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The measurement of dynamic radii for passenger car tyre

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Abstract. The tyre dynamic rolling radius is an extremely important parameter for vehicle dynamics, for operation of safety systems as ESP, ABS, TCS, etc., for road vehicle research and development, as well as for validation or as an input parameter of automotive simulations and models. The paper investigates the dynamic rolling radii of passenger car tyre and the influence of rolling speed and inflation pressure on their magnitude. The measurement of dynamic rolling radii has been performed on a chassis dynamometer test rig. The dynamic rolling radii have been measured indirectly, using longitudinal rolling speed and angular velocity of wheel. Due to the subtle effects that the parameters have on rolling radius magnitude, very accurate equipment has to be used. Two different methods have been chosen for measuring the wheel angular velocity: the stroboscopic lamp and the incremental rotary encoder. The paper shows that the stroboscopic lamp has an insufficient resolution, therefore it was no longer used for experimental investigation. The tyre dynamic rolling radii increase with rolling speed and with tyre inflation pressure, but the effect of pressure is more significant. The paper also makes considerations on the viability of simplified formulae from literature for calculating the tyre dynamic rolling radius.

1. Introduction

The dynamic radius of rolling tyre is an extremely important parameter for vehicle dynamics, for operation of safety systems as ESP, ABS, TCS, etc., for road vehicle research and development, as well as for validation or as an input parameter of automotive simulations and models. The dynamic rolling radius is influenced by many factors, determined not only by the tyre, but also by the working conditions, such as inflation pressure, load, speed etc. [1]. The study of influencing parameters is essential also for controlling the operation of tyre pressure monitoring systems [2].

The study of the rolling speed influence on tyre dynamic rolling radii is rarely mentioned in literature; the few existing investigations [3], [4] are mainly concerning large tractor tyres with limited speed range.

The authors have extended experience in tyre-road phenomena research and modelling, and they have frequently needed very accurate information about the tyre dynamic rolling radii. The paper investigates through experiments the dynamic rolling radius defined according to [5], and the influence of rolling speed and inflation pressure on the dynamic rolling radii of passenger car tyre.

2. Experimental setup

The measurement of dynamic rolling radii has been performed for a passenger car tyre, in laboratory conditions, using a chassis dynamometer in the Automotive Engineering Department of the University POLITEHNICA of Bucharest. A Dacia Logan, equipped with tyres Bridgestone Turanza ER300, 185/65R15 88H, has been installed with the wheels of the front axle rolling on the dynamometer rollers, as it can be seen in Figure 1.

The tyre rolling on the drum has a slightly curved contact patch, which is different compared to the real rolling conditions, thus influencing the tyre dynamic rolling radii to some extent. Despite this fact, the mentioned influencing parameters (inflation pressure and rolling speed) affect in the same way the tyre dynamic rolling radii.

The dynamic rolling radii r_d have been measured indirectly, using two input parameters: longitudinal rolling speed V and angular velocity of wheel ω, as expressed in equation (1). Due to slight effects that the influencing parameters have on the dynamic rolling radius magnitude, very accurate equipment has to be used.

$$r_d = \frac{V}{3.6 \cdot \omega} \ [m] \tag{1}$$

The longitudinal rolling speed has been precisely controlled and measured using the MAHA AIP ECDM chassis dynamometer in the "constant velocity" mode, as shown in Figure 2. The passenger car front wheels have been driven by the chassis dynamometer.

Figure 1. Passenger car used for experimental research on the chassis dynamometer

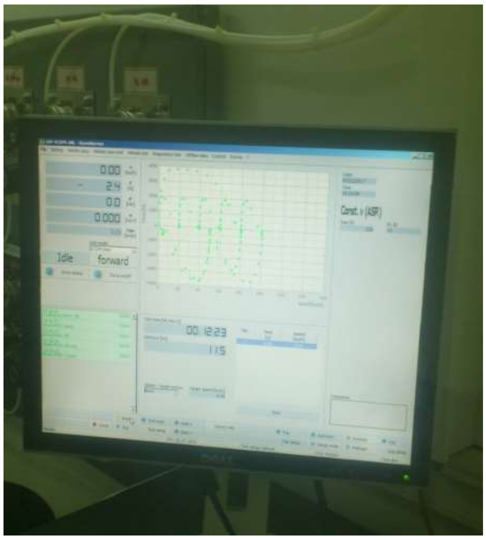

Figure 2. Measurement of rolling speed using the chassis dynamometer

Two different methods have been chosen for measuring the wheel angular velocity: the stroboscopic lamp and the incremental rotary encoder. The equipment used for measuring the wheel angular velocity through the two different methods is shown in Figure 3. The stroboscopic lamp method allows measuring the wheel angular velocity without contact, but requires a visible mark traced on the passenger car tyre. The incremental rotary encoder needs to be mounted on the rim nuts using a special flange with hexagonal adapters, and also needs to be attached to the car body using a mounting system with suction cups. The pulse signal has been recorded using a counter on the data acquisition card National Instruments USB-6211 and a LabVIEW application, shown in Figure 4.

Tyre inflation pressure has been measured using a pressure gauge with digital display, having a resolution of 1 kPa, shown in Figure 5. The tyre pressure has been adjusted after warm-up before each measurement and has been checked after performing the tests.

Measurements have been performed at different values of tyre inflation pressure, between 140 kPa and 260 kPa, and at different values of rolling speed, between 20 km/h and 120 km/h.

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Figure 3. Measurement of wheel angular velocity using the stroboscopic lamp and the rotary encoder

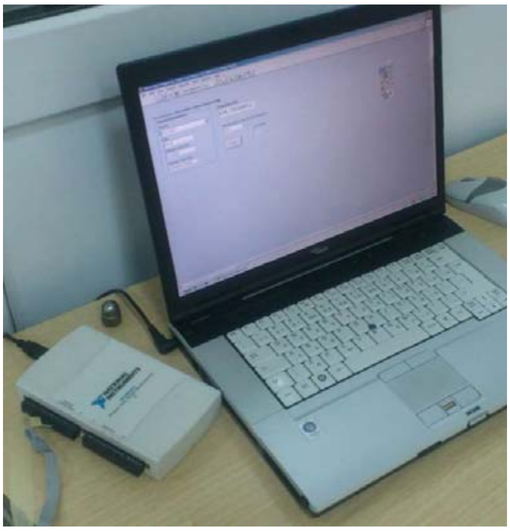

Figure 4. Data acquisition system for measuring wheel angular velocity

Figure 5. Measurement of tyre inflation pressure using a pressure gauge with digital display

Tyre temperature has an important effect on inflation pressure, and consequently all the measurements have been performed in quasi-stationary conditions, after a time of rolling for warm-up.

3. Measurement results

3.1. The resolution depending on the measurement method

The resolution of the stroboscope method is 1 rev/min. The resolution of the encoder method, recorded through measuring system, is theoretically of 1 Hz. Due to rolling tyre and wheel vibrations, this better resolution can practically be read only at lower speeds. At higher speeds, the resolution of encoder method is 5 Hz or even 10 Hz.

The resolution of dynamic rolling radius is obtained from the previous mentioned values, but taking into consideration the speed values obtained from rollers of chassis dynamometer. The resolution depends both on the speed and on the tyre inflation pressure, as shown in Table 1.

Analysing the data in Table 1, some conclusions could be drawn referring to the measuring resolution of stroboscope method:

- considering that the variation in dynamic rolling radius is small depending on speed and tyre inflation pressure, the resolution values obtained are insufficient;
- the resolution of dynamic rolling radius is strongly influenced by the speed, providing better values at higher speed;
- the tyre inflation pressure has a very slight influence on the resolution of dynamic rolling radius, better resolution values being obtained at lower pressure.

Table 1. Resolution of the dynamic rolling radius measurement

Inflation pressure (kPa)	Speed (km/h)	Dynamic rolling radius resolution (mm)	
		stroboscope method	encoder method
140	20	1.67	0.10
140	100	0.34	0.10
260	20	1.70	0.10
260	100	0.34	0.10

Analysing the measuring resolution of encoder method, some conclusions could be drawn:

- the resolution of encoder method remains relatively constant, regardless of speed and tyre inflation pressure;
- a resolution of 0.1 mm allows investigating the influence of speed and tyre inflation pressure on the tyre dynamic rolling radius.

Comparing the resolution values obtained through the two different methods, it can be observed that the encoder method provides a resolution at least three times better than the stroboscope method.

Figure 6 gives an example of the influence of resolution on the dynamic rolling radius measurement. The compared results have been obtained by simultaneously measuring through the two different methods.

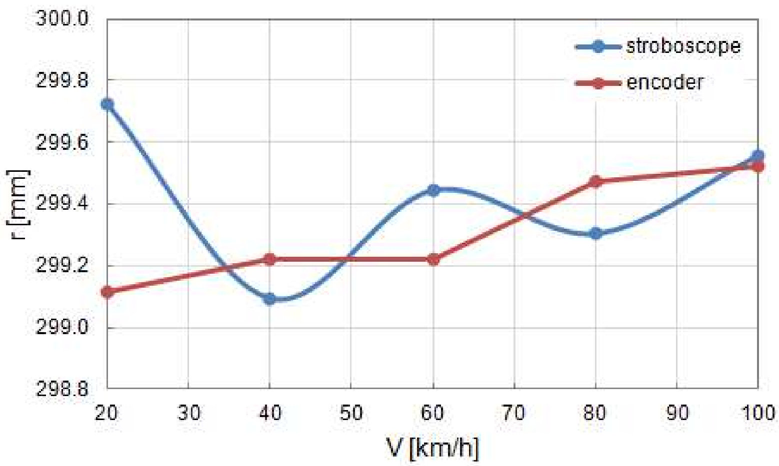

Figure 6. Comparative example of dynamic rolling radius measurement through the two methods

The dynamic rolling radii are similar at 100 km/h, since the stroboscope method provides better resolution values at higher speed. When speed decreases, the differences between the results of the two methods tend to increase, so the most important gap, of 0.6 mm, occurs at 20 km/h. This gap is about one third of the resolution of stroboscope method at the mentioned speed (about 1.7 mm according to Table 1), and consequently the measured value is uncertain. The sign of the difference between results of the two methods varies, thus at some speeds the difference is positive, at other speed values it is negative.

The resolution of the stroboscope method does not allow highlighting the influence of speed and tyre inflation pressure on the dynamic rolling radius, because the errors generated by insufficient resolution are higher than the effect of changing the rolling speed. However, it can be noticed that the resolution of the encoder method allows emphasizing the increase in dynamic rolling radius due to growing rolling speed and tyre inflation pressure. Therefore, from this point, the paper analyses only the results obtained using the encoder method.

3.2. The influence of rolling speed and inflation pressure

The measured values of dynamic rolling radius are presented in Figure 7 as a function of rolling speed. The speed has been adjusted between 20 km/h and 120 km/h, in steps of 20 km/h. Measurements have been performed at several values of tyre inflation pressure, between 140 kPa and 260 kPa.

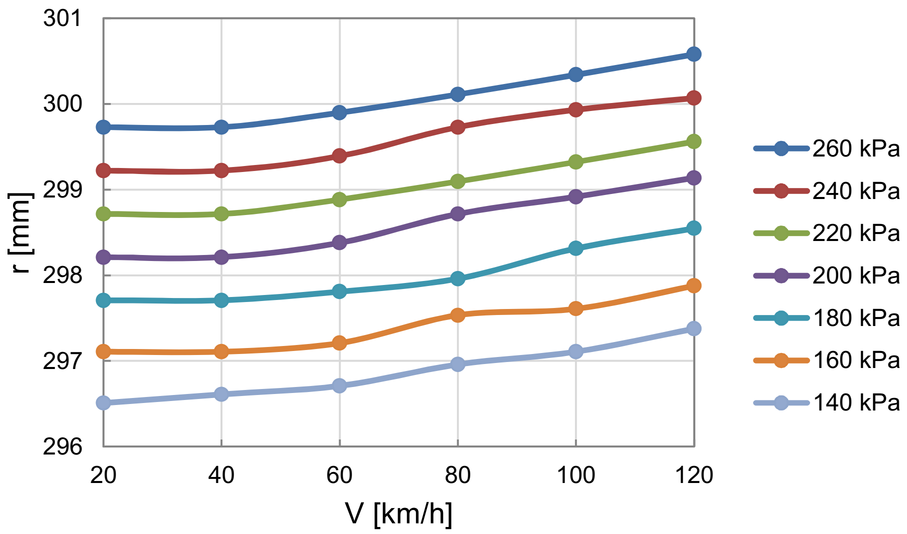

Figure 7. The influence of rolling speed on the tyre dynamic rolling radius measured at different inflation pressures

The values of dynamic rolling radius at 20 km/h and 40 km/h tend to remain constant or change insignificantly, but at rolling speeds above 40 km/h they tend to increase with speed. In some cases, such as those measured at 220 kPa and at 260 kPa, a linear behaviour is noticed, but the rest of the curves are slightly nonlinear, which could be caused by the encoder method resolution.

The absolute and relative increases of dynamic rolling radius corresponding to a growth of rolling speed from 20 km/h to 120 km/h are presented in Table 2. The increase of dynamic rolling radius has absolute values between 0.77 mm and 0.92 mm, therefore the stroboscope method would not allow accurately detecting the variation of dynamic rolling radius.

Table 2. Increase of dynamic rolling radius due to changing rolling speed from 20 km/h to 120 km/h

Inflation pressure (kPa)	Increase of dynamic rolling radius	
	absolute (mm)	relative (%)
140	0.86	0.29
160	0.77	0.26
180	0.84	0.28
200	0.92	0.31
220	0.84	0.28
240	0.85	0.28
260	0.85	0.28

The increase of dynamic rolling radius has relative values between 0.26 % and 0.31 %, although the speed increases six times, from 20 km/h to 120 km/h. Therefore, for all the considered values of inflation pressure, the rolling speed has a very small influence on the tyre dynamic rolling radius.

The measured values of dynamic rolling radius are presented in Figure 8 as a function of inflation pressure. The inflation pressure has been adjusted between 140 kPa and 260 kPa, in steps of 20 kPa. Measurements have been performed at several values of speed, between 20 km/h and 120 km/h.

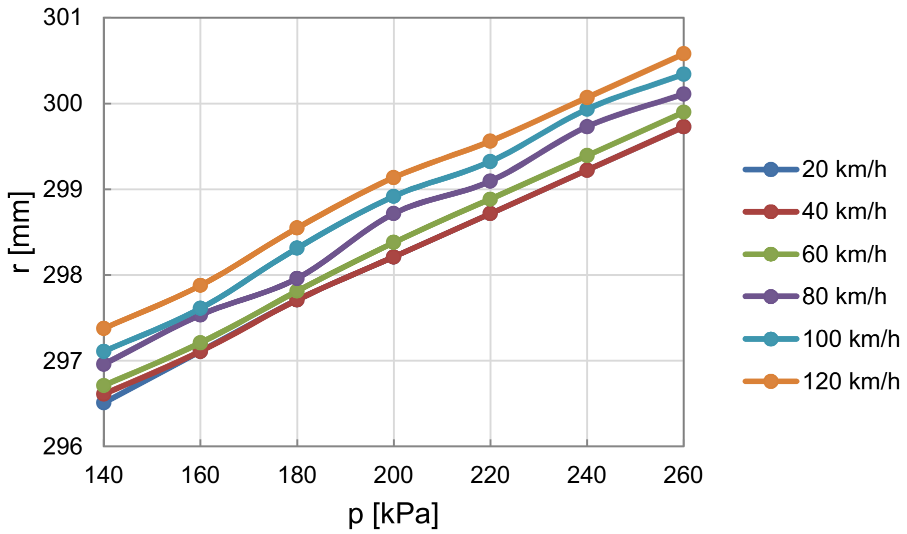

Figure 8. The influence of inflation pressure on the tyre dynamic rolling radius measured at different rolling speeds

The values of dynamic rolling radius clearly increase when inflation pressure is increased. Although several of the measured curves are linear, there are also some cases in which a slightly nonlinear behaviour is noticed, such as those measured at 80 km/h and at 100 km/h, possibly because of the encoder method resolution. It can be seen that the curves measured at 20 km/h and 40 km/h are overlapping and that they are almost linear.

The absolute and relative increases of dynamic rolling radius corresponding to a growth of inflation pressure from 140 kPa to 260 kPa are presented in Table 3, for all the considered values of speed.

Table 3. Increase of dynamic rolling radius due to changing inflation pressure from 140 kPa to 260 kPa

Speed (km/h)	Increase of dynamic rolling radius	
	absolute (mm)	relative (%)
20	2.71	0.91
40	2.61	0.88
60	2.68	0.90
80	2.77	0.93
100	2.82	0.95
120	2.69	0.91

The increase of dynamic rolling radius due to changing inflation pressure from 140 kPa to 260 kPa has absolute values between 2.61 mm and 2.82 mm, and these results are almost independent of speed.

When the inflation pressure is changed by ± 30 % with respect to the nominal value, the increase of dynamic rolling radius has relative values ranging between 0.88 % and 0.95 %, therefore close to 1 %. It can be asserted that, for all the considered values of rolling speed, the inflation pressure has an important influence on the tyre dynamic rolling radius.

The measured values of dynamic rolling radius are presented in Figure 9 as a function of both rolling speed and inflation pressure.

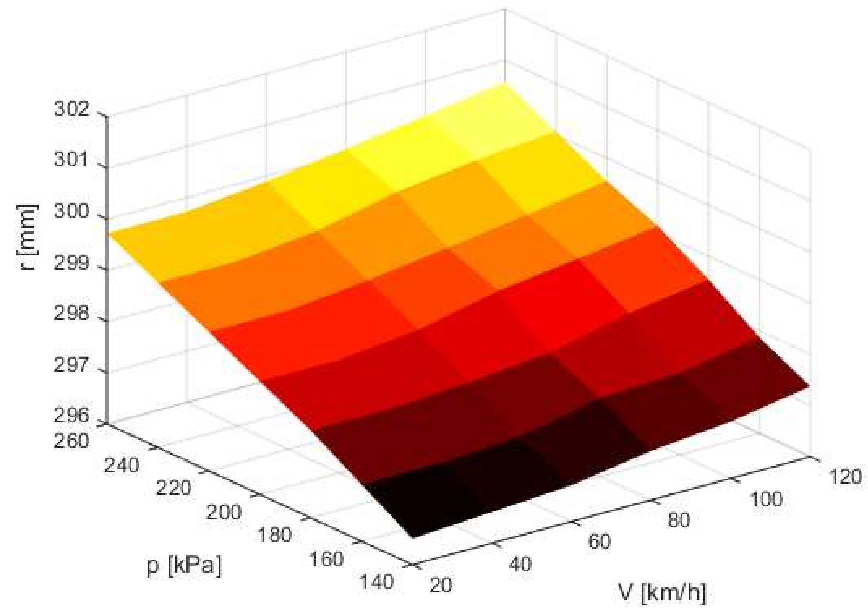

Figure 9. The influence of rolling speed and inflation pressure on the tyre dynamic rolling radius

It can be noticed that the influence of inflation pressure on the measured tyre dynamic rolling radius is stronger than the influence of rolling speed, with absolute values almost three times larger, although the speed changes up to six times while the inflation pressure is changed by only ± 30 % with respect to the nominal value.

3.3. Aspects regarding validation of technical knowledge

The tyre catalogue corresponding to the investigated tyre [6] includes specifications based on which the dynamic rolling radius can be calculated, obtaining the value of 301.4 mm. Comparing with the results shown in Figure 9, it can be observed that all the results for tyre dynamic rolling radius are smaller than that mentioned above. The main reason refers to the cylindrical shape of the tyre contact patch achieved on chassis dynamometer rollers, which leads to dynamic rolling radii smaller than those obtained when rolling on the real roads.

Another aspect concerns checking the validity of the equations (2.38) from [7] and (2.28) from [8] (but also from other references) which provide an approximate calculus for the tyre rolling radius:

$$r_r = \lambda \cdot r_0 \tag{2}$$

where λ is the tyre deformation coefficient, ranging from 0.930 to 0.935 for low pressure tyres, and from 0.945 to 0.950 for high pressure tyres, and r_0 is the tyre unloaded radius [7], [8].

For the tyre tested in this paper, the catalogue indicates an unloaded radius of 310.5 mm. When equation (2) is applied for the tested tyre, dynamic rolling radii of 288.8 mm to 295.0 mm are calculated. Irrespective of the terminology referring to the tyre radius definitions, the calculated values are considerably smaller than those obtained experimentally and shown in chapters 3.2 and 3.3. Taking into consideration that in real rolling conditions the tyre dynamic rolling radii are greater than those on the chassis dynamometer, the tyre radii calculated with equation (2) are significantly lower than in reality. This aspect shows the inadequacy of results obtained using equation (2) as input parameter for analytical and numerical tyre / automotive models.

In the book [9], the value of 0.98 is indicated for the coefficient λ that leads to 304.3 mm dynamic rolling radius, which is closer to the experimental values.

4. Conclusions

Since almost every researcher uses different definitions for the same radius, it is useful to unify the terminology in terms of tyre radii.

The tyre dynamic rolling radii measured on the drum are smaller than those measured in the real rolling conditions because of the slightly curved contact patch generated by the drum. Despite this fact, the tyre dynamic rolling radii are influenced by the inflation pressure and rolling speed in the same manner as they would be on the road.

Indirect measurements allow measuring the tyre dynamic rolling radii. The resolution of the stroboscope method does not allow highlighting the influence of speed and tyre inflation pressure on the dynamic rolling radius, as the resolution of measuring method should be smaller than 0.1 mm. The pressure gauge should have a resolution of at least 1 kPa to allow accurately adjusting the inflation pressure.

The tyre internal pressure for rolling tyre changes in time and with rolling speed. For obtaining valid results, quasi-stationary conditions are required for the measurements.

Many references give simplified formulae for calculating the tyre dynamic rolling radius, but calculated results do not match the real values.

The values of dynamic rolling radius slightly increase with speed. The values of dynamic rolling radius clearly increase with inflation pressure. The influence of inflation pressure on the measured tyre dynamic rolling radius is almost three times larger than the influence of rolling speed.

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