

Experimental Characterization of the Lateral Response of a Tire under Hydroplaning Condition

Stefano Melzi, Marco Sbrosi, Edoardo Sabbioni and Vincenzo d'alessandro
Politecnico di Milano

ABSTRACT

Hydroplaning represents a threat for riding safety since a wedge of water generated at the tire-road interface can lift tires from the ground thus preventing the development of tangential contact forces. Under this condition directionality and stability of the vehicle can be seriously compromised. The paper aims at characterizing the tire lateral response while approaching the hydroplaning speed: several experimental tests were carried out on a special test track covered with a 8-mm high water layer using a vehicle equipped with a dynamometric hub on the front left wheel. A series of swept sine steer maneuvers were performed increasing the vehicle speed in order to reach a full hydroplaning condition. Variations of tire cornering stiffness and relaxation length were investigated while the vehicle approaches the hydroplaning speed. Experimental tests stated that a residual capability of generating lateral forces is still present also close to the full hydroplaning condition.

CITATION: Melzi, S., Sbrosi, M., Sabbioni, E. and d'alessandro, V., "Experimental Characterization of the Lateral Response of a Tire under Hydroplaning Condition," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(2):2012, doi: 10.4271/2012-01-0769.

INTRODUCTION

As well known, hydroplaning [1][2][3][4][5] significantly affects safety since it leads to the loss of contact between tires and road, thus reducing the capability of the vehicle to respond to the driver's inputs (steering and braking/accelerating). This phenomenon is due to a water layer present at the tire-road interface. When the vehicle speed increases, the water pressure in front of the wheel pushes a wedge of water under the leading edge of the tire. As a consequence the contact area progressively reduces till the central part is completely detached from the ground and contact remains only on the shoulders of the tire (hydroplaning speed). Hydroplaning is influenced by a series of parameters: height of the water film with respect to tread depth, tread pattern design, inflation pressure, road texture.

In recent years, sensorized tires (generally known as smart tires) were presented [6][7][8][9][10] as new measuring devices able to provide data directly related to the dynamics of the contact patch and, thus, to the interaction between tires and road. In a previous study, the authors presented an algorithm for identifying the hydroplaning condition based on the measurements carried out through a smart tire developed in cooperation with Pirelli Tyre [11]. The proposed algorithm allows the detection of hydroplaning risk (i.e. the presence of a significant layer of water between tires and road) 40-50

km/h before the hydroplaning speed is reached. Moreover hydroplaning risk can be evaluated by comparing the actual speed with the hydroplaning speed estimated by means of smart tires. It is straightforward to understand that smart tires can open perspectives for new control systems allowing the prevention of hydroplaning by limiting the vehicle velocity (braking or reducing the engine torque) before hydroplaning speed is achieved. Moreover, innovative control systems able to recover vehicle stability and directionality when hydroplaning conditions eventually occur can be designed. The first step towards the implementation of these innovative control systems is represented by the characterization of the tire response when hydroplaning speed is approached. At the purpose, the present study investigates variations of tires cornering stiffness and relaxation length as hydroplaning conditions come closer.

The performed analysis were supported by an experimental campaign carried out with the test vehicle of Dipartimento di Meccanica of Politecnico di Milano. During the tests, the vehicle was equipped with a dynamometric hub at the front left wheel to measure contact forces, an inertial gyroscopic platform to measure vehicle accelerations and angular rates, an optical sensor to measure vehicle lateral and longitudinal velocities and a dynamometric steering wheel to measure the steer angle imposed by the driver. A series of

swept sine steer tests was carried out on a straight track covered with a 8-mm high water layer. During the tests, speed was increased from 40 to 95 km/h stepwise. Experimental data were then post-processed in order to determine the relation between lateral force and slip angle on the front left tire. In particular, in order to evaluate how approaching hydroplaning speed affects tire cornering stiffness and relaxation length, the parameters of a linearized tire model accounting for its transient response were identified for the different tested speeds. The obtained results highlighted that, although contact forces are significantly reduced when hydroplaning speed is approached, a margin is still present, which may be exploited by an active control system.

EXPERIMENTAL ACTIVITY

Experimental tests were performed on a 400 m long straight track, covered with an 8-mm high water layer. Considering an ordinary passenger car, this amount of water leads to full hydroplaning when speed ranges between 70 and 90 km/h. Tests were carried out with the instrumented front wheel drive sedan shown in [Figure 1](#) equipped with four 205/50/R16 summer tires.



Figure 1. Test vehicle.

Table 1. Quantities recorded through the on-board measurement set-up.

Sensor	Measured quantities
Inertial platform	Chassis angular rates, c.o.g. acceleration
Optical sensor (Correxit)	Longitudinal speed, sideslip angle
Dynamometric steering wheel	Steer angle (positive for right turns)
Dynamometric hub (Front left wheel)	Wheel angular speed, forces and moments

[Table 1](#) lists the measured quantities and the corresponding sensors. In particular the front left tire was instrumented with a dynamometric hub allowing the measure of vertical, longitudinal and lateral contact forces. Accelerations and angular rates (roll, pitch and yaw) of the

vehicle center of gravity (c.o.g.) were measured by means of an inertial gyroscopic platform, while its lateral and longitudinal velocities were assessed through an optical sensor. Finally, the steer angle imposed by the driver was measured with a dynamometric steering wheel.

A first series of tests was devoted to the identification of the hydroplaning speed. As already mentioned, at this speed the central part of the contact area is completely lifted from the ground and contact remains only on the shoulders of the tire. The tire thus preserves a very limited capability of generating tangential forces. In this condition, if a driving torque is applied to the wheel, it starts spinning. The longitudinal slip of driving wheels can thus be used to identify the hydroplaning speed.

[Figure 2](#) shows the time history of the longitudinal slip of the front left wheel during an acceleration test: the sudden increase of the longitudinal slip up to 20% at 5.5 s clearly identifies the hydroplaning speed (85 km/h). During the test, the vehicle was equipped with new 205/50/R16 summer tires characterized by a tread depth of 7 mm (comparable with the water layer thickness) and the static load on the front left wheel was 5400 N. Hydroplaning speed can significantly vary if vertical load, inflation pressure, tread design and wear, depth of the water layer and road texture are changed [4][5]. The ratio between the tread and the water layer depth particularly affects hydroplaning speed. As an example, hydroplaning speed is reduced to 60 km/h if the same tires worn up to a tread depth of 1.6 mm (the minimum legal limit) are used.

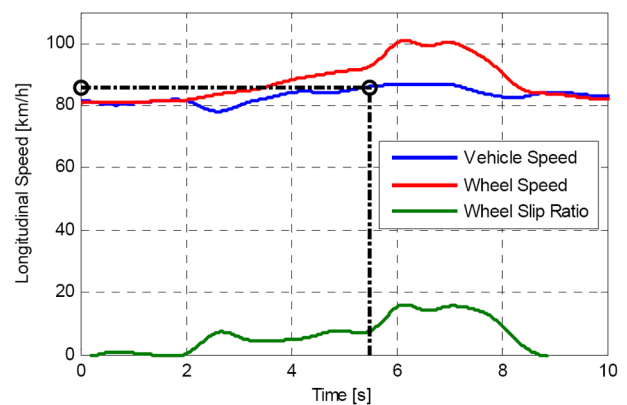


Figure 2. Longitudinal acceleration test aiming at the identification of hydroplaning speed.

Once the hydroplaning speed was identified, another series of tests was carried out to investigate the tire lateral response and in particular cornering stiffness and relaxation length variation as hydroplaning speed approaches. At the purpose, swept sine tests were carried out increasing the speed from 40 to 95 km/h stepwise. Tests were performed by a professional driver able to apply a steer angle in the range $\pm 90^\circ$ with a frequency up to 2-2.5 Hz.

EXPERIMENTAL DATA ANALYSIS

The procedure for estimating the slip angle of the front left tire from the measurements carried out during the experimental tests is presented in this section. Identification of the tire cornering stiffness and relaxation length is instead presented in the next section.

It is to point out that the water layer unfortunately prevented the optical sensor from working properly during the tests due to waves and splashes caused by the vehicle passage at high speed. While disturbances on the longitudinal speed measurement are negligible, the lateral speed measurement results significantly affected by errors. This prevented the possibility of directly measuring the vehicle sideslip angle, which is needed for estimating the slip angle of the front left tire. To address this issue, the sideslip angle was estimated using a kinematic approach based on a single-track vehicle model [12]:

$$A_y \cong \dot{\beta}V_x + \dot{\psi}V_x + A_x\beta; \Rightarrow \dot{\beta} \cong \frac{A_y}{V_x} - \frac{A_x\beta}{V_x} - \dot{\psi}; \quad (1)$$

Equation (1) allows estimating the vehicle sideslip angle β from the measurements of the longitudinal and lateral accelerations (A_x , A_y), of the yaw rate ($\dot{\psi}$) and of the longitudinal speed V_x . The main concern when using equation (1) is related with the integration process, which usually leads to numerical drift when applied to measured signals. To avoid integration drift, a high-pass filter with a cut-off frequency of 0.5Hz was applied. Swept sine steer maneuvers in fact present an harmonic content ranging from 0.5 Hz to 2.5. As an example of the obtained results, Figure 3 shows the comparison between the sideslip angle estimated using eq. (1) and the one measured by the optical sensor during a slalom maneuver on dry asphalt. A good agreement can be noticed, even if a low-pass filtering effect is introduced with the integration process.

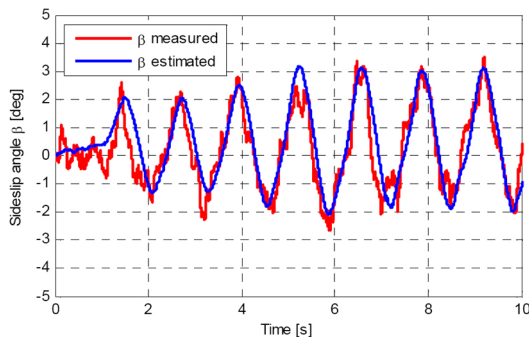


Figure 3. Comparison between estimated and measured sideslip angle on dry asphalt

Once estimated the vehicle sideslip angle, the slip angle of the front left tire α_{LF} can be easily obtained as:

$$\alpha_{LF} = \arctan\left(\frac{V\beta + a\dot{\psi}}{V - c\dot{\psi}}\right) - \delta; \quad (2)$$

In eq. (2) a represents the distance between the front axle and the vehicle c.o.g., c is the front half track of the vehicle and δ is the steer angle.

The time histories of the estimated slip angle and of the measured lateral force (F_y) of the front left tire are compared in Figure 4. A swept sine steer maneuver at 50 km/h (well below the hydroplaning speed of 85 km/h) is considered. The harmonic content of both the signals gradually increases from 0.5 Hz up to 2 Hz. Amplitude of the tire slip angle ranges between $1\div4^\circ$, while amplitude of the lateral contact force remains almost constant and equal to 2 kN. A symmetric behavior can be noticed during left and right turns. A phase shift can be easily observed, slightly increasing with frequency.

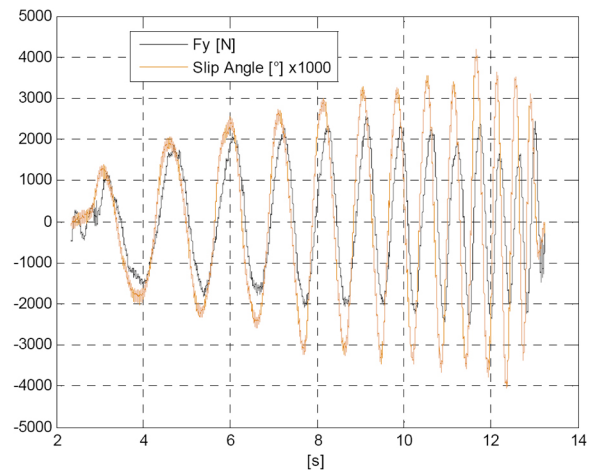


Figure 4. Time history of the slip angle [$^\circ \times 1000$] and of the lateral force [N] at 50 km/h.

Figure 5 depicts the slip angle and the lateral contact force of the front left tire during a swept sine steer maneuver carried out at the hydroplaning speed (85 km/h). The slip angle, even at this speed, presents a symmetric behavior during rear and left turns, showing a peak amplitude close to 4° . An asymmetric behavior can instead be noticed for the lateral contact force. For positive slip angles, peak values of 2 kN can be noticed, while for negative slip angles peak values of 1 kN are reached.