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INFLUENCE OF LOAD AND INFLATION PRESSURE ON THE TYRE ROLLING RESISTANCE

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ABSTRACT– Tyre load and inflation pressure are important factors controlling rolling resistance of road vehicles. The article presents results obtained in the Technical University of Gdańsk during laboratory and road measurements of different car tyres rolling on different pavements. The knowledge of rolling resistance characteristics is important for modelling car dynamics as well as fuel consumption. It is also necessary to establish proper test conditions in the future standardized on-road method of measuring rolling resistance. The results indicate that while an increase of load always leads to the increase of rolling resistance force, the influence on Coefficient of Rolling Resistance is more complicated and unpredictable. They also indicate that tyres with high rolling resistance are more sensitive to inflation pressure changes than low rolling resistance tyres.

KEY WORDS : Tyres, Rolling Resistance, Inflation Pressure, Load, Measuring Standard

NOMENCLATURE

C_{RR} : coefficient of rolling resistance

F_{RR} : rolling resistance force, N

F_L : tyre load, N

1. INTRODUCTION

Tyre rolling resistance is one of the most important parameters characterizing the interaction between tyres and road surfaces. Under certain traffic conditions (low and moderate constant speed driving) rolling resistance may be responsible for up to 25-30% of the energy consumption of the vehicle (Ejsmont, Świeczko-Żurek, Ronowski, 2014). The more energy is consumed by a moving vehicle, the higher the cost of transport and the greater emissions of CO_2 as well as other toxic compounds is. Furthermore, in the case of electric vehicles, it results in a smaller practical operating range as, in contrast to vehicles with combustion engines, the renewal of energy in these vehicles is very time consuming.

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Most of the energy dissipation in running tyre is due to the hysteretic losses (Lee *et al,* 2014) that are dependent on tyre deflection thus on load and inflation pressure. This paper discusses issues related to the impact of load and tyre inflation pressure on rolling resistance of passenger cars. Information regarding these issues, available in literature, is not comprehensive. Most often it is assumed that the rolling resistance coefficient C_{RR} expressed by the formula (1) is independent of the load which is not necessarily true. It is well known that reducing the inflation pressure increases rolling resistance, but there is no knowledge of whether the increase is similar for all tyres and all kinds of road pavements. One of the reasons, is difficulty in performing the measurements of rolling resistance, especially in road conditions. The knowledge of the effect of pressure and load on the tyre rolling resistance is important for the optimization of vehicle operation, modelling vehicle dynamics and technical development of tyres and road pavements. This knowledge is also very important for the work associated with the creation of standardized test methods for rolling resistance measurements on the road. At the moment there are no international standards describing road measurements of rolling resistance as opposed to laboratory tests which have been already standardized (SAE J1269, 2006; ISO 18164, 2005; ISO 28580, 2009). Wrongly established standardized load and inflation pressure requirements can lead to insufficient accuracy of the measurements, and even the lack of representativeness. In 2013 the 7th Framework Programme project ROSANNE was launched with intention to prepare all the necessary background for future standardized method of rolling resistance measurements.

$$C_{RR} = \frac{F_{RR}}{F_L} \tag{1}$$

For issues related to standardization of test methods not only the absolute values of load and inflation pressure are critical, but also the conditions under which the inflation pressure is measured and set. Some methods, such as ISO 28580, require that the pressure must be set before the measurement (so called "capped" or "cold" inflation), when the tyre has ambient temperature. In the case of ISO standard, ambient temperature is set to 25°C while in SAE standards it is set to 24°C. In contrast to the ISO 28580 method, the procedure recommended by the SAE J1269 in case of multi-point "Alternate" measurements requires that the inflation pressure must be regulated after stabilization of the temperature of the tyre during operation (so called "regulated" or "warm" inflation). Similarly, standard ISO 18164 requires capped inflation adjustment for basic tests and regulated inflation for optional tests.

For many years certain industrial products have been marked with labels informing about their impact on the environment. According to the Regulation of the European Parliament tyres are divided into three classes for which there are different demands related to the labels. EC Regulation 1222/2009 requires that tyre labels contain indicators evaluating tyres in terms of fuel efficiency (rolling resistance), wet grip and external noise. Each tyre class has specific values of the reference parameters. Rolling resistance must be tested according to ECE Regulation No. 117 that specifies drum method of measurements and smooth steel surface. The regulation requires that class C1 (for passenger cars) tyres must be loaded to 80 % of maximum load capacity and inflated to 210 kPa (capped inflation pressure). In real life situations both the load and inflation of tyres usually differ from the standard values, thus it is important to investigate the influence of the load and inflation on tyre rolling resistance.

There are several studies of load and inflation pressure influence on tyre rolling resistance (e.g., Pillai, 2004; Gusakov *et al*, 1977) . However, they were performed on smooth steel drums instead of real road surfaces or their replicas. Smooth steel is not the best surface to investigate tyre rolling resistance characteristics, as the road surface texture has a very important influence on tyre/road interaction. The authors are also not aware of any comprehensive investigation of load and/or inflation influence performed on the road by the trailer method. The above triggered the idea to perform such measurements within ROSANNE project.

2. TEST METHODS AND MEASURING DEVICES

Tyre rolling resistance may be measured by several methods (Ejsmont, Świeczko-Żurek, 2014; Sandberg *et al*, 2012). In general, measurement methods are divided into laboratory and road methods. The laboratory methods utilize roadwheel facilities with drums, usually of external type, that is drums where tyres roll on outer surface of the drum. There are only a few exceptions where inner drums are used. ISO and SAE standards require that drums have smooth steel surface or that they are covered by material similar to the sandpaper with "80" grit. This is a significant limitation for the representativeness of these methods, because neither smooth steel surface, nor sandpaper "80" have a texture similar to the texture of typical road surfaces. It is generally not possible to use real road surfaces on external drums due to centrifugal force that tears away the surface. Only inner drums are immune to this problem and may be "paved" with real road surfaces as the centrifugal force helps to keep the surface in right position.

In some roadwheel facilities, including three facilities at the Automotive Group of the Technical University of Gdańsk (TUG), replica road surfaces casted or laminated with polyester or epoxy resins are used. To manufacture such replicas it is necessary to use complex system of forms, utilizing semi-flexible "negatives" of road pavements. Roadwheel facilities that were used for investigations reported in this article are shown in Fig. 1 and Fig. 2.

Measurements of rolling resistance on roadwheel facilities can be done in several ways, including direct measurement of the forces on the wheel axle. Two other common methods are: measurements of the torque required to maintain the rotation of the test drum with constant angular velocity and coast-down (deceleration) of the drum. Roadwheel facilities of TUG presented in Fig. 1 and Fig. 2 use torque method, which in the opinion of the authors, is the most practical and accurate.

Road measurements are much more complicated than laboratory testing, because of an increased number of confounding factors that may cause substantial errors, often in excess of the measured values (Ejsmont, Taryma, Ronowski, 2008). Two road methods are the most popular. The first one is based on the coast-down of the vehicle (at certain speed "neutral" is selected in the gearbox and the vehicle slows down due to resistive forces). Deceleration of the vehicle moving under the

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force of inertia after disconnecting the drive is monitored and used for calculations of the rolling resistance force. The second method is the so-called trailer method with the test tyre mounted on a special test vehicle (usually the trailer). In this method the rolling resistance force is measured during constant speed driving directly in the wheel hub or indirectly in the certain parts of its suspension. There are only a few trailers in the world that may be used for rolling resistance measurements, but according to the authors' knowledge only four trailers are used intensively. One of those trailers was built in BRCC (Belgium), one by BASt (Germany) and two by the Technical University of Gdansk. Trailer R^2 Mk.2 built by Technical University of Gdansk and used to study the effect of pressure and tyre load reported here is shown in Fig. 3. This trailer uses a vertical measurement arm and a patented system that compensates for the effect of the longitudinal acceleration and grade of the road. The trailer may accommodate tyres of different sizes (in contrast to BRCC trailer) and may measure a number of consecutive test sections in a single run (in contrast to BASt trailer).

The research presented in this article was carried out on real roads and replica road surfaces connected to the drums that are listed in Tab. 1. Both conventional car tyres and tyres specially designed for electric and hybrid cars were tested (Ejsmont, Świeczko-Żurek, Taryma, 2014). In order to obtain representative results the set of test tyres contained samples that are considered to become reference tyres in future standard, tyres with very high rolling resistance and tyres with exceptionally low rolling resistance. See Tab. 2 for details.

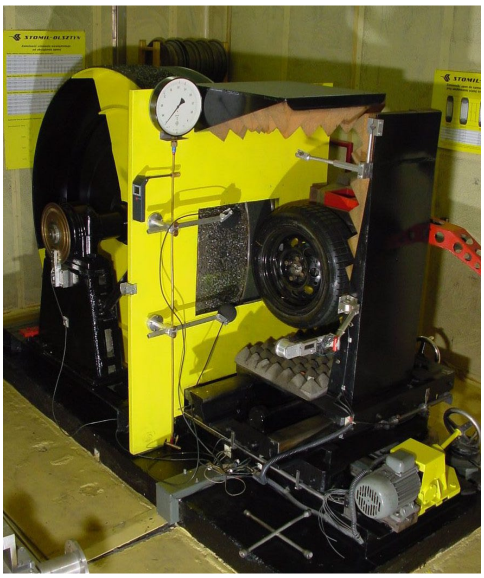

Figure 1. Roadwheel facility at TUG with external drum of 1.7 m diameter.

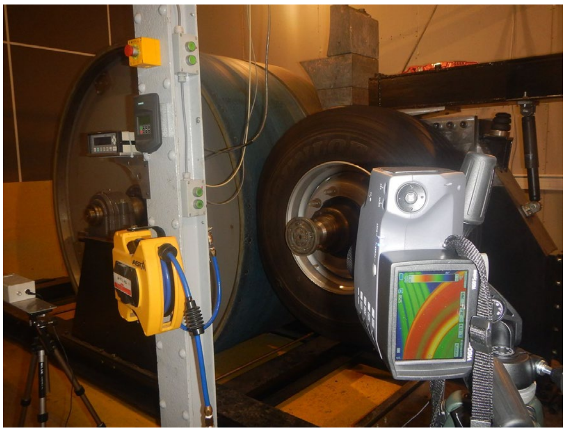

Figure 2. Roadwheel facility at TUG with external drum of 2.0 m diameter.

Figure 3. Trailer R^2 Mk.2 used to measure rolling resistance of passenger car tyres on Stone Mastic Asphalt SMA8.

3. RESULTS OF DRUM MEASUREMENTS

Tyre inflation and tyre load are not independent variables. Higher load requires higher inflation pressure in order to ascertain proper interface between tyre and road surface, good fuel economy as well as optimal resistance to wear and damage. Usually there is no problem to find maximum load for given tyre and corresponding maximum inflation pressure. There is however serious problem to establish proper inflation for partial loads. Tyre pressure selection in the case when the tyre load is below the maximum allowed load can be done by numerous methods described by Daws (2009). Generally all methods give different results so there is no single value of inflation pressure that may be considered "optimal". When tyre is in use, its temperature increases and it leads to the increase of inflation pressure thus "warm" inflation pressure is

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higher. For speed 80 km/h the pressure is usually increased by 5 - 20 kPa if the tyre is rolling for a long enough time. The increase of inflation pressure depends very much on cooling conditions that are controlled by air flow around the tyre.

To obtain a broad view on rolling resistance versus load and inflation relations 5 tyres were tested on the roadwheel facilities at different loads and different inflation pressures. All measurements were performed at ambient temperature of 25±1°C. During the experiments all the tyres were tested at speed 50 and 80 km/h, but as the influence of load and inflation was very similar for both speeds, only the results for 80 km/h are presented in this paper.

Table 1. Road surfaces and replicas used for the experiments.

Symbol	Surface Type	Location	Description
SMA8	Stone Mastic Asphalt, 8 mm aggregate	Highway leading to the airport in Gdansk, Poland	Typical, modern road pavement used in European countries
PERSr17	Poroelastic road surface	Roadwheel Facility 1.7m	Porous surface made on the basis of mineral and rubber aggregate and polyurethane resin. Pavement suitable for road and drum use, very smooth and flexible. Still in developing stage. For more details refer to (Świeczko-Żurek et al, 2014)
DAC16r20	Replica of dense asphalt concrete with 16 mm aggregate	Roadwheel Facility 2.0 m	Polyester laminate replica made on the basis of a typical DAC 16 mm (rather high texture)
ISOr20	Replica of ISO reference surface	Roadwheel Facility 2.0 m	Polyester laminate replica made on the basis of the reference road surface ISO 10844 (average texture)
APS4r17	Replica of surface dressing 8/10 mm aggregate	Roadwheel Facility 1.7m	Polyurethane /mineral replica of a single layer surface dressing 11 mm (very high texture)

Relations between tyre load and rolling resistance forces for two tyres and four replica road surfaces are presented in Fig. 4. For all tested loads the tyres were inflated to 210 kPa in this experiment (regulated inflation). Results for tyre T1077 are marked with solid lines while results for tyre T1063 are marked with dotted lines. It is clearly visible that sensitivity to load changes (slopes of the lines) is much higher for tyre T1063 than for tyre T1077. Since rolling resistance is usually described as Coefficient of Rolling Resistance (see equation 1) it is interesting to investigate how the values of C_{RR} vary with load changes (for constant inflation pressure) - see Fig. 5. In the case of tyre T1077 the coefficients of rolling resistance are fairly independent of load for pavements ISOr20, DAC16r20 and PERSr17, but decrease with load for very rough replica of surface dressing APS4r17. However, the behavior of tyre T1063 is different. For pavement APS4r17 Coefficients of Rolling Resistance are nearly constant, but for other pavements they increase with load. Exact reason of such behavior is not known, but one may speculate that this is related to the enveloping properties of the tyre treads. Tyre T1077 is "All Season" tyre with relatively flexible block that at high loads may better follow shape of the aggressive texture of APS4r17. One must observe that rolling resistance force for all tyres increases with load and only C_{RR} may decrease in certain cases.

Table 2. Test tyres.

Symbol	Manufacturer	Model	Size	Remarks
T1063	Avon	AV4	195R14C	Light truck tyre that is also a reference tyre according to ISO 11819-2
T1064	Michelin	Primacy HP	225/60R1 6	High performance summer tyre
T1075	Continental	Conti. eContact BLUEC O	195/50R1 8	Tyre designed for electric vehicles
T1077	Uniroyal	Tiger Paw	P225/60 R16	Standard Reference Test Tyre (SRTT)
T1093	Nokian	Hakka Green	195/65R1 5	Tyre for conventional and hybrid vehicles

Similar tests were performed for constant load but at variable inflation pressures. The results are presented in Fig. 6 and Fig. 7. The tests were performed for the load of 408 kG (4 000 N) as this load is considered to be "standard" in measurement methodology used by TUG. In all cases the inflation pressure was regulated after the tyre obtained stabile temperature. It was observed, that certain tyres required over 20 minutes of warming period to stabilize inflation and temperature while other tyres stabilized already after 10 minutes of rolling.

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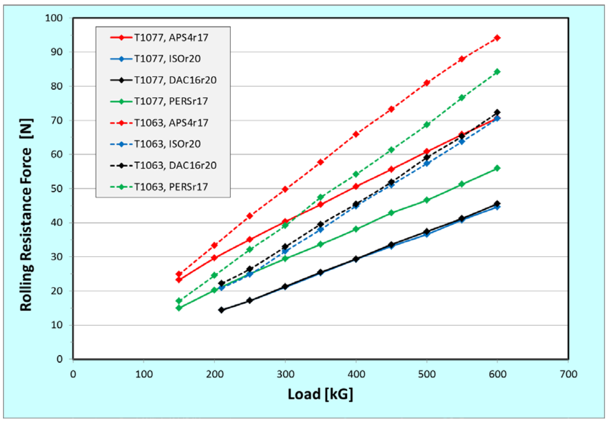

Figure 4. Influence of load on rolling resistance force for tyres inflated to 210 kPa at speed 80 km/h.

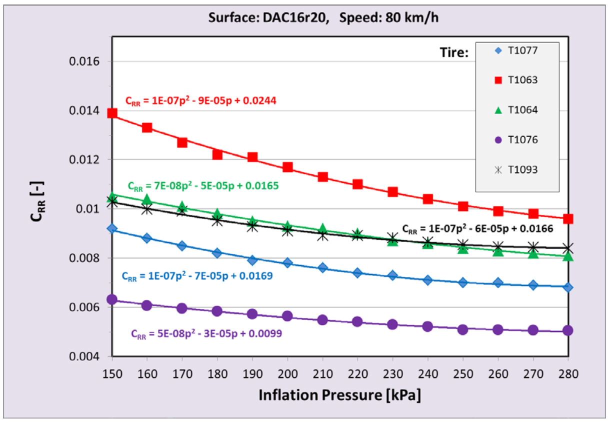

Figure 6. Influence of inflation pressure for different tyres; tyre load 408 kG.

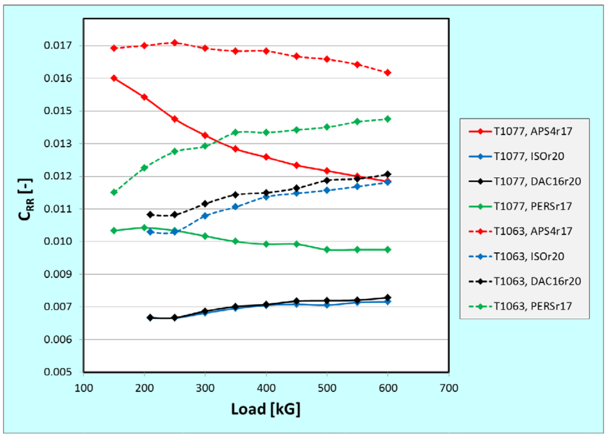

Figure 5. Influence of load on coefficient of rolling resistance for tyres inflated to 210 kPa at speed 80 km/h.

In Fig. 6 tyre rolling resistance versus inflation pressure characteristics of five tyres tested on replica of dense asphalt concrete DAC16 are presented. For all the tested tyres there is a tendency of lowering C_{RR} with increase of inflation pressure, but magnitude of changes ("the slope") is very different. C_{RR} characteristics are well approximated by the second-order polynomial regression lines marked in Fig. 6 and Fig. 7. To compare sensitivity of rolling resistance to inflation pressure changes it is more convenient to substitute second-order polynomial regression with linear regression and investigate the value of the slope. Values of the slope for tyres presented in Fig. 6 are shown in Tab. 3. It is interesting to note, that tyres that exhibit low rolling resistance (e.g. tyre T1076) have lower slope and tyres with high rolling resistance (e.g. T1063) have higher slope, thus are more sensitive to inflation pressure changes. A similar tendency was observed also for other road surfaces.

Table 3. Slope of the linear regression lines (tyres listed according to the ascending absolute values of the slope).

Tyre	T1076	T1093	T1077	T1064	T1063
Slope [1/bar]	- 0.0010	- 0.0014	- 0.0017	- 0.0019	- 0.0032

The relation between the value of C_{RR} at a certain reference inflation pressure and the value of the sensitivity slope was further investigated and a rather strong relation was found - see Fig. 8. Very similar relations were obtained for different reference inflation pressures and other pavements.

In Fig. 7 inflation pressure characteristics obtained for tyre T1077 on different road surfaces are compared. The characteristics may also be approximated by the second-order polynomial regression lines, but the slope is smaller for surfaces that exhibit high values of C_{RR}. This tendency was observed also for other tyres.

Experiments conducted at TUG included also the combined influence of load and inflation pressure on C_{RR}. Selected tyre/pavement combinations were tested according to the matrix: load from 350 to 450 kG with increment of 25 kG and inflation pressure from 170 to 250 kPa with increment of 10 kPa. Characteristic obtained for tyre T1077, which is a Standard Reference Test Tyre with so called all-season tread, and replica of Dense Asphalt Concrete are shown in Fig. 9. For this tyre/road combination an increase in inflation pressure leads to substantial decrease in C_{RR} while an increase in load leads to a very minor increase in C_{RR}. Such a tendency was observed for most of the "conventional" tyres tested on any surface.

Fig. 10 presents characteristics obtained for tyre NOKIAN Hakka Green rolling on replica of very coarse surface dressing designated APS4r17. For this

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tyre/pavement combination an increase in load reduces C_{RR} and an increase in inflation pressure leads only to a minor decrease in C_{RR}.

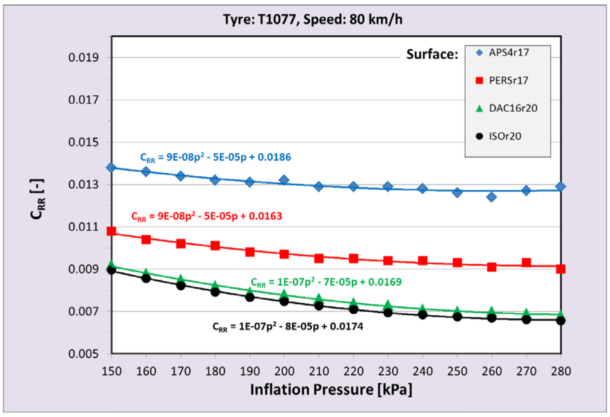

Figure 7. Influence of inflation pressure for different road surfaces; tyre load 408 kG.

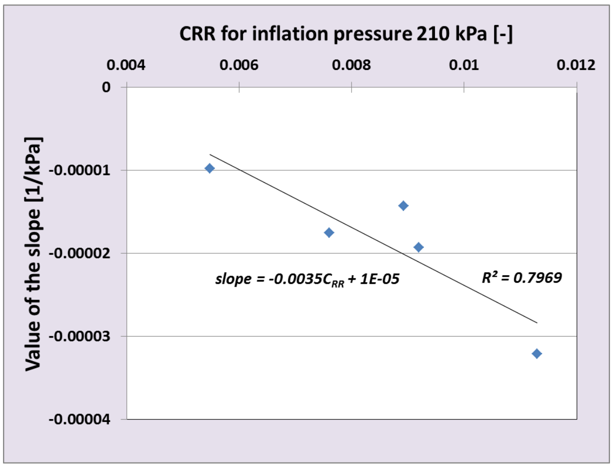

Figure 8. Relation between the sensitivity slope and C_{RR} measured for inflation pressure 210 kPa.

Fig. 11 presents characteristics obtained for tyre CONTINENTAL BluEco rolling on poroelastic road surface PERSr17. For this tyre/pavement combination the C_{RR} is nearly independent of inflation and load. Tests performed in TUG indicate that very low sensitivity of C_{RR} to inflation pressure is a rather typical behavior of tyres specially designed for electric vehicles.

In figures 9 - 11 different colors indicate constant values of C_{RR} (within ±0.0001 range). It is clearly visible that "constant C_{RR} conditions" cannot be predicted basing on any universal rule as the color straps have very unique layouts. Such conditions are different for different tyres.

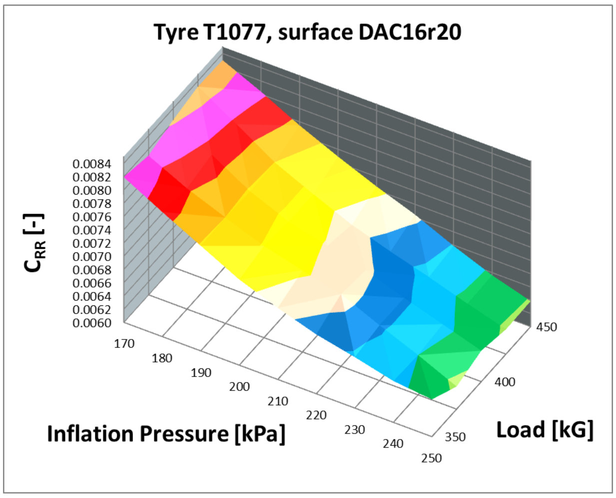

Figure 9. Combined influence of load and inflation for tyre T1077 rolling on replica road surface DAC16r20 at speed of 80 km/h.

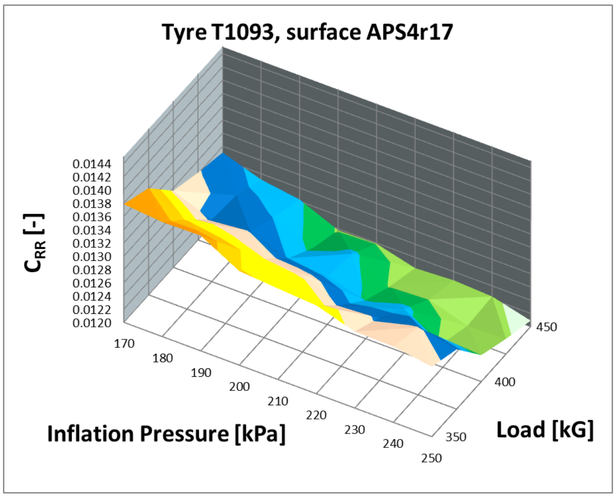

Figure 10. Combined influence of load and inflation for tyre T1093 rolling on replica road surface APS4r17 at speed of 80 km/h.

4. RESULTS OF ROAD MEASUREMENTS

Laboratory tests were validated by road tests performed with R² Mk.2 trailer described above. Road tests were restricted to constant load and variable inflation pressure, as changing of tyre load requires time consuming recalibration of the trailer measuring system. Tests were performed on Stone Mastic Asphalt SMA 8 that is very popular in European countries. In order to avoid temperature corrections, all the tests were performed at the air temperature 22 ± 2°C, at speed 80 ± 1 km/h. Unfortunately drum facilities at TUG are still not equipped with replica road surfaces of SMA8 so

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comparison was done with replica of Dense Asphalt Concrete DAC16r20. It was speculated that pavement DAC16r20 having bigger texture than SMA8 will cause bigger rolling resistance of tyres (Taryma *et al*, 2014). This assumption proved to be correct with the exception of tyre T1063, which has a very aggressive tread and strong carcass construction intended to cope with off-road and snow conditions. This tyre showed very similar rolling resistance on SMA8 and DAC16r20.

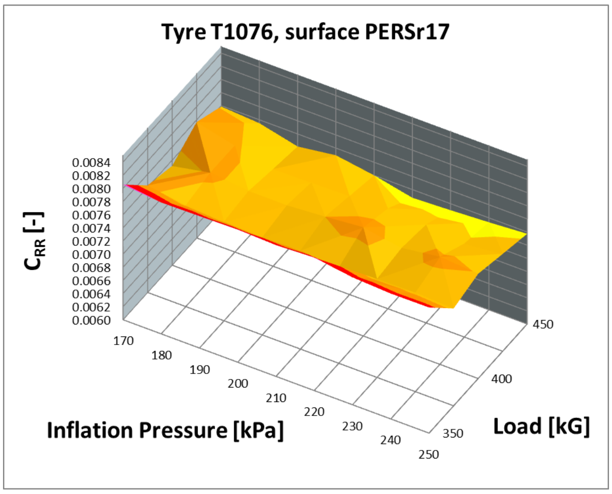

Figure 11. Combined influence of load and inflation for tyre T1076 rolling on replica road surfacePERSr17 at speed of 80 km/h.

In Fig. 12 the results of road and laboratory measurements are compared. For both methods an increase in inflation pressure leads to a decrease in the C_{RR} and the sensitivity slope is very much dependent on absolute values of C_{RR}. Tyres that have very low rolling resistance (that is tyres for electric vehicles) are rather insensitive to inflation pressure changes, while tyres having high rolling resistance are very sensitive.

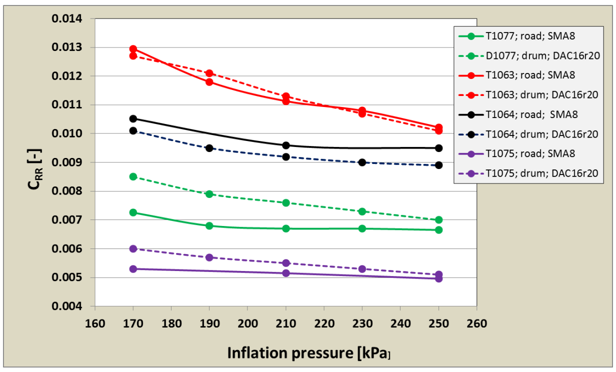

Figure 12. Combined influence of load and inflation for tyre T1076 rolling on replica road surface PERSr17 at speed of 80 km/h.

5. CONCLUSIONS

Following conclusions may be drawn from the experiments described above.

- Tyre load increase (for given tyre, road pavement and speed) always leads to increase in rolling resistance force at constant inflation pressure. Changes of the Coefficients of Rolling Resistance are, however, specific to the tyre and pavement combination thus C_{RR} may decrease, increase or stay fairly constant. Changes of C_{RR} due to load changes may be very substantial. For example for tyre SRTT (T1077) rolling on replica of coarse surface dressing (APS4r17) increase in load from 150 kG to 600 kG leads to decrease in C_{RR} from 0.0160 to 0.0118. For identical load change applied to tyre with aggressive tread pattern (T1063) rolling on poroelastic road surface (PERSr17) C_{RR} increases from 0.0116 to 0.0143. This observation indicates that future standard for on-road rolling resistance measurements must impose stringent limits (tolerances) to the load applied to test tyre(s).
- Inflation pressure increase (at constant load) always decreases C_{RR} but the rate of decrease (sensitivity slope) is very much dependent on "absolute level" of rolling resistance. Tyres with higher values of C_{RR} are more sensitive to inflation changes than low rolling resistance tyres. For low resistance tyres precision of inflation pressure adjustment is not critical but for tyres with high rolling resistance even small inflation pressure changes may lead to substantial changes of rolling resistance - up to 3.5% for change of inflation pressure by 10 kPa. This leads to the conclusion, that in order to assure good precision of on-road rolling resistance measurements it is better to regulate inflation pressure in warm conditions, as tyres that have capped inflation pressure may reach different final inflation pressure during tests due to different cooling conditions.
- Combined influence of inflation pressure and load on Coefficient of Rolling Resistance is generally very complicated and it may be different for different tyre/pavement combinations. If for any reason it is necessary to test tyre at non-standard load, it is not possible to predict which inflation pressure will ascertain that the coefficient of rolling resistance will be the same as in the case of standard load and inflation.

The results indicate that behaviour of tyres is very much dependant on the road surface texture, thus results of investigations performed on smooth steel drums, although very useful for tyre development, must be treated with great care.

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