Development of a Method for Measuring Rolling Resistance at Different Tyre Temperatures

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Abstract. Measurement methods to determine the rolling resistance of tyres during different operation conditions are essential in the work towards more energy efficient vehicles. One of the influential parameters is the tyre temperature distribution, which has a large impact on the rolling resistance. Today, the standardised test procedure to measure rolling resistance is steady-state measurement on drums. However, the steady-state temperature on a drum is not the same as the temperature during ordinary driving conditions. The aim of this work is to develop a measuring method that enables to set a desired measurement temperature, which would create the possibility to study the relationship between tyre temperature and rolling resistance in more detail. The measurement method was developed by the use of a flat track equipment but should be applicable to other rolling resistance measurement equipment such as drums. The resulting method gives a repeatable tyre temperature and rolling resistance and can be used for measurements on tyres heated to a chosen measurement temperature.

Keywords: Rolling resistance · Tyre temperature · Tyre inflation pressure · Measurement method · Flat track · Drum test

1 Introduction

In the development towards more resource efficient road vehicles, the tyre rolling resistance plays a vital role. A 10% reduction of the rolling resistance has shown to result in 0.5 to 3% lower fuel consumption for passenger cars [1]. The rolling resistance is defined as "the mechanical energy converted into heat by a tire moving for a unit distance on the roadway" [2]. The rolling resistance originates mainly from hysteresis, an energy loss caused by the tyre deformations, and from friction between the tyre and the road surface. This energy loss per distance can be treated as a longitudinal counteracting force, which is done in this work. Sometimes the rolling resistance coefficient, *RRC* (the rolling resistance divided by the tyre load), is used instead of the rolling resistance.

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Commonly when measuring and comparing tyre rolling resistance, standardised steady-state measurements are made on a drum, at certain operating conditions specified by speed, wheel load, inflation pressure, and ambient temperature, according to ISO and SAE standards [3–6]. The tyre is rolling on the outside of the drum until the rolling resistance reaches steady-state, which on a drum usually takes 20–30 min.

These standards also include the measurement of a parasitic loss, which is defined as the combined energy loss caused by the measurement equipment, through for example, bearing losses. This parasitic loss is independent of tyre load and can be measured as a rolling resistance measurement at the lowest load which maintains the rolling of the tyre without slipping.

The tyre rolling resistance is affected by its operating conditions [7]. Some of these operating conditions are limited by the measurement method and the equipment used. Regarding drum measurements, the drum's curvature affects the measurements in several ways. The curvature affects the choice of road surface since it prevents the use of real road surfaces such as asphalt. Commonly measurements on drums are made on steel or some replica surface. Another effect is that the influence of wheel angles such as camber and slip angles is very complex to evaluate on a curved surface. However, the most important effect is that the curvature increases the magnitude of the tyre deformations. This results in higher rolling resistance and tyre temperature for steady-state measurements, compared to flat track test equipment or driving on a road.

In a study on truck tyres, LaClair and Zarak [8] have shown that the internal tyre temperature difference between tests performed on a rolling-belt flat track and a drum was in the range of 10 to 20 °C, and increased with increased speed. Tyre temperatures when driving in traffic, are dependent on the weather and other driving conditions [9], but are generally less than drum test temperatures.

The tyre temperature distribution is affected by the ambient air temperature, the road temperature and the heating caused by the deformation of the tyre when rolling. The heating from the rolling resistance causes a tyre with higher rolling resistance to become warmer compared to a tyre with lower rolling resistance under the same operating conditions. However, it is also true that a heated tyre has a lower rolling resistance compared to when it is cold. This is mainly due to an increased rubber temperature resulting in a reduced hysteresis effect, but also because the heating will increase the inflation pressure which will consequently decrease the rolling resistance. The large impact of temperature on rolling resistance is illustrated in the results from Yokota et al. [10]. They simulated the tyre temperature distribution for different combinations of ambient air and road temperatures and studied the effect on rolling resistance for a variation of 10 to 30 °C in ambient air temperatures, and 10 to 50 °C in road temperatures. The different setups resulted in a variation of 23 to 52 °C in internal tyre tread temperature and a 30% difference in the corresponding estimated rolling resistance coefficient.

The aim of this work is to develop a rolling resistance measurement procedure that permits the setting of a desired measurement temperature. This would facilitate a more detailed study of the relationship between tyre temperature and rolling resistance. The measurement procedure is developed using a flat track where the tyre is fixed and a beam, representing the road, that moves underneath the tyre. Using this equipment has several advantages, as mentioned earlier, but the method could also be used on other equipment, for example a drum.

The outline of the paper is as follows. First, the tyre test facility used is described. This is followed by a presentation of rolling resistance measurements on unheated tyres, including the accuracy for the force sensor and the different measurements needed to calculate the rolling resistance. Then the proposed measurement procedure for heated tyres is described, including the characteristics of the chosen temperature sensors and the heat-up process. Thereafter some measurement results for heated tyres are presented. Finally, some discussion and conclusions along with recommendations for future work are given.

2 The Flat Track Tyre Test Facility

The test method is developed using the flat track tyre test facility at VTI (the Swedish National Road and Transport Research Institute), see Fig. 1a. In this test facility, the tyre is attached to a fixed rig which holds the tyre in place at a specific wheel load while the ground, represented by a 55 m long metal beam, is moving beneath it at speeds up to 36 km/h. The entire measurement is finished within seconds.

The test facility is originally built for measuring the forces acting on a tyre such as braking and steering forces. The force sensor measures the force in the longitudinal (F_X), lateral (F_Y) and vertical direction (F_Z), where F_X gives the rolling resistance when the tyre is free rolling. The tyre can be pre-heated by running the tyre on a rotating cylinder under a variable load, as can be seen in Fig. 1b. All three cylinders are needed to support the beam during measurements, but only the middle cylinder is used for heating. The wheel load is only applied to the tyre during heating and measurements.

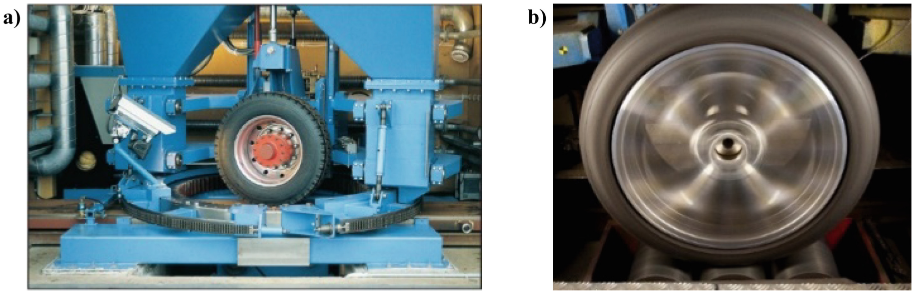

Fig. 1. a) The VTI's tyre test facility and **b)** the rig's heating cylinders [11].

3 Rolling Resistance Measurements

To develop a credible rolling resistance measurement procedure in the VTI tyre test facility some questions must be addressed. Compared to brake and steering forces, the rolling resistance force is much smaller, which increases the requirements on measurement accuracy. Since the rolling resistance of a tyre is dependent on the tyre temperature and inflation pressure, it is important to verify that those conditions are repeatable and comparable to real driving situations.

The experiments in this development process have mainly been made with a Standard Reference Test Tyre (SRTT) [12]. This tyre was chosen since it is regularly used for rolling resistance measurements and test results from different equipment and operating conditions can be found in literature. To ensure that the parasitic losses were not tyre dependent, the parasitic loss measurements were repeated on an SUV class A all-season tyre. Apart from the reduced load in the parasitic measurements, all presented measurements have been made on a steel surface with a load of 3.9 kN, and a capped inflation pressure, of 2.2 bar at 20 °C. For capped inflation pressure, the pressure is set at a specific temperature, then the amount of air is kept constant, while the pressure changes with the tyre temperature.

Section 3.1 focuses on the rolling resistance of the unheated tyre. This gives the advantage of enabling measurements and analyses of the accuracy of the measurement procedure and equipment used, without introducing temperature effects. Accuracy is here the combination of the trueness and repeatability of a measurement.

However, a realistic rolling resistance, requires a realistic measurement temperature, which includes both measuring and controlling the temperature. Section 3.2 focuses on the sensors used to measure the tyre temperature and inflation pressure. Then Sect. 3.3 examines how the temperature can be controlled and the accuracy and repeatability of the corresponding rolling resistance for a heated tyre.

3.1 Accuracy of the Rolling Resistance Measurements on Unheated Tyres

In order to evaluate the accuracy of the measurement procedure and measurement equipment, the first step is to perform rolling resistance measurements on an unheated tyre. The evaluation of an unheated tyre is chosen to remove the issues connected to controlling the tyre temperature. The accuracy of the measured rolling resistance force is limited by the force transducers accuracy, in our case a piezo-electric sensor. This kind of sensor is very exact in dynamic measurements but tend to drift over time. To get repeatable results the accuracy and drift of the sensor in the direction of travel are evaluated through calibration measurements with a scale connected to the sensor instead of a tyre. Static forces within the range of 8 to 80 N were applied in the longitudinal direction, and it was concluded that the sensor is linear within this range. These calibration measurements gave a standard deviation for F_X of 0.1 N, which is low for a sensor capable of measuring loads up to 10 kN. The deviation between the measured force and the applied force is shown in Fig. 2.

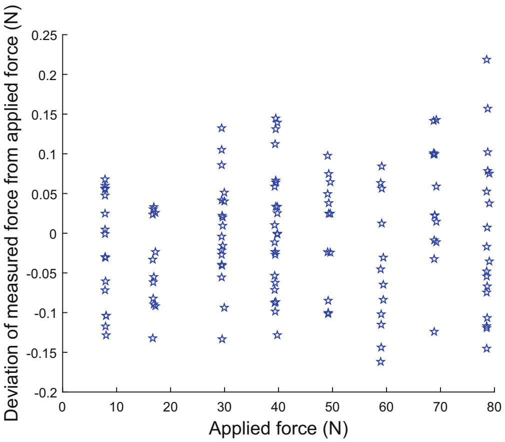

Fig. 2. Difference between the applied and measured force for different levels of applied load.

The drift of the F_X-sensor was found to be around -0.2 N/s and is estimated and compensated for at each measurement. The drift compensation has been done based on the fact that the applied F_X-force is zero before and after the measurement, with the assumption that the drift is linear in time.

In the VTI tyre test facility, F_X is measured with the force method. It is a standardised measurement method for drum measurements where the tyre spindle force is measured and used to calculate the rolling resistance. This method is sensitive to force misalignments, i.e., small deviations from the intended loading direction by the rig will result in a noticeable error. Here, this error is called the normal force alignment error (F_{NFAE}).

The measurements presented here, are conducted on an unheated tyre where the tyre temperature is assumed to be the same as the ambient air temperature. The rolling resistance is calculated from the average of F_X over the specified test distance. The signal is noisy due to both irregularities of the beam and the tyre, and it is therefore essential that the test distance is sufficiently long. F_X consists of the rolling resistance (*RR*), the normal force alignment error (F_{NFAE}), and a parasitic loss (F_{para}). The rolling resistance can thereby be calculated as:

$$RR = F_X - F_{para} - F_{NFAE} \tag{1}$$

F_{NFAE}, can be calculated as $F_{NFAE} = F_Z \cdot tan(\alpha)$, where α is the misalignment angle. The misalignment angle should be temperature independent but may change with load due to flexibility in the measurement rig. The F_{NFAE} can be estimated as the average of two slow measurements in forward and backward directions over the section of the beam which is used for rolling resistance measurements. The average of 30 F_{NFAE}-measurements, at 3.9 kN wheel load, is found to be 13.1 N with a standard deviation of 0.17 N. This corresponds to a misalignment angle of 0.2°. In this work, the F_{NFAE} measurements have only been made on one tyre. More tyres must be tested to conclude if the same misalignment angle can be used for different combinations of tyres and wheel loads. At loads above 1500 N, the linear relationship between F_{NFAE} and F_Z is clearly shown in Fig. 3a. The deviations at lower loads may be caused by some flexibility in the measurement rig, which causes the misalignment to change.

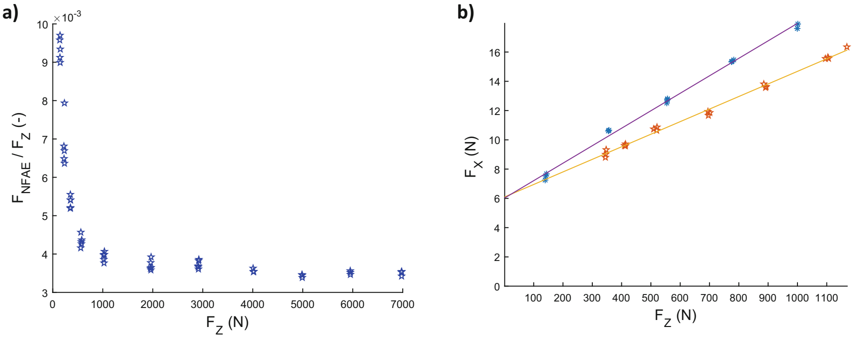

Fig. 3. **a)** The normal force alignment error for a tyre when increasing the load. **b)** Estimation of the parasitic loss with two measurement rounds with two different tyres.

The parasitic loss should be temperature independent and is assumed to also be independent of the measurement load. They are evaluated through a measurement series of F_X at low tyre loads. The results are then linearly extrapolated to zero load to find the parasitic loss, which is the remaining part of F_X when the load is removed. For two measurement rounds with different tyres, the parasitic loss has been found to be 6.06 ± 0.04 N, see Fig. 3b.

Measurements of rolling resistance for an unheated tyre as a function of inside tyre temperature can be seen in Fig. 4. Ambient air temperature variations between measurements affected the tyre temperature and therefore also the rolling resistance. To evaluate the accuracy and repeatability of the *RR* measurements, a series of repeated measurements was carried out on an unheated tyre with the aim to suppress the influence of tyre temperature variations. However, the ambient air temperature variation was large enough to affect the measurement results and had to be accounted for in the evaluation.

The standard deviation for the rolling resistance is calculated according to:

$$\sigma_{RR} = \sqrt{\sigma_{F_X}^2 + \sigma_{NFAE}^2 + \sigma_{F_{para}}^2} \approx \sqrt{\sigma_{F_X}^2 + \sigma_{NFAE}^2} \tag{2}$$

where σ_{RR}, σ_{F_X}, σ_{NFAE} and $\sigma_{F_{Para}}$, are the standard deviations for the rolling resistance, for the measured $F_{X,}$ F_{NFAE} and F_{para}, respectively. The resulting $F_{X,}$ for 29 measurements of an SRTT tyre with the same measurement conditions, had a standard deviation of 1.38 N. The standard deviation for F_{para} is unknown but is assumed to be small and negligible. It is however important to measure F_{para} regularly to identify long-term variations which could be caused by, for example, the bearings being worn. The resulting standard deviation from Eq. 2, for the conducted rolling resistance measurements, is 1.39 N. Adjusting the *RRC* for tyre temperature variations according to the line fit of Fig. 4 would reduce the standard deviation to 0.52 N.

To improve the accuracy, an average value of several measurements can be used instead of a single measurement. The accuracy of such an average will be improved by

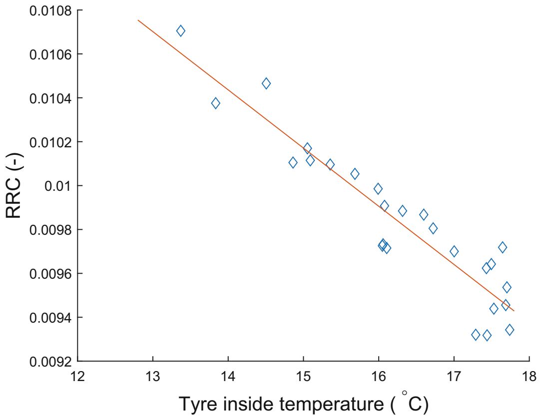

Fig. 4. Rolling resistance measurement results for an unheated tyre.

increasing the number of individual measurements, and can be quantified by a confidence interval, determined through $\overline{RR} \pm z \cdot \sigma_{RR}/\sqrt{n}$, where $\overline{RR}$ is the average rolling resistance, n is the number of samples and the standard normal variable z, is set to 1.96. It is an approximation of the number of standard deviations which corresponds to a 95% confidence interval. The average rolling resistance of 29 measurements is 38.0 N, which corresponds to an *RRC* of 0.0098. Table 1 presents the 95% confidence interval limits for different number of measurements. A column for temperature adjusted standard deviation is added for an estimation of the accuracy that could possibly be achieved with better ambient temperature control.

Table 1. Accuracy in terms of limits for a 95% confidence interval for RRC and RR for an unheated tyre.

No of samples	Accuracy of RRC	Accuracy of RR (N)	Accuracy in relation to average value	Accuracy in relation to average value for temperature adjusted data
2	$\pm 4.83\ 10^{-4}$	±1.92	±5.1%	±2.2%
3	$\pm 3.94\ 10^{-4}$	±1.57	±4.1%	±1.8%
5	$\pm 3.05\ 10^{-4}$	±1.21	±3.2%	±1.4%
8	$\pm 2.41\ 10^{-4}$	±0.96	±2.5%	±1.1%

3.2 Temperature and Pressure Sensors

The VTI tyre test facility has been modified for rolling resistance measurements by adding sensors to measure the inside tyre surface temperature, the outside tyre surface temperature as well as the inflation pressure. Since the rolling resistance is temperature dependent and the measurement with the VTI tyre test facility only takes seconds, the tyre must be heated to the desired tyre temperature or corresponding inflation pressure in a controlled manner before the test is started, which requires sensors to measure the temperature and inflation pressure.

The outside surface temperature of the tyre tread is measured with an infrared (IR) tyre temperature sensor, see Fig. 5a. This sensor uses 16 channels for measurements. Channels 1–3 and 14–16 have an accuracy of ± 2 °C, while channels 4–13 have an accuracy of ± 1 °C. An IR-sensor measures the IR-radiation from an object. The trueness of the result depends on the accuracy of the emissivity-factor used to calculate the corresponding temperature. The repeatability is however only affected by the random error, which is 0.1 °C, for this sensor. Here channels 5–6 and 11–12 have been used for the inside tyre surface temperature since these channels give the tyre temperature in the grooves for the measured tyres. An example of tyre temperature measurements for the different channels using the sensor is given in Fig. 5b, where the channels pointing down to the grooves in the tyre can be identified as the channels showing the two peak temperatures.

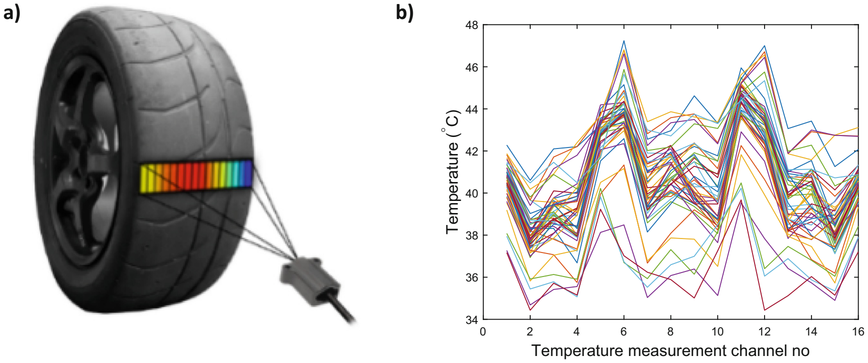

Fig. 5. **a)** The infrared tyre temperature sensor [13]. **b)** Test temperature results from the sensor, where the two largest peaks (channels 6 and 12) correspond to the channels pointing down into the grooves in the tyre.

The inside of the tyre carcass, beneath the tyre tread, here called the tyre tread inside surface temperature, the sidewall inside surface temperature and the inflation pressure are measured with a tyre temperature and pressure monitoring system sensor, see Fig. 6. This sensor uses 16 channels for the temperature measurements, where each channel has an accuracy of ±1 °C, and a random error of 0.1 °C. The pressure measurements have an accuracy of ±10 mbar, and the random error is 0.126 mbar. The temperature accuracy can be connected to the inflation pressure accuracy using the ideal gas law. A change in temperature of 1 °C corresponds to a change in inflation pressure of 11 mbar, which is comparable to the accuracy of the sensors. However, for the temperature measurements, the random error is 10% of the tolerance, compared to 1.26% for the inflation pressure measurements. Thus, the pressure sensor is expected to give more repeatable data than the temperature sensor.

Here, the sensor is placed in such a manner that the information from channels 1–5 represents the sidewall inside surface temperature, while channels 7–15 have been used for the tread inside surface temperature.

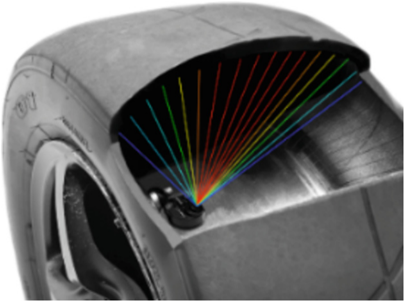

Fig. 6. The tyre temperature and pressure monitoring system [13].

3.3 Rolling Resistance Measurements on Heated Tyre

The main questions connected to the heat up procedure are: Can the tyre temperature distribution be summarised into one relevant temperature measure? Is it possible to heat-up the tyre in a way that gives a quasi-steady-state temperature and inflation pressure? If not, how can the tyre be heated so that both the tyre temperature and inflation pressure are repeatable?

A relevant temperature measure should be a scalar value representing the rubber temperature of the part of the tyre that is primarily exposed to the hysteretic deformation, and should therefore exhibit the known negative correlation with respect to the rolling resistance. In addition, keeping inflation pressure, speed, and wheel load constant, rolling resistance measurements with the same tyre temperature should produce repeatable results.

Temperatures from different parts of the tyre along with the inflation pressure during a 30-min heat-up and cool-down sequence are shown in Fig. 7a. The tyre is heated through running it under load on a rotating cylinder, as mentioned in Sect. 2. The rubber temperatures increase fast initially, and while the rate decreases with time the temperatures never reach steady-state. The same was noticed also for a longer 2-h heating period, which is most likely due to an increase of the rig temperature as well as the ambient air temperature in the rig room during the heat-up phase. The inside and outside tread temperatures differ by around 10 °C at the end of the heat-up phase, but will quite rapidly approach a common value during the cool-down phase, where the tyre has been lifted up from the rotating cylinder. It can be argued that allowing the tyre to cool down for a while and thus reducing internal temperature gradients would lead to a more stable temperature measure based on the inside and outside temperatures. That would also decrease the influence from the cylinder temperature, which may be difficult to keep constant between measurements, and to a high degree affects the tyre surface temperature during the heat-up phase.

The inside tyre sidewall temperature is substantially lower than the tread temperatures which indicates that the hysteresis mainly is occurring in the tread, in accordance with the literature [14]. This suggests that a suitable tyre temperature could be based on the inner and outer tread temperatures, which after a cool-down period would be very similar. The tyre air temperature, calculated from the measured inflation pressure and the ideal gas law, is very close to the sidewall temperature and is clearly mainly dictated by the rim and sidewall temperatures.

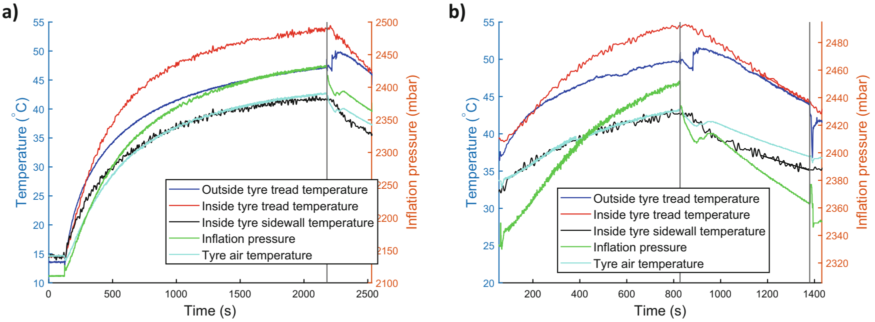

Fig. 7. **a)** Temperature and pressure variations during a long heat-up and cool-down sequence. The black vertical bar indicates the end of the heat-up when the tyre is lifted from the cylinder roll. **b)** Temperature and pressure variations during a measurement procedure, including heat-up, cooling phase, and conducting the measurement. The right vertical black line represents the launch of the test. The inflation pressure curve includes some stepwise changes. These changes are caused by the tyre being loaded and unloaded, which affects the inflation pressure.

Here, a quasi-steady-state is defined as a repeatable state where the internal tyre temperature deviates from its value at steady-state rolling resistance measurements, but the tyre temperature, inflation pressure, load and speed remain constant during the measurement, with the requirement that the relationship between the tyre temperature and the inflation pressure is unambiguous. If all conditions except the unambiguity condition are fulfilled, the tyre state is referred to as repeatable. As evident from Fig. 7b, the tyre air cools down slower than the tyre tread. This causes the relationship between tyre tread test temperature and test inflation pressure to depend on the cooling time required for the tyre to reach the requested test inflation pressure. Thus, the obtained inflation pressure at a specified tyre tread temperature depends on the specific settings for the heat-up procedure and is therefore not unambiguous.

For carrying out repeated measurements it is not practical to have long heat-up or cool-down periods. To examine the usefulness of a procedure with a relatively short heat-up period, a series of rolling resistance measurements was carried out where the inflation pressure during the measurement was set to constant value. Since it is difficult to obtain repeatable conditions with high accuracy of both inflation pressure and tyre temperature, it was determined to keep the pressure constant and allow a small variation of the tyre temperature. This was motivated by the relatively higher accuracy as well as lower noise of the pressure sensor compared to the temperature sensors. The procedure is illustrated in Fig. 7b. The heating process begins with the tyre already somewhat warm from a previous heat-up. The heat-up ends when the inflation pressure reaches a specific value, predetermined from an earlier measurement. The cool-down period was set to be long enough for the inner and outer tread temperatures to more or less coincide, and the average of the two temperatures was used as the tyre tread temperature. A relevant inflation pressure for the rolling resistance measurement was found by identifying the inflation pressure which corresponds to the requested temperature in an earlier heat-up process. In this case, a tyre tread temperature of 44 °C resulted in an inflation pressure of 2.36 bar, with the chosen the inflation pressure of 2.20 bar for the unheated tyre at the reference temperature of 20 °C. The rolling resistance measurement is then carried out with wheel load and speed that are independent of the heating process. In this case the wheel load was 3.9 kN and the speed 30 km/h.

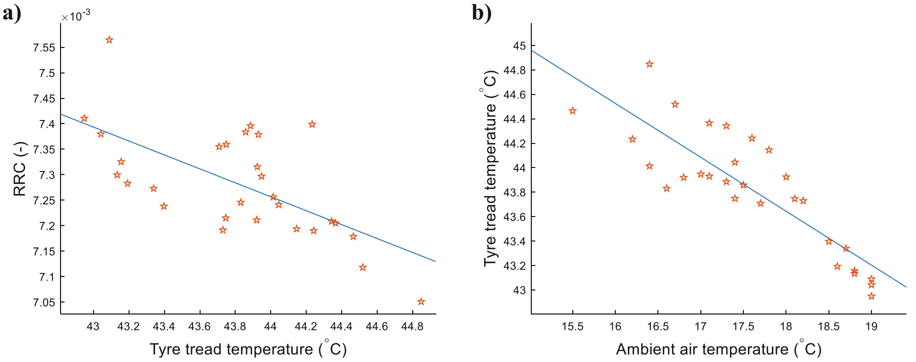

Fig. 8. **a)** Rolling resistance coefficient against the tyre tread test temperature for a heated tyre. **b)** The relationship between tyre tread temperature and ambient air temperature.

The rolling resistance was calculated from the measured force F_X and the previously estimated values of F_{NFAE} and F_{para} according to Eq. 1. The average rolling resistance of the 29 measurements is 28.3 N, which corresponds to an *RRC* of 0.0073. Individual measurement results are plotted against the tyre tread temperature in Fig. 8a. The obtained tyre tread temperatures range from 43 to 45 °C, and as can be seen the temperature dependence on the rolling resistance is clear. From a line fit the change of *RRC* was found to be around 1.7% per degree Celsius This can be compared to simulation results by Yokota et al. [10], where the *RRC* of a passenger car tyre rolling at 80 km/h changed on average 1% per degree Celsius for a variation of the internal tyre tread temperature from 23 to 52 °C.

It is clear from Fig. 8b that the tyre tread temperature variations to a large extent can be attributed to a variation of the ambient temperature in the rig room. Better control of the ambient temperature should improve the repeatability of the measurements. The standard deviation for the 29 conducted rolling resistance measurements is 0.44 N (calculated using Eq. 2), which corresponds to 1.5% of the average rolling resistance value. To improve the accuracy, an average value of several measurements can be used instead of a single measurement. Table 2 presents the 95% confidence interval for a different number of measurements, calculated using the standard deviation of the measurements, assuming that temperature variations are random and not systematic. The values in the table should be considered as worst case, since ambient temperature variations, and consequently tyre tread temperature variations, are less for a smaller number of measurements.

Table 2. Accuracy in terms of limits for a 95% confidence interval for RRC and RR for a heated tyre.

No of samples	Accuracy of RRC measurements	Accuracy of RR (N) measurements	Accuracy in relation to average value
2	$\pm 1.53\ 10^{-4}$	±0.61	±2.2%
3	$\pm 1.25\ 10^{-4}$	±0.50	±1.8%
5	$\pm 9.7\ 10^{-5}$	±0.39	±1.4%
8	$\pm 7.7\ 10^{-5}$	±0.30	±1.1%

For the development of this procedure, the inflation pressure has been set as a capped pressure. The procedure could readily be adapted to regulated pressure measurements, i.e., that the pressure is kept constant during the entire process, instead the amount of air within the tyre varies. The measurement procedure would in this case be simpler since the pressure can be set independent of the tyre temperature.

4 Discussion and Conclusions

In this work, a measurement procedure that can be used to measure rolling resistance at different temperature and pressure states has been proposed and evaluated. The measurement procedure is repeatable, but the relationship between the tyre temperature and inflation pressure, at the measurement varies, if the heat-up load is changed.

The accuracy of rolling resistance measurement results is higher for measurements on heated compared to unheated tyres. This difference could be explained by the larger variations in tyre test temperature and test inflation pressure, for the measurements on the unheated tyre compared to the heated tyre. The test inflation pressure for the unheated tyres depended on the tyre temperature which varied. For the heated tyre, the inflation pressure was kept constant with very small tolerance. If the variations in ambient air temperature could be reduced, the accuracy would increase for measurements on both heated and unheated tyres. Still, with the current ambient temperature variations, the relative accuracy of the *RR* would be within ± 1.5% by using an average of five measurements.

To compare measurement results from this proposed measurement procedure on the VTI flat track tyre test facility with test results from other equipment, not only the test surface, tyre load and capped inflation pressure must be the same, but also the tyre temperature and test inflation pressure. In a quasi-steady-state measurement, it would be sufficient to control either the tyre temperature or test inflation pressure, but since they are not connected here, both must be controlled. Otherwise, the comparison will result in tests at different states which will not be meaningful to compare.

As mentioned earlier, the SRTT-tyre used is often used for rolling resistance tests at different conditions. Bergiers et al. compared the rolling resistance measured on an external drum, an internal drum and with a trailer [15]. The *RRC* varied between 0.005–0.016 for different measurement conditions and equipment. Using an external drum, only varying the ambient air temperature and the road surface, the *RRC* still varied between 0.006–0.015 [16]. The most similar test case had an inflation pressure of 2000 mbar, tyre load of 4 kN, on an external drum with a steel surface, in a temperature between 14.2 and 18 °C [15]. Their test resulted in an *RRC* of 0.008 for a heated tyre and 0.011 for an unheated tyre, which are slightly higher than our values: 0.0073 for the heated tyre and 0.0098 for the cold tyre. However, *RR* on a flat surface is typically reduced 10% compared to drum measurements [7], and adjusting for this makes the results very close indeed.

Regarding future work, the heating and cooling should be studied further, with the aim of reducing test variability. Measurement results from this measurement procedure on the VTI equipment should also be compared with measurement results from other test equipment, for example test drums, which are used for the standardised measurements. It would also be interesting to evaluate how this measurement procedure could be applied for studies of the effect of tyre temperatures and wheel angles on rolling resistance.

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References

1. Aldhufairi, H., Olatunbosun, O.: Developments in tyre design for lower rolling resistance: a state of the art review. Proc. Inst. Mech. Eng. Part D: J. Autom. Eng. **232**(14), 1865–1882 (2018). https://doi.org/10.1177/0954407017727195
2. Schuring, D.: A new look at the definition of tire rolling loss. In: Proceedings of Tire Rolling Losses and Fuel Economy – An R&D Planning Workshop, Cambridge, USA, 18–20 October 1977 (1977)
3. ISO 18164. Passenger car, truck, bus and motorcycle tyres: methods of measuring rolling resistance (2005)
4. ISO 28580. Passenger car, truck and bus tyre rolling resistance measurement method: single point test and correlation of measurement results (2018)
5. SAE J1269: Rolling resistance measurement procedure for passenger car, light truck, and highway truck and bus tires (2006)
6. SAE J2452. Stepwise coastdown methodology for measuring tire rolling resistance (2017)
7. Ydrefors, L., Hjort, M., Kharrazi, S., Jerrelind, J., Trigell, A.: Rolling resistance and its relation to operating conditions: a literature review. Proc. Inst. Mech. Eng. Part D: J. Autom. Eng. **235**(12), 2931–2948 (2021). https://doi.org/10.1177/09544070211011089
8. LaClair, T.J., Zarak, C.: Truck tire operating temperatures on flat and curved test surfaces. Tire Sci. Technol. **33**(3), 156–178 (2005). https://doi.org/10.2346/1.2174341

9. Jansson, H., Åsenius, M.: The relation between rolling resistance and tyre temperature in real driving scenarios. Unpublished master thesis. Linköping University (2021)
10. Yokota, K., Higuchi, E., Kitagawa, M.: Estimation of tire temperature distribution and rolling resistance under running conditions including environmental factors. SAE Technical Paper (2012). https://doi.org/10.4271/2012-01-0796
11. Nordström, O.: The VTI flat bed tyre test facility – a new tool for testing commercial tyre characteristics. SAE Tech. Pap. **933006**, 13–23 (1993)
12. ASTM F2493. Standard specification for P225/60R16 97S radial standard reference test tire (2019)
13. IZZE racing homepage. http://www.izzeracing.com/, Accessed 14 June 2021
14. LaClair, T.: Rolling resistance. In: Gent, A.N., Walter, J.D. (eds.) The Pneumatic Tire, 1st edn., pp. 475–532. NHTSA, Washington (2006)
15. Bergiers, A., et al.: Comparison of Rolling Resistance Measuring Equipment - Pilot Study (2011)
16. Ejsmont, J., Taryma, S., Ronowski, G., Swieczko-Zurek, B.: Influence of temperature on the tyre rolling resistance. Int. J. Autom. Technol. **19**(1), 45–54 (2018). https://doi.org/10.1007/s12239-018-0005-4