IOP Conference Series: Materials Science and Engineering

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To cite this article: M Failli *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1275** 012039

Scooter Tire Pressure Influence on a Hard Braking Manoeuvre

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Abstract. The mortality of road accidents quadruples when, in addition to motorists, a motorcyclist is also involved. The higher mortality is influenced by the greater exposure of the rider to injuries during the impact. This problem can be mitigated by reducing, even slightly, the impact's speed. Bench tests carried out by previous studies showed a considerable influence of the inflation pressure on the properties of motorcycle tires. It could therefore have significant effects on the deceleration achievable under braking. This study aimed to evaluate the effect of inadequate tire inflation pressure (excessive or insufficient) on the average deceleration achievable during a hard braking manoeuvre performed only with the rear wheel and with ABS intervention. Experimental tests were carried out on a Piaggio Beverly S 300 in a controlled road environment closed to traffic. Different inflation pressures of the rear braking tire were tested during multiple runs. The data were acquired through a smartphone used as an IMU. At the nominal pressure of 2.4 bar the measured average deceleration was 3.69 m/s^2 (SD = 0.12 m/s^2). When increasing the pressure to 3.0 bar and decreasing it to 1.8 bar the average deceleration was reduced respectively to 3.67 m/s^2 (-0.8%, SD = 0.10 m/s^2) and 3.59 m/s^2 (-3.0%, SD = 0.16 m/s^2). The reduction in achievable deceleration was partly mitigated by the reduced load transfer on the rear tire, which partially compensated for the reduction of the braking force coefficient. The results showed that a moderate inflation pressure variation on the rear braking tire modestly influences the achievable average deceleration.

1. Introduction

Powered Two Wheelers (PTW) riders have a much higher chance of severe body injuries than car drivers. Exposure of one's body during road accidents significantly determines the mortality rates associated with such events. Statistically, riders have a 2.7 times higher death rate than motorists (1.9 compared to 0.7 deaths every 100 accidents). [1]

More than 69% of motorists' accidents involve a frontal collision of a PTW with other vehicles or obstacles. [2] Reducing the speed at which such impacts occur would significantly reduce the severity of the injuries. One of the factors we can act upon is the entity of the deceleration achievable by the rider: a more effective braking manoeuvre will mitigate the impact effects.

Among the multiple factors that may influence the achievable deceleration while braking, the inflating pressure of the tires is one that the rider can easily control and, as suggested by previous studies, should play a role in tire behaviour.

1.1. Existing Literature on Tire Pressure Influence

Previous studies have partially examined the correlation between tire inflation pressure and its behaviour.

The study by Mahdi Ajami et al. [3] analysed how an insufficient tire pressure setting influences a car's stopping distance: experimental tests were conducted with an ABS-equipped car on dry asphalt. Only lower than nominal inflating pressures were tested, which reduced the stopping distance from the set speeds of 90 km/h and 100 km/h.

The study by Atul Bansal et al. [4] tested, using computer simulations, the influence of various pressure settings applied to the front and rear tires of a PTW on its stopping distance from the set speed of 72 km/h. No experimental counter-proof tests were carried out.

The tests reported in the study by Vittore Cossalter et al. [5] examined the variations in the lateral response of PTW tires when changing various parameters, one of which is the inflation pressure. No investigation on the longitudinal dynamics was made.

Although multiple studies have already been conducted on this topic, none experimentally analysed the effect of tire inflation pressure on the braking performance of a PTW.

2. Methods

In order to investigate this aspect, the average deceleration of a Piaggio Beverly S 300 Scooter was evaluated during the stationary phase of the hard braking manoeuvre. An experimental activity was conducted to gather acceleration data that were post-processed and analysed in the MATLAB environment.

2.1. Experimental Procedure

Three rear-tire pressure levels were tested: 1.8 bar, 2.4 bar, and 3.0 bar; for each pressure setting, five runs were carried out for a total of 15 runs. During the experiment, the front tire was set to the nominal pressure recommended by the scooter manufacturer (2.4 bar).

For each run, the longitudinal acceleration (a_{long}) was recorded to derive its average value ($\bar{a}_{\mathrm{long}}$); it would be consequently averaged with the results obtained within a pressure set to calculate $\mathrm{mean}(\bar{a}_{\mathrm{long}})$ with improved accuracy.

2.2. Test Protocol

Before every set of runs, the rear tire was inflated to 0.2 bar above the pressure of the given run and consequently deflated to the run pressure to overcome the inaccuracy caused by any hysteresis phenomenon in the inflator pressure gauge.

The run consisted of accelerating from a standstill condition up to 50 km/h followed by a sudden hard braking manoeuvre concerning the rear wheel only that led to the complete stoppage of the scooter.

At the beginning of each run, the asphalt temperature near the expected braking point was measured. The IMU logged the longitudinal acceleration during each run and stored it on MATLAB Drive.

2.3. Instrumentation

The instrumentation used was an Android smartphone (Motorola Moto Z2 Play) running the MATLAB Mobile application and used as an affordable alternative to a professional-grade IMU. The device recorded the longitudinal acceleration of the vehicle with a 100 Hz sample rate. The smartphone was connected to the scooter through a 3D-printed fixture (Figure 1).

The asphalt temperature was measured through the HT 3301 infrared thermometer (Figure 2), always in the same region of the tarmac, for consistent measurement. Every measured value was rounded off to the nearest unit.

The pressure measurements were made with an analog manometer (Figure 3), meeting the ANSI 40.1 B (±2%) standard. It was also used to set the required pressure for each set of runs making use of its release valve.

Two cameras recorded the experiment: the first one was placed on the edge of the testing area (Figure 4), keeping the whole test field in the frame, and the second camera was fixed to the rider's helmet (Figure 5), focusing on the cockpit of the scooter (the brake levers and the instrument cluster were visible). The recordings of both cameras were used for qualitative data analysis and subsequent reference.

Figure 1. 3D-printed fixture

Figure 2. HT 3301 infrared thermometer

Figure 3. Manometer

Figure 4. Wide field camera

Figure 5. Helmet camera

2.4. Data Processing

Raw data were processed in MATLAB to obtain the average deceleration during each run.

Denoise. The logged longitudinal acceleration had noticeable high-frequency noise due to external causes such as engine vibrations, asphalt roughness, and electronic disturbances. A low-pass filter with a cut-off frequency of 1Hz was used to obtain a cleaner signal (Figure 6). Its effect did not negatively affect the results since the noise component, having a high frequency, had a null mean value over the intervals of interest. Therefore, removing it from the raw data did not influence the calculated average longitudinal acceleration.

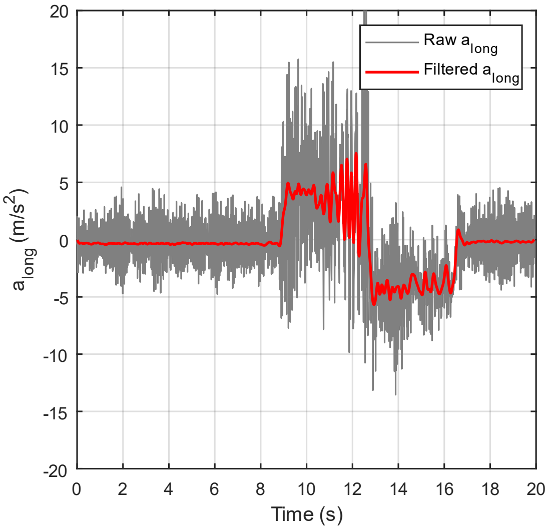

Figure 6. Signal denoise

Calibration. In steady conditions, the IMU did not lay level with the ground leading to an altered reading of the longitudinal acceleration. A component of the gravity acceleration projected along the y-axis of the IMU, resulting in an additive offset error. In order to compensate for said behaviour, a calibration was performed by calculating the average of the y-axis acceleration recorded in the samples from 50 to 500 (during the initial steady phase of each run). This quantity was subtracted from the data (Figure 7).

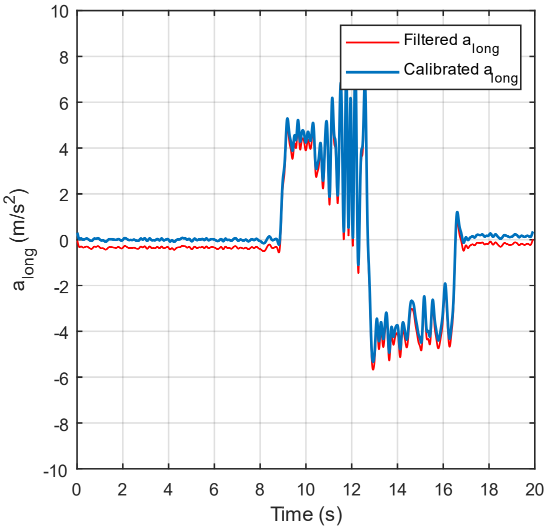

Figure 7. Signal calibration

Region of Interest (ROI) Identification. The stationary phase of the braking manoeuvre was considered to calculate the average longitudinal acceleration. This way, the effects of the initial and final transients were excluded. The ROI spanned from 0.2 s after the minimum peak of registered longitudinal acceleration up to 0.5 s before the positive acceleration peak generated by the rebound of the scooter suspensions (Figure 8).

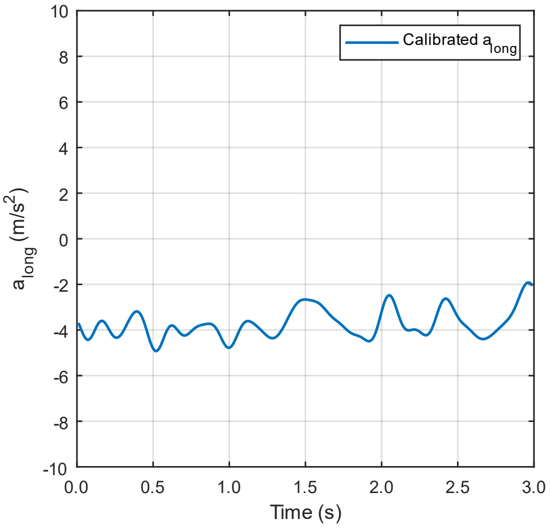

Figure 8. Region of interest

Average Longitudinal Acceleration Calculation. The mean of the acceleration values inside the ROI was calculated as the average longitudinal acceleration of each run.

Statistics of Values. The mean and standard deviation of the obtained averages were compared for each of the three pressure values.

T-test. A T-test was performed to check for the null hypothesis validity to investigate the results' meaning further. If the test was positive, the data did not provide enough information to state that the observed behaviour in the sample also existed in the population. In this case, the obtained averages might have come from normal distributions with equal means and equal but unknown variances.

Average Braking Force Coefficient Calculation. The average vertical load on the rear tire was calculated using the formula:

$$\bar{N}_{\mathrm{rear}} = mg\frac{l_1 + h_{\mathrm{G}}\frac{\bar{a}_{\mathrm{long}}}{g}}{l}, \tag{1}$$

where $\bar{N}_{\mathrm{rear}}$ was the average vertical load on the rear tire calculated for each run, m was the total mass of the PTW and the rider (including his safety equipment), g was the gravity acceleration, $\bar{a}_{\mathrm{long}} < 0$ was the average longitudinal acceleration calculated for each run, l_1 was the front wheelbase of the scooter, l was the wheelbase of the scooter and h_{G} was the height of the centre of mass. The parameters' values are shown in Figure 9 and summarised in Table 1. [6]

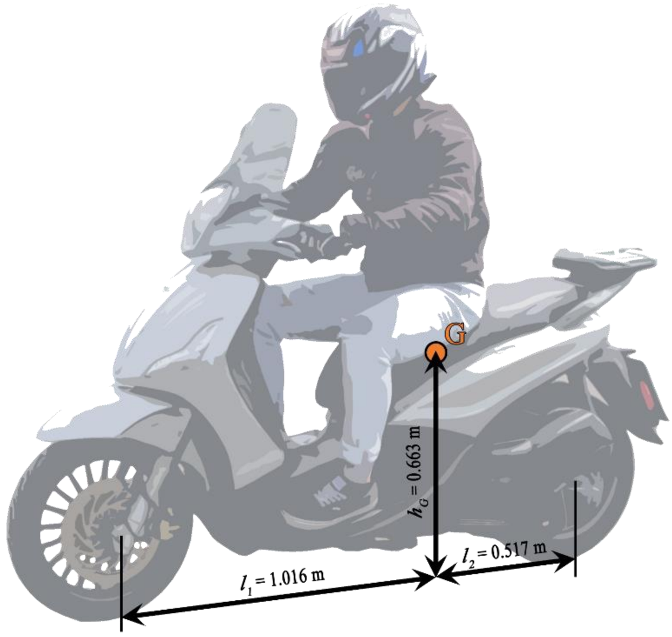

Figure 9. Centre of mass position

Table 1. PTW parameters

Parameter	Value
PTW mass	187 kg
Pilot mass	90 kg
Wheelbase (l)	1.53 m
Front wheelbase (l_1)	1.02 m
Rear wheelbase (l_2)	**0.52 m**
Center of mass height (h_G)	**0.66 m**

The average braking force coefficient was calculated for each run using the formula (2), and the obtained values were averaged among every pressure set.

$$\bar{\mu} = \frac{\bar{F}_{\text{long}}}{\bar{N}_{\text{rear}}} = \frac{m\bar{a}_{\text{long}}}{mg\dfrac{l_1 + h_{\text{G}}\dfrac{\bar{a}_{\text{long}}}{g}}{l}} \tag{2}$$

Where $\bar{\mu} < 0$ is each run's average braking force coefficient, and $\bar{F}_{\text{long}} < 0$ is the longitudinal braking force calculated for each run.

3. Results

Figure 10 shows the longitudinal acceleration recorded during Run no.3 at low inflating pressure. The run can be divided into four phases:

1. *Initial steady phase*. The scooter was not moving; the acceleration measured in this phase was used for the calibration process.
2. *Acceleration phase*. The scooter accelerated at an approximately constant rate, up to 50 km/h.
3. *Braking phase*. The scooter was decelerating due to the hard braking manoeuvre; the recorded longitudinal acceleration was approximately constant except for the peaks caused by the ABS intervention (marked by red dots).
4. *Final steady phase*. The scooter was not moving; the run was complete.

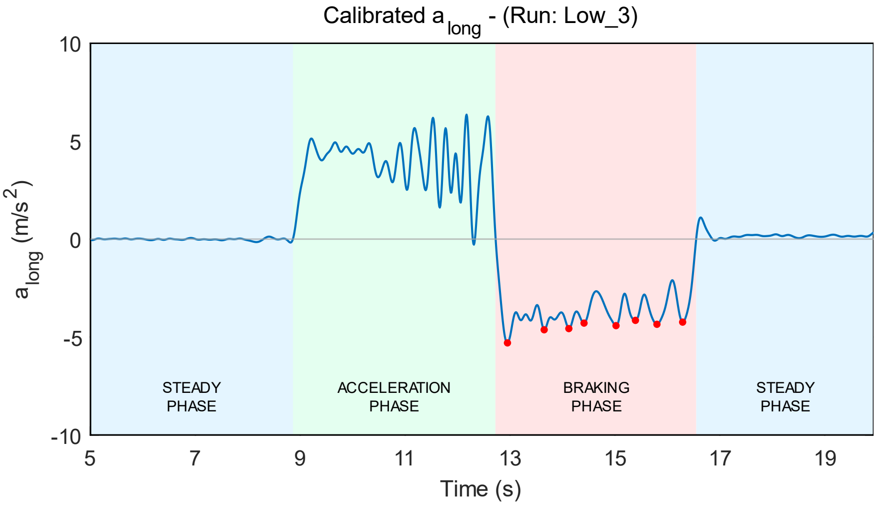

Figure 10. Acceleration logged during Run no.3 at low pressure (1.8 bar)

The results (Table 2) showed that the highest mean deceleration was achieved with the nominal tire pressure (2.4 bar), with a -3.69 m/s^2 mean and a 0.12 m/s^2 standard deviation. On the other hand, for the lower (1.8 bar) and higher (2.3 bar) pressure, we obtained means of respectively -3.58 m/s^2 and -3.66 m/s^2 with a standard deviation of 0.16 m/s^2 and 0.10 m/s^2. Underinflation reduced the magnitude of the average longitudinal acceleration by 3.0% compared to the nominal condition, while overinflation resulted in a 0.8% reduction.

The average braking force coefficient followed a similar behaviour to the average longitudinal acceleration. At nominal pressure, the mean was -0.75; in the underinflation and overinflation cases, it was -0.72 (-3.8% magnitude) and -0.74 (-1.0% magnitude).

Table 2. Results and statistics

Pressure	mean($\bar{a}_{\text{long}}$)	$\sigma\bar{a}_{\text{long}}$	$\Delta(\text{mean}\,\lvert\bar{a}_{\text{long}}\rvert)$ From Nominal	mean($\bar{\mu}$)	$\Delta(\text{mean}\,\lvert\bar{\mu}\rvert)$ From Nominal
(bar)	(m/s^2)	(m/s^2)	(%)	(-)	(%)
1.8	-3.58	0.16	-3.0	-0.72	-3.8
2.4	-3.69	0.12	-	-0.75	-
3.0	-3.66	0.10	-0.8	-0.74	-1.0

4. Discussion

The results showed a modest, albeit measurable, magnitude reduction of the achievable average deceleration. However, comparing the moderate difference among the obtained mean($\bar{a}_{\text{long}}$) values to the calculated standard deviations, a student's T-test was performed before concluding. With the significance level set to 5%, the test did not reject the null hypothesis, assuming that the obtained averages came from normal distributions with equal means and equal but unknown variances; therefore, the observed behaviour might not exist in the population. Previous bench tests conducted to analyse the lateral dynamics of scooter tires showed modest variations in tire behaviour when changing the inflation pressure in the range we tested (1.8÷3.0 bar). It is, therefore, plausible that similar, approximately invariant behaviour was observed in the results we obtained for the longitudinal dynamics tests. The same study also reveals that, with more significant pressure differentials, the lateral response of the tire worsened in a non-linear manner, both with insufficient and excessive inflation pressure.

A trend was visible in the standard deviation, which decreased while increasing the inflating pressure. This phenomenon could be linked to the reduction of the contact area between the tire and the asphalt.

The percentage variation of the average braking force coefficient was higher than the variation in average longitudinal acceleration. This result was expected and is explained by the fact that the former is also affected by the vertical load on the tire, which in turn varies with the load transfer caused by the longitudinal acceleration. The variation, albeit more notable than the one in the longitudinal acceleration, was still modest.

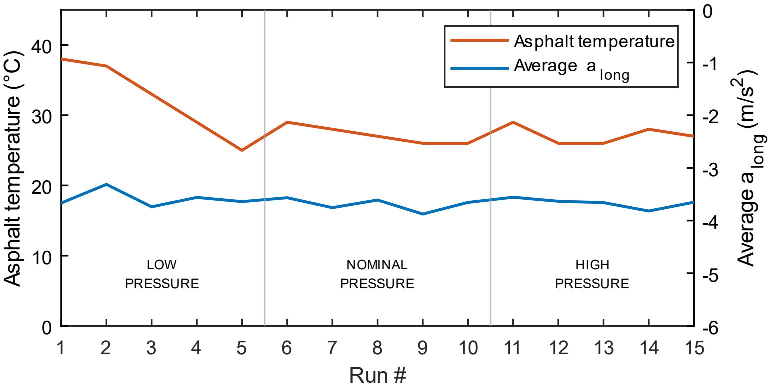

Figure 11. Asphalt temperature measurements of each run

During the experiment, the asphalt temperature changed due to the Sun irradiation, leading to a 13°C difference between the highest and lowest measured temperatures (+38°C and +25°C, respectively). A qualitative analysis showed no evident influence of the asphalt temperature on the achieved average deceleration (Figure 11).

5. Conclusion and Perspectives

Due to the small entity of the measured acceleration differences, considering the calculated standard deviation obtained for each of the three pressure values and with the support of the performed T-test, we cannot assert that the evaluated pressure differentials (±0.6 bar) measurably affected the braking performance of the performed straight-line hard braking manoeuvre.

As the tire pressure increases, the descending trend appreciable in the standard deviation values (Table 2) suggests that the achieved average deceleration value is more consistent among runs, resulting in a more predictable braking performance.

Future studies may be conducted in different conditions or with other objectives. When braking with the front wheel only, said wheel is subjected to an increase in the vertical force due to the load transfer. Such a situation is the opposite of what was analysed in this experiment. With a more significant pressure difference between the nominal and the excessive/insufficient values, as discussed above, the non-linear relation between tire pressure and its lateral dynamics should also imply a more appreciable variation in the results regarding the longitudinal dynamics. When altering the pressure of the rear tire, during the straight-line hard braking manoeuvre, the riding feel was not affected, probably because the change effects remained confined to the rear frame. Changing the inflating pressure of the front tire would likely impact the riding feel, particularly the steering torque and responsiveness, due to its influence on the steering assembly. These changes might influence the rider's behaviour during a hard braking manoeuvre, especially in an emergency.

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