ROlling resistance, Skid resistance, ANd Noise Emission measurement standards for road surfaces

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Project Coordinator	Manfred Haider, AIT Austrian Institute of Technology GmbH, Giefinggasse 2, 1210 Vienna, Austria. Tel: +43(0) 50550-6256 , Fax: +43(0) 50550-6599. E-mail: manfred.haider@ait.ac.at. Website: http:/rosanne.fehrl.org

Contributor(s)

Main Contributor(s)	Name, organisation, phone, e-mail
Contributor(s) (alphabetical order)	Niels Skov Dujardin, Vejdirektorate, Denmark, nidu@vd.dk Leif Sjögren, VTI Sweden, leif.sjogren@vti.se

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Reviewer(s)	1. Marek Zoeller, BASt, Germany

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Abbreviations

Abbreviation	Meaning
C_r	Coefficient of Rolling Resistance
$C_{r(210)}$	Coefficient of Rolling Resistance at inflation pressure 210 kPa
t_a	Air temperature, °C
t_p	Pavement temperature, °C
t_t	Tyre temperature, °C
K_t	Coefficient of temperature influence, 1/°C
F_{t25}	Rolling resistance force at 25°C, N
F_r	Rolling resistance force at temperature t_a, °C

Executive Summary

This report presents results obtained within WP3 of ROSANNE project in relation to influence of load, inflation pressure, temperature, road wetness and direction of tyre rotation on rolling resistance. Drum and trailer measurements reported were performed by the Technical University of Gdańsk on their drum facilities and on the road utilizing their test trailer R^2 Mk.2.

1 Introduction

This report summarizes detailed results of rolling resistance measurements performed within WP3 of Rosanne project during the first year of the project execution. Rough results (without analyses) of laboratory measurements were included in the Deliverable D.3.2 [1]. Mentioned report includes also description of the drum facilities used for laboratory measurements of rolling resistance.

For estimation of parameters influence on rolling resistance performed by TUG not only laboratory method was used. Certain tests were performed on the road using test trailer designed and built by TUG. TUG has two test trailers for rolling resistance measurements but for measurements reported in this deliverable only newer trailer designated as R^2 Mk.2 was used. 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 [2]. The trailer may accommodate tyres of different sizes and may measure a number of consecutive test sections in a single run. The trailer is presented in Fig. 1.

Fig. 1. Rolling resistance test trailer R^2 Mk.2.

2 Test tyres and road pavements

2.1 Test tyres

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. 1 for details.

Tab. 1. List of test tyres used for rolling resistance measurements

Symbol	Manufacturer	Model	Size	Remarks
T1044	UNIROYAL	Tiger Paw	P225/60R16	Standard Reference Test Tyre (SRTT) according ASTM F2493-08
T1047	AVON	AV4	195R14C	Light truck tyre that is also a reference tyre according to ISO/TS 11819-3
T1063	AVON	AV4	195R14C	Light truck tyre that is also a reference tyre according to ISO/TS 11819-3
T1064	MICHELIN	Primacy HP	225/60R16	High performance summer tyre
T1071	VREDESTEIN	Quatrac 3	195/50R15	Modern market tyre
T1075/ T1076	CONTINENTAL	Conti.eContact BLUECO	195/50R18	Tyre designed for electric vehicles
T1077	UNIROYAL	Tiger Paw	P225/60R16	Standard Reference Test Tyre (SRTT) according ASTM F2493-08
T1093	NOKIAN	Hakka Green	195/65R15	Tyre designed for electric vehicles
T1112	PIRELLI	Cinturato P1	195/60R15	Modern market tyre
T1120	BRIDGESTONE	Ecopia EP500	155/70R19	Tyre designed for electric vehicles
T1084	DUNLOP	SP242	385/65R22.5	Truck tyre for semitrailer
T1085	BRIDGESTONE	R168	385/65R22.5	Truck tyre for semitrailer
AAV4D	AVON	AV4	195R14C	Light truck tyre that is also a reference tyre according to ISO/TS 11819-3. Nominally the same like T1063
SRTTD	UNIROYAL	Tiger Paw	P225/60R16	Standard Reference Test Tyre (SRTT) according ASTM F2493-08. Nominally the same like T1077
MCPRD	MICHELIN	Primacy HP	225/60R16	High performance summer tyre , Nominally the same like T1064
VTICD	PIRELLI	P1 Verde	195/60R15	Market tyre for medium size passenger cars.

2.2 Test pavements

The research presented in this report was carried out on real roads and replica road surfaces mounted to the drums that are listed in Tab. 2.

Tab. 2. List of road pavements and replica road surfaces used for rolling resistance measurements

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	Druml 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.
PERSr20	Poroelastic road surface	Drum Facility 2.0 m	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.
DAC16r20	Replica of dense asphalt concrete with 16 mm aggregate	Drum 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	Drum 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	Drum Facility 1.7m	Polyurethane /mineral replica of a single layer surface dressing 11 mm (very high texture)
DAC11	Dense Asphalt Concrete 11 mm	Old landing strip in Horsenes, Denmark	MPD = 0.44 mm
SMA8S	Special version of SMA8	Denmark	
CD5	Surface dressing with aggregate 25mm	Rokinge, Sweden	Very coarse surface dressing, MPD=2mm

3 Tyre load and inflation pressure

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 a maximum load for a given tyre and a corresponding maximum inflation pressure. There is however a 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 [3]. Generally all methods give different results so there is no single value of inflation pressure that may be considered as "optimal". When tyre is in use, its temperature increases and it leads to the increase of inflation pressure thus "hot" inflation pressure is 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 and ambient temperature.

During execution of the ROSANNE project 5 tires were tested on the drum facilities at different loads and different inflation pressures [4]. 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. Laboratory measurements were supplemented with trailer measurements performed on the road paved with SMA8. Unfortunately due to the particularities of the test trailers R^2 Mk.2. (change of the load requires time consuming recalibration) only inflation pressure influence was tested on the road.

Analyses of the results indicated that both inflation pressure influence and load influence on rolling resistance are rather independent on the test speed (see Fig. 2 and Fig. 3) so only the results obtained for speed 80 km/h will be presented in the following part of the chapter 3.

3.1 Tyre load

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 pressure). 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 C_r (see equation 1) it is interesting to investigate how the values of C_r 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 behaviour of tyre T1063 is very different. For pavement APS4r17 Coefficients of Rolling Resistance are nearly constant, but for other pavements they increase with load.

$$C_r = \frac{F_{RR}}{F_L}, \qquad (1)$$

where:

C_r - Coefficient of Rolling Resistance [-],
F_{RR} - Rolling Resistance Force [N],
F_L - Tyre Load [N].

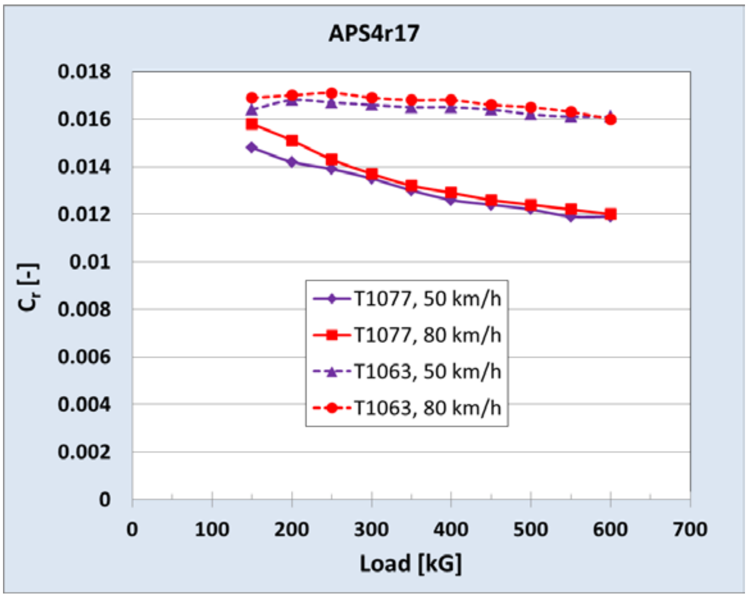

Fig. 2. Load influence on C_r for speeds 50 and 80 km/h. Inflation pressure 210 kPa.

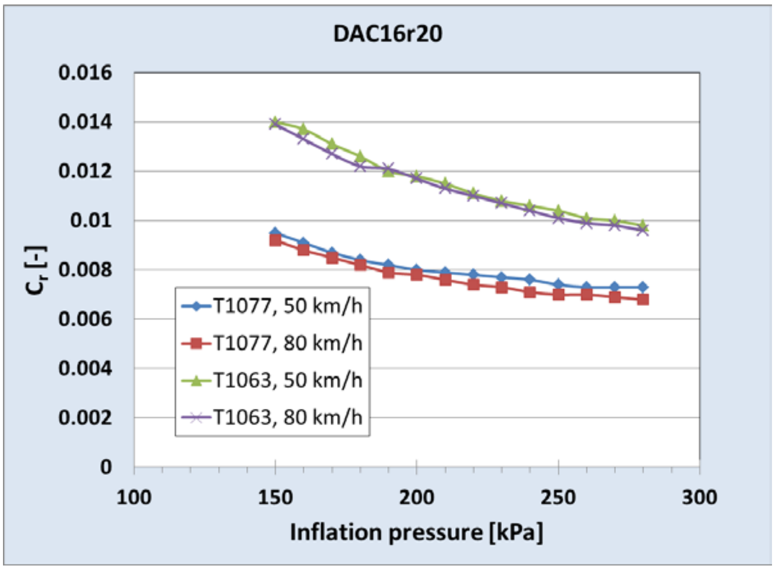

Fig. 3. Inflation pressure influence on rolling resistance for speeds 50 and 80 km/h. Load 4002 N (408 kG) [1].

[1] In this paper the load is reported in [kG] (kilogram-force) as it is based on tyre Load Index that is indicated in [kg]. 1kG=9.81 N.

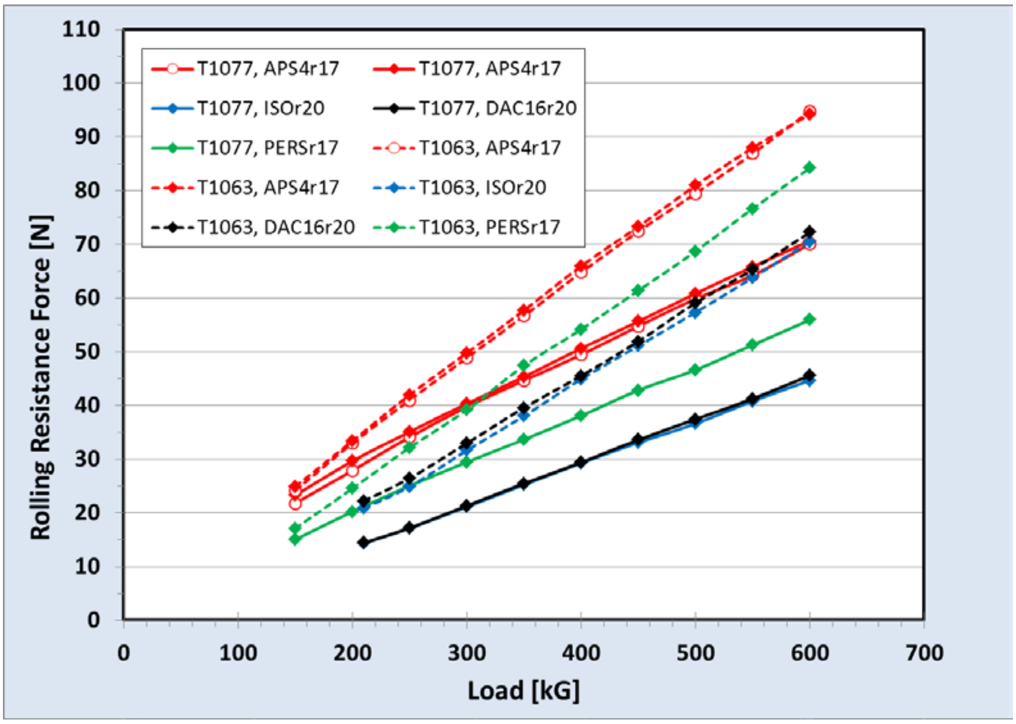

Fig. 4. Influence of tyre load on tyre rolling resistance force. Regulated inflation pressure - 210 kPa.

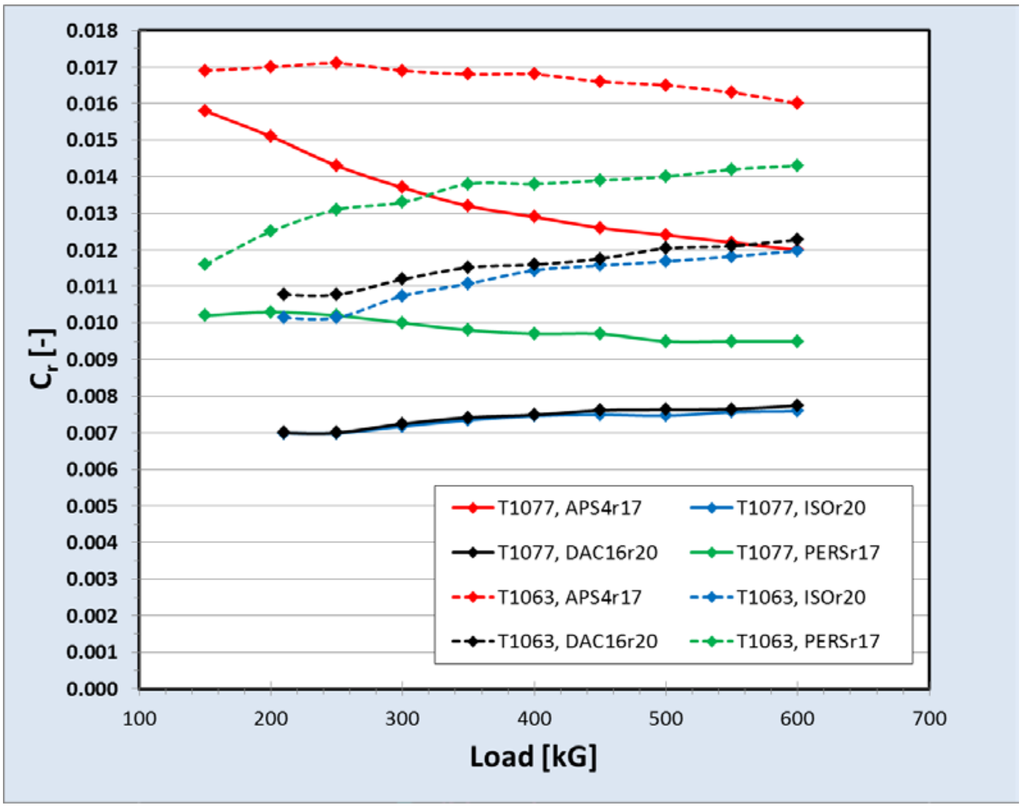

Fig. 5. Influence of tyre load on the coefficient of rolling resistance. Regulated inflation pressure - 210 kPa.

3.2 Tyre inflation pressure

Tyre inflation pressure influence on rolling resistance was tested both in the laboratory and on the road. During the tests the tyre load was kept constant and inflation pressure has varied from 150 to 280 kPa. Inflation pressure was always adjusted after initial warm-up of the tyre (so called regulated inflation pressure). 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. The results are presented in Fig. 6 and Fig. 7. The tests were performed for the load of) 4 002 N (408 kG) as this load is considered to be "standard" in measurement methodology used by TUG.

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_r with increase of inflation pressure, but magnitude of changes ("the slope") is very different. C_r characteristics are well approximated by the second-order polynomial regression lines but in the opinion of the authors it is more practical to use linear regression. Values of the slope of the linear regression line calculated 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. tire 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.

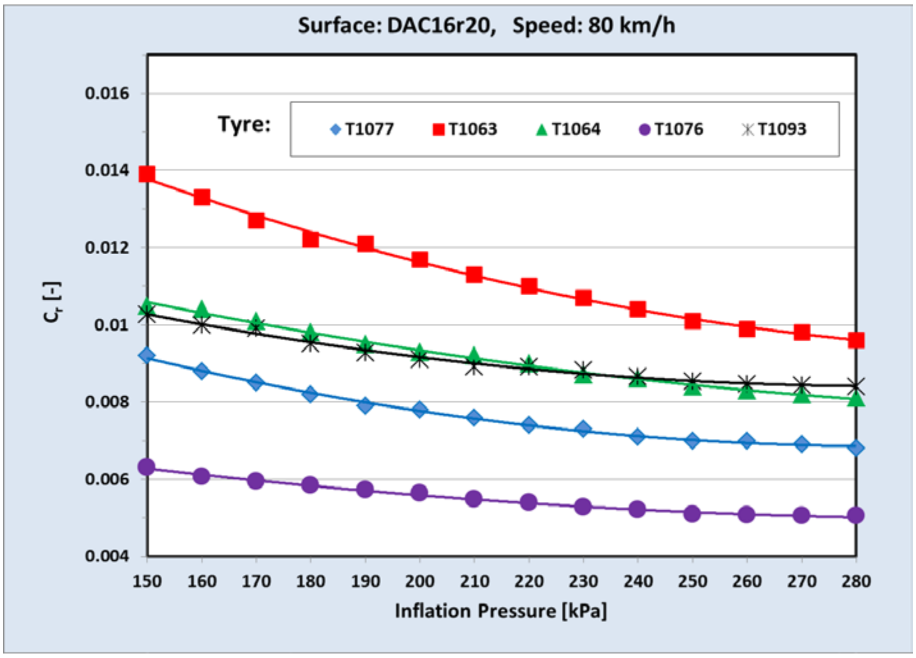

Fig. 6. Influence of inflation pressure on the coefficient of rolling resistance for five different tyres tested on replica road surface DAC16r20 at constant load of 4002N (408 kG).

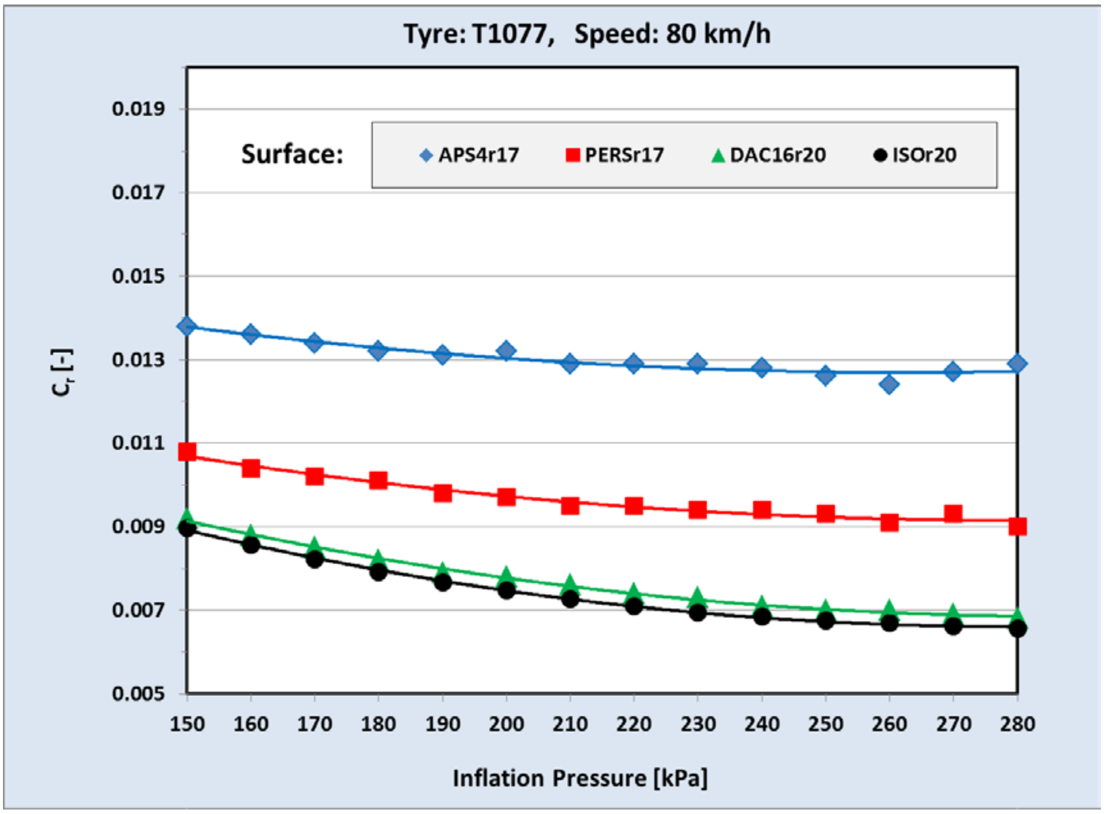

Fig. 7. Influence of inflation pressure on the coefficient of rolling resistance for four different surfaces tested with tyre T1077at constant load of 4002N (408 kG).

Tab. 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	- 0.0010	- 0.0014	- 0.0017	- 0.0019	- 0.0032

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_r. This tendency was observed also for other tyres.

The relation between the value of C_r at a certain "reference" inflation pressure and the value of the sensitivity slope was further investigated and a rather strong relation was found (R^2=0.8) - see Fig. 8. Very similar relations were obtained for different reference inflation pressures and other pavements.

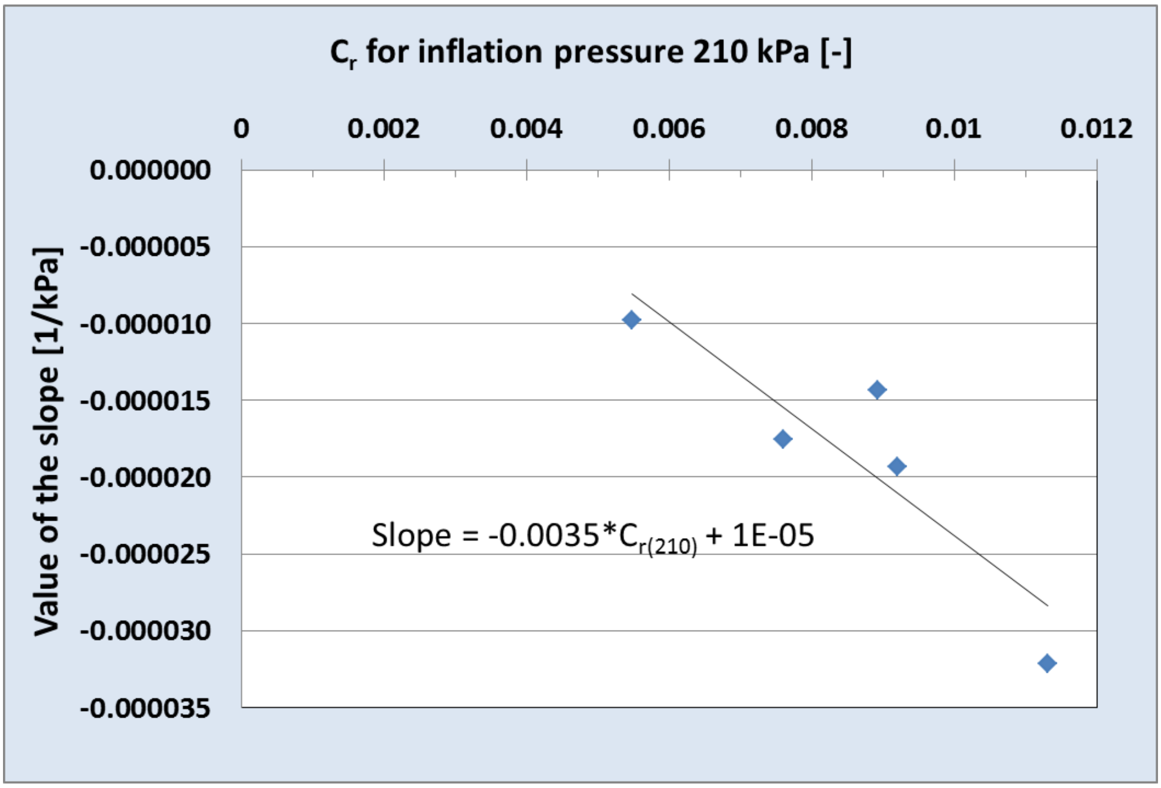

Fig. 8. Influence of inflation pressure on the coefficient of rolling resistance for four different surfaces tested with tyre T1077at constant load of 408 kG.

Laboratory tests were validated by road tests performed with R^2 Mk.2 trailer. 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 which is a very popular pavement in some EC countries (e.g. Poland and Germany). In order to avoid considerable temperature corrections, all the tests were performed at an air temperature of 22 ± 2°C and at a speed of 80 ± 1 km/h. Unfortunately drum facilities at TUG are still not equipped with replica road surfaces of SMA8 so comparison was done with a replica of Dense Asphalt Concrete DAC16r20. It was speculated that pavement DAC16r20 having bigger texture than SMA8 will cause bigger rolling resistance of tyres [5]. This assumption proved to be correct with the exception of tyre T1063, which has a very aggressive tread pattern and strong carcass (reinforced construction) . This tyre showed very similar rolling resistance on SMA8 and DAC16r20.

In Fig. 9 the results of road and laboratory measurements are compared. For both methods an increase in inflation pressure leads to a decrease in the C_r and the sensitivity slope is very much dependent on the level of absolute values of C_r. 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.

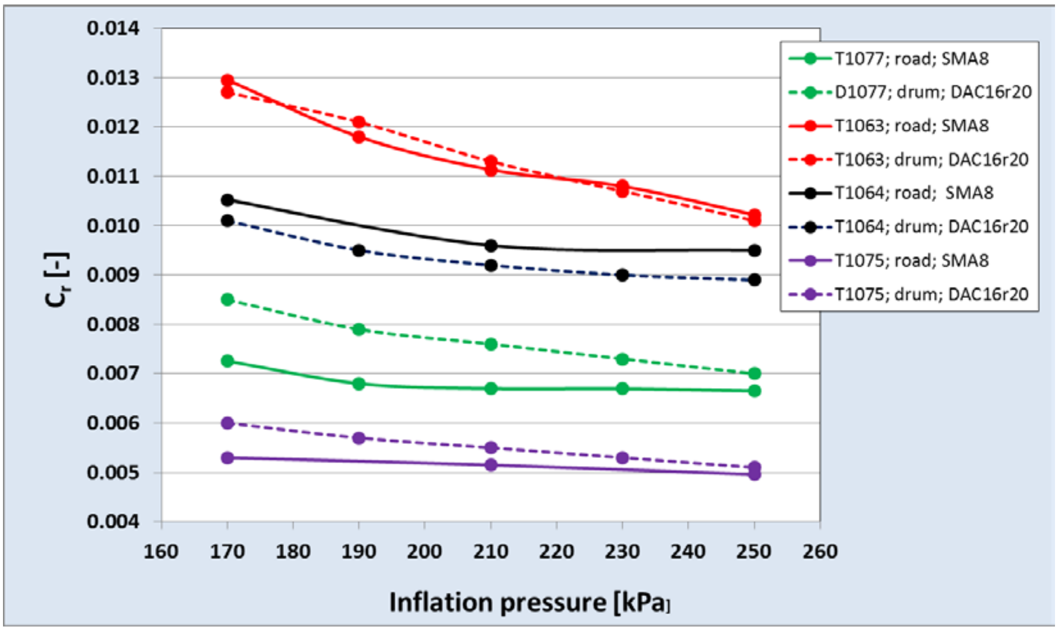

Fig. 9. Influence of inflation pressure on Cr established during road tests on SMA8 and drum tests on DAC16r20 at speed of 80 km/h and tyre load 4002 N (408 kG).

3.3 Combined influence of tyre load and inflation pressure

Laboratory experiments covered also the combined influence of load and inflation pressure on coefficient of rolling resistance C_r. 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. Characteristics obtained for tyre T1077, which is a Standard Reference Test Tire with so called all-season tread, and replica of DAC16r20 are shown in Fig. 10. For this tyre/road combination an increase in inflation pressure leads to substantial decrease in C_r while an increase in load leads to a very minor increase in C_r. Such a tendency was observed for most of the "conventional" tyres tested on any surface.

Fig. 11 presents characteristics obtained for tyre T1093 that is specially designed for electric vehicles rolling on replica of very coarse surface dressing designated APS4r17. For this tyre/pavement combination an increase in load reduces C_r and an increase in inflation pressure leads only to a minor decrease in C_r.

Fig. 12 presents characteristics obtained for tyre T1075 rolling on poroelastic road surface PERSr17. For this tyre/pavement combination the C_r is nearly independent of inflation and load. Tests performed in TUG indicate that very low sensitivity of C_r to inflation pressure is a rather typical behaviour of tyres specially designed for electric vehicles.

In figures 10 - 12 different colours indicate constant values of C_r (within ±0.0001 range). It is visible that "constant C_r conditions" cannot be predicted basing on any "general" rule as the colour areas have very unique layouts. Such conditions are different for different tyres.

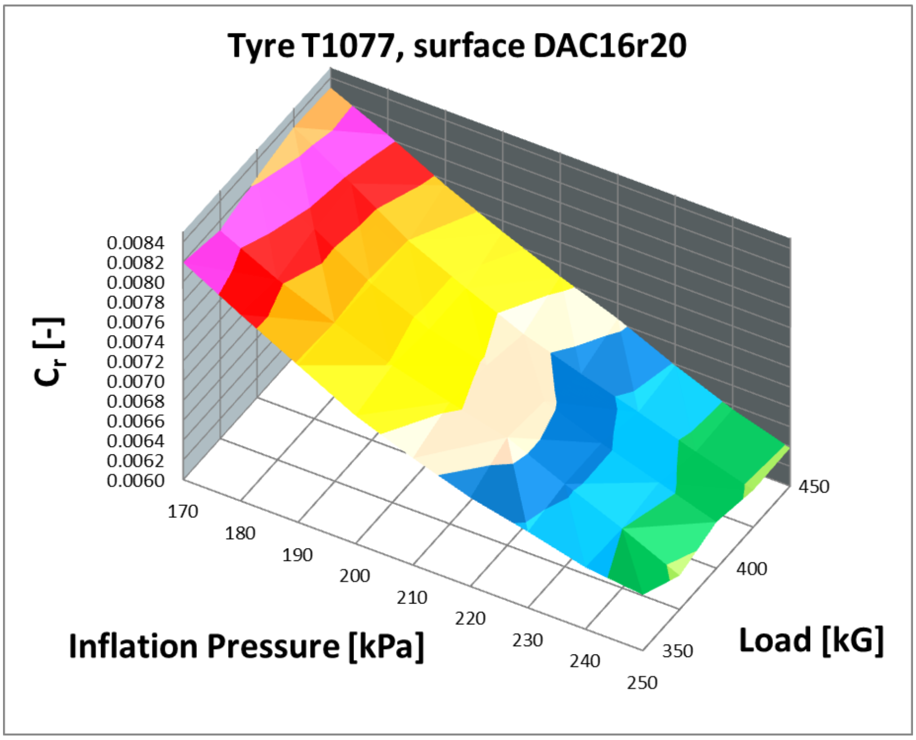

Fig. 10. Combined influence of load and inflation for tyre T1077 rolling on replica road surface DAC16r20 at a speed of 80 km/h.

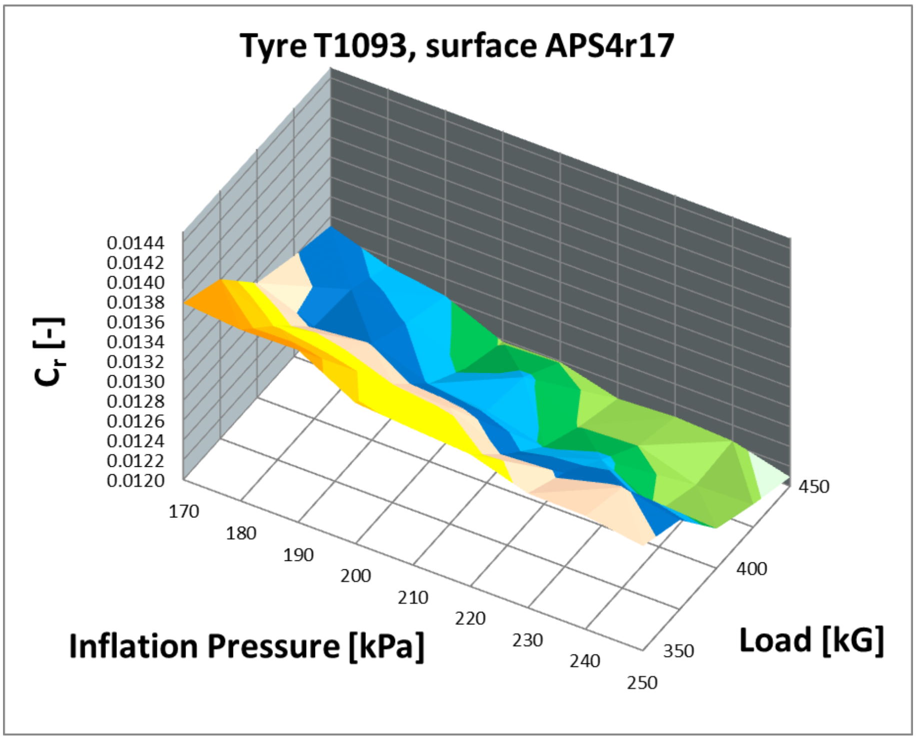

Fig. 11. Combined influence of load and inflation for tyre T1093 rolling on replica road surface APS4r17 at a speed of 80 km/h.

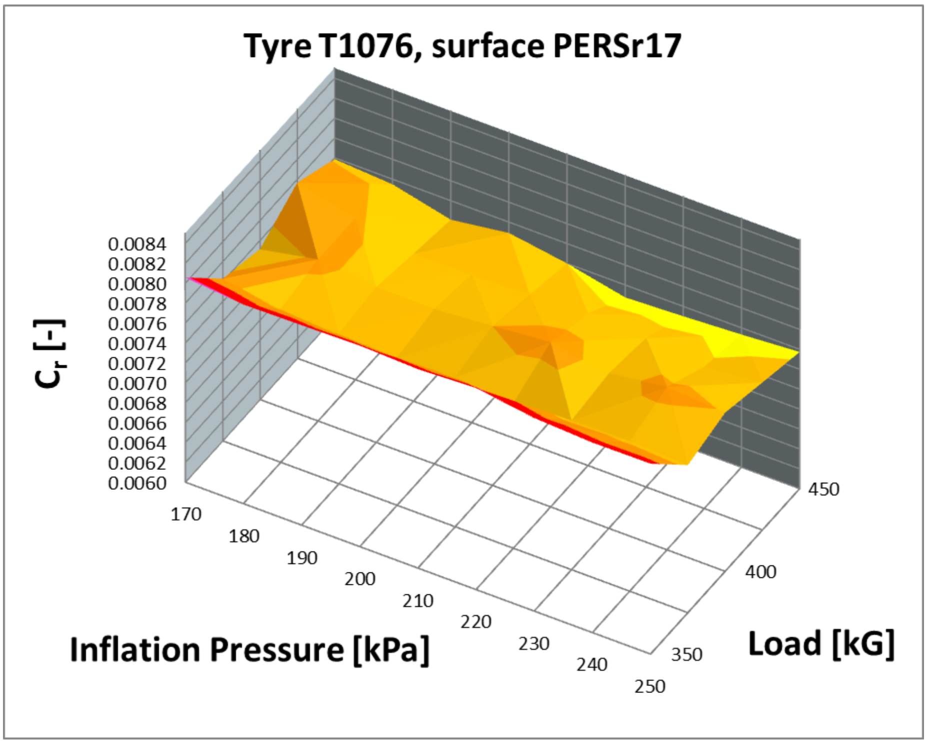

Fig. 12. Combined influence of load and inflation for tyre T1075 rolling on replica road surface PERSr17 at a speed of 80 km/h.

4 Influence of temperature on the tyre rolling resistance

Tyre rolling resistance is influenced by tyre temperature (or more precisely by a three-dimensional tyre temperature field) and sometimes also by pavement temperature.

It is not possible to describe tyre temperature by a single value, as each part of the running tyre has its own, specific temperature that is different during warm-up and steady state operation. A typical temperature field of the tyre (measured 30 seconds after stopping) is presented in Fig. 13. However, for simplification it is desirable to average surface temperatures for certain regions of the tyre, for example: tyre tread, tyre shoulder, tyre sidewalls and tyre bead. On top of it there is also the temperature of air inflating the tyre.

Tyre temperature is dependent on many factors, most notably on energy losses in the tyre, cooling effects by the air of a certain temperature and a certain airflow, solar radiation, road temperature and possible cooling by snow or water on the pavement - see Fig. 14.

Road temperature is controlled by air temperature, solar radiation and precipitation, if any. Road temperature may be also be influenced by tyres rolling on it. This phenomenon is seen on drum facilities used for tyre testing where tyres that are rolling periodically on the narrow drum surface strap may increase surface temperature even by a few degrees centigrade. Road temperature influences tyre temperature to a rather small extend, but in certain cases road temperature may influence pavement dynamical characteristics (stiffness and hysteresis) in such a way that this may influence tyre rolling resistance, thus also tyre temperature.

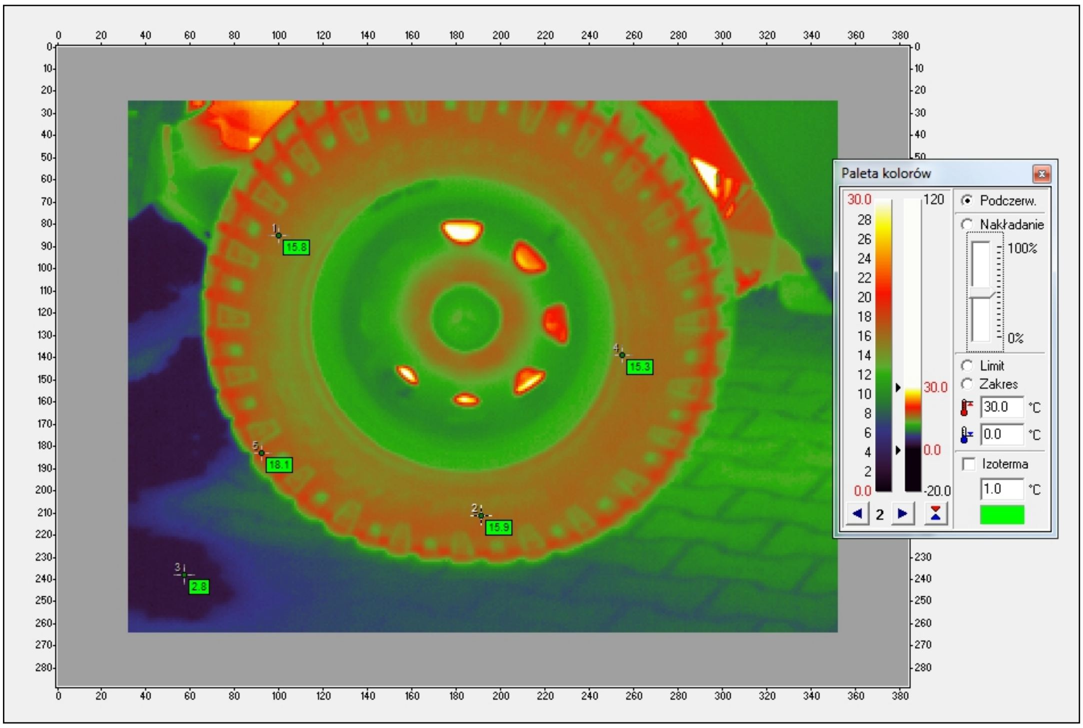

Figure 13. Thermogram of a tyre that was run for 30 minutes at a speed of 80 km/h. Air temperature 1 ºC, road temperature 2.8 ºC.

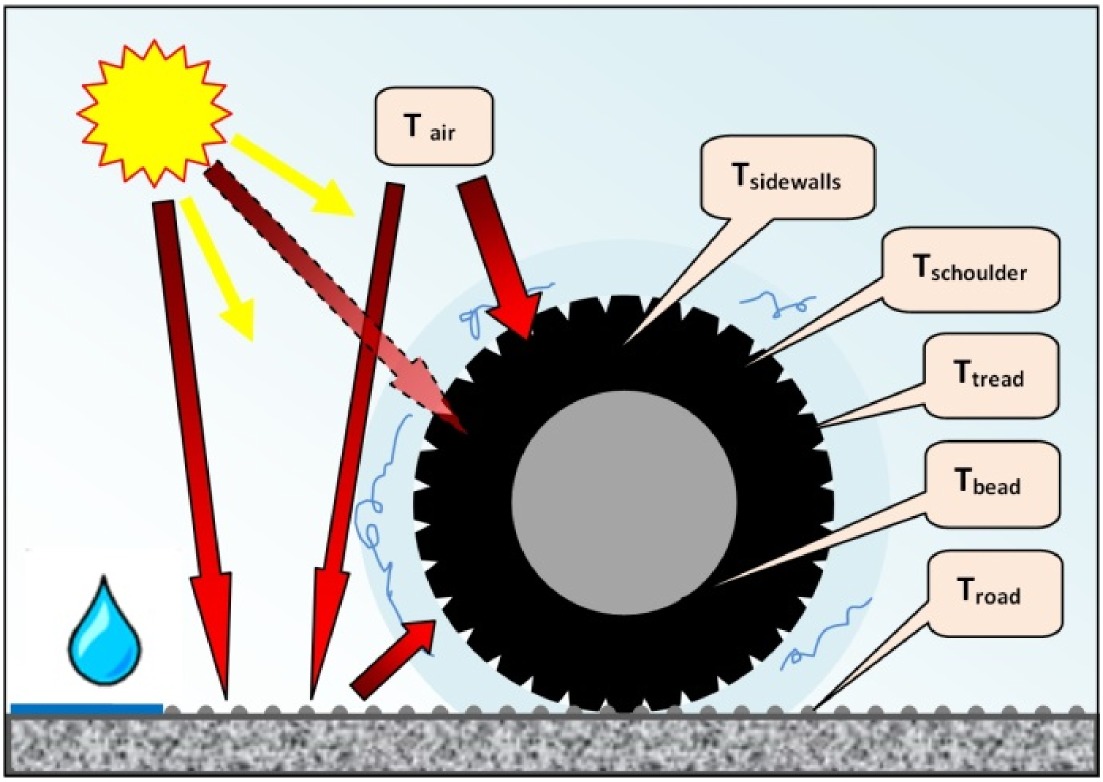

Figure 14. Schematic view on relations between tyre, air and road temperatures.

Laboratories of TUG have standard heating and A/C systems designed to ascertain that the air temperature near drum facilities during measurements is kept within the range of 20 - 25ºC. In order to perform tests of temperature influence it was necessary to supplement the system with a 50 kW heat pump unit with four portable heat exchangers that were located near the drum facilities - see Fig. 15.

During the tests passenger car tyres were loaded to 4002 N (408 kG) and inflated to 210 kPa (regulated pressure). Truck tyres were loaded to 29430 N (3000 kG) and inflated to 600 kPa.

Figure 15. Heat exchangers (on the left) in laboratory with 2.0 m diameter drum facility.

4.1 Influence of air temperature on rolling resistance for passenger car tyres

Influence of temperature on rolling resistance for passenger car tyres was established both in the laboratory and on the road. In the laboratory seven passenger car tyres were tested on five replica road surfaces at four temperatures covering a range from 5 ºC to 35 ºC. Each tyre was tested at 50, 80 and 100 km/h, but for each speed the temperature influence on rolling resistance was very similar (see Fig. 16), so results obtained for 80 km/h will be mostly reported in this report.

Although influence of temperature on rolling resistance coefficients is generally similar for all tested tyres, (see Fig. 17) the magnitude of influence (the slope) may differ up to 40%. In Fig. 18 and in Fig.19 the influence of temperature is compared for different pavements. Also in this case the difference in slope is clearly visible.

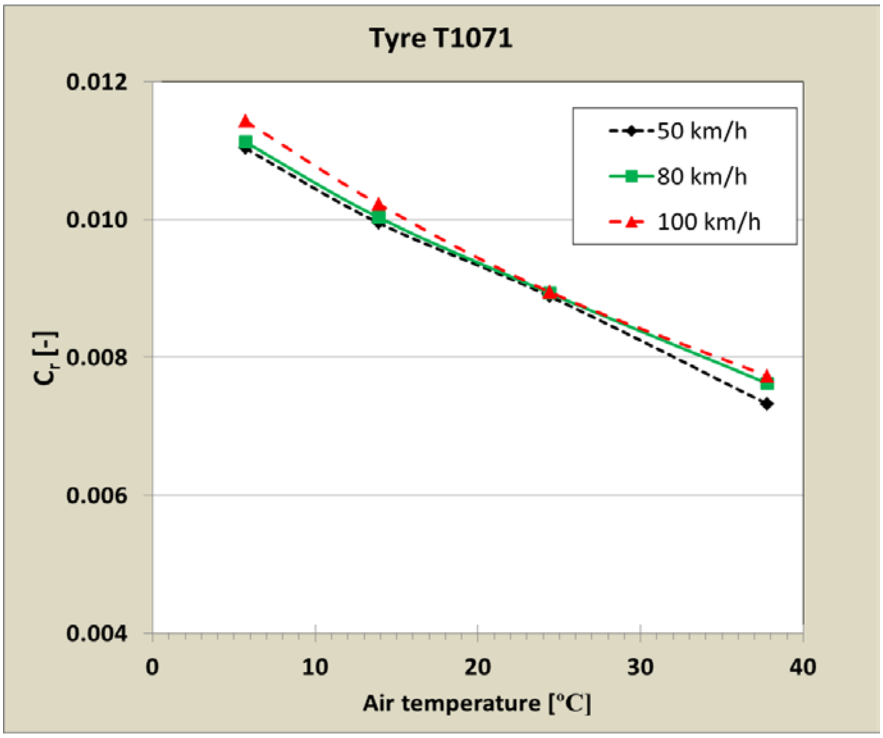

Figure 16. Influence of air temperature on the coefficient of rolling resistance for tyre T1071 rolling on replica ISOr20 at different speeds.

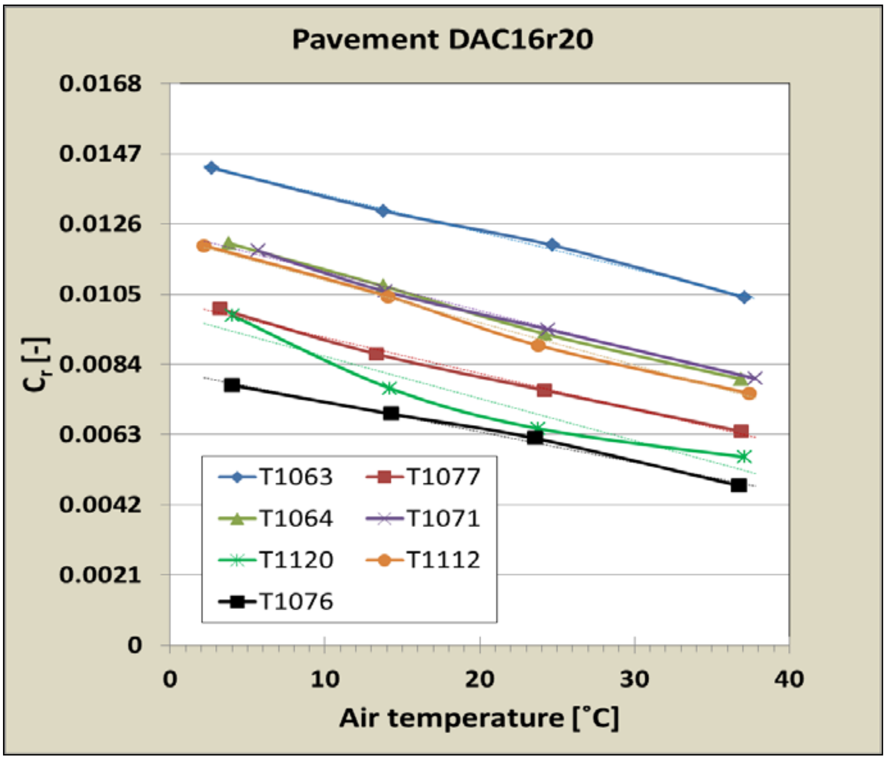

Figure 17. Influence of air temperature on the coefficient of rolling resistance for different tyres rolling on replica DAC16r20 at 80 km/h.

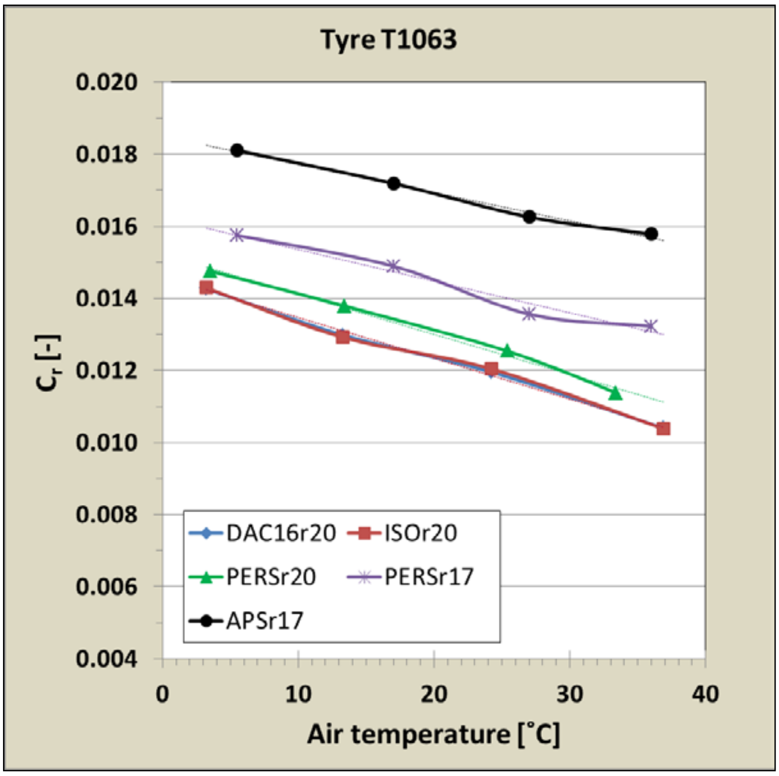

Figure 18. Influence of air temperature on the coefficient of rolling resistance for tyre T1063 rolling on different pavements at 80 km/h.

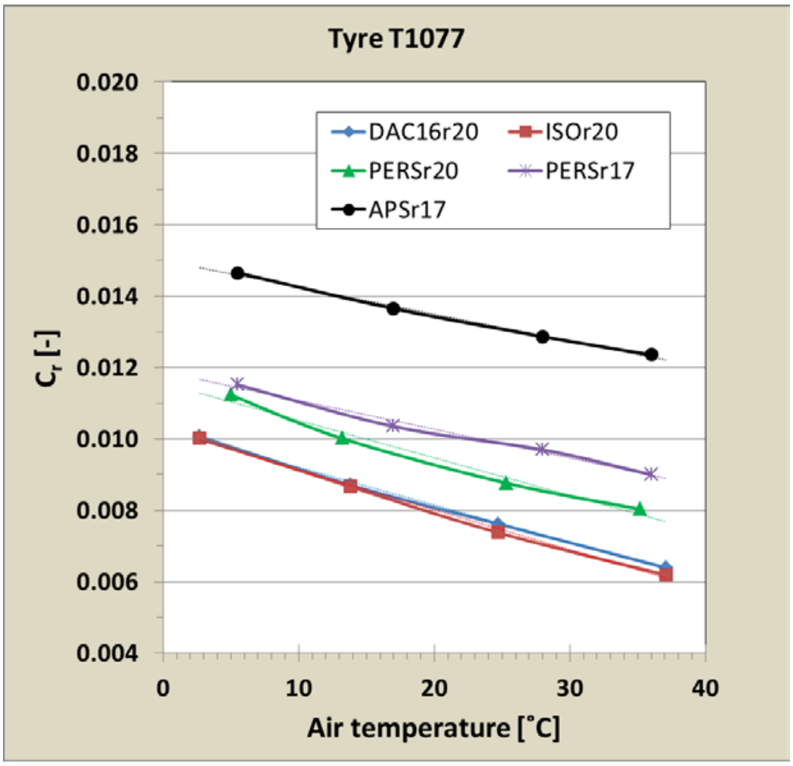

Figure 19. Influence of air temperature on the coefficient of rolling resistance for tyre T1077 rolling on different pavements at 80 km/h.

Values of the slope for linear regression lines for all tested tyres and all tested replicas are summarized in Tab. 4. In Fig. 20 slope values for each replica averaged for all tyres are presented, while in Fig. 21 slope values for each tyre averaged for all replicas are shown. The table and figures indicate that at low speeds the temperature influence is more pronounced than for high speeds. Tyre T1064 exhibits a higher influence of temperature on rolling resistance than other tested tyres. Temperature influence on replica DAC16r20 and ISOr20 is very similar.

The value of the regression line slope gives a good indication of temperature influence but according to ISO 28580 standards temperature correction should be performed on the base of equation 2.

$$F_{r25} = F_r \left[1 + K_t (t_{amb} - 25)\right] \tag{2}$$

where:

K_t	-	coefficient of temperature influence, 1/°C
F_{r25}	-	rolling resistance force at 25°C, N
F_r:		rolling resistance force at temperature t_a, N
t_a	-	air temperature, °C

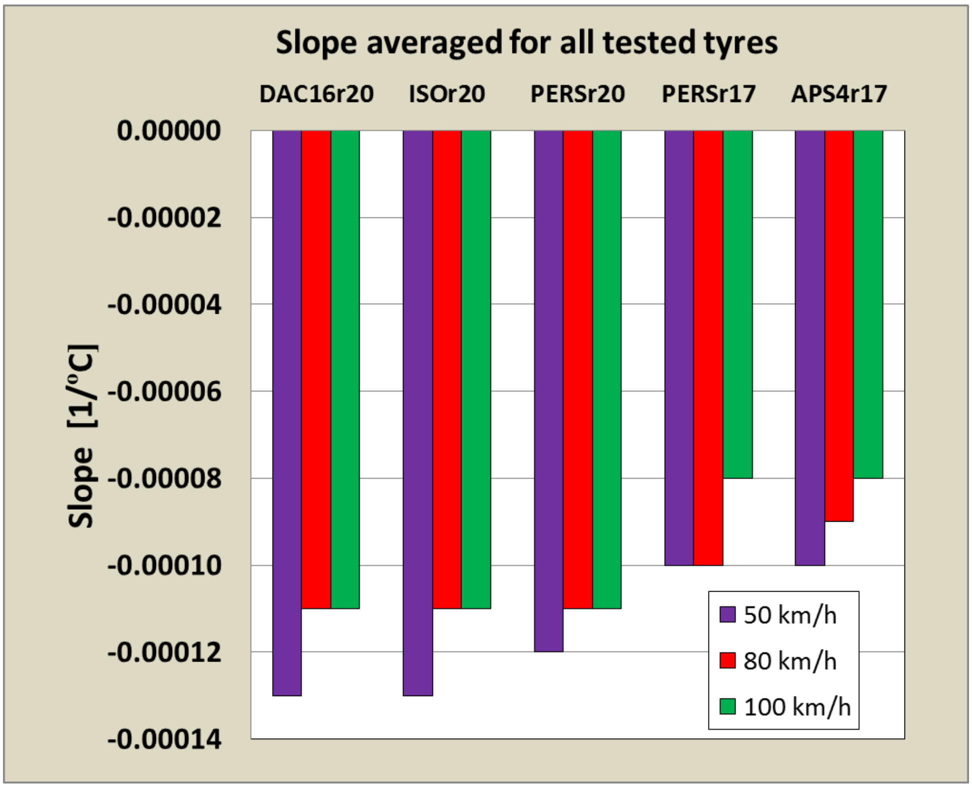

Figure 20. Slope values for replica road surfaces averaged for all tyres.

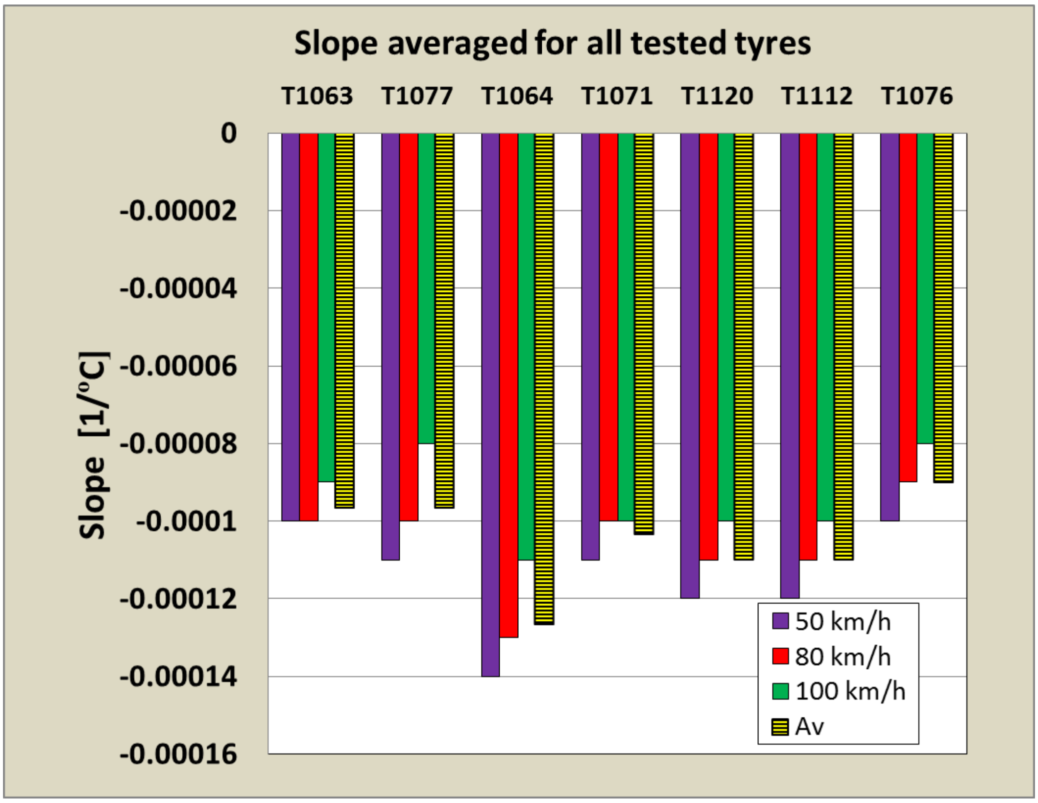

Figure 21. Slope values for tyres averaged for all replica road surfaces.

To obtain values of the coefficient K_t it is necessary to perform very simple arithmetic calculations based on the slope and intercept values of the linear regression lines approximating the temperature influence on rolling resistance. The results of calculations are presented in Tab 5. The authors decided to average the values for DAC16r20 and ISOr20 replica road surfaces, as well as for both two poroelastic surfaces PERSr17 and PERSr20. The replica APS4r17 was treated separately as, although its texture closely emulates the texture of a surface dressing, the material is based on polyurethane instead of asphalt binder. A polyurethane/mineral mix may behave differently than a typical asphalt/mineral pavement in different temperatures. The results are presented in a graphic way in Fig. 22.

Table 4. Values of the slope for passenger car tyres.

Tyre	Speed [km/h]	Slope					
		DAC16r20	ISOr20	PERSr20	PERS17	APSr17	Av
T1063	50	-0.00013	-0.00012	-0.00010	-0.00010	-0.00007	**-0.00010**
	80	-0.00011	-0.00011	-0.00011	-0.00009	-0.00008	**-0.00010**
	100	-0.00011	-0.00011	-0.00011	-0.00008	-0.00006	**-0.00010**
T1064	50	-0.00015	-0.00016	-0.00015	-0.00012	-0.00013	**-0.00014**
	80	-0.00012	-0.00013	-0.00015	-0.00012	-0.00011	**-0.00013**
	100	-0.00012	-0.00011	-0.00014	-0.00010	-0.00011	**-0.00012**
T1071	50	-0.00013	-0.00012	-0.00010	-0.00010	-0.00011	**-0.00011**
	80	-0.00012	-0.00011	-0.00010	-0.00009	-0.00008	**-0.00010**
	100	-0.00012	-0.00012	-0.00010	-0.00008	-0.00008	**-0.00010**
T1075	50	-0.00011	-0.00010	-0.00010	-0.00009	-0.00011	**-0.00010**
	80	-0.00009	-0.00008	-0.00010	-0.00009	-0.00009	**-0.00009**
	100	-0.00008	-0.00008	-0.00010	-0.00007	-0.00007	**-0.00008**
T1077	50	-0.00012	-0.00012	-0.00012	-0.00010	-0.00011	**-0.00011**
	80	-0.00011	-0.00011	-0.00011	-0.00008	-0.00008	**-0.00010**
	100	-0.00009	-0.00010	-0.00010	-0.00007	-0.00006	**-0.00008**
T1112	50	-0.00014	-0.00014	-0.00011	-0.00010	-0.00011	**-0.00012**
	80	-0.00013	-0.00012	-0.00010	-0.00011	-0.00008	**-0.00011**
	100	-0.00012	-0.00012	-0.00008	-0.00008	-0.00006	**-0.00010**
T1120	50	-0.00014	-0.00013	-0.00013	-0.00010	-0.00010	**-0.00012**
	80	-0.00013	-0.00012	-0.00012	-0.00012	-0.00009	**-0.00012**
	100	-0.00012	-0.00011	-0.00011	-0.0008	-0.00008	**-0.00010**
Av		**-0.00012**	**-0.00012**	**-0.00011**	**-0.00009**	**-0.00009**	**-0.00011**

Table 5. Values of the coefficient K_t obtained during laboratory measurements.

Tyre	**Surfaces**		
	ISO+DAC	**PERS**	**APS4**
T1063	0.009	0.007	0.005
T1077	0.014	0.010	0.007
T1064	0.014	0.011	0.009
T1071	0.012	0.009	0.007
T1120	0.018	0.012	0.010
T1112	0.013	0.009	0.008
T1076	0.015	0.012	0.010

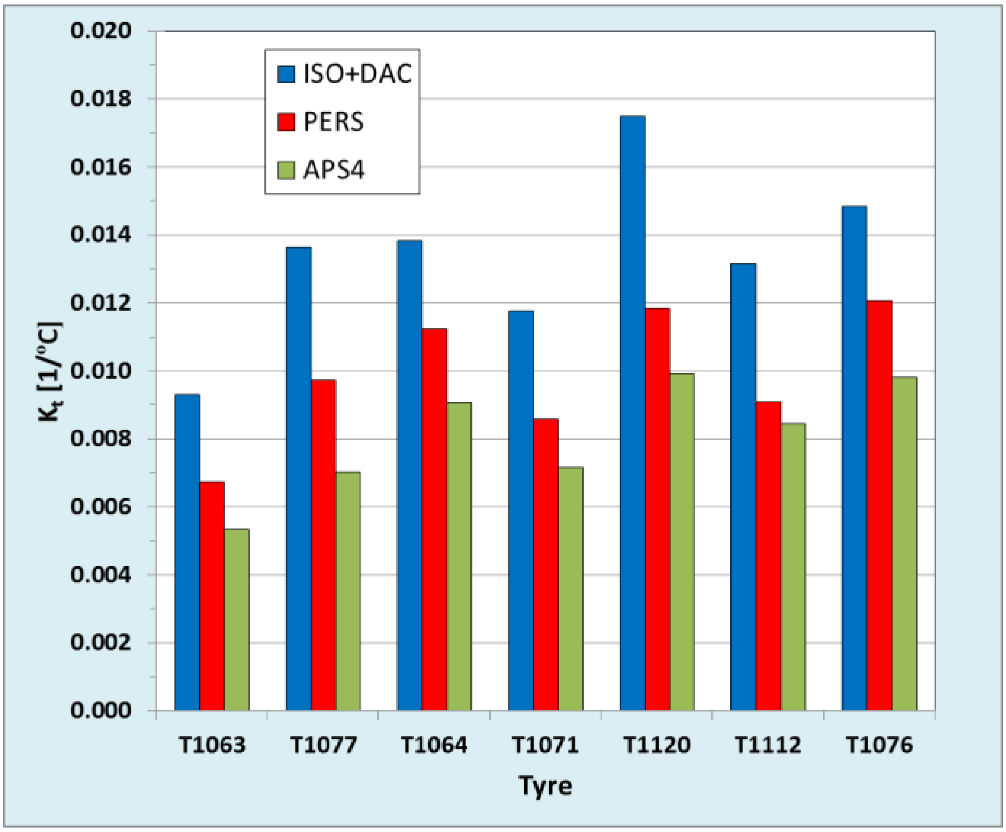

Figure 22. Coefficients K_t for different tyres and road surfaces.

4.2 Influence of air temperature on rolling resistance for truck tyres

Two heavy truck tyres were tested for temperature influence on a facility with a drum of 2.0 m diameter. Results obtained on replica road surface DAC16r20 are presented in Fig. 23 and on a replica ISOr20 in Fig. 24. The temperature influence for both tyres and both road surfaces exhibit similar trends. It is interesting to note, that while characteristics for passenger car tyres are nearly linear, characteristics for truck tyres are much better approximated by the second order regression line.

As the linear regression lines are not appropriate for approximation of temperature influence for truck tyres, it is not possible to establish a single "slope" value for tyre/pavement combination. In all cases the slope is much steeper for low temperatures and less steep for higher temperatures. As the rolling resistance measuring ISO standards require nominal temperature to be 25 ºC (in case of SAE it is 24ºC) the authors decided that slope should be evaluated for temperature range from 20 ºC to 30 ºC. On the base of slopes for this temperature range the coefficients K_t were evaluated (see Tab. 6).

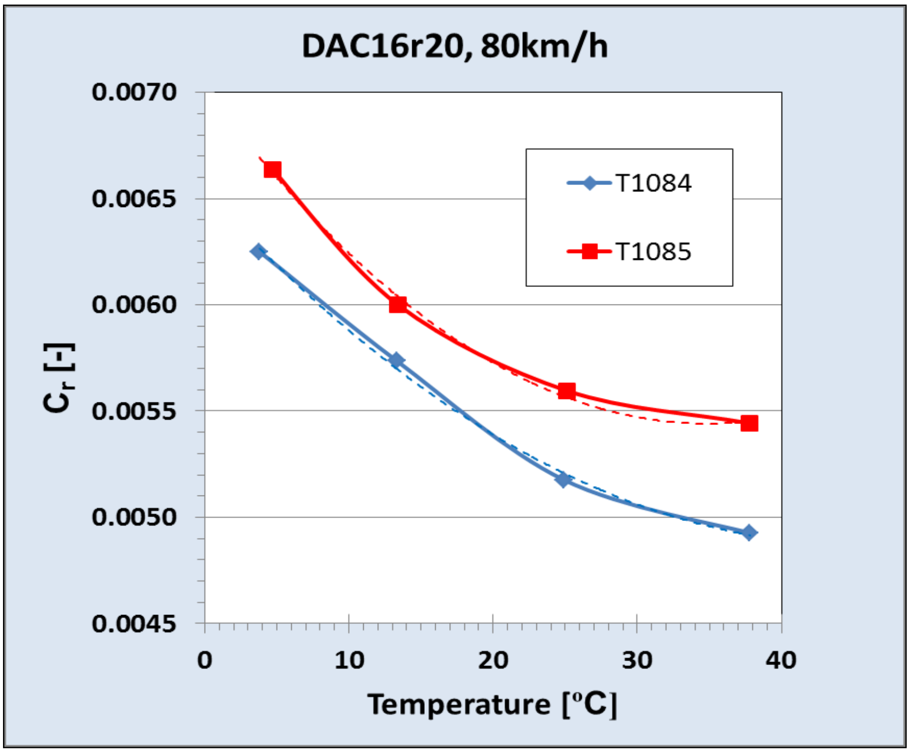

Figure 23. Influence of air temperature on the coefficient of rolling resistance for truck tyres rolling on replica DAC16r20 at 80 km/h.

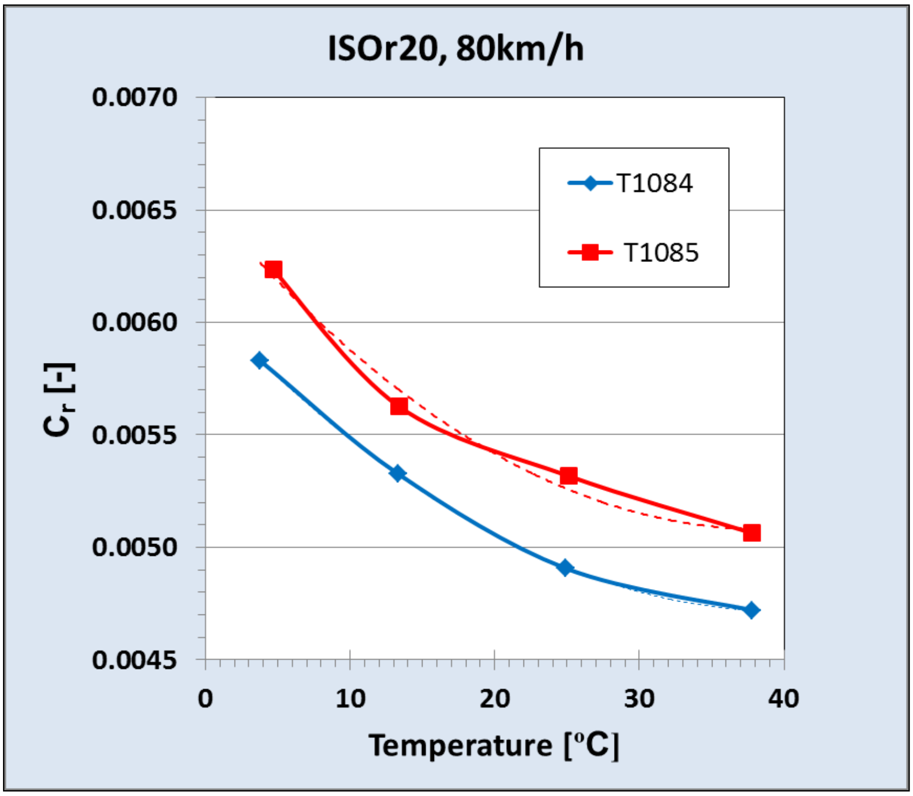

Figure 24. Influence of air temperature on the coefficient of rolling resistance for truck tyres rolling on replica ISOr20 at 80 km/h.

Table 6. Values of the coefficient K_t for truck tyres.

Tyre	Coefficient K_t		
	DAC16r20	ISOr20	Average
T1084	0.006	0.006	**0.006**
T1085	0.004	0.004	**0.004**
Av.	**0.005**	**0.005**	**0.005**

4.3 Warm-up period

Rolling resistance of tyres is associated with energy losses that mainly occur in the structure of the tyre, and to a much lesser extent in the road pavement. The overwhelming majority of the energy is dissipated as heat, which induces tyre temperature to rise, occurring as long as the cooling effect does not offset the supply of thermal energy. During the warm-up period of the tyre that is in normal use, the increase of temperature leads to an increase of inflation pressure. In case of rolling resistance measurements the increase may be compensated by the adjusting system that keeps inflation pressure at the desired ("regulated") value. TUG performed several rolling resistance tests in the laboratory and on the road to investigate the warming-up period concerning tyre temperature and rolling resistance.

A first series of measurements were performed on the facility with a drum of 2.0m diameter. Two passenger car tyres and one truck tyre were tested on three replica road surfaces with constant monitoring of temperatures of different parts of the tyres and replicas. At the same time rolling resistance was also measured. From the beginning to the end of each test the inflation pressure was regulated to standard value (210 kPa for passenger car tyres and 600 kPa for truck tyres). Every two minutes a thermographic image of the tyre and the replica was recorded.

In Fig. 25 the warming process of passenger car tyre T1083 on replica ISOr20 is presented. The ambient temperature in the laboratory was 25ºC so all temperatures start from this value. Within 1600 s of measurements the Coefficient of Rolling Resistance C_r dropped from the initial value of 0.0160 to stabile value of 0.0141 at the end of test. At the same time the temperature of tyre shoulder increased to 33.2ºC, the temperature of the sidewall to 37.5ºC and the temperature of the tyre bead to 40.3ºC. The temperature of the replica increased to 26.8 ºC that is only by 1.8 ºC.

In Fig. 26 the warming process of passenger car tyre T1088 on poroelastic pavement PERSr20 is presented. Also in this case the ambient temperature in the laboratory was 25ºC. Within 1600 s of measurements C_r dropped from the initial value of 0.0157 to stable value of 0.0138 at the end of test. At the same time the temperature of the tyre shoulder increased to 33.2ºC, the temperature of the sidewall to 39.6ºC and the temperature of the tyre bead to 42.3ºC. The temperature of the replica increased to 29.7 ºC that is by 4.7 ºC. The increase of pavement temperature was three times higher than in case of the stiff replica ISOr20.

In Fig. 27 the warming process of truck tyre T1084 on replica DAC16r20 is presented. For this measurement the ambient temperature in the laboratory was 24ºC. Within 1600 s of the measurements C_r dropped from the initial value of 0.0073 to a stable value of 0.0052 at the end of test. At the same time the temperature of the tyre shoulder increased to 37.7ºC, the temperature of the sidewall to 36.1ºC and the temperature of the tyre bead to 40.7ºC. The temperature of the replica increased to 29.9 ºC, that is by 5.9 ºC.

In Fig. 28 the warming process of truck tyre T1084 on replica PERSr20 is presented. For this measurement the ambient temperature in the laboratory was 26ºC. In contrast to the experiments described above, initially the replica PERSr20 had ambient temperature, but the tyre was warm (after running on replica DAC16R20). This procedure was adopted in order to avoid long lasting overload of the replica PERSr20 that is still in the developing stage. Within 1000 s of the duration of the measurements C_r was nearly stable at the value of 0.0086. At the same time the temperature of the tyre shoulder increased to 41.8ºC, the temperature of the sidewall to 38.7ºC and the temperature of the tyre bead to 44.1ºC. However, the temperature of the replica increased to 44.0ºC, that is by 18 ºC.

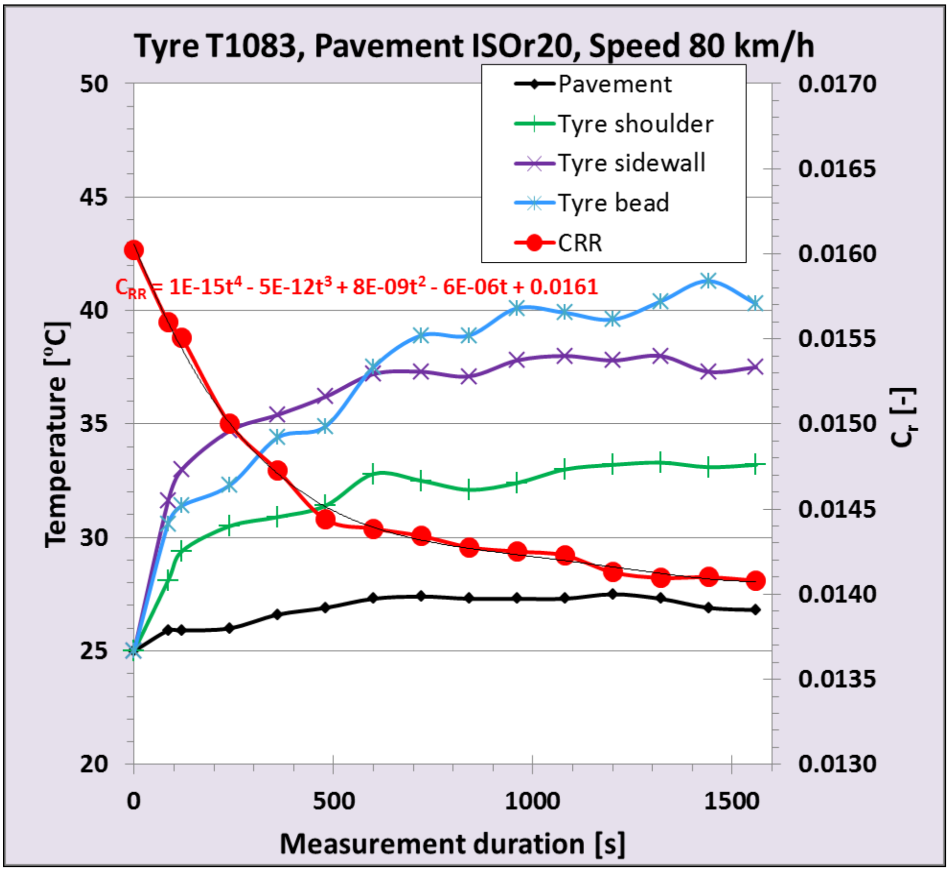

Figure 25. Warming-up of tyre T1083 running at 80 km/h on pavement ISOr20.

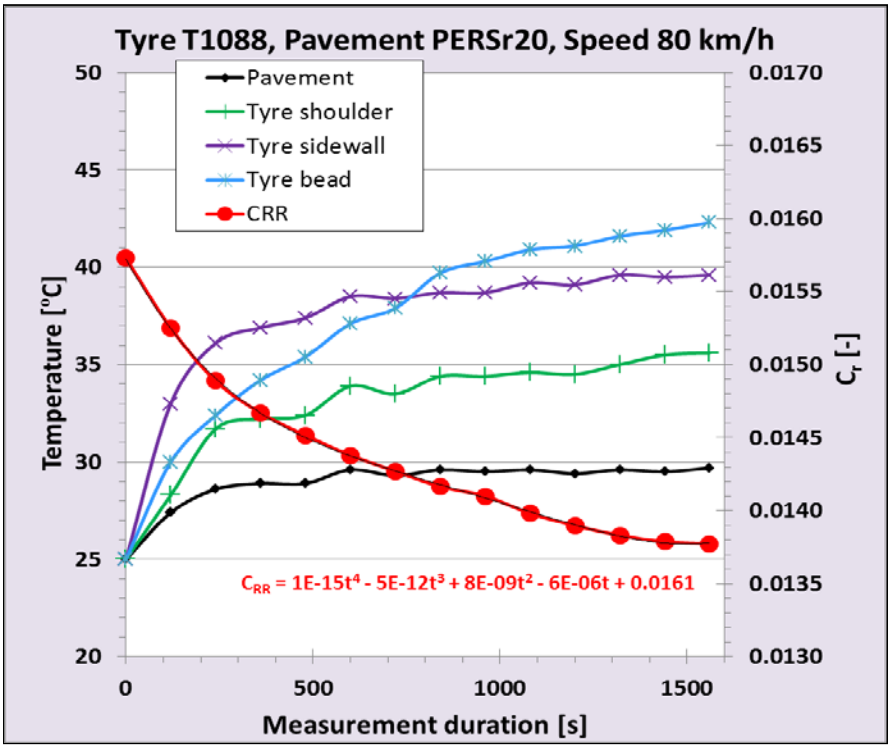

Figure 26. Warming-up of tyre T1088 running at 80 km/h on poroelastic pavement PERSr20.

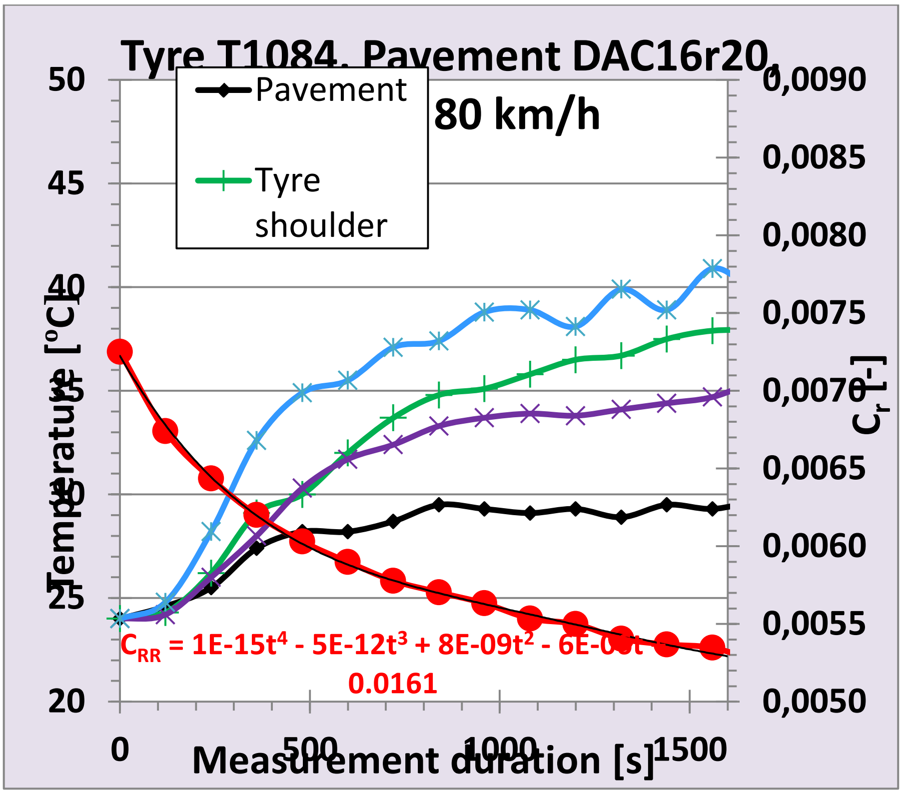

Figure 27. Warming-up of truck tyre T1084 running at 80 km/h on stiff replica DAC16r20.

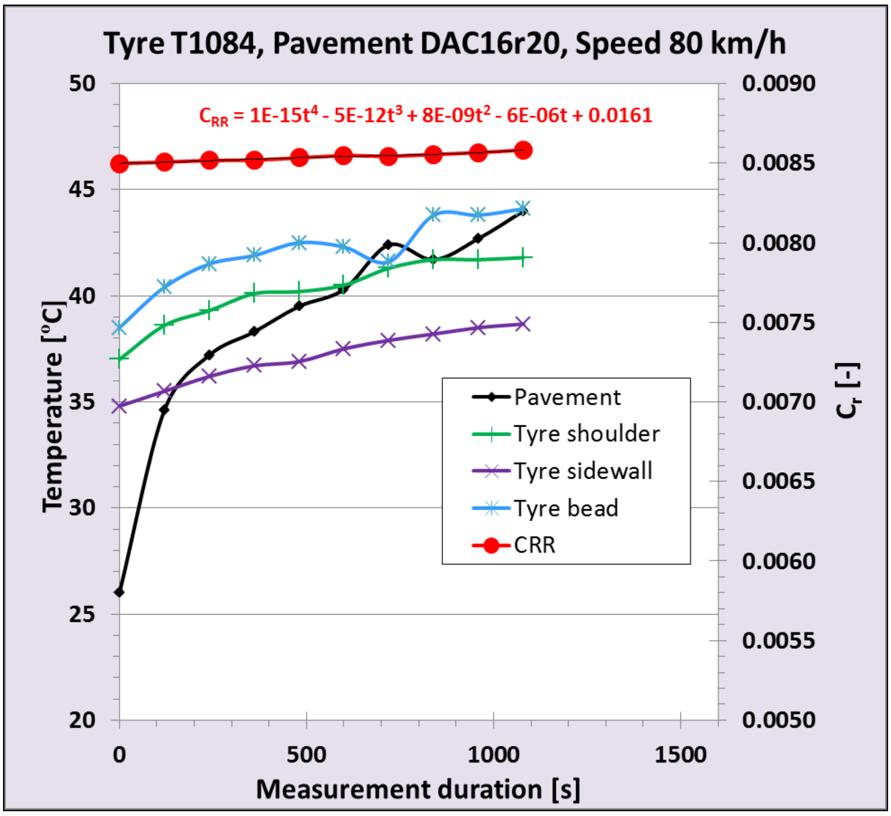

Figure 28. Warming-up of tyre T1088 running at 80 km/h on poroelastic pavement PERSr20.

The investigation of the warming-up period influence on rolling resistance was performed also on the road with R2 Mk.2 trailer. The results for tyre T1063 are presented in Fig. 29. It must be observed that during road tests the measurements were always performed for regulated inflation pressure so natural build-up of the inflation due to temperature increase was equalized. Data presented in Fig. 29 indicate that the decrease of rolling resistance is bigger than during laboratory measurements. At the same time tyre temperature increases more than during drum tests. This may be explained by the cooling effect acting on a tyre during laboratory tests. During road measurements the test tyre is screened from the airflow by the protective chamber so the cooling effect is much smaller.

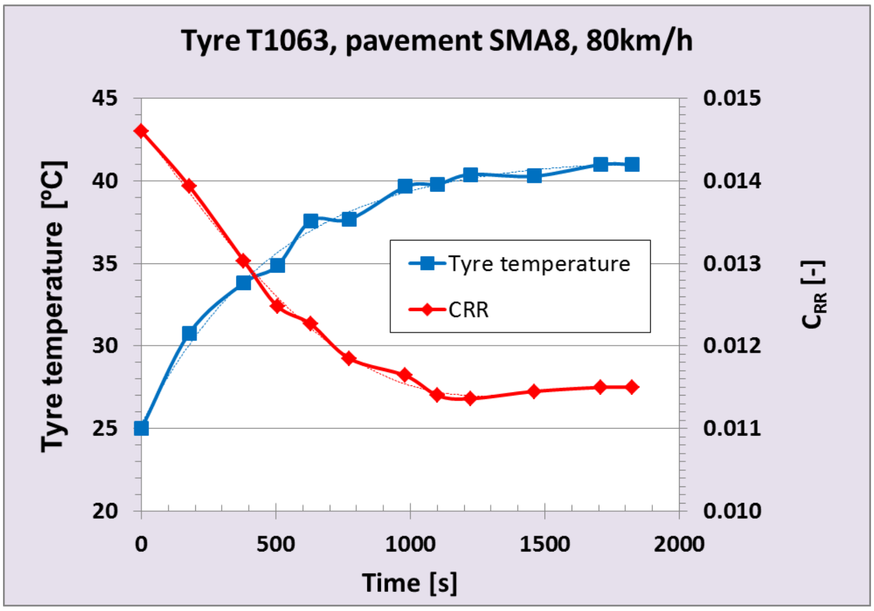

Figure 29. Warming-up of tyre T1063 running at 80 km/h on the pavement SMA8.

4.4 Temperature correction of rolling resistance coefficients

All measurements performed by TUG indicate strong influence of temperature on rolling resistance. The warming-up tests indicated that the most important factor is the temperature of the tyre structure. Unfortunately measuring the temperature of a tyre is not very practical during general tests. Fig 30 indicates that the temperature field in a running tyre is very complicated and even a small change in location of the temperature measuring point may lead to important differences. For example for the tyre presented in Fig. 30 in the shoulder region the temperature is at about 32ºC but just 2-3 centimetres away on the sidewall it is 37ºC. So it is much more practical to use the ambient temperature that is easy to measure. In the case of using the air temperature, it is, however, very important to provide enough time for warming-up the tyre and ascertaining some kind of "normalized" tyre cooling conditions.

The authors believe that if certain tyres are selected to be the "reference", they must be tested for temperature influence and individual coefficients of temperature influence must be establish for each of them.

The authors propose the following influence factors K_t for tyres that are potential candidates to became reference tyres for rolling resistance measurements:

- tyre Avon AV4: K_t=0.010
- tyre SRTT (ASTM F2493-08): K_t=0.015

For other tyres it is proposed to use:

- passenger car tyres: K_t=0.012
- truck tyres: K_t=0.005

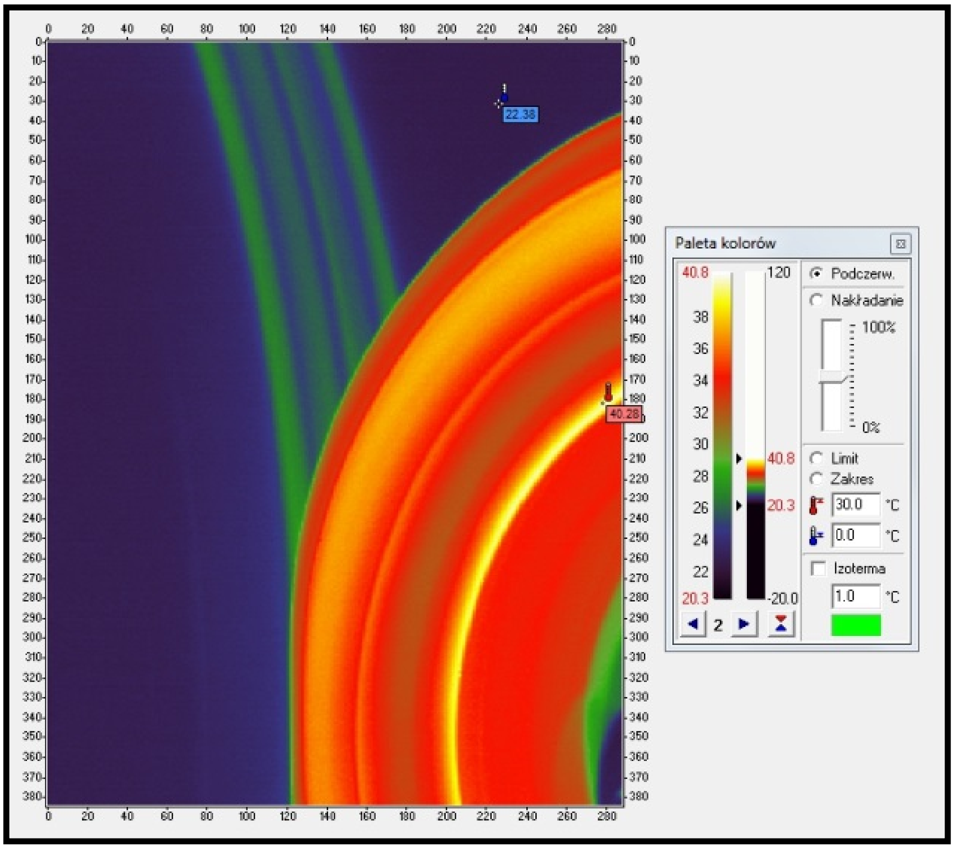

Figure 30. Thermographic image of tyre T1063 rolling on replica ISOr20.

5 Influence of road wetness on tyre rolling resistance

A water film covering a road pavement influences many important characteristics of the tyre/pavement interaction, most notably friction and rolling resistance. This chapter discusses experiments performed by TUG and VTI in order to establish influence or road wetness on rolling resistance of tyres.

5.1 Results of experiments performed in Horsenes

In October 2013 TUG together with VTI performed tests of water film influence on rolling resistance on a runway at the old landing strip in Horsenes, Denmark - see Fig 31. The measurements were related to the MIRIAM project but the results are relevant also for the ROSANNE project. The facility in Horsenes is equipped with water film sensors mounted in the pavement of the road. There is also a weather station that constantly records weather conditions and water film thickness over each sensor - see Fig. 32.

Fig. 31. View on the test facility at Horsenes

Fig. 32. Water film sensor on the test track in Horsenes.

The test road is paved with dense asphalt concrete probably based on aggregate 11 mm. Texture measurements performed on this section revealed that the MPD is in a range of 0.38 – 0.56 with an average of 0.44 mm.

Before the measurements it was planned to test all tyres on a dry pavement and after that, to wetten the surface by a water-truck and adjust the water film by more or less frequent passes of this truck. Unfortunately at the day of the measurements the weather was rainy, and in the evening the hurricane "Christian" reached Denmark. Due to weather problems it was not possible to test the tyres in 100% dry conditions. On the other hand, it was possible to test the tyres on a considerably thick water film that was provided both by the rainfall and water-truck - see Fig. 33. The driest conditions that were tested that day may be described as "damp", which means that the road surface was "black" but without a visible and shiny water film on it. The sensors indicated a water film of 0.08mm during these "damp" conditions.

As no dry measurements were performed, in order to complete the results with missing "dry" values of rolling resistance coefficients, the data were supplemented with results obtained on a similar surface and at a similar air temperature elsewhere. During the measurements the tyres were loaded to 4002 N (408 kG) and inflated to regulated pressure of 210 kPa. The results are presented in Figs. 34 - 39. For all tested tyres and all speeds a considerable increase of rolling resistance was observed.

Fig. 33. Water-truck in action.

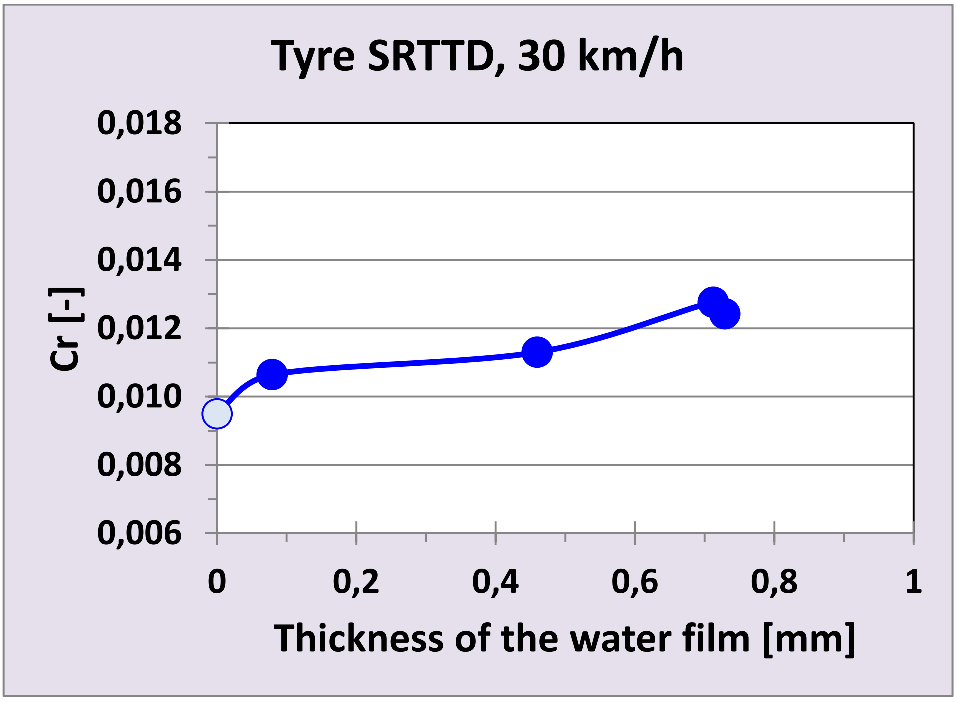

Fig. 34. Influence of water film thickness for tyre SRTTD at a speed of 30 km/h.

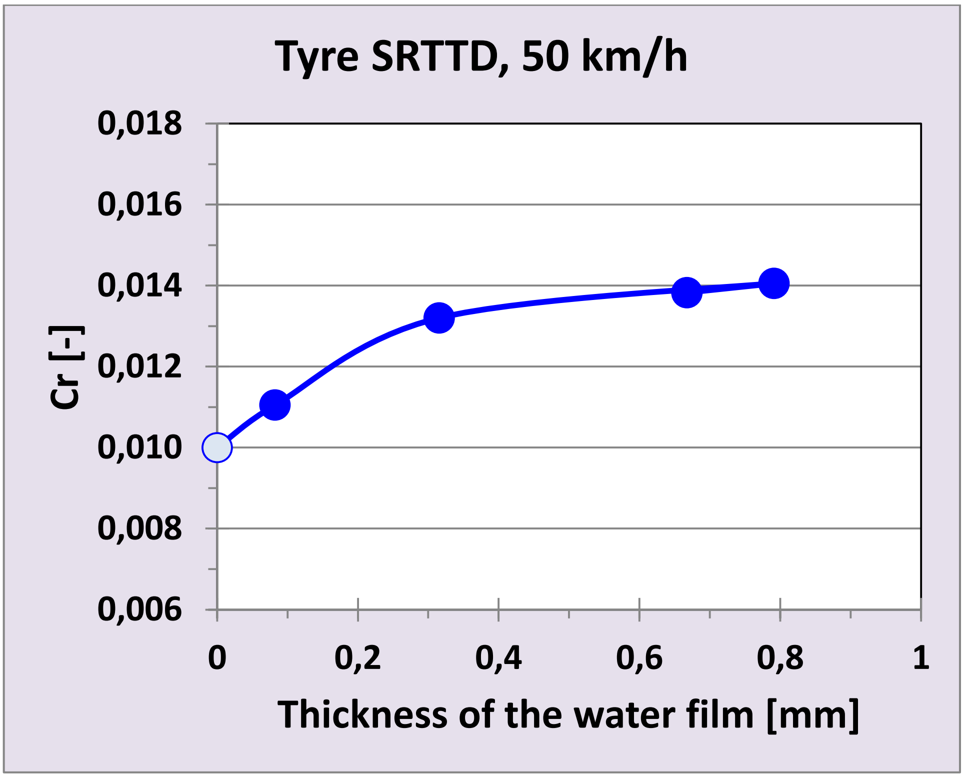

Fig. 35. Influence of water film thickness for tyre SRTTD at a speed of 50 km/h.

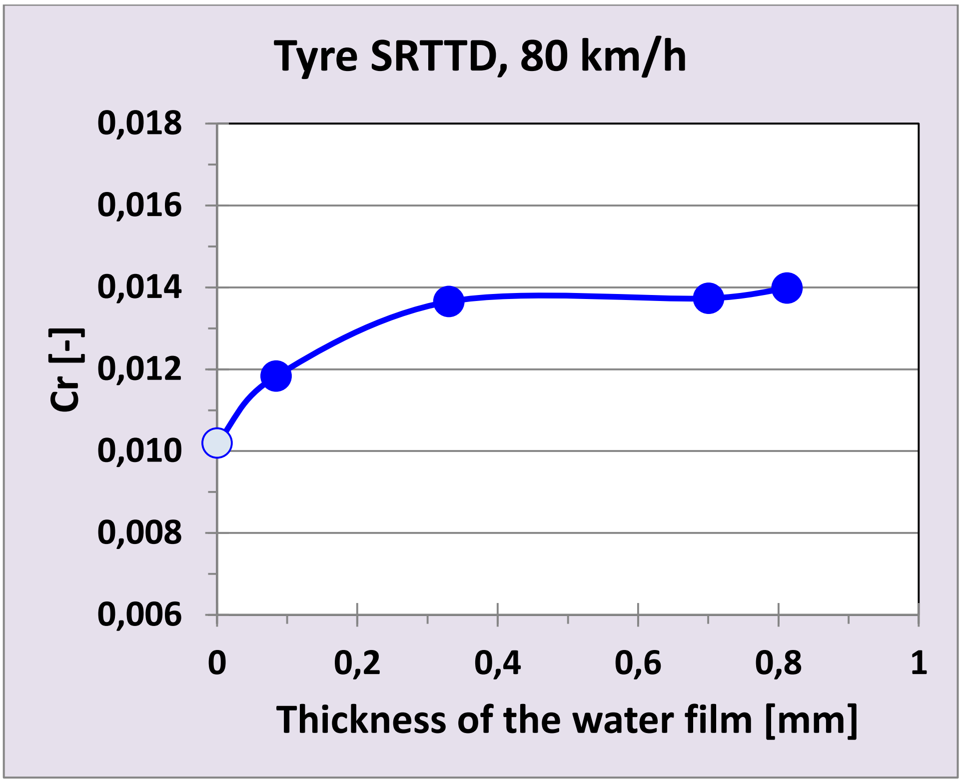

Fig. 36. Influence of water film thickness for tyre SRTTD at a speed of 80 km/h.

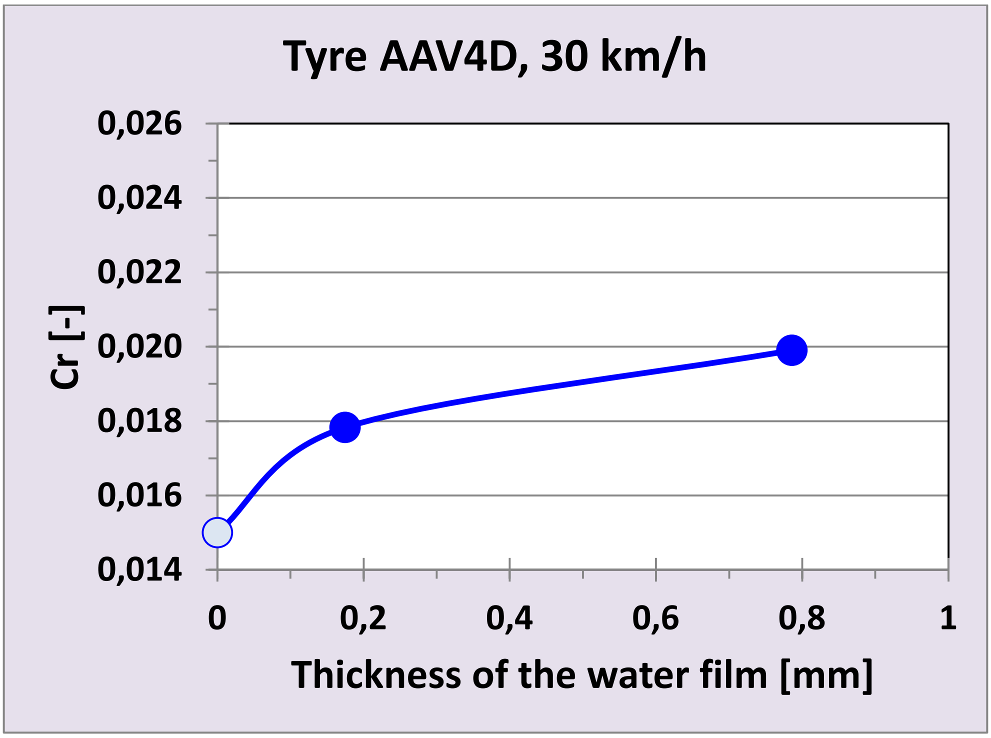

Fig. 37. Influence of water film thickness for tyre AAV4D at a speed of 30 km/h.

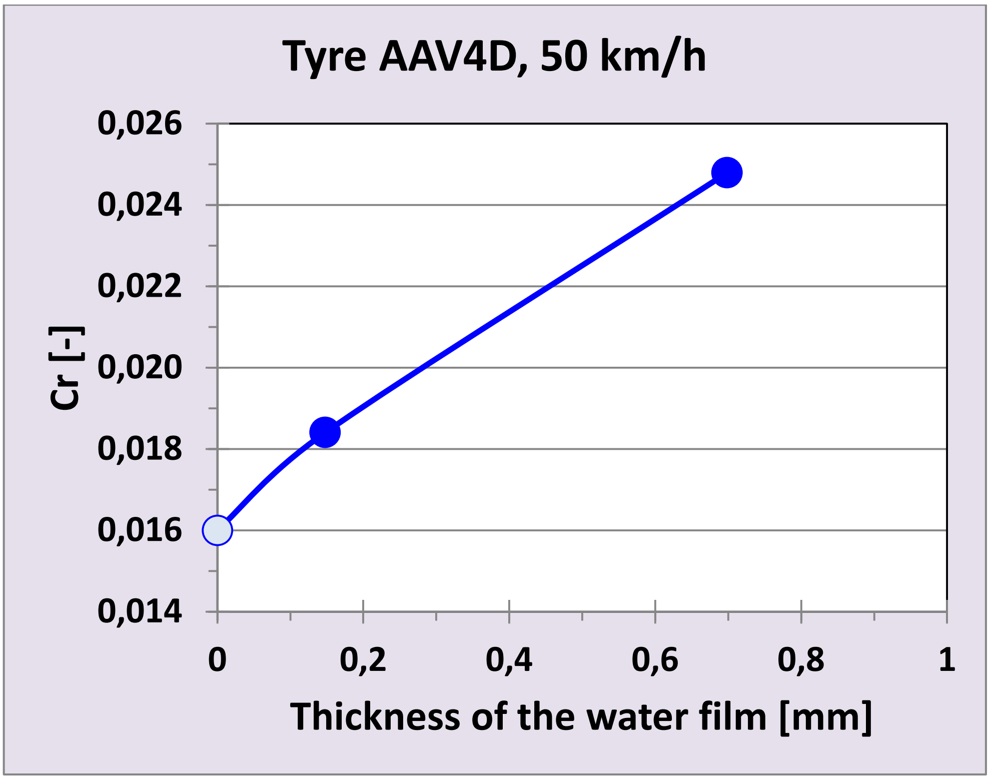

Fig. 38. Influence of water film thickness for tyre AAV4D at a speed of 50 km/h.

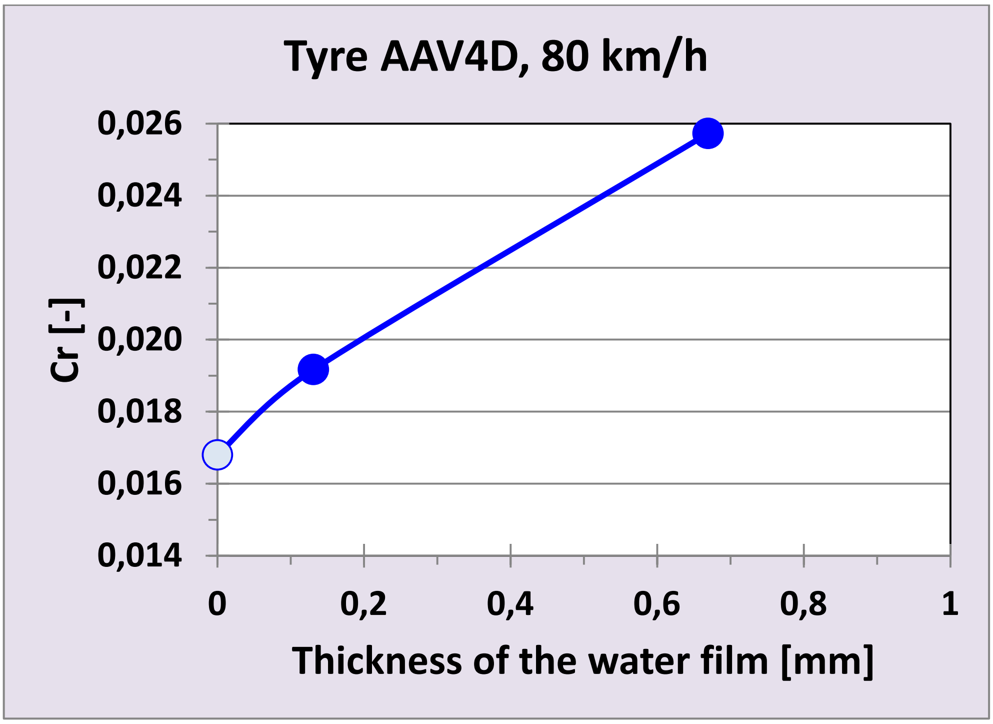

Fig. 39. Influence of water film thickness for tyre AAV4D at a speed of 80 km/h.

5.2 Results of experiments performed during routine measurements

Routine measurements that are performed within different projects from time to time are interrupted by periods of rain. A typical procedure in the case of rainfall is to stop measurements and wait until tested pavements are dry. In order to obtain more data about influence of pavement wetness on rolling resistance in 2014, in a few cases the measurements were carried out despite pavement wetness. Unfortunately in such a case there is no chance to measure thickness of water film, so only qualitative description of the "wetness" is possible. It must be noted that measurements in Horsenes were performed in 2013 with TUG's R^2 trailer while measurements reported in this chapter were performed in 2014 with new TUG's trailer designated as R^2 Mk.2.

During the summer of 2014 three tyres were tested on special SMA8S surface, at a speed of 50 km/h at dry and wet conditions. In this case "wet" surface means that light to moderate rain was raining during the measurements. Pictures of the surface are presented in Fig. 40. In Figs. 41 - 43 the results of measurements performed on a special SMA8 test section are presented.

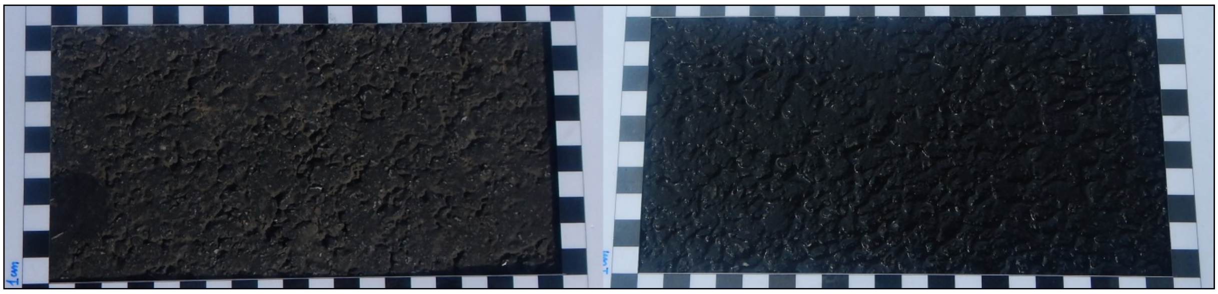

Fig . 40. Dry (left) and wet (right) SMA8 surface.

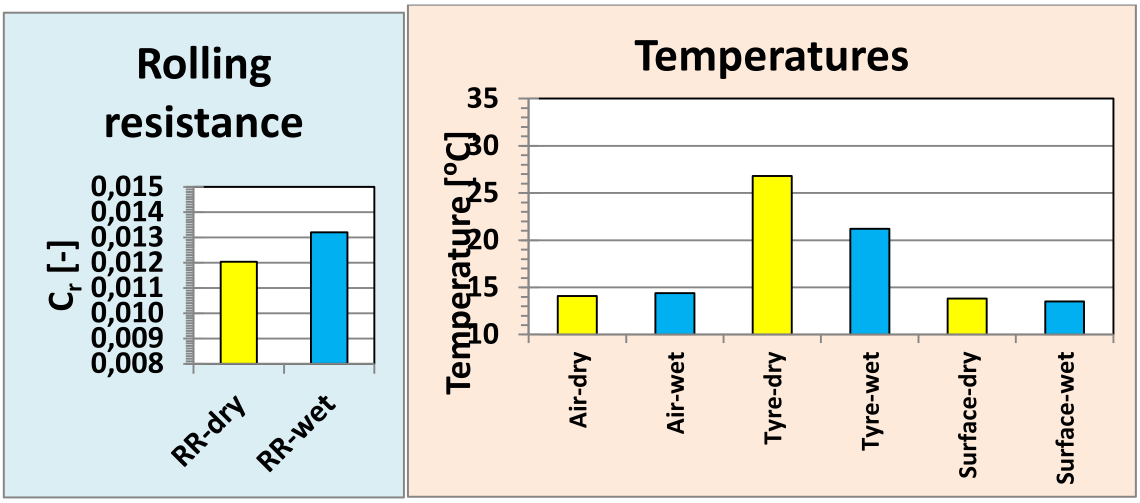

Fig. 41. Influence of wetness on coefficient of rolling resistance and temperatures during measurements for tyre AAV4D at a speed of 50 km/h .

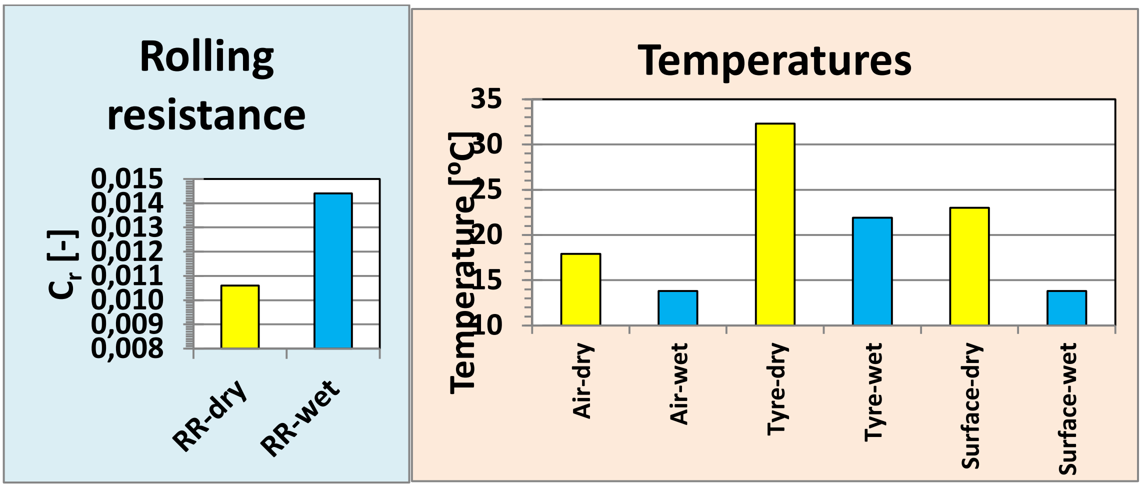

Fig. 42. Influence of wetness on coefficient of rolling resistance and temperatures during measurements for tyre MCPRD at a speed of 50 km/h .

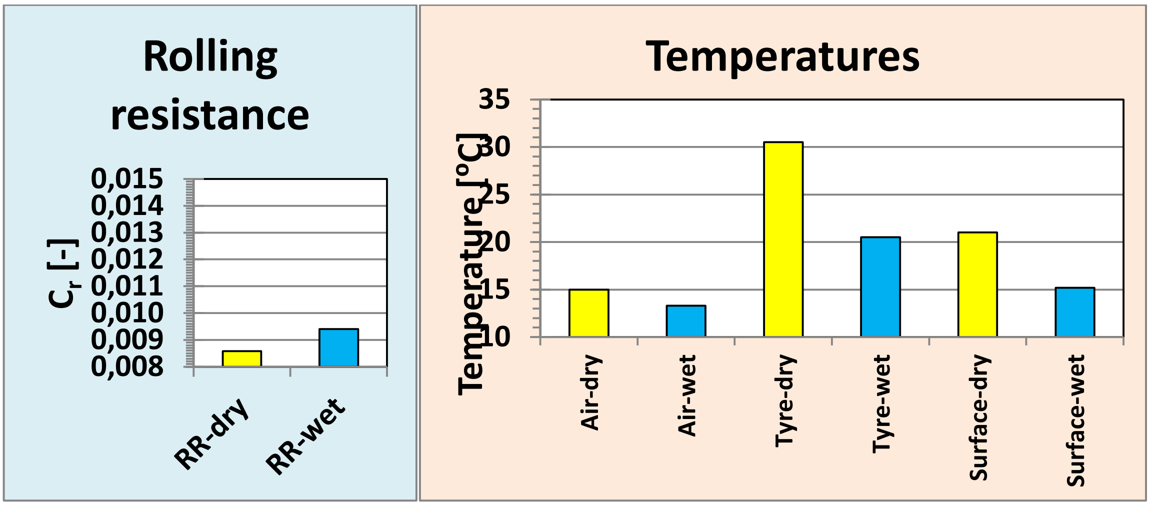

Fig. 43. Influence of wetness on coefficient of rolling resistance and temperatures during measurements for tyre SRTTD at a speed of 50 km/h .

For each tested tyre and speed increased road wetness leads to an increase of rolling resistance. Wetness of the road decreased tyre temperature by up to 10ºC in comparison to tyre temperature during rolling on a dry surface. The highest influence of wetness on rolling resistance was observed for the tyre MCPRD.

During measurements performed within the ROSANNE project in 2014 on a test section close to Rokinge in Sweden the measurements were also interrupted by rain. On the next day it was however possible to perform measurements on a dry surface, so the obtained data may be used for wetness influence evaluation. The pavement at Rokinge test site is rather unique, as it is a kind of a very coarse surface dressing with 25 mm aggregate (see Fig. 44 and Fig. 45). The MPD value for this surface is 2 mm. Due to the weather it was possible to test the pavement in damp condition (light rain) and very wet condition (heavy rain).

Results of rolling resistance measurements are presented in Fig. 46. The increase of rolling resistance coefficient is clearly visible. During dry conditions the tyre temperature was 14ºC higher than the air temperature, at the beginning of rain, when the pavement was just damp, the tyre temperature was 10ºC above the air temperature and during heavy rain it was only 8ºC higher.

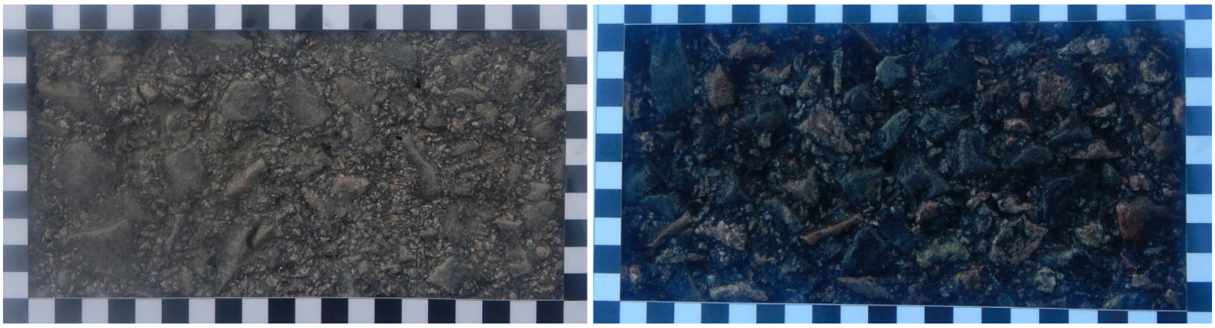

Fig. 44. Pavement at the test site Rokinge - dry conditions (left), damp conditions (right).

Fig. 45. View on test site in Rokinge (damp conditions).

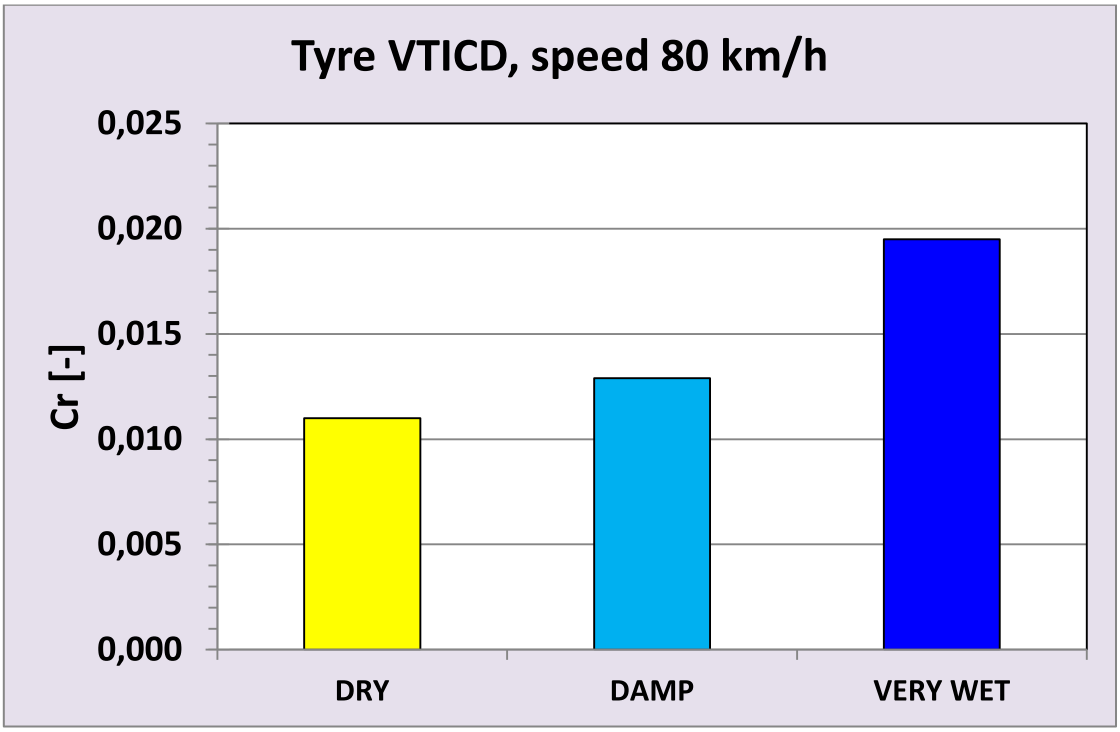

Fig. 46. Influence of wetness on coefficient of rolling resistance and temperatures during measurements for tyre VTICD at a speed of 80 km/h .

5.3 Results for truck tyres

Bode [9] investigated influence of road wetness on roling resistance of truck tyres. He performed tests at speed of 15 km/h with 385/65R22.5 tyres loaded to 4500 kG. Tyres were tested on asphalt and cement concrete road surfaces during dry and wet conditions using specially designed trailer towed by the truck. Rolling resistance force was measured on trailer/truck coupling element. During wet conditions water film depths was 0.5 to 1.0 mm. Bode noted 6.5% increase of C_r on cement concrete surface and 8% increase on asphalt concrete, due to road wetness. He measured that water film on the pavement decreased tyre temperature by 5°C and in consequence tyre inflation pressure decreased by 10 kPa. He estimated that on cement concrete C_r increase of 3.5% was due to energy lost for pumping out water from the tyre/pavement intersection and 3% was due to temperature decrease.

5.4 Conclusions

Water film on the pavement increases passenger car tyre rolling resistance considerably. The increase is dependent on the "degree of wetness", tyre properties and road surface texture. During measurements the increase of C_r up to 70% was observed. It was also observed, that even a slightly damp surface considerably increases rolling resistance. The authors believe that slightly wet road surfaces increase the cooling effect on the tyre thus decreasing its temperature and increasing rolling resistance. A change of tyre temperature by just 4°C may lead for certain tyres to a 6% increase of tyre rolling resistance. When there is more water on the road the cooling effect is even stronger and on top of this, certain energy must be supplied by the tyre to pump-away water from the tyre/road interface region leading to further increase of rolling resistance.

It was not possible to test water film influence on rolling resistance of truck tyres, but literature data indicate that the influence is less than for passenger car tyres. According to [8] on wet surface at 90 km/h the increase of rolling resistance for truck tyres is about 10%.

6 Direction of rotation

Majority of modern tyres are unidirectional, so in principle they may rotate both ways during normal driving. Some researchers speculate, however, that direction of rotation may influence tyre behaviour to some degree. In order to test this problem rolling resistance of two tyres was tested for both tyre directions. TUG always mounts tyres on rims in such a way, that the DOT number indicating week and year of production is facing outward and that the tyre rotates like right wheel on the vehicle. For this experiment, after tests with this standard direction of rotation, the tyres were mounted other way around and tested once more. The results obtained on plain steel drum 2.0 m diameter are presented in Tab. 6 and in Fig. 47.

Table 6. Results of rolling resistance measurements performed on steel surface for two directions of rotation.

Tyre	Speed [km/h]	DOT outward	DOT inward
T1044	50	0.0074	0.0076
	80	0.0078	0.0079
	110	0.0081	0.0082
T1047	50	0.0122	0.0122
	80	0.0124	0.0124
	110	0.0129	0.0129

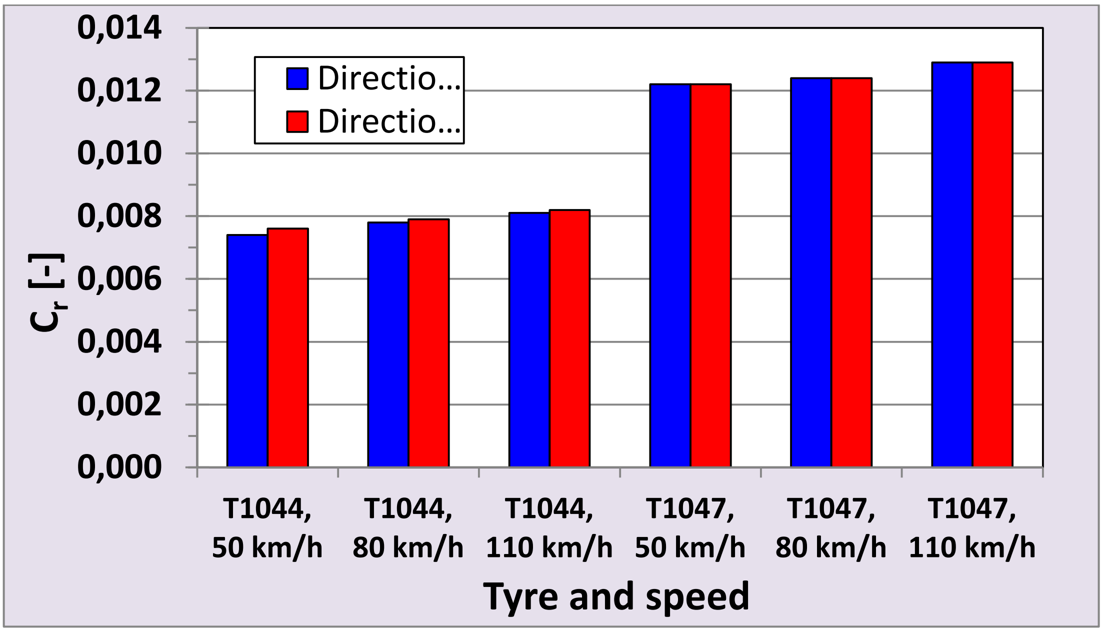

Fig. 45. Influence of the tyre direction of rotation.

Data presented above indicate that direction of rotation of unidirectional tyres doesn't influence rolling resistance. The differences are within measuring error.

7 Conclusions

Results presented in this report indicate that during measurements of rolling resistance tyre load, inflation, ambient temperature and road wetness are important factors and must be precisely controlled. Direction of rotation however is not important, at least for unidirectional tyres. Influence of the road texture must be further studied.

8 Acknowledgements

Although the best part of this report was prepared based on achievements of ROSANNE project, part of the information about road wetness influence was obtained within project MIRIAM, results for tyres designed for electric vehicles were based on research performed within Polish-Norwegian Research Programme CORE 2102, project "LEO" and results for truck tyres were based on research performed within project ROLRES. Projects LEO and ROLRES are sponsored by the Polish National Centre for Research and Development (NCBiR).

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