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At what temperature should the tire rolling resistance be measured?

Jerzy Ejsmont[1], Grzegorz Ronowski[1], Truls Berge[2], Sławomir Sommer[1], Wojciech Owczarzak[1], Anna Szerszyńska[1]

[1] Gdańsk University of Technology, ul. Narutowicza 11/12, PL 80-233 Gdańsk, Poland
[2] SINTEF Digital, P.O.Box 4160 Torgarden, NO 7465 Trondheim, Norway

Corresponding author:

Jerzy Ejsmont, Gdańsk University of Technology, Faculty of Mechanical Engineering and Ship Technology, ul. Narutowicza 11/12, PL 80-233 Gdańsk, Poland

Email: jerzy.ejsmont@pg.edu.pl

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Tire, Rolling resistance, Temperature, Tire label, Energy consumption, Road texture, Standardization

Abstract

The climate crisis is already an indisputable fact and therefore, it is necessary to reduce energy consumption, and especially energy wasting. One of the ways to reduce energy consumption of motor vehicles is to decrease vehicle movement resistance, including rolling resistance. In order for the optimization of tire rolling resistance to be efficient, it is necessary to apply appropriate optimization criteria that are closely related to typical vehicle traffic conditions. The article discusses the influence of the temperature at which tire rolling resistance tests are carried out on the results obtained. Currently applicable standards require testing of tire rolling resistance at ambient temperatures of 25°C (ISO) and 24°C (SAE). However, these temperatures are far from the typical temperatures in most areas with intense road traffic. The results obtained at a temperature of 25°C do not allow clear conclusions about the tires' performance in more typical thermal conditions prevailing in different seasons. The analyzes presented in the article indicate that better representativeness of the rolling resistance estimates can be obtained by testing summer tires at a temperature of +15°C and winter tires at a temperature of -5°C.

1. Introduction

Reducing the rolling resistance of tires has been one of the main goals of development work in the tire industry for several years. This is due to the increasing share of rolling resistance in energy consumption of vehicles [1]. The use of hybrid and electric drive systems allowed for a significant reduction in energy losses associated with vehicle braking and driving on roads with a significant longitudinal slope. Advanced airflow simulation methods allowed for a very significant reduction in aerodynamic drag. Unfortunately, this is not accompanied by a reduction in the weight of the vehicles, on the contrary, electric and, to some extent, hybrid vehicles are usually heavier than their classic counterparts because they must be equipped with high-capacity batteries, which currently are rather heavy. Since rolling resistance is proportional to the wheel load on the road surface, its share in the total energy losses during vehicle operation has not decreased, but has even increased. The data presented in [2] indicate that statistically tires with a Rolling Resistance Coefficient (CRR) of 0.011 are responsible for approximately 30% of the energy consumption in a car equipped with a classic drive system and as much as 40% of the energy consumption in a comparable electric car. Based on many investigations, it is currently assumed that reducing the rolling resistance of currently available quality tires by 10% leads to a reduction in energy consumption (and CO_2 emission) by approximately 3-4% in typical traffic conditions [3]. During the last 25-20 years tire manufacturers have made a great progress in reducing the rolling resistance of their tires. In the initial period, progress was made mainly by introducing to the market tires with a large outer diameter and small width (for example size 155/70 R19). Currently, tire manufacturers have mastered the production of low rolling resistance tires of more typical sizes.

To promote ecological products, Economic Commission for Europe (ECE) has developed Regulation No. 117 [4] specifying methods for testing tires in terms of noise, wet grip and rolling resistance, and in 2009 they introduced the obligation to mark tires with labels indicating their performance in terms of grip on wet surfaces, noise and rolling resistance. In 2020, Regulation 2020/740 [5], which is still in force, was published, which corrected the 2009 version. Unfortunately, the conditions for measuring tire rolling resistance adopted in the labeling procedure from the ISO 28580 standard [6] are not very realistic, which significantly reduces the representativeness of the results obtained. There are two serious objections to the adopted method. The first one concerns the texture of the drums of the roadwheel facilities, which, according to the standard, are to be steel and smooth. It is obvious that in real road conditions the tire never rolls on such a surface, and that the surface texture significantly affects the rolling resistance, as the deformations of the tread elements depend on it [7, 8]. The second serious shortcoming of the adopted test conditions is the temperature, which, according to the requirements, should be 25°C. Without a doubt, a temperature of 25°C is convenient from the point of view of the ease of conducting measurements, but it is unrealistic from the point of view of its purpose. The average annual temperature in Europe and the USA is much lower, so the results obtained at 25°C cannot be considered representative. It is also a complete misunderstanding to measure the rolling resistance of winter tires at this temperature, as such tires should not be permanently used at temperatures higher than 7°C [9]. The research conducted as part of the ELANORE project [9] has shown that the temperature at which the rolling resistance of car tires is tested affects not only the value of measured Coefficients of Rolling Resistance (CRR) but also the tire ranking, since for different tires there are different dependencies between temperature and rolling resistance. This observation was confirmed by research conducted by Goodyear [2], which also showed different sensitivity of individual tire models to temperature.

According to the ISO 28580 standard [6], rolling resistance tests can be conducted in the temperature range of 20°C to 30°C but the results must be corrected to 25°C using the following relationship:

$$F_{r25} = F_r[1 + K_t(t_{amb} - 25)] \quad (1)$$

Where:

F_{r25}	-	Rolling resistance force at 25°C
F_r	-	Rolling resistance force at temperature t_{amb}
t_{amb}	-	The ambient temperature during measurements
K_t	-	The constant, with following values:

- 0.008 for passenger tires
- 0.010 for truck and bus tires with LI ≤ 121
- 0.006 for truck and bus tires with LI > 121

Unfortunately, the K_t coefficients quoted above do not allow to obtain appropriate corrections for all types of tires or surfaces and for a wider temperature range. For 130 car tires that were tested at the Gdańsk University of Technology during execution of ELANORE project in accordance with ISO 28580, but in the temperature range -15°C to 25°C, K_t coefficients ranging from 0.005 to 0.014 were obtained. The distribution of the values of these coefficients is presented in Fig. 1. The reported values of the K_t coefficients were determined from formula (1) into which, after transformation, the rolling resistance forces measured for temperatures of 25°C and -15°C were substituted. Since a rather broad range of the K_t coefficient was obtained, it can be concluded that the use of the standard coefficient K_t = 0.008 to compensate large temperature differences leads not only to an incorrect estimation of the rolling resistance force of a given tire, but also it may lead to wrong ranking in the case of tires with different K_t coefficients. This means that the rolling resistance of a tire cannot be assessed at low temperatures based on measurements taken at high temperatures and using the "universal" coefficient K_t = 0.0008.

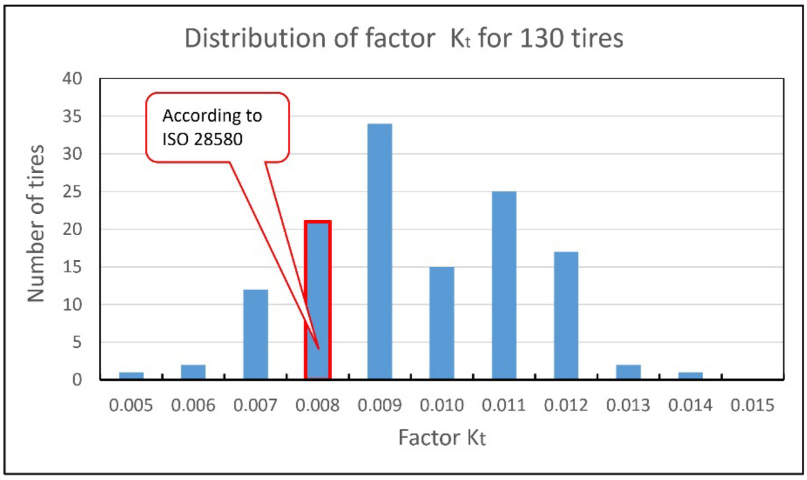

Figure 1. Distribution of K_t coefficient values for 130 car tires tested on a steel drum in the temperature range from -15°C to +25°C.

As it was proven during the ELANORE project execution, the smooth steel drum surface required by the currently applicable ISO and SAE standards causes significant distortions in the measurement of rolling resistance because it is devoid of the texture characteristic of real road surfaces.

Different parts of the tire are made of different materials that may behave differently at low temperatures. For this reason, in order to obtain the required representativeness of tests conducted at low and high temperatures, it is necessary to ensure that the texture of the drum surface is as close as possible to the texture of road surfaces, because it determines the nature of deformations of the tread elements in contact with the road surface. Due to this, in parallel with the tests on the steel drum required by ISO 28580, the measurements presented in this article were also performed on a drum covered with a replica of the Stone Matrix Asphalt surface symbolically marked as SMA8 (see Fig. 2).

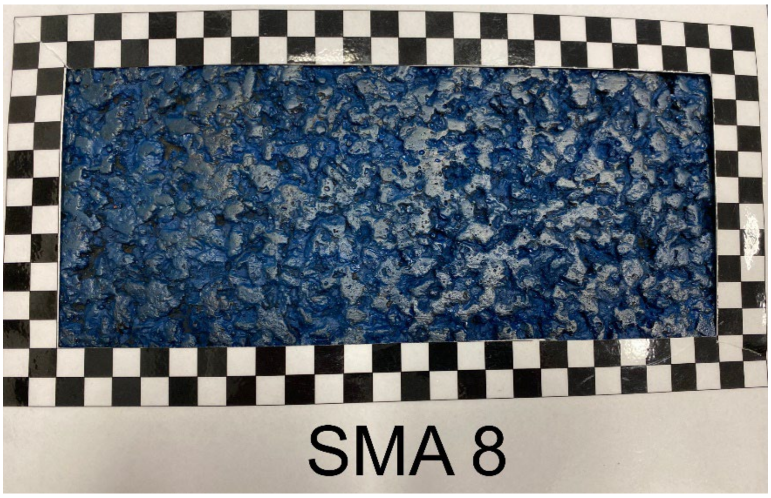

Figure 2. Replica road surface SMA8.

Analyzing the effects of adopting unrepresentative test conditions, it must be stated that the obtained CRRs values are practically always lower than the CRR values found in road conditions on surfaces with typical textures and at typical temperatures. What's worse, the tire ranking gained under standard measurement conditions is generally not the same as the tire ranking obtained under road conditions. As a consequence, tire labels may, to some extent, be granted on distorted data preventing fair comparison of tires in terms of rolling resistance. What is more, the absolute values of CRR coefficients associated with individual tire classes cannot be directly used to predict fuel consumption or car range, which is particularly important for electric vehicles.

This article focuses on the results of research performed within ELANORE project [10] aimed at finding thermal conditions during rolling resistance measurements that would allow to obtain more representative results than those currently available.

2. Representative ambient temperature

Car tires are used in all geographical latitudes, from extremely hot regions such as Iran, Australia or Libya to subarctic and arctic regions such as Northern Canada, Svalbard and northern regions of Norway. This means that in particular regions of the world the average temperature at which tires are being used may differ significantly, and this significantly affects the performance of the tires. A solution is to introduce several types of tires, such as summer tires, winter tires and all-season tires, which, both in terms of tread pattern and rubber mixes used, are optimized for the expected conditions of use. Therefore, summer tires achieve the best parameters at positive temperatures, usually exceeding 7 - 10^{o}C [11], while winter tires are optimized for subzero temperatures, and the tread shape takes into account the requirements for good grip on icy and snow-covered surfaces. All-season tires have been gaining popularity for some time. By definition, these tires are intended to fill the gap between winter and summer tires, because in many regions of the world winters are not very severe and even in the season defined as winter mixed conditions prevail, with temperatures fluctuating around zero and the road surface is covered with snow only occasionally. If very hot days also occur sporadically in these regions, the compromise provided by all-season tires seems to be optimal for many vehicle users. It should be noted, however, that in some regions of the world seasonal differences in air temperature may reach up to 100^{o}C (e.g. the Oymyakon region in Siberia [12]) so dedicated winter and summer tires should be used.

Determining the optimal ambient temperature when testing tire rolling resistance requires taking into account that the air temperature also changes during the day. Daily temperature fluctuations can reach several dozen degrees Celsius (tropical regions), although they are usually a few or a dozen degrees. In cities and suburban areas, statistically the most intense road traffic occurs in the morning (7:00 a.m. - 9:00 a.m.) and in the afternoon (3:00 p.m. - 5:00 p.m.). In most cases, the morning rush hours occur in the period when the daily temperature is the lowest, and the afternoon rush hours occur in the period when the daily temperature is the highest, which further complicates determining the optimal parameters for conducting research. For car tires, it is also important that rainfall causes a significant reduction in road and tire temperature, which leads to a significant increase in the rolling resistance of "wet" tires [13], so in areas with frequent rainfalls, tires reach a lower temperature than in dry areas with the same air temperature. Unfortunately, only in motor sports is it possible to precisely adapt the tires used to current road conditions. All other users must limit themselves to selecting tires best suited to the typical seasonal conditions in which they will travel.

The above considerations show that it is impossible to adopt measurement conditions that will be representative always and everywhere. Nevertheless, efforts should be made to ensure that these conditions are as representative as possible for the largest possible group of tire users. Tab. 1 contains the most important statistical data on temperatures in selected regions of the world, which come from various primary sources [14]. It should be noted that not all data comes from exactly the same, usually 10 years long period and that in many countries there are very significant differences for different geographical zones, so locally even large deviations from the presented data are possible. Classic examples here are Canada and the USA.

Table 1. Average temperatures for selected countries.

Country	Annual Averaged temperature [°C]	Averaged temperature for summer [°C]	Averaged temperature for winter [°C]
Norway	4.5	11	-6
Poland	7.8	18	0
Italy	13.4	21	5
Germany	8.5	16.5	3.3
France	10.7	20	4.5
USA	8.6	21	-2
Canada	5.4	19	-9
Japan	11.2	21.3	0.8
South Korea	11.5	24	-1
Australia	21.6	30	17

In none of the countries discussed in Tab. 1 does the average annual temperature reach 25°C, and for most countries it does not even come close to this value. Even in summer, in most countries the average temperature does not reach 25°C (the only exception is Australia). Taking into account that summer tires are used not only in summer, but also in spring and autumn, it can be assumed that the average temperature in this period is around 10-15°C for most countries. In winter, in countries where winter tires are commonly used, it can be assumed that the average temperature is around -5 to 0°C. For practical reasons, the temperature of 0°C is not favorable for rolling resistance tests, because it is on the verge of freezing/thawing of water and, consequently, it may lead to surface moisture and cause problems with the measurement system. Therefore, it seems that for winter tires the testing temperature should be -5°C. Assuming a reference temperature of +15°C for summer tires and -5°C for winter tires, the problem of reference temperature for all-season tires remains. The authors believe that, taking into account that these tires can be used both in winter and summer, they should be tested both at temperatures of +15°C and -5°C and the result should be averaged.

3. Factors influencing the rolling resistance of tires

Tire rolling resistance depends on many factors [15], some of which are related to temperatures (see Fig. 3). Temperature-independent factors include: tire construction, tread pattern characteristics, tire load, surface texture, driving speed, and the presence of water (or snow) on the surface. The remaining factors are directly or indirectly related to the thermal condition of the tire, road surface and air [16]. While the temperature of the air and road surface is easy to define and measure, the temperature of the tire causes many problems in this respect. One can talk about the temperatures of individual zones of the tire measured on outer surface of it (which is not easy due to the intensive cooling by the stream of air flowing around the tire), about the temperatures of the inner surface of the tire, or about the temperatures occurring inside the individual layers that make up a modern car tire. Tire temperature has a direct impact on rolling resistance by influencing the hysteresis phenomena of the materials used to construct the tire. The higher the tire temperature, the lower the rolling resistance. However, it should be noted that the relationship between tire temperature and rolling resistance is bidirectional, as increased rolling resistance in turn causes an increase in tire temperature. Tire temperature is also influenced by slippage related to tangential forces occurring in the contact area between the tire and the road, related to the transmission of driving, braking or lateral forces. It is also influenced by "the history" of the speed profile, because the tire has high thermal inertia and requires a relatively long time to heat up or cool down due to changes in operating conditions. Fig. 4 shows the tire heating process during drum tests conducted on a replica of the SMA8 surface at an ambient temperature of -7.5^{o}C. The influence of temperature measured at different areas of the tire on the rolling resistance coefficient CRR is clearly visible. As the figure shows, temperature and rolling resistance stabilize only after approximately 20-25 minutes from the start of the measurement. Subject of non-steady-state conditions influence on tire rolling resistance is covered in details in [17, 18].

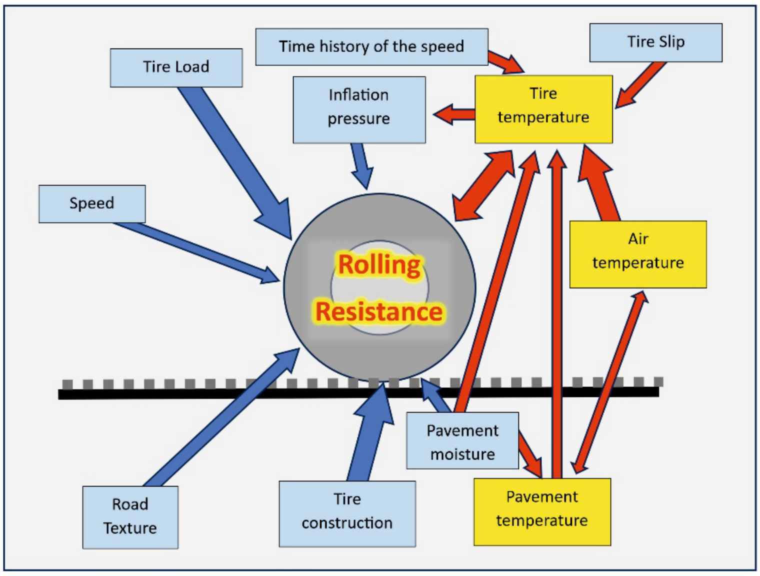

Figure 3. Factors influencing the rolling resistance of tires.

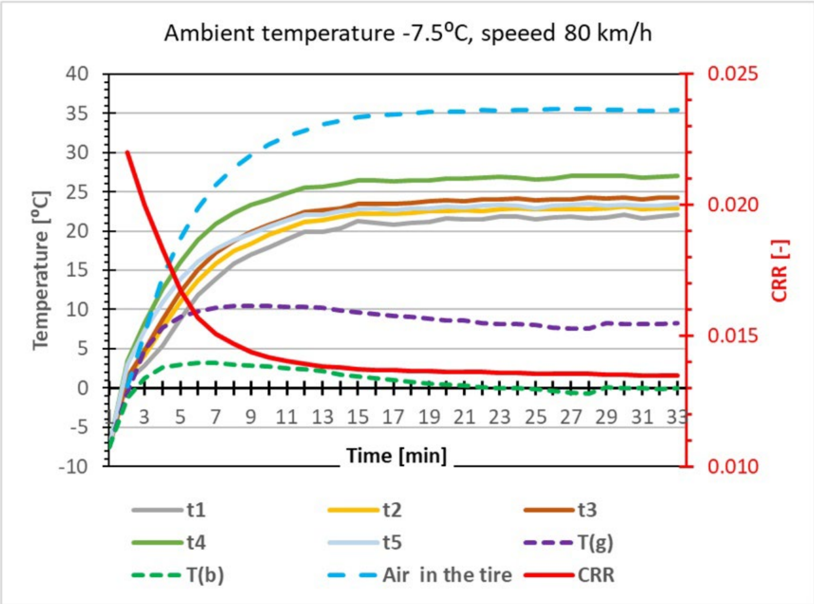

Figure 4. Change in rolling resistance and temperature of individual zones of the tire during the warming period; ambient temperature -7.5ºC, speed 80 km/h, load 4 kN, inflation pressure 210 kPa (set at -7.5ºC); *t1* – *t5* temperatures of inner surface of the tire in different regions, *T(g)* – external temperature (groove), *T(b)* – external temperature (blocks in central part of the tread), *Air in the tire* – averaged temperature of the air inflating the tire (estimated on the basis of inflation pressure increase).

Speed is one of the factors affecting tire temperature. However, it so happens that in the speed range of 50 - 110 km/h there is a specific compensation for the influence of temperature and the increased rate of deformation of the tire elements. Tab. 2 shows the influence of speed on the temperature of the outer and inner tread surfaces and on the CRR for a high-quality summer tire. There is no doubt that the increase in tire deflection frequency associated with increasing speed tends to increase rolling resistance, but this effect is offset by an increase in tire temperature and corresponding minimal increase in inflation pressure. As shown in the Tab. 2 in the discussed speed range, rolling resistance remains practically independent of speed. This is beneficial from the point of view of the representativeness of the rolling resistance labels evaluated at 80 km/h as they remain adequate to the conditions of fast urban driving, driving in suburban areas and driving on expressways.

Table 2. Influence of speed on the Coefficient of Rolling Resistance and tire temperature.

Speed [km/h]	CRR [-]	Tread temperature – outer [°C]	Tread temperature – inner [°C]
50	0.0067	30.1	35.8
80	0.0068	31.2	38.4
110	0.0067	34.4	41.4

The temperature of the surrounding air has a significant impact on the tire temperature, and the pavement temperature also has some influence. If the surface is wet or damp, it may cause the tire to cool down significantly compared to the situation in which the tire rolls on a dry pavement. In turn, the pavement temperature is influenced by air temperature, sunlight, wind and the presence of moisture or water.

As the above considerations show, thermal interactions affecting rolling resistance are of a complex nature. It is true that the rolling resistance of a tire is strongly related mainly to the thermal condition of the tire (air and road temperatures have only an indirect effect), but it is practically impossible to adopt the tire temperature as a parameter controlling the rolling resistance measurement. Firstly, it is very difficult to determine a representative point for measurements of the tire temperature. Change of the measurement point by a few centimeters may result in temperature difference by several degrees (see Fig. 5). Secondly, the more serious reason is that the tire temperature both influences rolling resistance and is dependent on this resistance. Such feedback makes it impossible to introduce tire temperature as an independent parameter defining the conditions for measurement. Therefore, it seems that only air temperature can be a parameter characterizing thermal conditions for measuring rolling resistance, which is consistent with all present standards in this area.

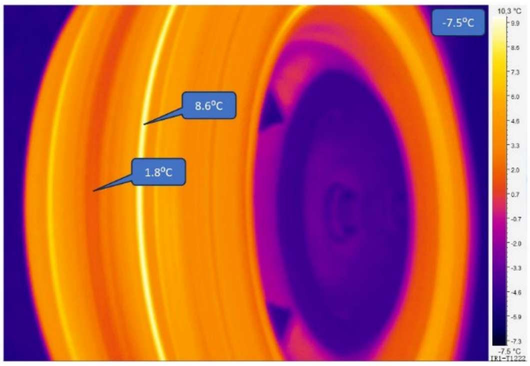

Figure 5. Thermogram showing the temperature distribution on the tire tread surface after 30 minutes of rolling at a speed of 80 km/h on a replica of the SMA8 road surface, air temperature -7.5°C.

4. The influence of air temperature on the rolling resistance of car tires

The importance of correctly adopting the temperature at which tire rolling resistance tests are performed can be seen in Fig. 6, which compares the measured CRR's for temperatures of 25°C and -10°C. The results refer to rolling resistance measured on a roadwheel facility with a smooth steel drum, which is in accordance to the ISO standard. Since, as already mentioned, the smooth steel surface of the drum is not representative for real road conditions, Fig. 7 presents analogous results, but obtained on a drum covered with a replica of the SMA8 surface. As the procedure of performing measurements at a temperature of -10°C is not covered by the ISO standard, in order to obtain the proper inflation pressure, it was set (capped) at ambient temperature of -10°C, and not at +25°C as stipulated in the standard. Results presented in the Fig. 6 and 7 show the coefficients of determination for both cases are low and amount to R^2 = 0.48 and R^2 = 0.57, respectively. This means that based on the results obtained for an air temperature of +25°C, it is not possible to predict, with satisfactory accuracy, what results will be obtained at a temperature of -10°C, which may lead for example to an incorrect assessment of winter tires. In Fig. 6, the results for two tires are marked with red circles. These tires at a temperature of +25°C show an almost identical CRR = 0.0071. However, at a temperature of -10°C, one of these tires has CRR = 0.0096 and the other one CRR = 0.0120, i.e. its rolling resistance is 25% higher. However, following the present labeling procedures, both tires would be equally classified as class "B" due to similar CRR at +25°C.

Fig. 8 shows examples of temperature characteristics obtained for summer, all-season and winter tires. It is clearly visible that winter tires have the highest CRR, but the increase of rolling resistance at low temperatures is smaller for these tires than for summer tires. While at a temperature of +25°C the difference between the rolling resistance of the tire with the highest and lowest CRR is as much as 54%, at a temperature of -10°C it decreases to 17%.

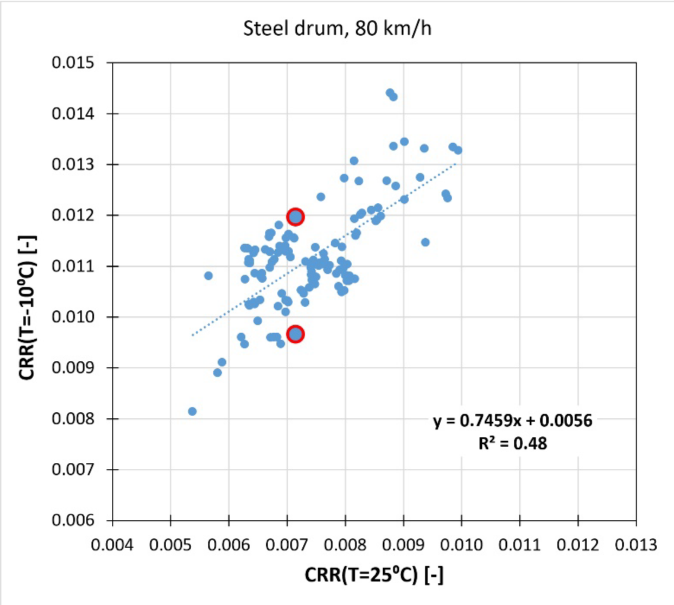

Figure 6. Comparison of rolling resistance coefficients for tires tested in the manner specified in ISO standards (on a steel drum) at temperatures of +25°C and -10°C.

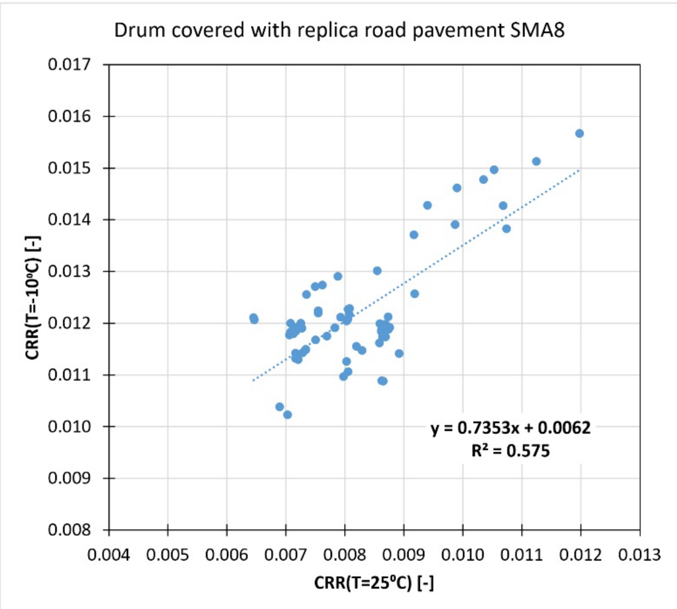

Figure 7. Comparison of rolling resistance coefficients for tires tested on a drum covered with a replica of the SMA8 surface at temperatures of +25°C and -10°C, speed 80 km/h.

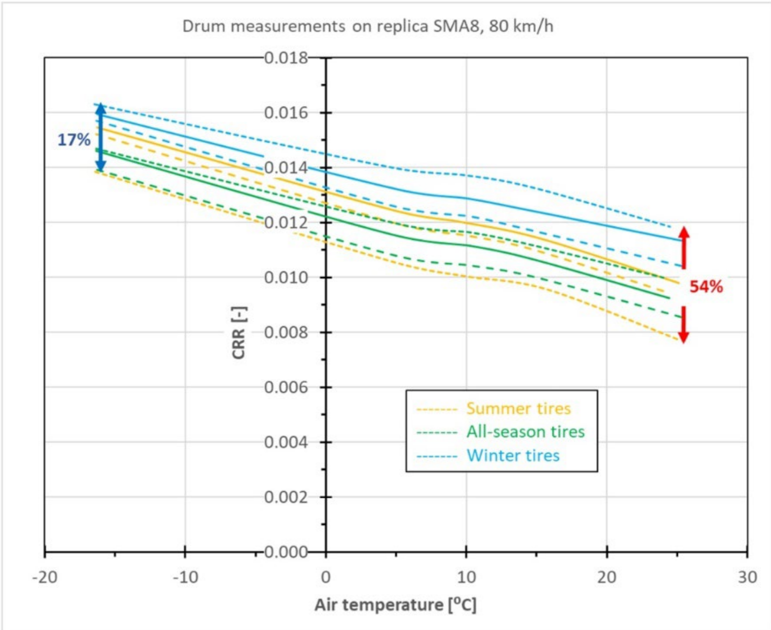

Figure 8. Examples of characteristics of the influence of temperature on the rolling resistance for summer, winter and all-season tires.

Since the ELANORE project proposes that tests should be conducted at +15°C for summer tires and -5°C for winter tires, instead of 25°C, it is worth checking how big differences in the CRR values can be expected. Fig. 9 shows a comparison of the results obtained at a temperature of -5°C and +15°C on a replica of the SMA8 surface with the results of standard measurements performed in full compliance with ISO standards, i.e. on a smooth steel drum at a temperature of +25°C. It is visible that even at a temperature of +15°C, the tire ranking (see also Fig. 10) and the CRR values differ significantly, and even greater differences occur when tested at a temperature of -5°C. This means that the currently used method of measuring rolling resistance does not allow to obtain realistic "real life" results.

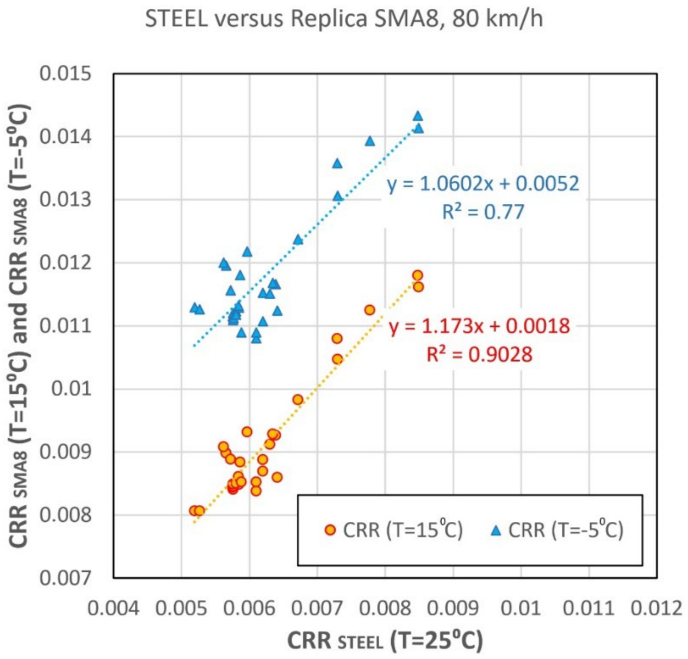

Figure 9. Comparison of rolling resistance obtained during measurements on a drum covered with a replica of the SMA8 road surface at temperatures of -5°C and 15°C with the measurement results according to ISO 28580.

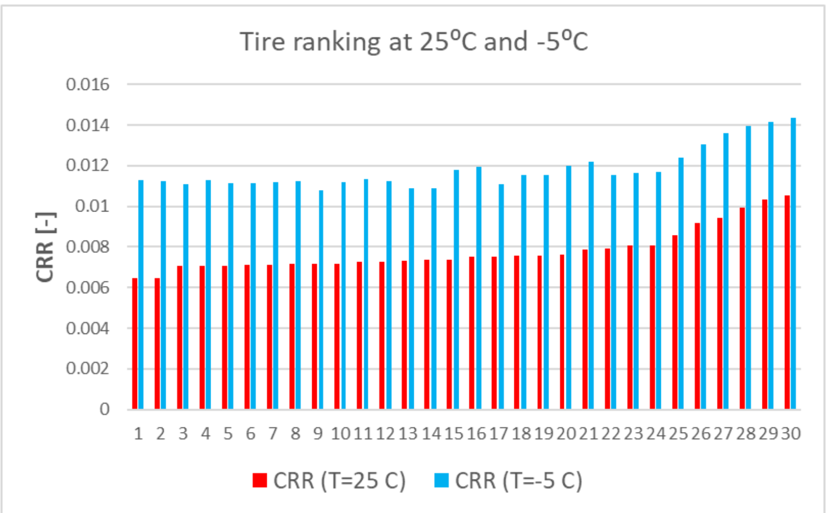

Figure 10. Tire ranking depending on temperature. Tires ranked according to increasing rolling resistance obtained during tests in accordance with ISO 28580 (red) and the corresponding CRR coefficients obtained at a temperature of -5°C.

Fig. 11 shows a similar comparison of results as in Fig. 9, but in this case also measurements at a temperature of +25°C were performed on a replica of the SMA8 surface. Despite the fact that the coefficient of determination has significantly improved and the difference in the absolute value of CRR has decreased, inferences about rolling resistance at low temperature (-5°C) based on the results obtained at 25°C are still subject to large errors. It is worth noting, however, that the correlation between the results obtained on the SMA8 replica pavement at +15°C and +25°C is very good. This indicates that if changing the tire testing temperature from 25°C to 15°C would be considered by tire manufacturers to be too difficult to carry out for technical or organizational reasons, it may be possible to leave the test temperature of 25°C for summer tires, provided that the tests are carried out on proper replica of the road pavement and not on a steel drum. In such a case, to obtain consistent absolute values of CRR coefficients representing temperature of 15°C, it would be necessary to increase the values obtained at 25°C by 17%.

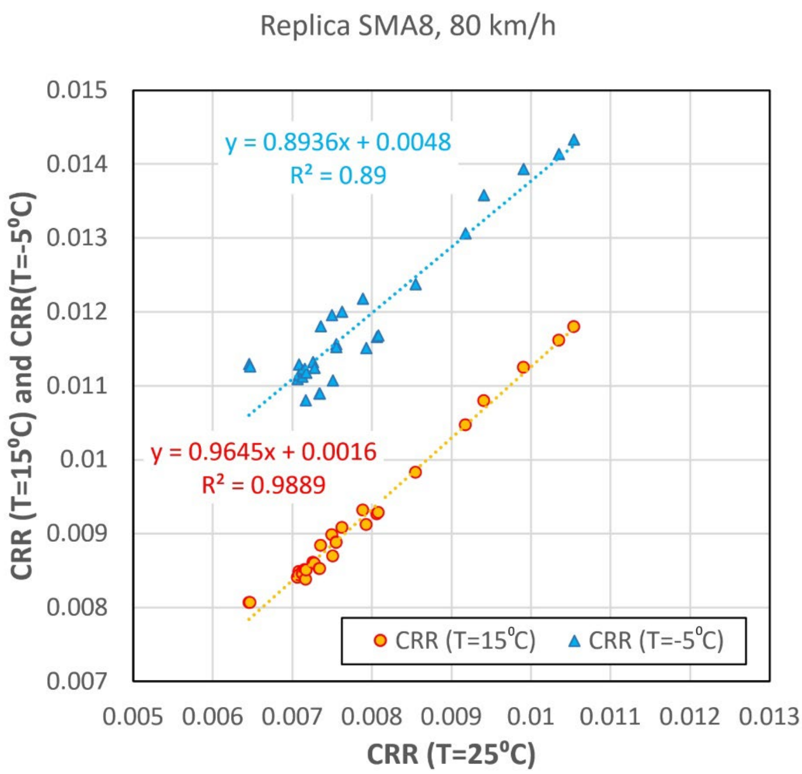

Figure 11. Comparison of rolling resistance obtained during measurements on a drum covered with a replica of the SMA8 road surface at temperatures of -5°C and 15°C with the results of measurements performed at a temperature of 25°C also on a replica of the SMA8 road surface.

5. Conclusions and recommendations

The current ISO and SAE standards for tire rolling resistance measurements ensure high accuracy and repeatability of measurements, but the results obtained are not fully adequate to the actual performance of tires in typical road conditions. What's worse, the results of rolling resistance tests are made available to users in the form of tire classes visualized in the labels, which may lead to wrong consumer's decisions. Problems with the representativeness of the tests are mainly related to the use of a smooth steel surface for testing instead of a surface with a realistic texture similar to typical road surface textures such as AC16, SMA8 or SMA11, and to carrying out measurements at a too high temperature. As shown above, in the overwhelming majority of trafficked zones, average annual temperatures and even average summer temperatures are significantly lower than the 25^{o}C required by ISO standards or the 24^{o}C required by SAE standards. It's hard to believe, but winter tires, by definition designed for low temperatures, are also tested at such high temperatures. As shown in the article, due to the fact that the effect of temperature on rolling resistance may vary significantly for individual tires, adopting too high temperature during tests not only leads to too low CRR values, but also disturbs the ranking of tires.

Therefore, it is advisable to introduce changes in the standards to make more realistic test conditions for rolling resistance measurements. The authors recommend that the ambient temperature for testing summer tires be +15^{o}C, and -5^{o}C for winter tires, and on this basis the class shown on the labels should be determined. For all-season tires that can be used at both low and high temperatures, it seems advisable to average the results obtained at -5^{o}C and +15^{o}C. Since there is a large difference in the CRR coefficient between the results obtained at low and high temperatures, which would in the eyes of users discriminate winter tires, separate class ranges should be introduced for winter, all-season and summer tires. It seems that the peripheral CRR values for individual classes of summer tires should be increased by 10-15% for all-season tires and 20-30% for winter tires. Taking into account the forecasts for further intensive work aimed at reducing the rolling resistance of tires, parallel to introduction of the above changes, it would be worth to add one more class of tires with resistance lower than the current class A.

If, due to technical or organizational reasons, changing ambient temperature from 25^{o}C to 15^{o}C for summer tires would be too troublesome the alternative procedure may be applied. In such a case the results obtained at 25^{o}C on replica road pavement should be increased by 17% (averaged increase for tested summer tires within the ELANORE project) to represent results that would be obtained at 15^{o}C. Such a procedure, however, will not be appropriate for winter tire testing that must be performed in subzero temperature.

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Declaration of conflicting interests

The Authors declare that there is no conflict of interest.

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