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Effects of tire wear on motorcycle dynamic

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Abstract

Dealing with the study of motorcycle behavior, tires properties must be carefully analyzed as they strongly influence the safety of these vehicles. For the safety of the rider it's important to consider how the tire properties changing due to operational conditions variation (such as tire inflating pressure and tire wear) affect the stability and the vehicle performances.
Some measure about tire wear and tire stiffness as well as wear impact on maximum grip are referred in some scientific papers ([1],[2]). In [3] is shown a possible strategy to identify tire wear while driving monitoring tire cornering stiffness. However, the most widely used empirical model (Magic Formulae from Pacejka) includes the effect of tire inflation pressure but the effect of tire wear is not considered yet.
The aim of this paper is to quantify the effects of tire wear on tire longitudinal and lateral behavior, to propose a modification of Pacejka Magic Formulae and to understand the influence on both the motorcycle lateral and longitudinal dynamic.
To get this target, numerical and experimental investigation were carried out. They confirmed how the wear affects both the quasi-steady lateral dynamic and the transient longitudinal dynamic. The tire characteristics variation due to wear have been proven both by the objective measurements and the subjective riding feeling.
To better investigate the wear effect on motorcycle lateral behavior, correlating it with subjective feeling, a numerical approach has been followed: simulations of the same steering pad maneuver has been implemented. Thanks to this approach it was possible to correlate wear effect to MF coefficients.
Instead indoor tests have been carried out to properly quantify the longitudinal MF coefficients change due to tire wear.
To double-check the results, additional on road tire characterization was done, confirming a good agreement with respect to indoor tests and allowing to establish an outdoor procedure aimed to characterized tire properties directly while riding the vehicle.

Introduction

The tire properties influence the motorcycle behavior in almost every riding condition. Experimental evidences, collected by means of both subjective assessments and objective measurements, highlight how stability, drivability and safety of a motorcycle depend on tire operative conditions, such as inflating pressure and wear ([4][5][6][7]). The latest formulation of the MF ([8]) includes the effects of inflating pressure over tire response ([9]). Instead, the wear effects are still not included.

The aim of this paper is to quantify the effects of tire wear on tire longitudinal and lateral behavior, to propose a modification of Pacejka Magic Formulae and to understand the influence on both the motorcycle lateral and longitudinal dynamic.

To get the target, some maneuvers have been performed on a track with an instrumented motorcycle aimed to quantify the motorcycle dynamic behavior when equipped with new and worn tires. Concerning lateral dynamic, steering pad tests were performed; for longitudinal dynamic straight-line braking maneuvers on high friction surface was executed.

The proposed methodology follows three steps: 1. the assessment of the subjective rider feeling, 2. the on-board data measurement and 3. the correlation of the identified effects with respect to the coefficients of tire characteristic model.

By this way the wear-dependent tire parameters variation is correlated to both the vehicle dynamic response and the subjective riding feeling.

Collecting subjective feelings, all the riders clearly felt the difference between the two sets of tires. The increasing of the outbound steering torque during the steering pad and the increasing of the maximum deceleration during braking were perceived when riding a bike with worn tires.
The subjective responses were confirmed by the analysis of the acquired data.
In the further sections (respectively 2 and 3) of the manuscript the obtained results are provided.

To better understand the motivation of higher required steering torque in case of worn tires, a numerical approach has been followed. Numerical simulations of the same steering pad maneuver have been implemented and sensitivity analysis has been carried out aimed to investigate which are the most relevant tire parameters affecting required steering torque. Results are provided in section 4.

To evaluate the MF coefficients change due to tire wear, indoor tests have been carried out. The results of section 5 highlights how the tire characteristic curve changes due to wear. Moreover, an on-road characterization methodology has been developed to be able to get motorcycle tire information even if indoor tests are not available. This allowed to establish an outdoor procedure aimed to characterized tire properties while riding the vehicle. This procedure is presented in section 6.

Finally, in section 7 a new formulation of the MF *.tir is proposed, where the coefficients have been modified to include wear dependency. By this way we have been able to properly account for the effects of wear on tire behavior and, thus, on vehicle dynamic also when dealing with numerical simulations.

1. Motorcycle instrumentation

The experimental tests have been carried out both in a closed track and in open road. In this section the list of the instrumentations mounted on the motorcycle is provided.

An high accuracy GPS has been used to measure the vehicle speed, the longitudinal acceleration and the lateral acceleration of the motorcycle. All the channels have been low-pass filtered with a digital filter up to 3 Hz, see in figure 1-a.

Additional encoders have been placed on both front and rear tire for the measurement of wheel rotational speed, see figure 1-c and 1-d. The encoders measurer the wheel rotational speed that is then multiplied by the tire radius to calculate the wheel peripheral speed at tire-ground contact point. Finally using the wheel peripheral speed and the vehicle speed the longitudinal slip ratio is calculated.

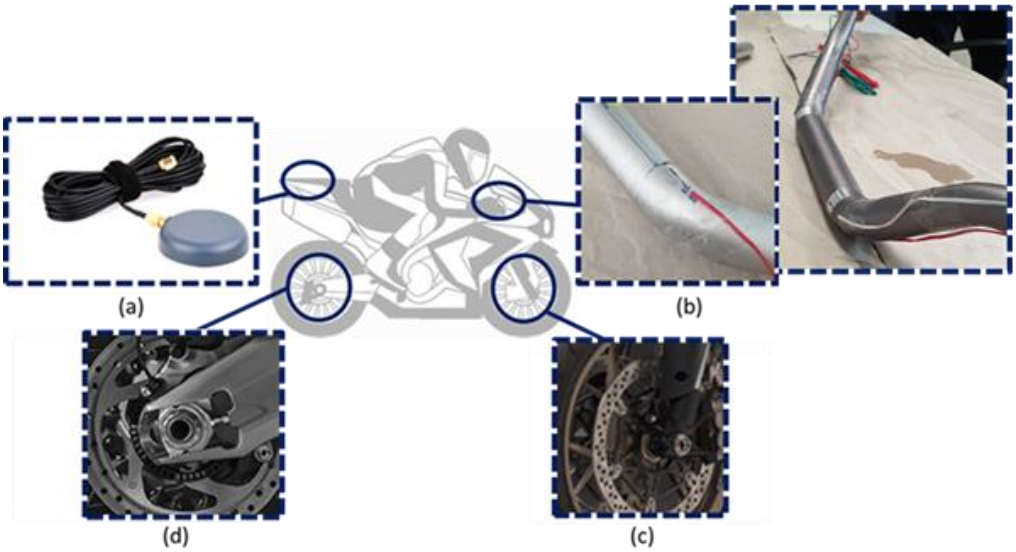


Figure 1 Motorcycle instrumentation, from top left to bottom right in clockwise direction: (a) high performance GPS for speed and acceleration measurements; (b) strain gauges for steering torque measurement; (c) and (d) respectively front and rear encoders for wheels speed measurements.

Two half-bridges strain gauge were placed on the motorcycle handlebar, one half-bridge each side, see figure 1-a. A calibration procedure was carried out to calculate from voltage measurement the steering torque. By summing up the signals coming from the two side of the handlebar, the overall steering torque applied by the driver is measured. The sign convention considers positive steering torque when it is applied in counterclockwise direction (steering torque vector positive when directed downwards along the steering axis), see figure 2.

Figure 2 Experimental test: sign convention for the steering torque measurement. Positive torque when applied in counterclockwise direction, negative torque when applied in clockwise direction.

The experimental tests have been repeated with the same tire model at different levels of thread wear. Thread wear is defined as referred into eq. 1; "h_0" is the thread height while new tire, "h" refers to the thread height at a generic wearing condition.

$$dTW = -(h-h_0)/h_0 \qquad \text{(eq.1)}$$

In figure 3 are reported the images of the new tires on the left side with yellow box (first row front tire, second row rear tire) and after about 70% of tire wear on the right side with red box (first row front tire, second row rear tire).

Figure 3 Experimental test: tires used during the test. New – left side with yellow box, and about 70% worn – right side with red box, conditions. Front tire on first row and rear tire on second row.

In the table below are reported the values of thread height both for the front and the rear tire:

Table 1. Tread height for front and rear tires, new and worn.

	FRONT TIRE		*REAR TIRE*	
	Mid-section	*Side section*	*Mid-section*	*Side section*
h0 [mm]	*3*	*2*	*5*	*3*
h [mm]	*0.45*	*0.7*	*0.75*	*1.05*
dTW [-]	*0.85*	*0.65*	*0.85*	*0.65*

2. Lateral dynamic: tests, results and drivers feeling

A steering pad track, having radius of 45m, was used to evaluate the effect of tire wear on the lateral dynamic. This test was performed with the new tire and with the same tires having almost 70% of tire wear, calculated as previously defined.

The performed maneuver was a quasi-steady run: from riding velocity equal to zero till the maximum reachable by the rider in safe. Longitudinal jerk has been limited to about 0,1m/s^2/s. By this way, both the lateral acceleration and the roll angle slowly increase during the test. The maximum reached speed depends on the rider capability, the motorcycle typology and on the equipping tires.

This test has been done first with new tire (after a run-in procedure) and then repeated with the same tire model but worn. All the riders perceived an increasing of the outbound steering torque needed when using the worn tire. Instead, the maximum lateral acceleration reached was not perceived to change.

The most important signal to be analyzed regarding lateral characterization is the measured overall steering torque as function of the lateral acceleration.

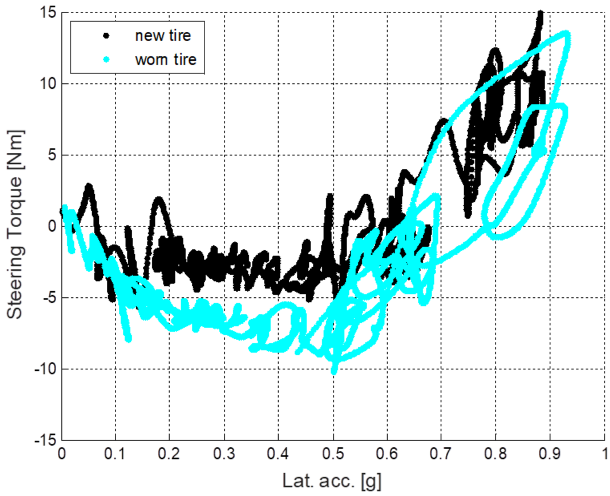


Figure 4 Experimental test: steering torque variation as function of lateral acceleration. In black the trend for the new tire, in light blue the trend for the worn tire. The steering torque is initially negative, thus directed outbound for both the conditions, but the worn tire has an higher absolute value of the outbound torque.

In figure 4 the measured overall steering torque is plotted as a function of the lateral acceleration of the motorcycle. The data obtained during the experimental test are shown.

In black the trend for the new tire: up to 0.6 g of lateral acceleration the torque is negative. This means how it is in clockwise direction and thus it is directed outbound with respect to motorcycle trajectory. The value remains always below 5 Nm. For higher acceleration the torque inverts the trend becoming positive, or inbound. This is due to the increasing of the gyroscope effect of the front wheel in relation to the yaw rate (~ V^2, direction outbound steering torque contribute).

In light blue the same curve for the worn tire: the steering torque is negative up to 0.7 g of lateral acceleration, but it reaches an higher absolute value of the outbound torque, around 8 Nm.

Different tires models have been tested. Each new tire provides a specific trend of steering torque, setting the so-called steering behavior. Some induces the steering torque to remain closer to zero while other reaches larger negative amplitude. The trend between new and worn tire is the same: the worn tire requires higher outbound steering torque than the corresponding new one.

3. Longitudinal dynamic: tests, results and drivers feeling

A longitudinal braking maneuver from the initial speed of about 80 km/h has been performed on dry tarmac. This test was performed with the new tire and with the same tires having almost 70% of tire wear, calculated as previously defined. It was confirmed how the wear affects the transient longitudinal dynamic as well.

In order to guarantee repeatability and comparability, the driver applied full brake force to both front and rear brakes, reaching the limit of the tire-road available friction. Therefore, the anti-block system, ABS, was engaged. Up to 15/20 runs for each configuration were done. This maneuver allowed to evaluate the performance of the tire in terms of maximum longitudinal force at tire-ground contact point, that is strictly related to the maximum available friction value.

Almost all the riders judged the vehicle with worn tires to better perform (12 over 13; while 1 didn't notice any difference). The subjective responses were confirmed by the on-board data acquisition.

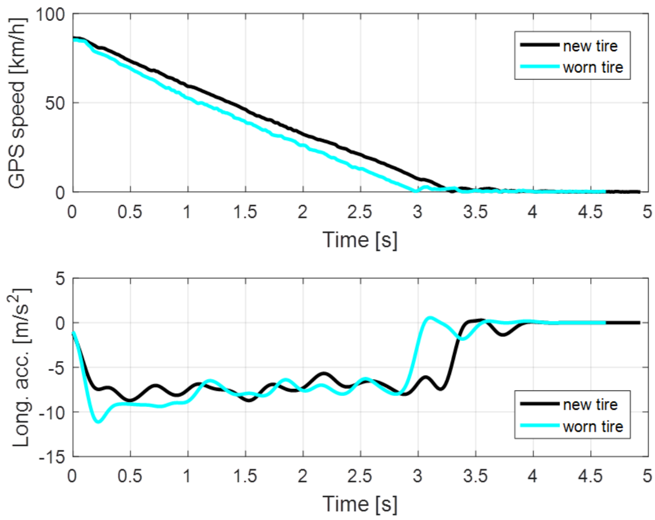


Figure 5 Experimental test: longitudinal brake maneuver from 80 km/h. In the upper part the speed time history, in the bottom part the longitudinal acceleration time history. In black the signal measured with the new tire, in light blue the ones measured with the worn tire. The worn tire reached higher values of deceleration thus obtaining lower braking distance.

In figure 5, the time histories obtained during one braking maneuver are plotted as example. In the upper part the speed time history, in the bottom part the longitudinal acceleration time history. The signals measured with the new tire are plotted in black, in light blue the ones measured with the worn tire.

The worn tire reaches higher values of deceleration thus obtaining as overall a lower braking time and braking distance.

This demonstrates how a worn tire on a dry tarmac surface is able to perform higher longitudinal forces, thus having higher maximum friction coefficient on the same surface with respect to the new tire.

Different tire models confirmed the trend: worn tires demonstrate higher braking performances than new ones on dry tarmac.

4. Lateral dynamic: wear effect investigation on lateral tire parameters through numerical simulation.

In section 2 the effect of tire wear on lateral dynamic has been identified by means of both subjective and objective assessment. Tire wear has been recognized to mostly influence the steering torque applied by the rider.

To better comprehend which tire characteristic parameter influence the different steering torque response while running in steady-state, lateral behavior, a numerical approach has been followed: numerical simulations of the same steering pad maneuver has been implemented.

The lateral force generated from the tire is the sum of two major contributions: the force generated by the roll angle and the force generated by the slip angle.

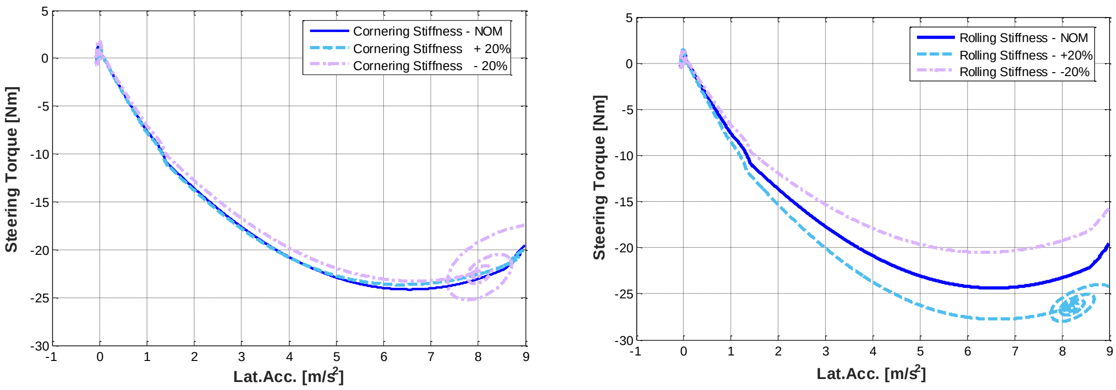
For this reason, both the rolling and the tire cornering stiffness coefficients have been taken into account. The nominal values of rolling and cornering stiffness at nominal vertical force and inflating pressure of both the front and the rear tire are reported in the table 2 below.

Table 2. Nominal tire parameters for simulations

	Nominal values			
	Vertical force [N]	*Inflating pressure [MPa]*	*Rolling stiffness [(N/rad)/N]*	*Cornering stiffness [(N/rad)/N]*
Front tire	1650	0,24	1.0	12.6
Rear tire	1650	0,20	1.1	15.0

A sensitivity analysis was performed in order to evaluate the effects of these parameters on the steering torque variation.

A variation of ±20% have been implemented with respect to the nominal value both for the front and the rear tire.



(a) (b)

Figure 6 Steering torque vs. lateral acceleration recorded during a simulated steering pad maneuver with fixed path radius; (a): steering torque variation by changing the cornering stiffness; (b): steering torque variation by changing the rolling stiffness.

In figure 6, the steering torque variation as a function of the lateral acceleration obtained during the simulations is shown, as already presented in figure 4 for the experimental data. In 3-a, the three different cornering stiffness values are considered: nominal in blue solid line, +20% in light blue dashed line and -20% in violet dashed-dot line. In figure 6-b, the results related to the rolling stiffness. The simulations outcomes highlighted how the rolling stiffness has high influence on the resulting steering torque, while the cornering stiffness coefficient seems not to cause relevant changes. Thus, the increasing of the steering torque observed during the experimental session could be driven by the progressive rolling stiffness increasing due to wear: the lower the tread depth, the higher the tire-road contact surface, the higher the rolling stiffness: same resulting contact force due to the same maneuver but higher contact patch results in lower longitudinal slip to provide the same force, thus higher tire longitudinal stiffness.

Performing the same trajectory over the same radius trajectory means to guarantee a similar roll angle for the same lateral acceleration.
With higher rolling stiffness the later force generated by the roll angle exceeds the needed one to perform the maneuver. Therefore, the force generated by the slip angle must be opposite in sign

to balance. The tire slip angle changes, even flipping direction. Remaining the pneumatical trail the same due to shear deformation, it follows how the resulting auto-aligning torque becomes now misaligning. This effect is compensated by the rider who shall increase the out-bound steering torque to maintain the trajectory.

5. Longitudinal dynamic: wear effect investigation on longitudinal tire parameters through indoor tests.

To better comprehend the effects of tire wear on longitudinal dynamic, the analysis of available indoor tire longitudinal characterization data has been carried out. The same sample tire was tested at different thread wear, reached by regular open road usage: new, 30% and 70% worn.

In this section, a description of the indoor tests performed will be presented. These indoor tests represent the standard methodology adopted to characterize the tire behavior and to determine the fitting coefficient of the Magic Formula.

Different test methodologies allowed to identify different tire parameters. We focused our attention into the identification of the following:

- the longitudinal relaxation length;
- the longitudinal stiffness;
- the maximum longitudinal friction coefficient.

In all these characterizations a dynamic slip ratio test has been performed. The indoor machine is controlled by means of an electric motor that allows either to provide a desired profile of slip ratio or longitudinal force as input. Depending on the parameter to be identified, different levels of slip ratio or longitudinal force were imposed. Only pure longitudinal dynamic is taken into account; in fact, both the slip angle and the inclination angle were imposed to be equal to zero. The vertical load is kept constant during each test[1].

The sample rate is 250 Hz and the data acquired are processed in order to characterize the tire coefficients. All the signals are filtered by a low-pass Butterworth digital filter of order 3; frequency band is up to 5 Hz.

The relaxation length (shortly named RL) controls the lag of the response of the longitudinal force to the given slip ratio.

To identify the relaxation length a slip ratio sinusoidal profile was imposed with a slip ratio frequency: of 1 Hz.

Then, the existing time delay between the input (slip ratio) and the output (longitudinal force) is measured. The time delay is directly related to the relaxation length value.

In figure 7 and 8, an example of procedure is given.

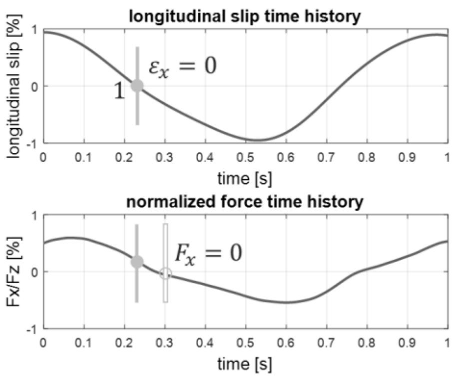


Figure 7 Indoor test for tire relaxation length characterization: input slip ratio time history and resulting longitudinal force Fx.

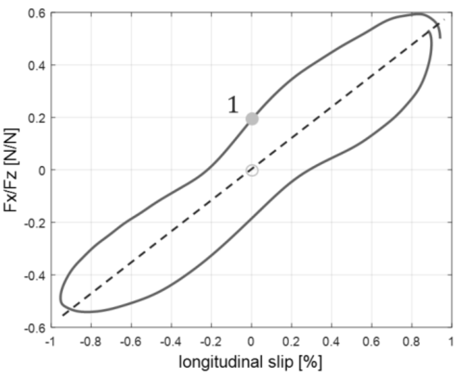


Figure 8 Indoor test for tire relaxation length characterization: hysteretic cycle between slippage and force.

[1] Additional tests have been performed by changing the vertical load to verify the vertical load dependency.

Using the filtered longitudinal (Fx) and vertical forces (Fz) signals the engaged friction coefficient μ is computed:

$$\mu = - Fx / Fz \qquad \text{(eq.2)}$$

In figure 9, the engaged friction is plotted as function of the slip ratio. In figure 9-a, due to the harmonic excitation, the hysteretic behavior is observed. This is due to the delay between the input and the output.
The amplitude of this cycle increases as the tire wear increases; in blue the data for the new tire, in black for the 30% worn tire and in pink the data of the 70% worn tire.

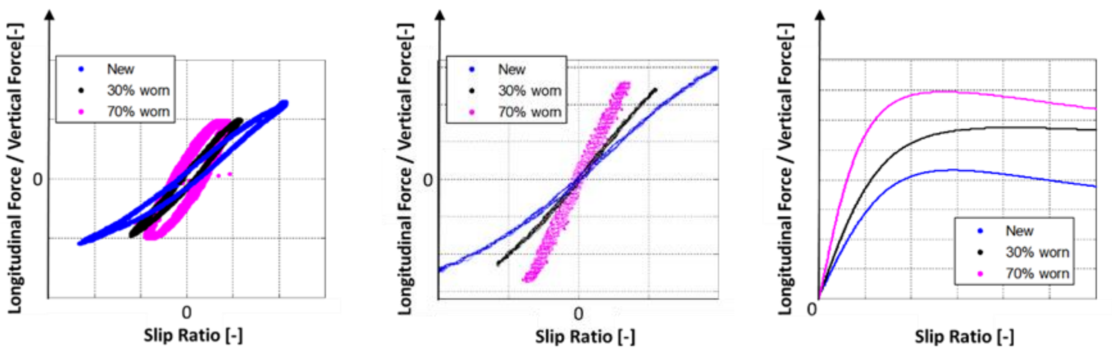
It is also possible to notice how the cycle changes in inclination with respect to the axis. This is related to the change of tire longitudinal stiffness.

To identify the tire longitudinal stiffness a similar test was performed, inputting a quasi-steady state sinusoidal slip ratio having a lower slip ratio frequency.

The obtained measurements are plotted in figure 9-b. In this case no cycles are visible and as tire wear increase the inclination increases. The inclination of the curves in the origin corresponds to the tire longitudinal stiffness values thus, as tire wear increase the tire longitudinal stiffness increases.

Finally, a full characterization of the tire has been performed, including both the linear and the non-liner response. In this case the slip ratio input is not a sinusoidal function. Slip ratio amplitude goes from 0 to max value with a variable rate to avoid tire heating effect.

In figure 9-c the resulting tire characteristic curve μ = f (slip ratio) is shown. As already said, as the tire wear increases, the slope of the curve increases as well as for the maximum available friction.

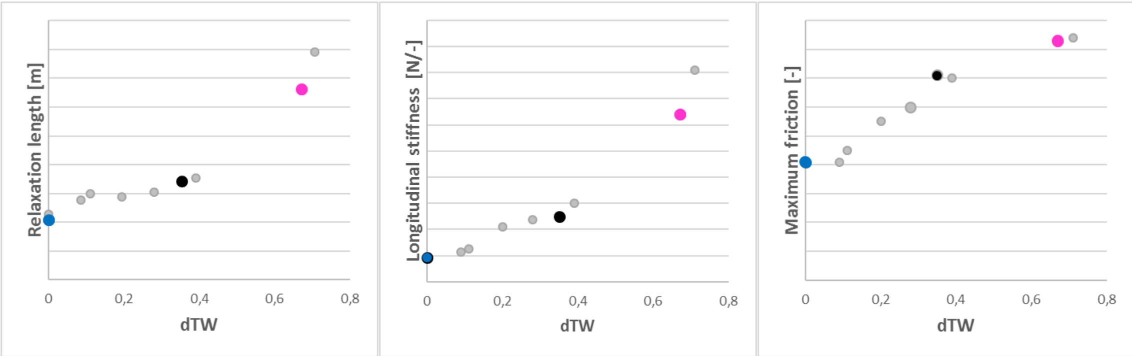


(a) (b) (c)

Figure 9 Flat Track test measurements on tire kinematic-dynamic plane for tire indoor characterization over wear. In particular aimed to characterize: (a): the relaxation length; (b): the longitudinal stiffness; (c): the maximum friction coefficient.

The proposed results highlight how the tire properties changes according to wear. In particular, the longitudinal stiffness, the maximum friction coefficient and the relaxation length increase as the tire wear increases.

In Figure 10, the identified values of relaxation length (Figure (10),a), longitudinal stiffness (Figure (10),b) and maximum friction (Figure (10),c)) have been referred at the three wear level already shown in Figure 9. The data have been acquired at several tire wear conditions. Gray dots refer to all the other tire wear conditions.



(a) (b) (c)

Figure 10 Flat Track test results for tire indoor characterization: (a): relaxation length characterization over wear; (b): longitudinal stiffness characterization over wear; (c): maximum friction coefficient characterization over wear. Colored dots refer to the tests shown in Figure 9. Gray dots refer to all the other available tests.

As the tire longitudinal stiffness increases as function of the wear, it is plausible to assume as the lateral rolling stiffness is increasing for the same physical reasons. This agrees to what achieved by the numerical simulations for lateral dynamic investigation (as previously described).

6. On road tire characterization

In the previous sections, the riders' feelings have been related to objective measurements and tire wear has been proven to modify drivability and dynamic of the motorcycle, both in lateral and longitudinal maneuvers.

These effects have been, then, correlated to specific tire model coefficients. By this way, it is possible to correctly simulate the motorcycle behavior with either new or worn tire and to forecast its performances variations as well as stability analysis.

While for passenger vehicles it is quite common to have several indoor tire characterizations, in particular for the first equipment, for motorcycles usually few information are available even about OE tires.

Driven by this reason, an on-road characterization methodology has been developed with the final target to obtain a good estimation of the principal tire characteristic curve coefficients. Only longitudinal dynamic has been considered, now.

The starting point is a geometrical and inertial characterization of the vehicle. Semi-wheelbases, center of gravity height, wheels radii, both the vehicle and the rider masses are measured in order to properly identify the tire-ground contact forces.

The vertical force acting on each tire is evaluated from the static vertical load and considering the dynamic load transfer while transient maneuvers.

The slip ratio is measured exploiting high precision GPS speed (or optical head, alternatively) and the rotational speed measurements provided by the encoders. Since the vertical load acting on each tire changes considerably during the transient maneuvers, the tires radii must be coherently characterized, aimed to obtain a more precise estimation of the slippage.

The longitudinal force is calculated from the longitudinal dynamic equation equilibrium, including the vehicle inertia, the aerodynamic and the rolling resistance contributes. During the acceleration phase, the rear tire is characterized only; in fact, it is the only one providing slippage. While the braking phase, instead, both the front and the rear tire can be characterized through a single brake (front or rear) activation only.

The aerodynamic drag contribute is characterized by performing coast down tests.

It is then fit by a second order polynomial function of the vehicle speed.

Each maneuver is performed trying to apply a desired jerk value. This in order to have enough data spreading all over the tire working usage.

For each maneuver, two runs are done:

- the first with a low jerk value (around 2 $m/s^2/s$), aimed to have a good estimation of the linear part of the curve, the one with low slip and low engaged friction;
- the second with high jerk value (around 5 $m/s^2/s$), in order to reach the maximum friction limit; it is remarked how the exact value depends on the motorcycle performances.

The experimental data obtained with this methodology are shown in figure 10. Engaged friction (ratio between longitudinal force F_x and vertical load F_z) as function of longitudinal slip ratio (SR) is shown; respectively in (a) for the front tire and (b) for the rear tire.

The experimental data are fitted by means of an optimization algorithm in order to minimize the error minimization between the experimental data and the Pacejka MF [1]:

$$F_x/F_z = \mu_x * \sin(C_x * \mathrm{atg}(B_x * SR-(E_{x1})*[1 - E_{x4} \cdot \mathrm{sgn}(SR)]*(B_x * SR-\mathrm{atg}(B_x * SR)))) \qquad \text{(eq. 3)}$$

Through the equation (3), it is possible to identify the main *.tir coefficients: μ_x, C_x, B_x, E_{x1}, E_{x2}.

For the front tire (Figure 11 (a)), since no data are available about the traction part of the curve, the experimental data are mirrored symmetrically with respect to the zeros.

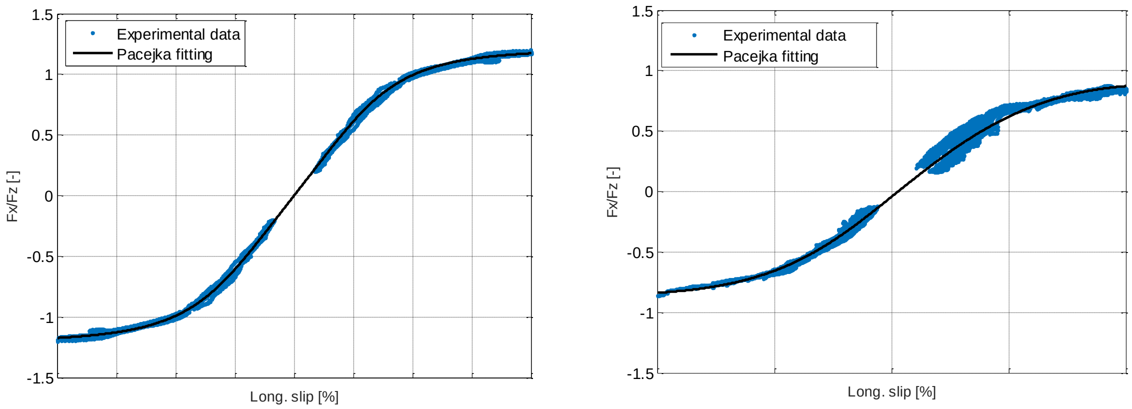


Figure 11 Experimental data and tire characteristic curves obtained from the fitting procedure: (left side) front tire; (right side) rear tire. Black line refers to the fitting curve using equation (eq. 3).

Usually, the maximum friction coefficient is easily reached by the rear tire while braking due to the decreasing of the vertical load acting on the tire. On the contrary, the maximum friction coefficient is more difficult to be reached by the front tire while braking. For the rear tire, while accelerating, the engaged friction (F_x/F_z) strictly depends on the available engine power.

Deeper observing the rear tire results, it can be noticed how the traction part of rear tire (positive slippage) reaches lower friction coefficient than the braking one (negative slippage).

Through the proposed methodology, a complete characterization of the rear tire longitudinal behavior is achievable. For the front tire only the brake part can be obtained. Through mirroring the braking domain, the traction part can be considered reliable for the fitting scope.

Repeating the procedure with the worn tire it is possible to obtain the same fitting coefficients and proceed with the evaluation of the changes due to wear effect also by means of the on-road characterization.

7. MF modification to include wear effect

In order to include the effect of tire wear on longitudinal dynamic a modification of the MF is here proposed both for the longitudinal stiffness and for the longitudinal relaxation length.

The starting point is the Pacejka 6.1 formulation ([1]). The longitudinal stiffness has a linear and exponential dependency from vertical load and a quadratic dependency from the inflation pressure[2]:

$$K_{x\kappa} = F_z\,(p_{kx1} + p_{kx2}df_z)\,\exp(p_{kx3}df_z)(1 + p_{px1}dp_i + p_{px2}dp_i^2) \qquad \text{(eq.4)}$$

The longitudinal relaxation length has a quadratic dependency from the vertical load and a linear dependency from the inflation pressure:

$$c_x = c_{x0}\,(1 + p_{cfx1}df_z + p_{cfx2}df_z^2)\,(1 + p_{cfx3}dp_i) \qquad \text{(eq.5)}$$

For both the parameters a quadratic dependency from tire wear, expressed by means of the quantity dTW (eq. (1)) has been added. This includes four new fitting parameters: p_{tx1} and p_{tx2} for the longitudinal stiffness and p_{cfx4} and p_{cfx5} for relaxation length, thus:

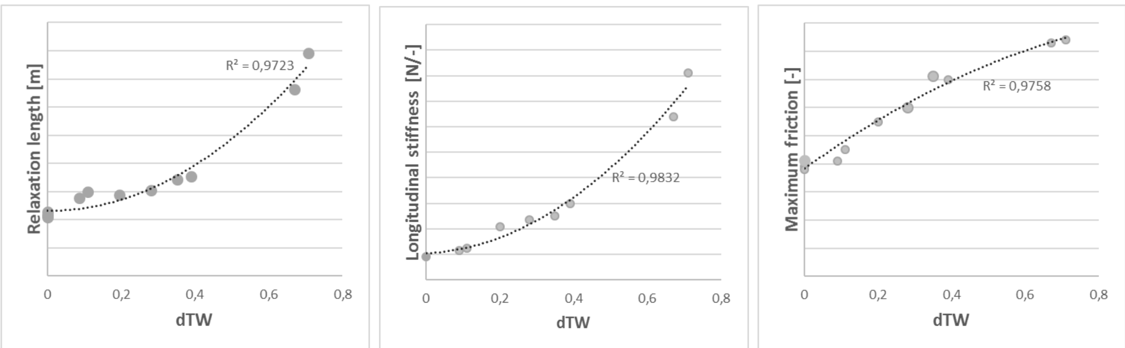
$$K_{x\kappa} = F_z\,(p_{kx1} + p_{kx2}df_z)\,\exp(p_{kx3}df_z)(1 + p_{px1}dp_i + p_{px2}dp_i^2)\,(1+ p_{tx1}dTW + p_{tx2}\,dTW^2) \qquad \text{(eq.6)}$$

$$c_x = c_{x0}\,(1 + p_{cfx1}df_z + p_{cfx2}df_z^2)\,(1 + p_{cfx3}dp_i)\,(1+ p_{cfx4}\,dTW + p_{cfx5}\,dTW^2) \qquad \text{(eq.7)}$$

About the maximum friction coefficients, from figure 9-c its dependency from TW is lower than quadratic. Also in this case a parabolic trend with TW indicator is proposed. Negative value of p_{tx4} is expected. This parabolic fitting allows also to account for maximum friction decreasing in case of different tire compound under the thread depth indicator.

$$\mu_x = (p_{Dx1} + p_{Dx2}df_z)\,(1 + p_{px3}dp_i + p_{px4}dp_i^2)\,(1 - p_{Dx3}\gamma^2)\,(1+ p_{tx3}\,dTW + p_{tx4}\,dTW^2) \qquad \text{(eq.8)}$$

These new parameters can be determined fitting with the proposed function the plots of figure 9. In Figure 12 the original dataset (gray dots), the trendline and the correlation coefficient R^2 have been proposed for the relaxation length (a), the longitudinal stiffness (b) and the maximum friction (c).



(a) (b) (c)

Figure 12 Tests results for tire indoor characterization: (a): relaxation length characterization over wear; (b): longitudinal stiffness characterization over wear; (c): maximum friction coefficient characterization over wear. Gray dots refer to all the other available tests, dashed line refers to the trendline and R^2 is the trendline correlation coefficient.

[2] Refer to [8] and [9] for the definitions of the coefficients included inside equations (eq.2) and (eq.3).

8. Conclusion

The proposed research focuses on tire wear affecting motorcycle behavior and leads to a preliminary wear effects objectification affecting riding feeling. These effects have been correlated with the tire model coefficients and the analytical MF *.tir coefficients dependency with tire wear has been proposed.

The open-road methodology allows to save time and effectively identify the tire properties even on several different road surfaces. Additionally, the real-time dynamic behavior can be performed obtaining crucial information about tire during riding, with implication for diagnostic applications (either for vehicle development or for mass production).

The on-road characterization permits to obtain usable coefficients of the Magic Formula, Those lead to the *.tir files filling (modelling tire wear and/or different road surfaces) to be then used in simulation environment.
A more and more realistic tire model, including tire wear for simulations, allows a better overview of the desired tire performances and how those interact with vehicle dynamic and riding feeling. Finally, this approach can be adopted to objectify acceptance criteria for tire coefficients variation over wear to be forwarded to tire supplier.

As further investigation tire indoor tests for pure lateral dynamic characterization can be planned in order to confirm/verify the hypothesis and on-road riders' feeling.

References

[1] *A.Andrieuxa, P.O. Vandanjonb*, R. Lengellec and C. Chabanon. New results on the relation between tyre–road longitudinal stiffness and maximum available grip for motor car. Vehicle System Dynamics Vol. 48, No. 12, December 2010, 1511–1533*

[2] *Carlson C.R., Gerdes J.C., "Consistent Nonlinear Estimation of Longitudinal Tire Stiffness and Effective Radius", IEEE transactions on control systems technology, vol. 13, No. 6, 2005*

[3] *Kanwar Bharat Singh. Tire wear state estimation system and method. United States Patent Application Publication. US 2015/0231932. Aug 20th ,2015.*

[4] *V. Cossalter, Motorcycle Dynamics, Lulu.Com; 2nd ed. (2 ottobre 2006).*

[5] *V. Cossalter , R.Lot , F. Maggio. "The influence of tyre properties on the stability of a motorcycle in straight running and curves " SAE paper 2002 - 01 - 1572 (2002)*

[6] M. Massaro*, V. Cossalter, G. Cusimano. *The effect of the inflation pressure on the tyre properties and the motorcycle stability. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering 227(10):1480-1488 · October 2013.*

[7] *M.Bocciolone, F. Cheli, E. Leo, M. Pezzola. Numerical And Experimental Approacches To Investigate The Stability Of A Motorcycle Vehicle. 8. Biennial ASME Conference ESDA 2006. Torino, p. 1-10.*

[8] *H. B. Pacejka, Tyre and Vehicle Dynamics, Butterworth and Heinemann, Oxford, 2002.*

[9] *Besselink, I.J.M, Schmeitz, A.J.C, Pacejka, H.B., "An improved Magic Formula/Swift tyre model that can handle inflation pressure changes", Proceedings of the 21st Symposium of the IAVSD, 2009.*