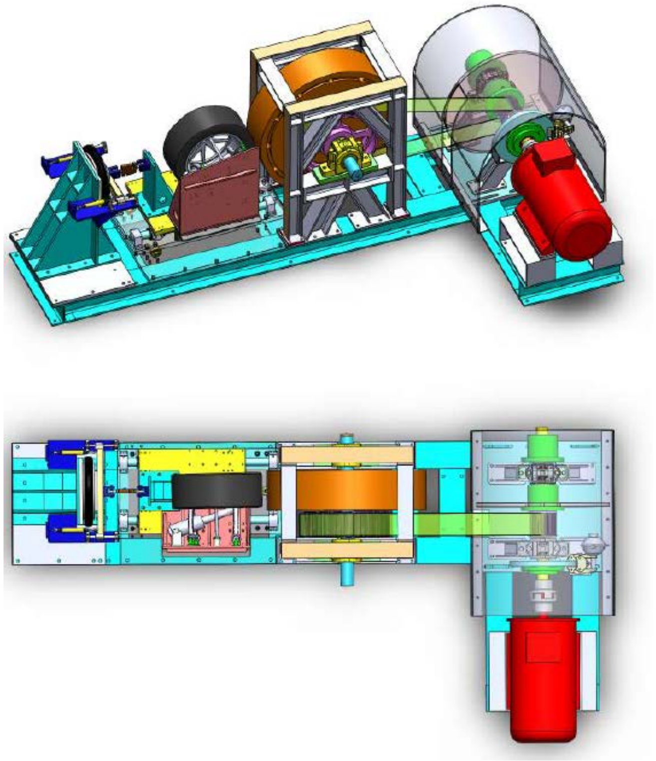

Figure 1. BRAD, Brembo Automotive Dynamometer.

The BRAD is a complex machine. A pneumatic wheel is pressed on the drum and rotates with it. The drum is connected to a system (transmission and flywheels) that mimics the inertia of the vehicle (Figure 1). As the brake is activated, the wheel applies a longitudinal force to the drum that is decelerated until the rest condition is reached.

The wheel is carried by a suspension system (Figure 2, 3). The suspension system is carried by a sledge that mimics the unsprung mass of the vehicle (Figures 1,3). Since the wheel approaches the drum along the horizontal direction, a pneumatic spring applies the force that mimics gravity (Figure 2). The pneumatic spring provides near-constant force, independent of deflection.

Figure 2. BRAD: drum, brake, suspension, and pneumatic spring.

In Figure 3 a CAD rendering of the complete front left suspension system mounted on the sledge is shown. The L-shaped structure (in red) has been designed to avoid high frequency vibrations. It houses the suspension together with its arms. The overall mass of the sliding system is maintained around to 400kg, so that the inertia of a quarter of a vehicle is correctly reproduced.

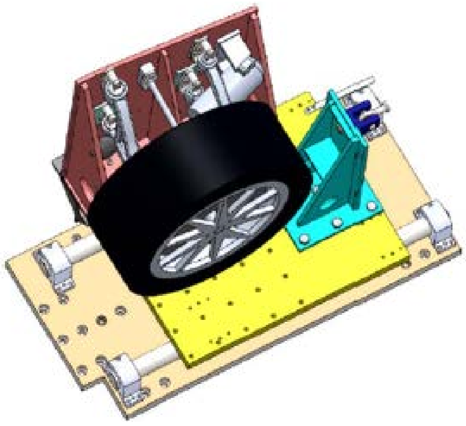

Figure 3. BRAD, detail of sledge and suspension system housing.

The overall apparatus can be divided into five main sub-systems: the drum, the sledge, the transmission and the flywheels, the driving motor and the controller (Figures 1,4).

BRAD concept design

In Figure 4 the scheme of the BRAD is shown. By inspection of Figure 5, the equations of motion of the wheel and of the drum read

$$M_b + J_w d\omega/dt - F_x r + M_{rr} = 0$$
$$F_x R_d + J_d d\Omega/dt + M_l + M_{rr} = 0$$

where the symbols, reported in Figure 5, have the following meaning

F_x longitudinal force
F_z radial force
M_b moment applied to the brake
M_l moment due to dissipation at the drum (e.g. aerodynamics, transmission bearings).
M_{rr} moment due to rolling resistance
J_d moment of inertia of the drum (plus transmission and flywheels)
J_w moment of inertia of the wheel around its axis
ω angular speed of the wheel
Ω angular speed of the drum

M_{rr} refers to the moment due to the offset of the resultant forces coming from the pressure distribution in the wheel-drum contact region (Figure 5). For more details see [39].

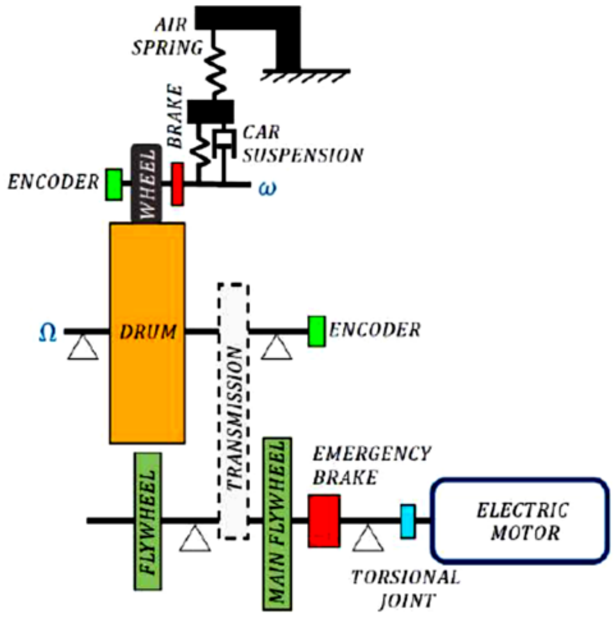

Figure 4. BRAD, test rig architecture.

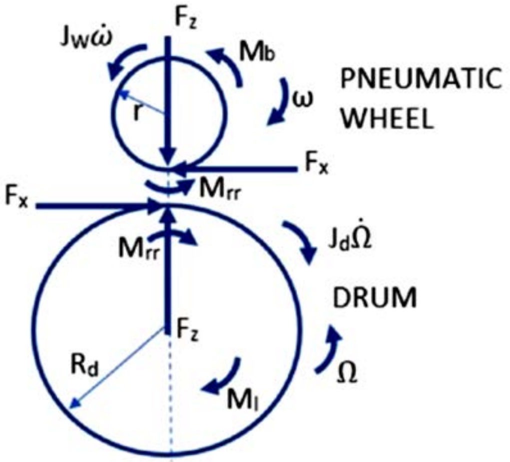

Figure 5. Forces at the wheel-drum interface (adapted from [39]).

The core innovation of the BRAD is the location of load cells that allow the monitoring of all of the relevant forces acting at the brake and at the tire during braking (Figure 6).

Four load cells are placed as shown in Figure 6. One load cell measures the load applied by the pneumatic spring, three load cells are used to measure all the forces and torques that arise during the braking phase. In detail, the main load cell LC_1 is positioned in order to have its axis tangential to the drum surface and to detect directly the force F_x (see Figure 5 or Figure 6).

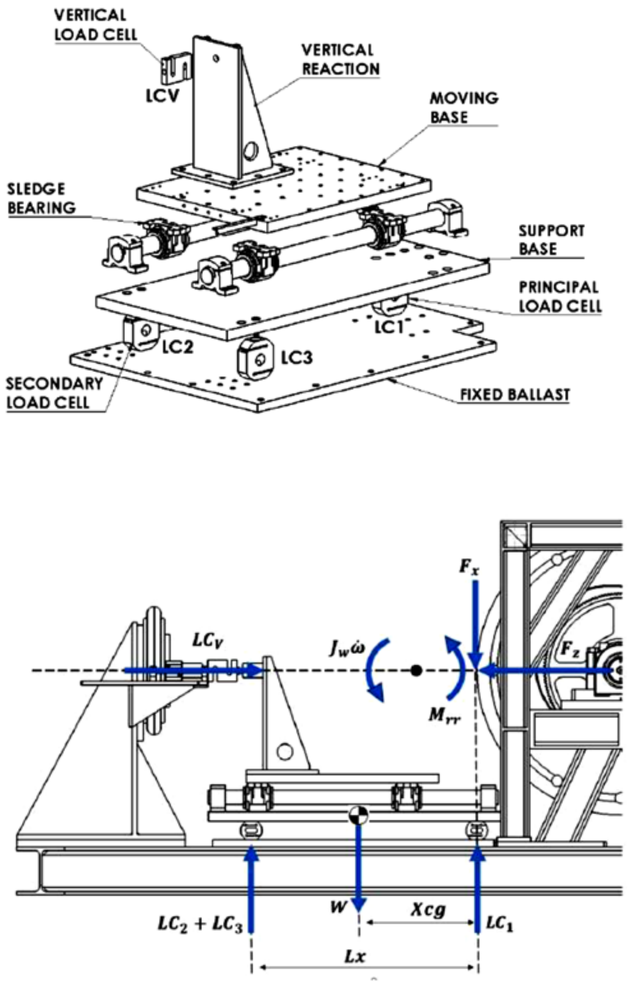

Figure 6. BRAD load cell location. Adapted form [39].

Variables measured by the BRAD

The forces and moments relevant for studying the brake and tire interaction are

$$\begin{cases} F_z = F_{LC_V} \\ F_x = F_{LC_1} + F_{LC_2} + F_{LC_3} - W \\ M_{rr} = (F_{LC_2} + F_{LC_3})L_x - W x_{cg} - J_w \dot{\omega} \end{cases}$$

where the meaning of the symbols is reported in Figs. 5 and 6.

Two important performance variables can be obtained:

- the *power dissipated by the brake and wheel system*, which reads

$P_d = F_x \Omega R_d$

- the *power dissipated by the brake*, which reads

$P_b = M_b\omega = (F_x r - J_w \mathrm{d}\omega/\mathrm{dt} - M_{rr})\omega$

Knowing the overall dissipated power and the contribution of the brake system, the *power dissipated by the resistance forces acting on the tire* can be computed

$$P_w = P_d - P_b - J_w\, \omega\, d\omega/dt$$

The above formula can be rewritten as

$$P_w = F_x\,(\Omega R_d - \omega\, r) + M_{rr}\,\omega \;=\; F_x\, \Omega R_d\, s_x + M_{rr}\,\omega$$

where s_x represents the longitudinal slip (for the definition of slip see [28], chapter 17 by H Pacejka, pag.563, Eq.17.1).

Another important variable that can be measured with the BRAD is the *rolling resistance moment,* which reads

$$M_{rr} = -W * X_{CG} + (F_{LC2} + F_{LC3})L_x - J_w \frac{d\omega}{dt}$$

again, the meaning of the symbols can be obtained by inspection of Figure 5 or 6.
Since the M_{rr} depends on the position of the center of gravity (X_{CG}), the estimation of such a position is crucial. The position depends by the attitudes of a number of different elements (see Figure 3) of the suspension. A proper analysis has been conducted to get the instantaneous value of X_{CG}. For sake of space such an analysis is omitted here. The result is that an excellent estimation of X_{CG} could be obtained [40].

Finally, as partially addressed above, the measured variables coming from kinematic sensors, load cells and geometric data are processed to obtain the linear deceleration of the drum, the longitudinal force at wheel-drum interface, the drum angular velocity, the rolling resistance moment at the wheel, the torque at the brake and the torque at the wheel.

Accuracy

For sake of space the complete accuracy analysis is omitted here, but relevant results are reported. A complete analysis of the accuracy of the BRAD is presented in [39].

The uncertainty Δf of a generic measurement f, defined by the function $f(x_1, x_2, \dots, x_3)$, can be calculated calculated as

$$\Delta_f = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \Delta x_i \right)^2}$$

where x_i is the generic variable that can be measured directly or indirectly. This formula has been used to fill Table 1.

In Table 1, the uncertainties of measured variables provided by BRAD are reported.
By inspection of Table 1, we can see that the uncertainties are all within sufficient ranges to study the phenomenon of wheel locking with a convenient confidence and accuracy. Actually, the values obtained show, referring to the mean value of the measured quantities, an uncertainty of less than 1% for the power dissipated by the brake and wheel system and similar values for the power dissipated by the brake. The BRAD proves to be not suitable for the measurement, at a certification level, of the phenomena linked to the tire rolling resistance while it can be considered quite accurate for the evaluation of the phenomena occurring during the braking action, including the longitudinal force and the dissipated powers.

Table 1. Uncertainties of measured variables provided by BRAD

variable	*description*	*uncertainty*	*uncertainty % FS*
F_x	braking force	15 N	0.15
M_{rr}	rolling resistance moment	4 Nm	4
P_d	dissipated power at the brake and wheel system	180 W	0.04
P_b	dissipated power at the brake	600 W	0.12
P_w	dissipated power at the tire (wheel)	630 W	0.13

Tests

Figure 7 shows the input variables and kinematic variables of a typical testing procedure at the BRAD. The focus here is to extrapolate the needed information about the brake-tire interaction and dissipated powers.

In the initial phase, the pneumatic spring (Figure 2) provides the required force F_z at the contact between the drum and the tire. The tire and the suspension system are displaced towards the drum surface and the stationary condition is simulated. Then, the drum is accelerated up to a speed slightly above the reference one considered for the test and, at this point, the motor is disconnected.
After some seconds of free deceleration, the target speed is reached, and the brake pressure is applied. Both the drum and the wheel start to decelerate and the slip value is recorded thanks to the acquisitions coming from two different encoders. After about five seconds, the brake is released and the vertical load brought back to zero.

Power dissipated during braking

Our attention was focused on measuring the power dissipated by the brake only and the tire (wheel) only. In Figure 8 a plot shows how the brake power is distributed among brake and tire.

To understand the tire contribution to the total dissipated power during a hard brake, a wide testing campaign has been carried out adopting different values of tire vertical load, tire inflating pressure and braking pressure (Table 2).

Table 2. Test campaign to investigate the power losses in brake and tire.

tire pressure	*tire load*	*brake pressure*
2.2 bar	3000 N	30 bar
2.4 bar	3500 N	35 bar
2.6 bar	4000 N	40 bar

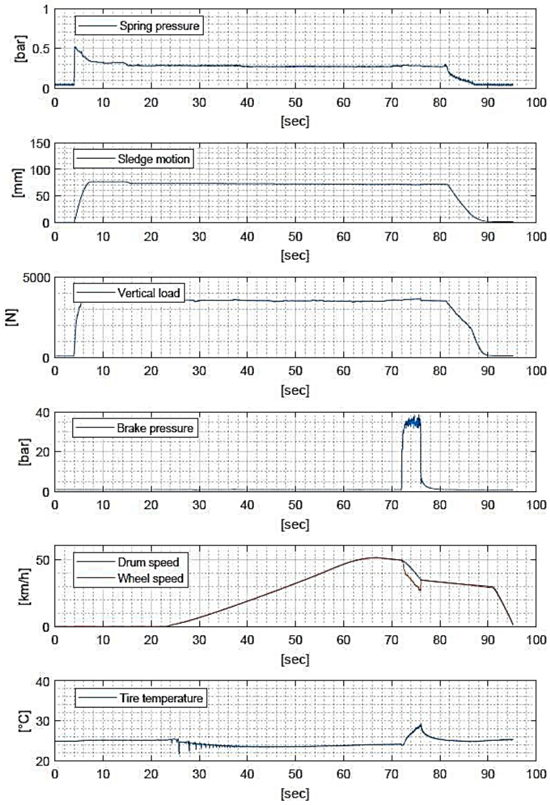

Figure 7. BRAD, typical testing procedure.

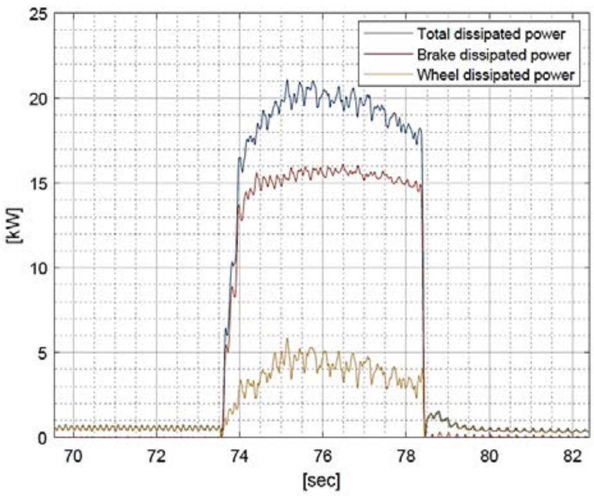

Figure 8. BRAD typical output during a hard braking. Total power dissipated by brake and tire, power dissipated by brake only, and power dissipated by tire (wheel) only.

In Figure 9 the results of the test campaign described in Table 2 are shown.

At least 2 tests for each combination of vertical load, brake pressure and tire pressure have been performed.

As expected, the obtained results show how the tire dissipated power has a trend similar to the one of the longitudinal slip. Less slip and, consequently, less dissipated power by the tire, can be obtained with an increase of the vertical load and tire pressure.

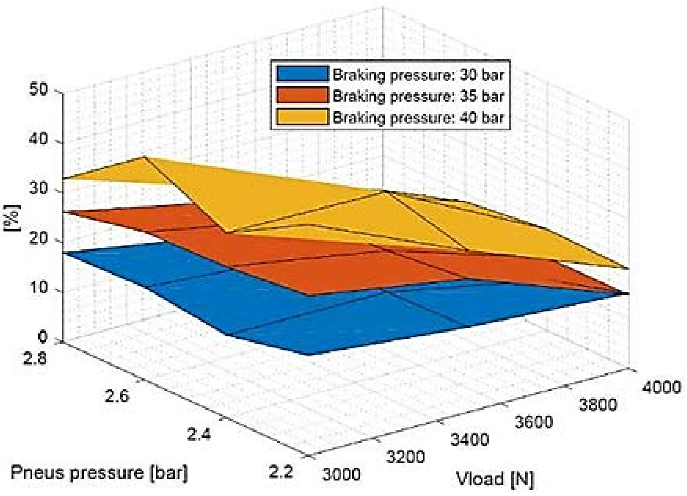

Figure 9. Percentage of tire power losses with respect to the total dissipated power during a hard brake. Measurements performed by the BRAD.

According to the knowledge of the Authors, the measurement in Figure 9 appears to be unreferenced. In the classic literature dealing with vehicle dynamics, such phenomenon seems not properly highlighted [28-38].

The obtained results appear to be meaningful for brake design (optimal design), for brake durability assessment, for the thermal management of the brake and for the design of the aerodynamics of wheel systems.

In addition, these results could be extremely important in order to predict the temperature variation of the tire in accordance with its dissipated power and, consequently, to predict the change of the tire characteristic curve as a function of the driving-braking conditions.

Obviously, any -even simple- road vehicle mathematical model may easily provide a plot similar to the one in Figure 9.

The advantage proposed here is that BRAD can provide actual experimental results. According to the knowledge of the Authors, sophisticated tire models accounting for temperature effects need a calibration. Tire is a dynamic component and tends to change its properties over time. In particular, mechanical properties of the tire and of its rubber compound change very much during hard braking. BRAD could provide some experimental feedback to tire model changing characteristic during hard braking.

Role of tire during hard braking

The experimental information on dissipated power obtained above turns out to be of great importance in the analysis of the behavior of the tire and in the study of its interaction with the braking system.

In Figure 10, eight hard braking maneuvers at the BRAD are shown. Despite the brake pressure is constant, the longitudinal slip increases (and the longitudinal force increases, too). This fact is normally reputed to depend on ‘equivalent’ brake friction rise with temperature. The duration of the braking actions is not constant because the system monitors the derivative of the longitudinal slip and cuts the brake pressure if a couple of thresholds are reached on such derivative and on longitudinal slip. This introduces some random effect that does not influence the quality of the experiment. The signal of the derivative is noisy and a random effect is inherent.

Our preliminary experiences with the BRAD seem highlighting that a role could be played by the tire, too.

A comprehensive description of this topic is provided in [40]. For sake of space we report here the main conclusion only.

Plots in Figures 11,12,13 have been obtained after an identification performed by a mathematical model of the whole BRAD, tire, brake and suspension included.

During braking, the power dissipated by the tire entails an increment in its tread temperature. A variation is generated both in the longitudinal slip stiffness (Figure 11) and in the friction coefficient at the contact patch (Figure 12). The consequence is a change in the tire characteristic curve (Figure 13).

Figure 13 shows that at limit slip, the tire characteristic seems raising considerably. This could worsen the spikes of the red curves shown in Figure 10.
Further studies are needed to assess both qualitatively and quantitatively the actual importance of tire characteristic on hard braking.

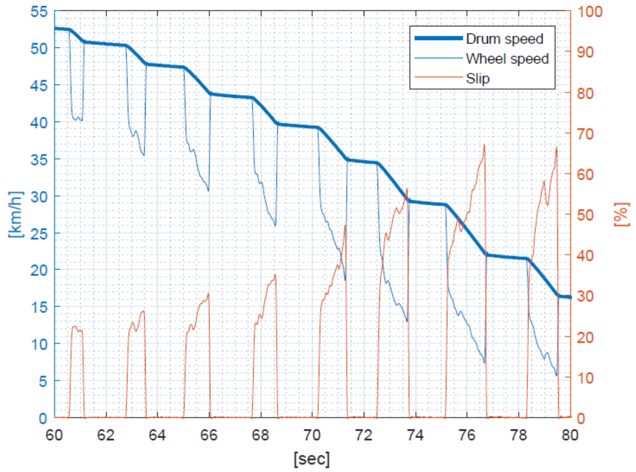

Figure 10. Repetition of hard brakings at the BRAD. Filtered data.

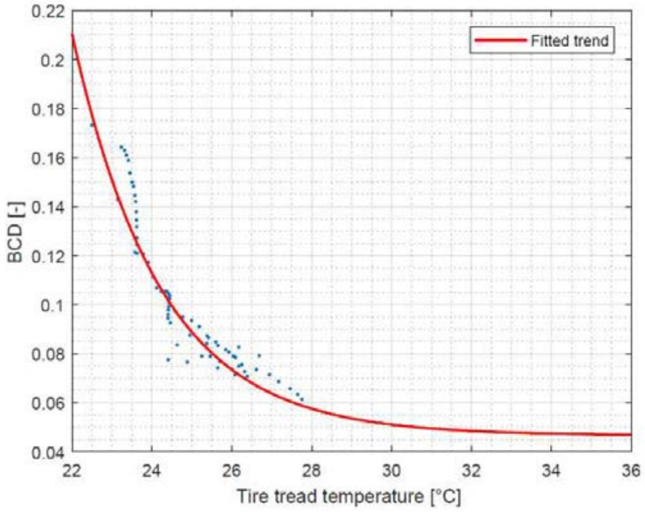

Figure 11. Tire longitudinal slip stiffness variation with tread temperature. Subsequent brakings of Figure 10. BCD is the product of three coefficients of Pacejka's Magic Formula [32].

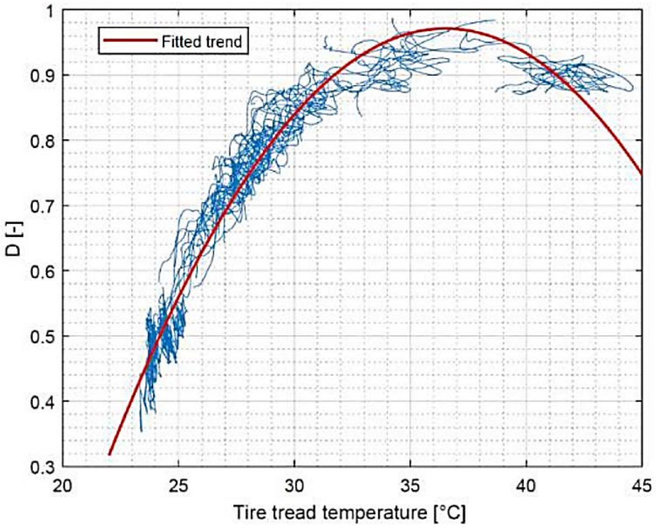

Figure 12. Variation of tire peak friction as function of tread temperature. Subsequent brakings of Figure 10. D is a coefficients of Pacejka's Magic Formula [32].

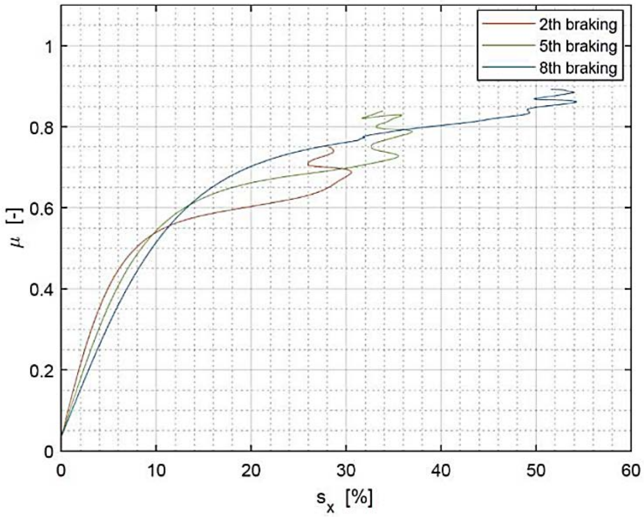

Figure 13. Variation of tire longitudinal characteristic during subsequent brakings of Figure 10.

Conclusions

We have presented a new test rig for studying braking, especially at wheel locking. The new dynamometer includes additional features, which allows to measure the power dissipated by brake and tire, or, alternatively, the power dissipated by the brake only. The dyno's load cells are placed in such a way that forces applied by the pneumatic wheel at the drum are captured directly. Such a feature makes the dynamometer a quite unique test rig.
BRAD has been an exercise that allowed to measure the relevant external forces acting at a generic suspension system during braking. The simple single-axis load cells that have been used provide a

relatively high accuracy. One of the strong points of the BRAD is that a brake and a suspension system (a ‘corner’) can be studied during braking by measuring accurately the relevant forces and related powers.

We have shown that, in average, during hard braking, the dissipated power by the tire is some 30% of the one dissipated by the brake. In the future, motorsport designers dealing with electric vehicles will need a precise simulation of the power to be recovered. BRAD will provide some figures on this topic.

By the BRAD the tire and brake behavior during hard braking could be accurately studied in the future.

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