Assessing the Impact of the Change in the Tire Pressure on the Rolling Resistance and Fuel Consumption

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ABSTRACT

The value of tire pressure affects a number of important vehicle features. The article pays attention to assessing the impact of the change in the tire pressure on both the rolling resistance and fuel consumption. The measurements were performed with four different values of tire pressure. The impact of the change in the tire pressure on the rolling resistance was measured during the driving tests. In order to measure the rolling resistance during tests, the measurement methodology was devised and a device for measuring the rolling resistance was constructed. The measurement of the impact the tire pressure change on the fuel consumption was performed via vehicle dynamometer. The result showed a linear dependence between the tire pressure and rolling resistance. These results measured points to the importance of keeping the correct value of the tire pressure in relation to the fuel consumption.

Keywords: tire pressure, fuel consumption, rolling resistance.

INTRODUCTION

The value of tire pressure affects its stiffness [1, 2], lifespan as well as the vehicle stopping distance [3, 4, 5], its directional stability and performance while running [6, 7, 8,]; additionally, it influences the noisiness of driving [9, 10], the value of rolling resistance together with the value of fuel consumption [11, 12] and many other aspects that affect the level of driving safety and economy [13, 14, 15]. Such value of tire pressure is not stable, since it varies throughout its lifetime according to various factors. These include the tire inflation after being mounted on a rim, gradual tire pressure reduction resulting from leakages, and so on. The manufacturer defines a correct tire pressure; however, the owners, drivers or mechanics are responsible for its maintenance. Since 1.11.2012, all the new vehicle models in the European Union, and since 1.11.2014, all the vehicles constructed in the European Union, including the models produced before 1.11.2012, have to be equipped with a tire pressure monitoring system, known as TPMS [16]. However, the

information indicating that one of the tires does not have the pressure prescribed by the manufacturer does not mean that the drivers are to remedy it. The TPMS function is also connected with some problems such as battery life in the sensors located on the wheel valves or the necessity of calibration after each wheel replacement if the TPMS system is gaining the data from the ABS [17]. In practice, drivers do not carry out these duties and are driving with the low tire pressure indicator constantly alight. According to [18] 68% of vehicles is driven with low tire pressure, while 21% comprises the vehicles with a tire pressure of 180 kPa up to 160 kPa, and 27% with pressure of 160 kPa up to 110 kPa. Similar research can be also seen in [19] according to which up to 80% of vehicles do not have the prescribed tire pressure while driving. The tire pressure value affects the size of tire deflection during its rolling. Thus, part of the energy delivered to the engines and taken from the fuel is consumed for a tire to be rolled. The lower tire pressure, the higher tire deflection and the higher energy from the fuel needed for tires to be rolled [20].

Table 1. Tire energy efficiency class depending on the RRC value [22]

RRC in kg/t	Energy efficiency class
RRC ≤ 6.5	A
6,6 ≤ RRC ≤ 7.7	B
7,8 ≤ RRC ≤ 9.0	C
Empty	D
9.1 ≤ RRC ≤ 10.5	E
10.6 ≤ RRC ≤ 12.0	F
RRC ≥ 12.1	G

However, the deflection rate and the value of rolling resistance, although significant. are not only affected by the pressure in the tire alone. There are many other factors such as tire construction, materials used and so on that have certain influence on the tire deflection rate, as well as on the value of rolling resistance [21]. According to [22], the tire manufacturers are obliged to label the tires according to their energy efficiency class. Table 1 shows the division of tires for passenger vehicles into particular energy efficiency classes, according to the value of rolling resistance coefficient (RRC).

The values from Table 1 relate to the tire inflated to the prescribed pressure. At a certain load, a tire causes some rolling resistance. The purpose of the measurements was to find out the difference in the value of the tire rolling resistance in case that a tire pressure has changed. When the rolling resistance coefficient is changed, and thus – the value of rolling resistance – it is assumed that the fuel consumption will change as well. Hence, the difference in the tire pressure can also lead to a theoretical difference in the tire energy efficiency.

The measurements in this article were divided into two parts.

The first part comprises measuring of the change in rolling resistance based on the change in the tire pressure. The measurements were performed by a driving test with different

Table 2. The weight of particular wheels of vehicle during measurements

Wheel	Wheel weight [kg]	Axle weight [kg]
Left front	400	780
Right front	380	
Left rear	500	920
Right rear	420	

tire pressures via measuring the force needed for a vehicle to be towed.

The second part comprises measuring of the change in fuel consumption depending on the value of rolling resistance measured in the first part. The measurement results demonstrate the impact rate of the change in tire pressure on the rolling resistance as well as fuel consumption.

MEASUREMENT METHODOLOGY

The main goal of the measurements was to quantify the rate of change in the rolling resistance and the impact of change in the rolling resistance on fuel consumption depending on the tire pressure. The vehicle used for measurements was Škoda Fabia 1.9 TDi, 66 kW, engine code AGR. The vehicle tires were Continental Winter Contact TS 860 with size of 195/65 R15 91 T. The energy efficiency class of tires is "C" and the depth of the tread was approximately of 6 mm during measurements. The prescribed tire pressure was given in the value of 230 kPa. The values of rolling resistance and fuel consumption were determined at the tire pressures of 150 kPa, 190 kPa, 230 kPa and 260 kPa.

The load on particular wheels and axles during measurements is given in the Table 2. The loads were gained by means of Portable weighing system PW-10 with weighing accuracy of ± 10 kg per wheel [22].

As seen from the Table 2, the vehicle weight was 1700 kg during measurements.

The measurements can be divided into two parts. The first part is the measurement of the rolling resistance based on the tire pressure and the second part is the measurement of the change in the fuel consumption caused by the change in the rolling resistance.

The quantification of change in the rolling resistance was performed via driving tests. The principle of measuring was to measure the force needed for the vehicle to be towed with specific tire pressures. The positions while measuring the change in the rolling resistance caused by the change in the tire pressure are displayed in the Figure 1.

The position 1 symbolizes the vehicle towed, and the position 4 symbolizes the flange attached to the bumper beam. The dynamometer is under the number 6, and it was screwed to the towing bar which can be seen under the number 7. The towing bar was through the coupling device seen

Fig. 1. Measurement of the change in the rolling resistance value as a function of tire pressure change

under the number 8 attached to the tow vehicle marked by the number 9.

Such composition for the vehicle to be towed and tractive force to be measured had to enable the mutual vehicle asymmetry both horizontally and vertically while manipulating with vehicles. At the same time, the coupling device had to be located to the vehicle axis of gravity as far as possible in order to avoid the occurrence of parasite forces. In order to meet these requirements, joining the couple device with tow vehicle was done via bracket attached to the bumper beam and joint. Figure 2 displays in detail how is the coupling device attached to the tow vehicle.

As seen from the Figure 2, the position 1 symbolizes the tow vehicle to which is via bracket 3 that is screwed to the bumper beam 2 attached the towing bar seen under the number 7. Joint 5 enables mutual horizontal and vertical asymmetry of the vehicle. The device under the number 6 is a dynamometer reading the force in the device used for the vehicle to be towed.

During the measurement, the vehicle with a certain pressure in all 4 tires was towed by the towing vehicle with a constant speed on the trajectory of 400 m long. While towing, a force needed for the vehicle to be towed was recorded via dynamometer (Figure 2, position 5) and further, through the IPRE software communicating with the dynamometer, it was recorded at the frequency of 20 times per second. In order to avoid the impacts, the vehicle was towed uphill with a gradient of about 2%. This led to the fact that the towing vehicle had to make its tractive force constantly as well as the vehicle towed did not tend to get closer to the tow vehicle as a result of its inertia. Thus, it avoided the impacts in a tractive system. The driving tests through towing have always been performed under the same conditions with the same weight of vehicle towed. Thus, the value of other driving resistances was constant during all the driving tests, and the only driving resistance that varied was the rolling resistance due to change in the tire pressure.

The driving tests per particular tire pressures were repeated 5 times and the average value was calculated subsequently.

The change in fuel consumption caused by the change in the tire pressure and in the rolling resistance was measured on the MAHA MSR 1050 vehicle dynamometer. The main advantage of it is that other factors influencing the fuel consumption during the measurements through driving test, such as wind, road unevenness and so on are avoided. The MAHA MSR 1050 vehicle dynamometer enables a simulation of driving resistances via braking, or moving of dynamometer cylinders by a certain force. The measurements were performed at the driving speeds of 50 km·h^{-1}

Fig. 2. Detail of coupling device

and 80 km·h⁻¹ on 5 km long trajectory for each measuring. While driving at the speed of 50 km·h⁻¹, the third and fourth transmission gears were used, and at the speed of 80 km·h⁻¹, the fourth and fifth transmission gears used. Before measuring, it was necessary to insert the values of particular driving resistances into the dynamometer computer. The rolling resistance was calculated according to the relation:

$$O_r = m \cdot g \cdot CRR \qquad (1)$$

Where: O_r – rolling resistance [N], m – vehicle mass [kg], g – gravitational acceleration, [m·s⁻²], CRR – rolling resistance coefficient [-] [24].

The relation used to calculate the air resistance was as follows:

$$O_a = 0.5 \cdot \rho \cdot c_x \cdot S \cdot v^2 \qquad (2)$$

Where: O_a – air resistance [N], ρ – the specific air mass. 1.29 kg/m³ at 0 °C and pressure of 0.101325 MPa, c_x – the body shape coefficient [-], S – the size of vehicle front face [m²], v – the vehicle driving speed [m/s] [25].

The sum of driving resistances for the driving speed of 50 km·h⁻¹ was rounded to 200 N. At the same time, the effect of the change in the tire pressure was studied at the driving resistances of 100 N.

The sum of driving resistances with the driving speed of 80 km·h⁻¹ was 323 N. The value of the change in the rolling resistance caused by the change in the tire pressure at their lowest and highest points was added to the driving resistances.

The fuel consumption was determined through the VAG V.C.D.S 11.11.1. diagnostic software which is communicating with the engine control unit. The consumption is given in [l·h⁻¹], and therefore it needs to be converted into [l·100 km⁻¹] as usual. The first step was to calculate the fuel consumption per one second:

$$Q_s = Q_h/3600 \qquad (3)$$

Where: Q_s – the fuel consumption [l·s⁻¹], Q_h – the fuel consumed [l·h⁻¹]

Further, it was necessary to calculate the fuel consumed for the whole time of measurements:

$$Q_c = Q_s \cdot t \qquad (4)$$

Where: Q_c – the fuel consumed [l], t – time of measuring [s]

The last step comprised the calculation of fuel consumption in [l·100 km⁻¹] according to the formula:

$$Q_{100} = Q_c/s \cdot 100000 \qquad (5)$$

Where: Q_{100} – the fuel consumption [l·100 km⁻¹], Q_c – the fuel consumed [l], s – the trajectory of measurements [m]

RESULTS

The differences in the rolling resistance caused by the change in tire pressures are given in Table 3 .

The rolling resistance in the tires inflated to the pressure of 230 kPa that is prescribed by the manufacturer is considered as basic, and therefore signed as "0".

The difference between the rolling resistance in the tire with pressure of 260 kPa and of 150 kPa amounted to 49.6 N.

The impact of such change in the rolling resistance on the fuel consumption can be seen in Table 4.

Table 4 shows how the change in the tire pressure as well as the rolling resistance, affected the fuel consumption. The change in fuel consumption was not the same at each stage of measurement, since it varied from +4.3% up to +10.2%. While driving at the speed of 50 km·h⁻¹, the difference in the fuel consumption measured was higher than while driving at the speed of 80 km·h⁻¹. Such uneven change in the fuel consumption can be the result of the changes in specific fuel consumption and the share of the rolling resistance change on the overall driving resistance [26].

Changing into another transmission gear, together with the change in the value of the driving resistances, affected the engine load, which in turn influenced the value of specific fuel consumption. However, there was an increase in the fuel consumption due to the increase in the rolling resistance at each of the measurement.

While measuring, the tires used were of "C" energy efficiency class. It means that the value of rolling resistance coefficient "f" varies from 0.0078 up to 0.0090, as also seen in the Table 1. With interval f = 0.0084 and the vehicle mass substituted into the relation 4, and when avoiding mechanical resistances, it can be assumed that the value of rolling resistance would be of 140 N. The

Table 3. Difference in the rolling resistance due to different tire pressure

Tire pressure [kPa]	150	190	230	260
Difference in rolling resistance [N]	+17.8	+6.7	0	-31.8

Table 4. The impact of the change in the rolling resistance on the fuel consumption

Number of measurement	Driving speed [km·h⁻¹]	Transmission gear	Driving resistances [N]	Fuel consumption [l·100 km⁻¹]	Difference [%]
1	50	3	100	4.06	+9.6
			149.6	4.45	
2	50	4	100	2.75	+10.2
			149.6	3.03	
3	50	3	200	4.57	+7.2
			249.6	4.90	
4	50	4	200	3.31	+9.4
			249.6	3.62	
5	80	4	323	4.88	+4.3
			372.6	5.09	
6	80	5	323	4.08	+5.9
			372.6	4.32	

mechanical resistances can be avoided due to the neutral gear used in the vehicle towed since these resistances were of very low values. By deflating the tires down to the pressure of 150 kPa, the rolling resistance increased from 17.8 N to 157.8 N. When substituting again, it is possible to notice that the rolling resistance coefficient has reached the value of 0.0094 corresponding to the tire's energy efficiency class "E". By inflating the tires up to the pressure of 260 kPa, the rolling resistance decreased by 31.8 N, in comparison with the rolling resistance at the tire pressure of 230 kPa. Here, the tire rolling resistance is f = 0.0064 meaning it is of "A" energy efficiency class.

CONCLUSION

The article pointed out to the importance of having the correct tire pressure from the point of view of rolling resistance and fuel consumption. As seen from the measurements, a decrease in the tire pressure leads to an increase in the rolling resistance. The vehicle engine must perform some work in order to overcome the rolling resistance. Therefore, it is necessary to deliver a certain amount of energy from fuel to the engine, and thus, while increasing the rolling resistances, it the fuel consumption needs to be increased as well.

Such increase is also connected with higher emission production. Every litre of diesel fuel consumed leads to the production of at least 2.7 kg of CO_2 which is known as a major contributor to the global warming [27]. Driving with the tire pressure that is lower than its prescribed value

given by the manufacturer, thus, results in an unnecessary production of CO_2. It is important to keep the right value of tire pressure not only for the economic reasons but for the ecological issues concerning the emission production. Besides, driving with low tire pressure also leads to an unnecessary use of non-renewable fuels.

On the basis of the results from Table 3, it is possible to recommend driving with higher tire pressure than prescribed by the manufacturer, since there has been a decrease in the rolling resistance as well as fuel consumption (Table 4). However, the tire pressure does not only affect the rolling resistance, it also has impact on many other important aspects such as tire traction and lifespan, stopping distance, surface stability and so on [28]. Thus, intentionally increasing the tire pressure over the level recommended by the manufacturer, as well as its decreasing, would not be appropriate.

Changing the tire pressure led to such a change in the value of rolling resistance coefficient that the tire did not correspond to the values of the energy efficiency class according to which it had been classified [16]. During the measurements, decreasing the tire pressure caused such an increase in the rolling resistance that the tire of energy efficiency class "C" corresponded to the class "E". On the other hand, increasing the tire pressure would improve the tire energy efficiency to the level of "A". On the basis of these theoretical findings, it may be said that when purchasing the tires with energy efficiency class "A" that usually requires a higher purchase price, and driving with low tire pressure, it is possible to come into the state when the tire would be classified into the

energy efficiency class "C". Besides these, the effect of increasing the fuel consumption while driving with low tire pressure can be ranked as a less dangerous factor.

The measurement results were also affected by the vehicle used for measuring, specifically for the fuel consumption measuring. This compression ignition engine vehicle had relatively large volume of 1.9 l. In the case of using a spark ignition engine vehicle with lower volume, a substantial difference in the fuel consumed would be assumed.

The dependence between the tire pressure, rolling resistance and fuel consumption had a linear development. Similar results can be also seen in the publication [29] in which the measurements were performed according to the methodology from the SAE J1269 standard test that enables a simulation of any tire pressure and any tire load.

All of the measurements of rolling resistance from this article were performed while driving at the same speed. In the case of measuring at higher driving speeds, a slightly higher rolling resistance may be assumed. However, an increase in the rolling resistance would be the same at each tire pressure as also seen in the publication [11] in which the results represent the measurements simulated at the driving speeds falling within 70 km·h^{-1}.

The tire pressure is important from the various points of view and, therefore, it requires appropriate attention and maintenance.

Acknowledgments

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