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Comparison of Tire Rolling Resistance Measuring Methods for Different Surfaces

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Abstract
The rolling resistance of car tires is one of the most important parameters characterizing tires today. This resistance has a very significant contribution to the energy consumption of wheeled vehicles. The climate crisis has forced tire and car manufacturers to place great emphasis on the environmental impact of their products. Paradoxically, the development of electric vehicles has led to an even greater importance of rolling resistance, because in electric vehicles, a large part of the influence of grade resistance and inertial resistance has been eliminated due to re-generative braking, which resulted in rolling resistance and air resistance remain as the most important factors. What is more, electric and hybrid vehicles are usually heavier, so the rolling resistance is increased accordingly. To optimize tires for rolling resistance, representative test methods must exist. Unfortunately, the current standards for measuring rolling resistance assume that tests are carried out in conditions that are far from real road conditions. This article compares the results of rolling resistance tests conducted in road conditions with the results of laboratory tests conducted on roadwheel facilities. The overview of results shows that the results of tests conducted in accordance with ISO and SAE standards on steel drums are very poorly correlated with more objective results of road tests. Significant differences occur both in the Coefficients of Rolling Resistance (CRR) and in the tire ranking. Only covering the drums with replicas of road surfaces leads to a significant improvement in the results obtained. For investigations of rolling resistance in non-steady-state conditions, the flat track testing machine (TTF), equipped with asphalt cassettes, is shown to provide measurement data in agreement with the road test data.

Keywords Tires · Rolling resistance · Measuring methods · Tire labels · Road pavements

Abbreviations

CRR	Coefficient of rolling resistance, –
CRR_F	Coefficient of rolling resistance reduced to flat surface
CRR_R	Coefficient of rolling resistance measured on the drum
r	Tire radius, m
R	Drum radius, m

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1 Introduction

The rolling resistance of car tires is one of the most important parameters characterizing modern car tires, especially those intended for electric vehicles. In a typical car, the three most important resistances to motion are: rolling resistance, aerodynamic resistance, and inertial resistance. While in hybrid and electric cars, a large part of the energy associated with accelerating the vehicle can be recovered by charging the battery during braking, the aerodynamic drag of such a vehicle is essentially the same as in the case of a classic vehicle identical in shape and size. Unfortunately, the rolling resistance of hybrid cars and especially electric cars is usually higher than in the case of classic vehicles of the same size, because the weight of electric and hybrid vehicles is greater. This means that in electric and hybrid vehicles, the share of rolling resistance in the total motion resistance is significantly higher. For most vehicles, at speeds up to

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approximately 80–90 km/h, rolling resistance dominates in the vehicle's energy consumption.

Unfortunately, measuring tire rolling resistance is a relatively difficult task, even with today's very modern measuring devices. The first problem results from the fact that the rolling resistance force of modern tires is approximately 1% of the tire load. It is, therefore, necessary to measure very precisely a relatively small force in a system loaded with large and usually variable forces. For example, if the wheel load acting on the road is 5 kN, a rolling resistance force of 30–60 N is expected for typical road surfaces and good tires. If the goal is to measure with an accuracy of 1%, it means that the accuracy of the measurement must be in the range of 0.3–0.6 N which is a very difficult task, especially in road conditions.

The second problem is related to the measurement conditions, which must reflect the actual conditions in which the tires are used. Of course, the best representative conditions are obtained when the tests are carried out on the road. Unfortunately, there are numerous problems here. The first is the influence of weather conditions. Rolling resistance is strongly dependent on tire temperature, which depends on load, speed, road temperature, and air temperature (Ydrefors et al., 2021a). It is obvious that the air and road temperatures remain practically out of control, so the possibility of carrying out measurements in specific conditions is very limited and for most locations only possible during certain seasons. An additional problem is several factors disturbing the measurements, such as driving speed oscillations, road surface unevenness, and road traffic restrictions. However, the undoubted advantage of road tests is the representativeness of the road pavement, which is flat and has a realistic texture.

In the case of tests conducted in laboratories, controlling the temperature is not a major problem, as is controlling the speed, load, and inflation pressure. Unfortunately, in the overwhelming majority of cases, steel drums are used for testing, which, due to their curvature, cause very different tire deformations than on a flat road surface. Additionally, steel drums do not have the same texture as road surfaces, which changes the nature of the interaction between the tread blocks and the road pavement. Thus, while significantly improving the accuracy of the measurements, there is a loss in representativeness.

This article discusses the most commonly used methods for testing tire rolling resistance, selected test facilities that implement those methods, and presents the results of tests conducted on the same tires but by various research methods using unique test facilities of the Gdańsk University of Technology (GUT) in Poland and The Swedish National Road and Transport Research Institute (VTI) in Sweden.

It should be noted that while laboratory methods for measuring tire rolling resistance are currently largely standardized, e.g., (ISO 18164, 2005; ISO 28580, 2018; SAE J, 2452, 2017), road methods are not yet covered by international standards, although the first work on their standardization has already been carried out (Anfosso-Ledee et al., 2016).

2 Review of the Rolling Resistance Measuring Methods

2.1 Road Methods

Road methods should potentially ensure the greatest representativeness of the results obtained, but they are susceptible to numerous disturbing factors and are largely dependent on weather conditions beyond the control of the research team. Therefore, it can be concluded that with very high representativeness, they are difficult to perform and provide lower measurement accuracy in comparison to laboratory methods. These methods are preferred primarily by road builders, because only they provide a very good determination of the impact of road surfaces on the rolling resistance of tires. The three most commonly used measurement methods are discussed below.

2.1.1 Coastdown Method

The coastdown method has long been used to test rolling resistance, especially in the low rolling speed range. This method is described in detail in the literature—e.g., (Karlsson et al., 2011), and is based on recording changes in the speed of the vehicle, which is moving with the engine turned off, using its inertia. Even though the method is theoretically well developed, its application is difficult. The first and most important problem is the effect of air resistance, which depends on the speed of the vehicle in relation to the surrounding air. Since there is practically always wind in the environment and it does not have a constant direction and speed, it is very difficult to eliminate its influence on the test results. Even installing air flow speed sensors on the research vehicle (see Fig. 1) does not guarantee obtaining accurate results, because the air flow around the vehicle is very complex.

The second important factor is the tire temperature. Tire temperature depends on driving speed and has a strong influence on rolling resistance (Ejsmont et al., 2018, 2022). During tests carried out using the coastdown method, the tire temperature, for obvious reasons, does not correspond to the temperature that the tires would have at a given speed under steady-state conditions, because during coasting the speed is constantly changing. Attempts to assess the usefulness of the coastdown method were made, among others, in the ROSANNE project (Anfosso-Ledee et al., 2016).

Fig. 1 Test car equipped for coastdown rolling resistance measurements (Anfosso-Ledee et al., 2016)

Fig. 2 Test trailer R^{2}Mk.3 built by Gdańsk University of Technology

Unfortunately, it turned out that in a situation where relatively short (100–200 m) measurement sections are available, the method cannot be practically used. Therefore, no relationship was established between the results of tests conducted using the coastdown method and the results of other road methods of measuring tire rolling resistance.

2.1.2 Trailer Method

The method commonly called the trailer method is currently not covered by any formal standardization acts. It consists in placing a test wheel on the test vehicle (usually a trailer) and, while rolling freely, the force occurring on the wheel's axis is measured. At first glance, it seems like a simple and easy-to-implement measurement method, but this is not the case. First, it is necessary to measure a very small horizontal force in a system loaded with a large vertical force. Second, while the vehicle is driving, numerous dynamic impacts occur, which may manifest themselves in the form of measurement disturbances. The slope of the road also has a significant impact on the results. A road inclination of just 0.1% can cause a measurement error of up to several percent. For the rolling resistance measurement to be performed correctly, it is necessary to obtain a stabilized tire temperature, which requires at least 15, and preferably 30, min of driving at a constant speed corresponding to the test speed. While such tire heating is relatively easy to perform on certain test tracks, in road conditions, especially with heavy traffic, it is sometimes much more difficult or even impossible.

Over the last 20 years, several research trailers were built for measuring the rolling resistance of passenger car tires, but after not very encouraging attempts to perform tests with them, they were withdrawn from service, or at least nothing about their current use is known by the authors. An overview of some of these trailers can be found in (Anfosso-Ledee et al., 2016). The R^{2}Mk.3 trailer is one of two trailers, known by the authors, that are successfully used on the roads of many European countries and in the USA. It was built at Gdańsk University of Technology and can be seen in Fig. 2. The trailer uses the "vertical swingarm principle", whose deviation from the vertical position is a measure of the longitudinal force applied to the wheel axis. Advanced inertial and barometric compensators in this trailer allow to eliminate the influence of road grade (inclination) and longitudinal inertia forces, and the Foucault's currents damper allows to eliminate swingarm oscillations without influencing the average position. The trailer's position relative to the road surface is determined using a laser sensors system. The trailer can conduct tests at speeds of 30–130 km/h and an SUV is enough to tow it. An additional advantage of the trailer method is that it can be used to perform measurements even on very short, 50 m experimental sections, which is particularly valuable when examining the impact of the experimental road surfaces on the rolling resistance of tires. The results obtained using the R^{2}Mk.3 trailer constitute the basis for further comparative analyzes of road and laboratory methods presented in this article.

The second trailer, built and operated by BRRC, Belgium, is currently undergoing modernization. It is mainly adapted to assess the impact of the road surface on rolling resistance, because quick tire replacement in this trailer is difficult.

2.1.3 Method Based on Measuring Energy or Fuel Consumption

Since work to reduce the rolling resistance of tires is currently being carried out primarily to reduce the energy consumption of vehicles, it appears that the energy consumption of a vehicle running on given tires on a given surface at a given speed is a good measure of the rolling resistance of tires (Guillou & Bradley, 2010). With the current state of technology, the driver's influence on the results of the tests can be almost completely eliminated using cruise control to ensure very smooth and repeatable movement of the car on a given section of road. Modern vehicles also have the ability to continuously monitor fuel consumption (or electricity consumption), so measuring fuel consumption is also easy to perform. This means that virtually any modern car in very good technical condition can be used to assess tire rolling resistance by measuring energy consumption. Unfortunately, similarly to the coastdown method, the method based on measuring fuel consumption is sensitive to the wind occurring in the measurement section and requires the measurement section to be relatively long and horizontal. This means that this method is easier to implement on test tracks than on public roads. Moreover, the measurement results are expressed as fuel consumption of a specific test vehicle, and not as a classic rolling resistance coefficient that can be commonly used for other vehicles.

2.2 Laboratory Methods

The most important advantage of laboratory tests of tire rolling resistance is the possibility of strict control of test conditions (in particular air temperature) and very good repeatability of results related to the elimination of accidental disturbances that occur during road tests. However, this comes at the cost of very significant disadvantages related to, for example, the use of drums instead of a flat surface for testing. With very few exceptions, laboratory tests are carried out on roadwheel facilities equipped with a rotating cylinder with a diameter of 2 m or larger, which means that the deformations of the tire interacting with the drum surface are different than on a flat road. There are correction procedures intended to eliminate the influence of drum curvature, but these procedures are based on theoretical relationships obtained with far-reaching simplifications in which a car tire is treated as an idealized torus (Freudenmann et al., 2009). The correction does not take into account the fact that individual tire elements (sidewalls, belt, and tread elements) may have very specific properties that determine the deflection of a given element and its related energy losses.

The second very important problem typical for laboratory tests is related to the texture of the drums. On an industrial scale, only drums with a smooth steel surface are used, the texture of which does not resemble the texture of real road pavements in the slightest. It has long been known (Ejsmont et al., 2017) that the surface texture has a very important impact on the rolling resistance of tires. This implies that the tests are performed in non-representative conditions, which means that the values of the rolling resistance of individual tires are incorrectly determined and, additionally, the ranking of tires may be affected.

At the Gdańsk University of Technology (GUT), the drums of roadwheel facilities are covered with replica road surfaces, which have a very positive effect on the representativeness of the research conducted, but is not supported by any international standards describing the methodology of rolling resistance tests. An example replica of the Dense Asphalt Concrete 16 (DAC16) road surface is shown in Fig. 3.

Fig. 3 Replica DAC16 mounted to the drum of 2.0 m roadwheel facility

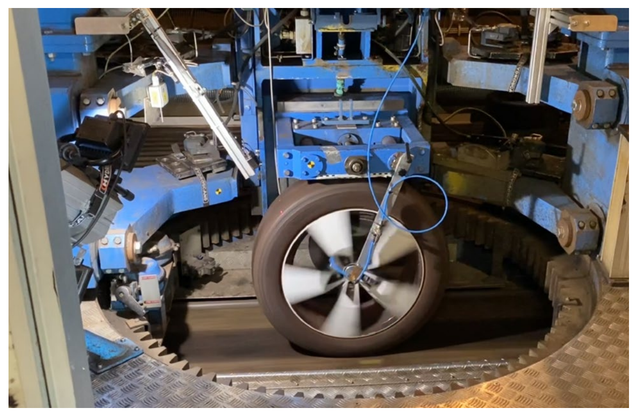


Fig. 4 VTI Flat Bed Tire Test Facility (TTF)

A very interesting research facility is operated at VTI (Sweden)—the Flat Bed Tire Test Facility (TTF). It can be said that this device resembles a roadwheel facility with a drum of an infinitely large radius, because a flat track moves under the tested wheel on which cassettes with real road surfaces can be placed (see Fig. 4). This is a unique device which, due to the limited length of the track, allows measurements to be taken at a speed not exceeding 36 km/h (Ydrefors et al., 2021b).

Laboratory methods are preferred by tire manufacturers and are now largely standardized. Unfortunately, currently applicable standards such as ISO 28580 (ISO, 2018), ISO

18164 (ISO, 2005), and SAE J2452 (SAE, 2017) specify unrealistic test conditions (smooth steel surface, steady-state measurements, air temperature of 25 ℃, or in the case of the SAE standard 24 ℃), which means that the obtained Coefficients of Rolling Resistance are not adequate to tires' performance in road conditions.

2.2.1 Force-Based Method

In this method, the tire rolling resistance is determined by measuring the force occurring in the hub of the test wheel as it rolls freely on the drum of the roadwheel facility. The method requires very precise adjustment of the load direction in relation to the measuring hub, so that there is no cross-talk between the load and the longitudinal force, which is a measure of rolling resistance. According to the ISO 28580 standard, the adjustment accuracy must be better than 1 milliradian, which is not easy to achieve with a massive running machine. The opinion of the authors is that even 1 milliradian is not enough for modern low rolling resistance tires where value of 0.3 milliradians is more appropriate.

2.2.2 Torque-Based Method

In the torque method, the rolling resistance of the tire is calculated based on the torque that must be supplied to the drum shaft, so that the tested wheel rolls at a constant speed. In both the drum bearings and in the wheel hub bearings, there is a resistance moment that interferes with the measurements. Therefore, after each measurement, the tested wheel is partly unloaded, so that it presses with a slight force on the drum surface and the resistance moment (so-called skim) is measured by which the result is later corrected. The torque method does not require such precise adjustments of the system as in the case of the force method and, therefore, it is easier to obtain high measurement accuracy. Figure 5 shows a roadwheel facility with a drum with a diameter of 2.0 m, built at GUT, which uses the torque method. All drum test results presented in Chapter 4 were obtained using this facility. The unique features of this machine are the ability to mount replicas of any road surfaces and the ability to perform measurements at air temperatures from – 15 to + 35 ℃.

2.2.3 Coastdown Method on a Test Drum.

The coastdown method involves the measurement of deceleration of the test drum and tire assembly. In the authors' opinion, this method has many drawbacks that make the results inaccurate. The test is carried out in an unsteady state and its result depends, among other things, on a very accurate determination of the moments of inertia of the drum and the tested wheel as well as on the resistances in the bearings. According to Anon, (2015), in comparative

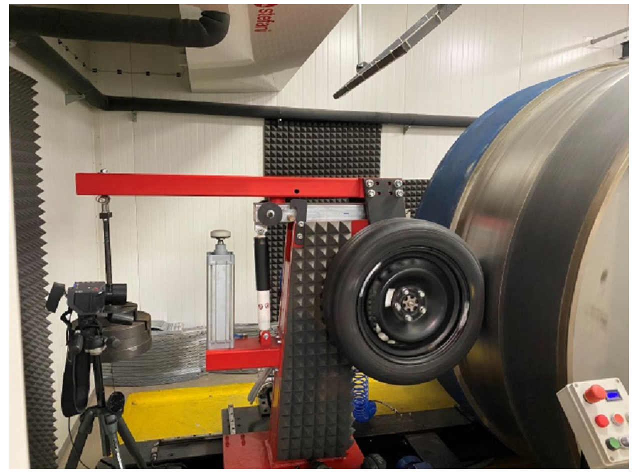


Fig. 5 A roadwheel facility built at the Gdańsk University of Technology. Three test surfaces are visible on the drum surface. From the left: replica of SMA8, steel, and Safety Walk M80

tests of truck tires on a roadwheel facility using the torque method and another facility using the coastdown method, the obtained results differed by as much as 45%! Since the tire industry usually requires measurement accuracy in the range of 1–3%, the error obtained in the above-mentioned tests should be considered unacceptable.

3 Experimental Comparison of the Methods.

As part of the ELANORE project (ELANORE, 2020), the results of research conducted using different methods were compared. This was possible thanks to the fact that the Gdańsk University of Technology has the ability to conduct road tests of rolling resistance using the trailer method and can also conduct laboratory tests on a roadwheel facility equipped with road surface replicas as well as to the collaboration between the GUT and VTI. The authors of the article have not yet encountered information about similar research by other centers.

Several tires in size 205/55R16 were selected for testing, covering the full range of available environmental labels classifying the impact on energy consumption (from A to F). The tires include both summer, winter, and all-season tires. Due to the specificity of the R^2Mk.3 trailer, during all tests, the tire was loaded to 4000 N. Most tests were carried out at a capped inflation pressure of 210 kPa (set at a temperature of 25 ℃), but some tests were also performed at regulated inflation pressure of 210 kPa. This article presents the results obtained at a speed of 80 km/h. The only exception is the comparison with the VTI TTF, which was performed at 30 km/h.

The ISO and SAE standards for measuring tire rolling resistance require that the air temperature during testing is either 25 ℃ (ISO) or 24 ℃ (SAE). In the authors' opinion, such requirements are very inadequate to the typical road conditions in Europe and in USA, because the average annual temperature in Europe is 5 ℃ and not 25 ℃. Therefore, it was decided that road tests will be carried out when the air temperature is 15 ℃–20 ℃, and laboratory tests will be performed for individual tires at the temperature at which road tests were carried out. This enabled effective testing and ensuring more or less identical thermal conditions, which is very important in the case of tire rolling resistance tests. Although the temperature span is rather narrow, temperature corrections of the rolling resistance measurements according to the ISO-standard were performed.

The tests were carried out on 6 road pavements and 5 replica road surfaces, which are characterized in Table 1. Some replicas had a texture identical to the texture of the tested road sections, and others were made on the basis of very similar but not identical pavements. The identical pairs are: ISO versus ISO-dr, SMA8 versus SMA8-dr. Pairs similar in terms of texture are: DAC16 versus DAC16-dr, SD versus APS4-dr, and AC12 versus SMA8-dr.

3.1 Comparison of Road and Laboratory Measurements Performed on Replica Road Pavements

To determine the relationship between the results of trailer road tests and laboratory tests performed on a roadwheel facility with a drum covered with replica road surfaces, the Coefficients of Rolling Resistance (CRR) obtained in identical thermal conditions were compared, defined as the ratio of the rolling resistance force to the tire load. Since using the drum method, both CRR coefficients for a curved surface and, after correction, CRR coefficients reduced to a flat surface are obtained, the first step was to investigate which of these coefficients that best reflects the results from the conducted flat surface trailer tests. Figure 6 shows the relationships between road and laboratory results without correction for a flat surface. Figure 7 shows the same results, but in this case, the CRR coefficient is reduced to a flat surface. The results presented in these figures concern the relationships obtained for the SD road surface and the APS4-dr replica. The following formula was used for reduction (Clark & Dodge, 1979):

$$\mathrm{CRR_F} = \mathrm{CRR_R}\sqrt{1 + r/R} \quad (1)$$

Comparison of Figs. 6 and 7 shows that the use of correction for a flat surface significantly improves the representativeness of laboratory test results in terms of absolute values of the rolling resistance coefficient. As can be seen from Fig. 7, representativeness for a very aggressive surface such as Surface Dressing is better for tires with relatively high rolling resistance (mainly winter tires) and worse for summer tires with low rolling resistance. This is probably due to the fact that the correction formula was created theoretically and only takes into account the difference in stresses caused by different deformations of the tire torus, and does not take into account the deformations of tread elements related to interaction with the surface texture. However, since this is the correction algorithm commonly used, in the rest of the article, all test results from the drum are presented in a form corrected for a flat surface.

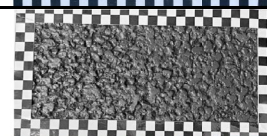
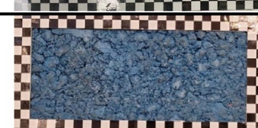
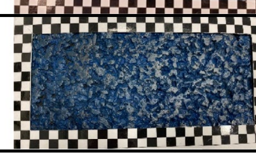
Figure 8 shows a comparison of the results obtained on a road covered with a very smooth ISO surface and those obtained on a drum covered with a replica of this surface. The obtained correlation is very high and the absolute values of CRR coefficients are very similar. The situation is similar when comparing the results obtained on a road with AC11 and on a drum covered with a replica of SMA8 having similar texture (Fig. 9). The results shown in Figs. 6–9 were obtained at a temperature of 17 ℃. This temperature is typical for summer and all-season tires, but it is too high for winter tires made of rubber compounds optimized for low temperatures. This is probably the reason for the poorer correlation obtained for this type of tires—see Figs. 6 and 7.

A very good correlation was also obtained for the DAC16 surface and its replica ($R^2 = 0.814$), for which the trend line shows a slope coefficient almost exactly equal to 1 (see Fig. 10). However, it should be emphasized here that, unlike other surfaces, the tests on the DAC16 surface were carried out at a regulated pressure of 210 kPa throughout the measurement (both road and laboratory), and not, as in the other cases, at a pressure set at the beginning of measurements (at a temperature of 25 ℃).

The adoption of such test conditions was related to the fact that the results of trailer tests in this experiment were compared not only with laboratory results obtained at the TUG roadwheel facility but also with the results obtained at the VTI Flat Bed Tire Test Facility (TTF), where regulated inflation pressure allows for more precise result due to less sensitivity to the thermal stabilization of the tire.

Since Surface Dressing is not a typical road surface in Europe and only occurs on secondary roads that may experience difficult weather conditions, taking into account more typical surfaces such as AC11, DAC16, and SMA8, it can be concluded that there is a rather high correlation between results of road test and results of drum tests conducted on corresponding replica road surfaces. The obtained coefficients of determination R^2 for such surfaces are greater than 0.8.

Table 1 Characteristics of road surfaces and replicas used in this research

DESI-GNATION	DESCRIPTION	MPD [mm]	PICTURE
Road pavements			
DAC11	Dense Asphalt Concrete 12 mm	0.60	
DAC16	Dense Asphalt Concrete 16 mm	0.8	
SMA8	Stone Matrix Asphalt 8 mm	1.07	
SD	Surface Dressing	3.15	
PCC-gr	Portland Cement Concrete	1.22	
ISO	Test pavement according to ISO 10844 [14]	0.50	
Replica road pavements on the 2.0 m drum			
STEEL-dr	Smooth steel (required by existing standards)	0.1	
DAC16-dr	Replica of DAC16 (similar but not exactly the same like DAC16)	1.33	
SMA8-dr	Replica of Stone Matrix Asphalt 8mm (exactly the same like SMA8)	1.31	
ISO-dr	Replica of the test pavement according to ISO 10844 (exactly the same like ISO)	1.06	
APS4-dr	Replica of the Surface Dressing (similar but not exactly the same like SD)	3.74	

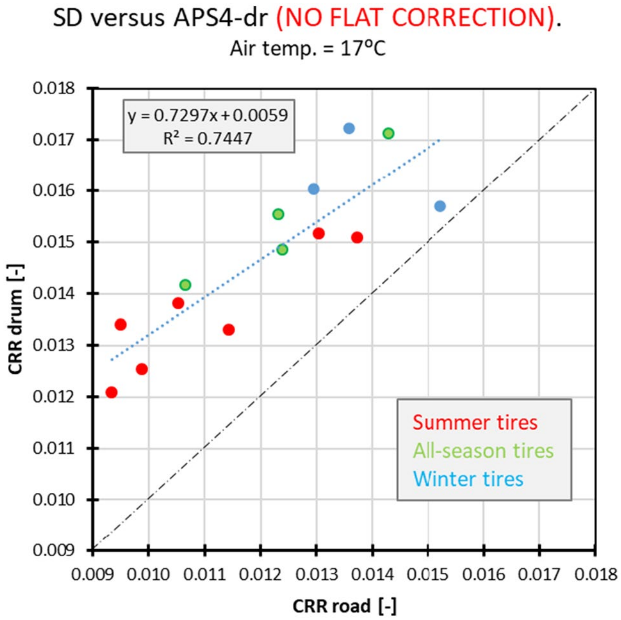


Fig. 6 Comparison of results obtained on the rough Surface Dressing pavement (SD) and its replica APS4-dr. Drum results without flat correction according to Eq. 1

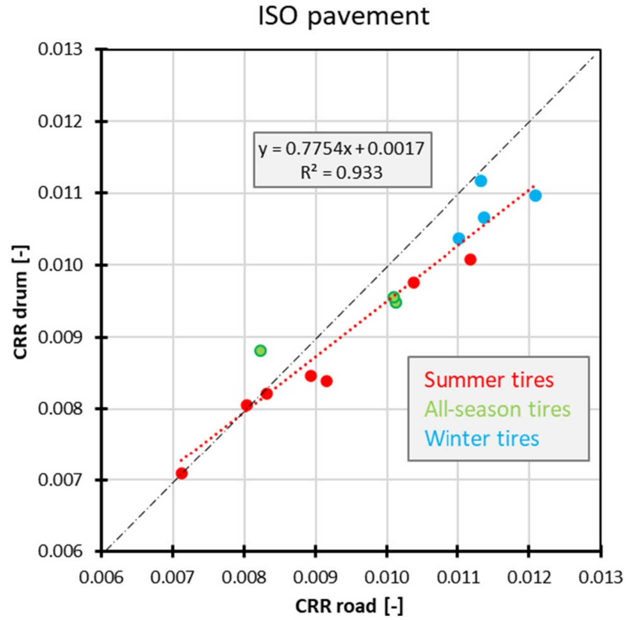


Fig. 8 Comparison of results obtained on the smooth ISO pavement and its replica ISO-dr. Drum results with flat correction according to Eq. 1

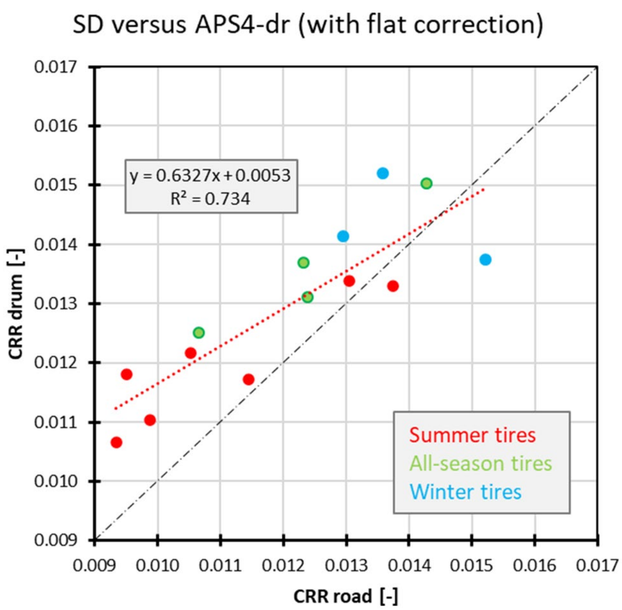


Fig. 7 Comparison of results obtained on the rough Surface Dressing (SD) road and its replica APS4-dr. Drum results with flat correction according to Eq. 1

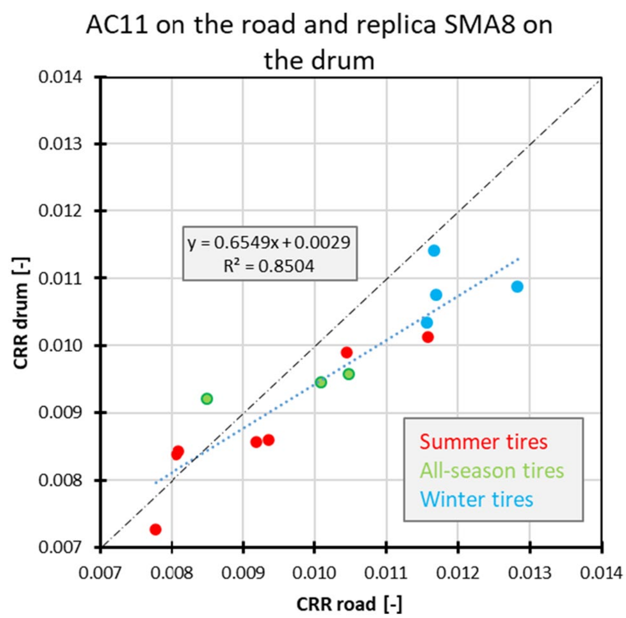


Fig. 9 Comparison of results obtained on the Asphalt Concrete AC11 and replica SMA8-dr. Drum results with flat correction according to Eq. 1

3.2 Comparison of Road and Laboratory Measurements Performed on Steel Drum.

The results presented in Sect. 3.1 clearly indicate that laboratory tests conducted on replica road surfaces allow for obtaining rolling resistance coefficients quite similar to those measured on a road with a similar surface texture. Unfortunately, the applicable ISO and SAE standards require that the drum surface be made of steel, while the SAE standard allows covering the surface with fine sandpaper with

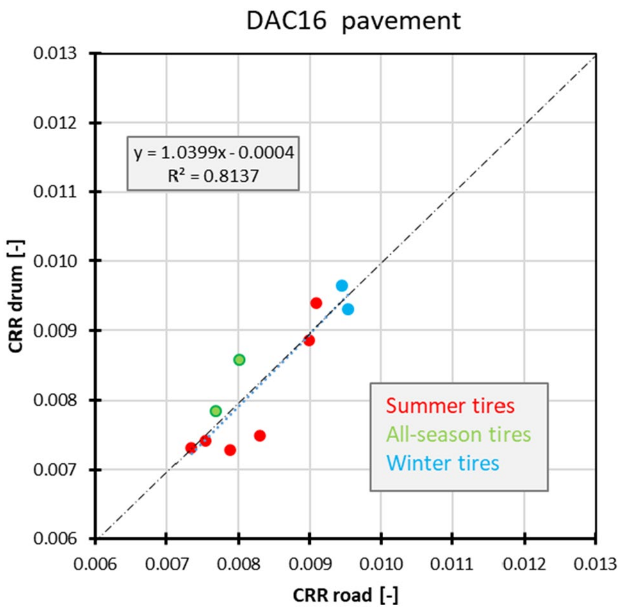


Fig. 10 Comparison of results obtained on the DAC16 pavement and its replica DAC16-dr. Drum results with flat correction according to Eq. 1

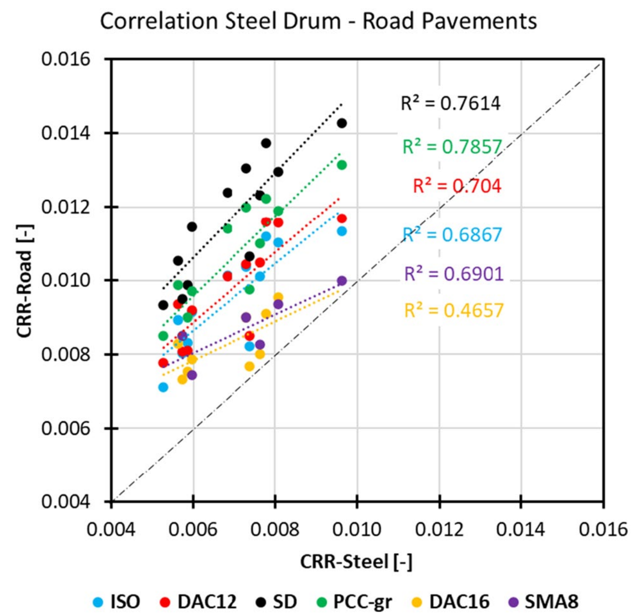


Fig. 11 Comparison of results obtained on a smooth steel drum and results of road measurements performed on different pavements. Drum results with flat correction according to Eq. 1

a grain size of "80". To the authors' knowledge, even car tire factories, with a few exceptions, do not use replicas of road surfaces and limit themselves to tests consistent with standards. It is, therefore, necessary to investigate the correlation between test results obtained on the steel surface and on a real road.

Figure 11 shows a comparison of CRR obtained on a roadwheel facility with a smooth steel drum and during road tests on a wide range of pavements, described in Table 1. A worse reproduction of the road rolling resistance (coefficient of determination R^2 between 0.46 and 0.78) compared to the laboratory measurements on replicas of road surfaces is clearly visible. However, this is not the only drawback of using smooth steel drum. As Fig. 11 shows, the values of CRR obtained on a steel drum can be much lower than the coefficients obtained on the actual road surfaces. For surfaces with a very aggressive texture (e.g., Surface Dressing), the rolling resistance of tires is almost twice as high as it is estimated by laboratory tests on a steel drum. This means that if a car manufacturer intends to use tire rolling resistance data obtained on a steel drum to predict the fuel economy or operational range of an electric vehicle on the road a significant error will occur. This is not just a hypothetical assumption as the authors have had discussions with manufacturers of electric vehicles that have these problems. As an example, if assuming that the error in the value of the rolling resistance coefficient is approximately 30% for typical surfaces, the resulting error in estimating the vehicle's range (or fuel consumption) for most typical traffic conditions (low and medium speeds) will be at least 10%, and for hybrid and electric cars even more due to their large mass (Wilde et al., 2014).

Tests conducted on a steel drum not only reduces the rolling resistance value compared to real conditions, but also influence the tire ranking. This is clearly visible in Fig. 12 where individual tires are ordered according to increasing rolling resistance measured on a smooth steel drum (red bars). In addition to the results from the drum, the results of road tests carried out on various surfaces using the trailer method are also presented (other colored bars). It is visible that if the tires were ranked according to the results obtained

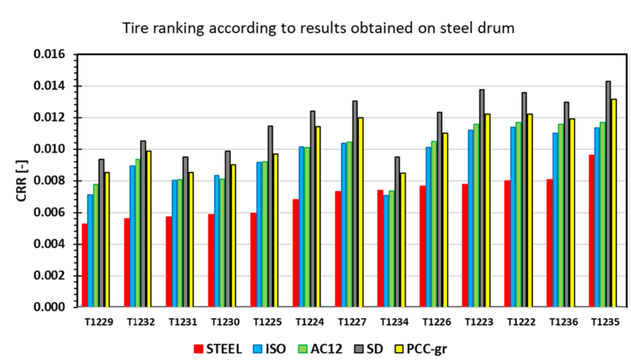


Fig. 12 Tire ranking according to measurements performed on the steel drum (red) and CRR results of measurements on real road pavements (other colors)

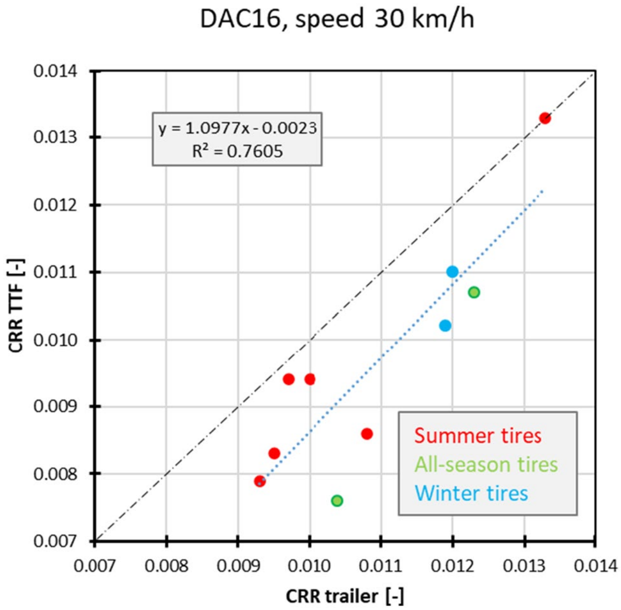


Fig. 13 Comparison of rolling resistance coefficients measured on the DAC16 pavement using the R^{2}Mk.3 trailer and a TTF system

on one of the "real" road pavements, the ranking would be completely different.

Tire tests performed on replicas of road surfaces do not result in excessive or unusual tire wear. A typical measurement of the rolling resistance of a passenger car tire takes about 1 h. After this period, tire wear is neither noticeable nor measurable in terms of weight loss, provided that the tests were conducted at zero tire slip angle. However, laboratory tests carried out at significant slip angles (greater than 1 degree) may cause significant thermal degradation of the tire tread surface.

3.3 Comparison of Results Obtained with the Trailer and on the Flat Bed Tire Test Facility

During the implementation of the ELANORE project, it was possible to compare the results obtained using the trailer method, the drum method and using a unique Flat Track Testing machine (TTF). Although this machine was built to test tire grip, including icy and snow conditions, due to its technical advancement, it can also be used to measure rolling resistance. Its main advantages are a flat bar (instead of the drum) and the ability to lay almost any road surface on this bar. The main disadvantages are: a relatively low maximum speed of only 36 km/h and the short measurement time which prevent steady-state measurements. The TTF device (see Fig. 4) consists of a stationary but steerable tire test rig and a flat, moving 55-m-long steel bar that can be covered with desired road pavement. The bar representing the road surface is moved back and forth under the measuring wheel, inside a 125-m-long climate controlled building. Since steady-state conditions cannot be achieved during a measurement, the desired tire temperature must be known a priori. The tire can then be heated to the requested tire test temperature using a steel roller beneath the steel bar before each test. For tyre temperatures below 25 °C, it is also possible to control the tire temperature by storing them in the temperature controlled rig room.

In the comparative tests between this equipment and the trailer, measurements were performed at the same test speed, 30 km/h. The tests were done using unheated tires; hence, this is not a comparison of steady-state properties. Ideally, the same tire temperature should be used for all tires in both the trailer and TTF measurements. However, due to altering weather conditions, the temperature range in the trailer tests was rather large, 15.0 °C–32.5 °C. Fortunately, previous measurements have indicated that it is possible to adjust the rolling resistance value for differences in tire temperature within this typical range (Ydrefors et al., 2021b). From measurement of four selected tires over a wider temperature range, it was found that a correction of the CRR of $-1.5*10^{-4}$ per degree C needs to be applied. A comparison between trailer and TTF rolling resistance coefficients adjusted to a tire temperature of 20 °C is shown in Fig. 13.

In spite of a rather broad range of tire temperatures in the measurements, the correlation between the two experimental equipments is quite high, ($R^2 = 0.76$). The TTF measurement results are a bit lower than the corresponding trailer measurement results. This difference is probably due to an incorrect estimation of the vertical alignment of the TTF wheel hub, which has not been measured on an asphalt substrate previously.

4 Conclusions and Recommendations

The conducted research shows that the drum method can replace road methods, provided that the tests are carried out on replicas of road pavements. Tests conducted on smooth steel drums are not representative either in terms of the rolling resistance coefficient values obtained or the tire ranking. This means that tire optimization with regard to rolling resistance, which is based on the results of tests conducted in accordance with the currently applicable ISO and SAE standards, does not necessarily lead to obtaining a tire with optimal parameters when driving on the road. Also, the CRR coefficients obtained as a result of such tests, which are published, for example, on tire labels, do not allow for accurate prediction of fuel consumption or vehicle operating range. It seems that changes to the applicable standards should be introduced, replacing the smooth steel drum surface with replicas with a texture representative of roads and highways in Europe and the USA.

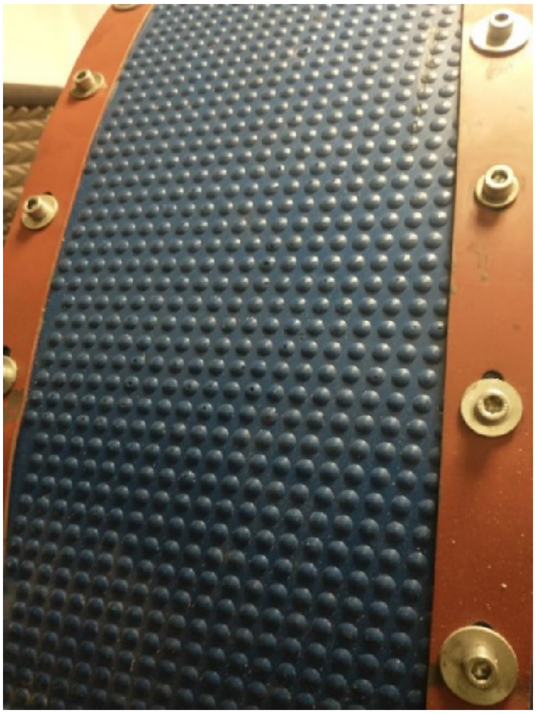


Fig. 14 Example of geometric pattern that may be used for standardized replica road surface for rolling resistance measurements

Of course, choosing a representative road surface is not easy, because different surfaces dominate in different regions of the world. Nevertheless, it appears that based on the available statistics, it is possible to select a surface that will be representative of most roads. Perhaps such a surface should be chosen from among the AC11, DAC16, and SMA8 surfaces, which are very popular and are characterized by similar rolling resistance.

Another approach to the problem of replicas intended for drum testing is also possible. Instead of replicas faithfully imitating existing surfaces, it is possible to design a replica with a simple geometric pattern selected, so that the rolling resistance of the tire is similar to that measured on AC11, DAC16, or SMA8 surfaces. Using this approach, it is possible to avoid problems that commonly occur in the case of noise tests on surfaces described in ISO 10844 (ISO, 2021), because nominally identical surfaces differ due to minor differences in production technology, which distorts the measurements. A simple geometric pattern could be easily transferred to the surface of the drums, ensuring a high degree of compliance. An example of such a geometric texture that allows obtaining rolling resistance results that correlate well with the results of road tests is shown in Fig. 14.

For investigations of rolling resistance in non-steady-state conditions, the flat track testing machine (TTF), equipped with asphalt cassettes, can provide measurement data in agreement with the road test data. The possibility to control the operational conditions as well as the asphalt properties in the TTF is an advantage compared to the trailer tests. Non steady-state investigations are becoming increasingly important to understand rolling resistance in real traffic conditions.

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Data availability All relevant data analyzed during this study are included in graphic form (figures) in this published article.

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