Licentiate Thesis in Vehicle and Maritime Engineering

The relationship between rolling resistance and tyre operating conditions, with a focus on tyre temperature

LISA YDREFORS

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Abstract

Efforts to reduce greenhouse gas emissions from today's increasing number of cars and trucks, are crucial in counteracting global warming. These efforts include the intent to reduce the effects of the resistive forces acting on the vehicle. Rolling resistance is one of these forces. A reduction in rolling resistance would aid in reducing greenhouse gas emissions, while also reducing the driving costs and increasing the driving range per charge for electric vehicles.

This PhD research contributes to these efforts by the development of a rolling resistance measurement method on a flat track test equipment that avoids the curvature effects present in the standardised drum test. Another contribution is the development of a rolling resistance model that can describe the relationship between the tyre deformation and the forces acting on the tyre. The model is parametrised by results from the developed measurement method and is simple enough to be included in complete vehicle dynamics simulations.

In this thesis, the effects of different operational conditions, such as inflation pressure, tyre temperature, speed, load, road surface or tyre angles, are investigated and presented. The results from this investigation were used for the development of the measurement method for flat track test equipment. Tyre temperature is an important operating condition influencing rolling resistance and the proposed measurement method can be used to investigate rolling resistance at different tyre temperatures. The results obtained with the proposed measurement method, which are comparable to drum measurements performed under the same operating conditions, are used to parameterise the developed rolling resistance model. The model gives a good fit for the relationship between rolling resistance and tyre deformation. The measurement method and the model build a good platform for deeper investigations of rolling resistance and its connection to tyre temperature.

Keywords: Rolling resistance, tyre temperature, brush model, parametrisation, rolling resistance measurement, drum measurements, operating conditions, tyre, flat track measurements

III

Sammanfattning

Arbete för att minska utsläppen av växthusgaser från det ökande antalet bilar och lastbilar är en viktig del i att motverka den globala uppvärmningen. Detta kan göras genom att reducera påverkan från de resistiva krafter som påverkar fordonet, med fokus på rullmotståndet. En minskning av fordonens rullmotstånd skulle medverka till att minska växthusgasutsläppen samt bidra till att reducera körkostnaderna och öka räckvidden per laddning för elbilar.

Denna licentiatuppsats bidrar till detta genom att skapa en metod för rullmotståndsmätningar på plant underlag, för att kunna undvika krökningseffekterna i den standardiserade trummätningen. Ett annat bidrag är en rullmotståndsmodell som beskriver växelverkan mellan däckdeformationer och däckkrafter. Modellen parametriseras med resultat från den framtagna mätmetoden och är tillräckligt enkel för att vara användbar i en komplett fordonsdynamiksimulering.

I denna uppsats presenteras påverkan av olika driftsvillkor som däcktryck, däcktemperatur, hastighet, last, underlag och kurvatur. Dessa resultat nyttjades i utvecklandet av nämnda mätmetod för rullmotståndsmätningar på plant underlag. Däcktemperatur är ett viktigt driftsförhållande med stor påverkan på rullmotståndet och den föreslagna mätmetoden kan användas för att mäta rullmotstånd vid olika däcktemperaturer. Denna mätmetod användes sedan för att parametrisera indata till den utvecklade rullmotståndsmodellen. Det visade sig att modelldata avviker från uppmätt data för förhållandet mellan hjullast och däckdeformation på grund av modellgeometrin. Men modellen ger en god överenstämmelse för förhållandet mellan däckdeformation och rullmotstånd. Mätmetoden är, tillsammans med den föreslagna modellen, en bra bas för mer genomgående undersökningar av rullmotstånd och dess korrelation med däcktemperatur.

Nyckelord: Rullmotstånd, rullmotståndsmätning, däcktemperatur, driftsförhållanden, trummätning, borstmodellen, parametrisering, däck,

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Acknowledgements

Dissertation

This Licentiate thesis is based on the following scientific papers:

Paper A
L. Ydrefors, M. Hjort, S. Kharrazi, J. Jerrelind and A. Stensson Trigell, *"Rolling resistance and its relation to operating conditions – a literature review"*, in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol 235, issue 12:2931-2948 (2021)

Ydrefors performed the literature review and produced the paper. Hjort, Kharrazi, Jerrelind and Stensson Trigell supervised the work and assisted in writing the paper.

Paper B
L. Ydrefors, M. Hjort, S. Kharrazi, J. Jerrelind and A. Stensson Trigell, *"Development of a method for measuring rolling resistance at different tyre temperatures"*, In Proceedings of IAVSD'21, Saint Petersburg, Russia, Springer.

Ydrefors performed the method development and produced the paper. Hjort, Kharrazi, Jerrelind and Stensson Trigell supervised the work and assisted in writing the paper.

Paper C
L. Ydrefors, M. Åsenius, H. Jansson, S. Kharrazi, M. Hjort and J. Åslund, "*Parametrisation of a rolling resistance model for extending the brush tyre model*", Submitted for publication.

Ydrefors performed the rolling resistance measurements and supervised Åsenius' and Jansson's Master thesis work that is part of this paper together with Kharrazi, Hjort and Åslund. Ydrefors wrote the paper together with Åsenius and Jansson, where Ydrefors contributed more than 50 %. Kharrazi, Hjort and Åslund assisted in writing the paper.

Publication not included in this thesis

L. Ydrefors, M. Hjort, S. Kharrazi, J. Jerrelind and A. Stensson Trigell, *"Development of rolling resistance measurement set-up in order to enable energy optimisation of vehicle-road interaction taking into account safety and performance"* in Proceedings from REV'21, Stockholm, Sweden (2021)

Contents

XI

1 Introduction

The number of vehicles on our roads is increasing. Estimates of the global number of cars surpassed 1 billion in 2010 [1] and is projected to reach 1.8 billion in the year 2035 [2], which corresponds to a large increase in transport related greenhouse gas emissions. In 2018, the global emissions from the transport sector accounted for 8 billion tonnes of CO_2 or CO_2-equivalents, where 74.5 % were caused by road transport, both passenger and freight vehicles [3]. These high emission levels need to be reduced. One potential solution is to decrease the resistive forces acting on the vehicle. The main resistive forces are aerodynamics, inertia, internal friction and rolling resistance (RR). The emphasis of the thesis is on the latter.

RR, defined as "the mechanical energy converted into heat by a tire moving for a unit distance on the roadway [4]", is a significant part of the fuel consumption for road vehicles.

RR constitutes between 5-20 % of the fuel consumption for conventional passenger cars and 15-40 % for trucks [5], [6]. Reducing the RR by 10 % would decrease fuel consumption between 0.5 % and 3 % for a passenger car [7]. This decrease in RR could be achieved by adjusting factors that affect RR. These factors can be divided into tyre properties and driving conditions. Vehicle settings and road surface are two important driving conditions. Some driving conditions such as inflation pressure or speed are controllable, while a driving condition such as tyre temperature is more difficult to control since it is decided by the combined influence from several factors, including the weather. Past efforts to reduce RR mainly focused on adjustments of either the tyre properties or the road surface. However, steps to reduce RR could be more effective if all these factors are considered.

Besides reduced emissions, a reduction in RR would also result in a reduced driving cost and an increased mileage per charge for electric vehicles. However, there are conflicts between optimising RR and optimising other tyre properties, such as wear and grip, which must also be considered. While grip is a traffic safety property, tyre wear is connected to environmental effects. Increased wear results in a higher level of particle emissions. As vehicle exhaust emission has largely

declined, the emissions of wear particles have been slowly increasing and are becoming a much larger share of overall emissions of small particles [8]. Especially in Sweden and Finland, where studded tires are widely used in winter, the non–exhaust emission contribution is much higher than the vehicle exhaust. The introduction of electric vehicles has increased the emissions of wear particles, because they are heavier than traditional vehicles and have a high instant torque when accelerating. Wear is also linked to a shorter lifespan for the tyres, implying both higher costs and more waste. The conflict between these properties is well-known and is commonly illustrated by the tyre magic triangle, illustrated in Figure 1. A reduction of RR should neither compromise safety, through a decreased grip, nor increase the tyre wear. The process to reduce RR, without undermining other tyre properties, would benefit from better knowledge about RR.

Tyre noise is another important tyre property. However, in contrast to wear and grip, there is no evident conflict between reducing RR and tyre noise [9].
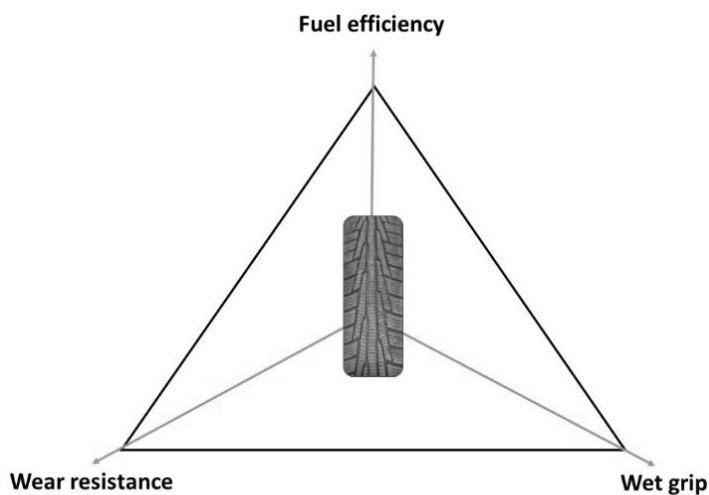

Figure 1. Magic tyre triangle

1.1 Research goal and method

The overall objective of this PhD research project is to fill part of the knowledge gap regarding tyre RR towards the development of energy efficient vehicles. This general objective has been concretised as two specific goals, illustrated in Figure 2. The first goal is to establish a reliable measurement method for RR on a flat road surface under controlled non steady state conditions, which can be used at different set tyre temperatures. The second goal is to create and parameterise a temperature dependent model of RR for complete vehicle dynamics simulations.

Project goals

1. **RR measurement method**
a) Method hypothesis
b) Method development
c) Compare with drum measurements
d) Examine RR-temperature relationship

2. **RR simulation model**
a) Model hypothesis
b) Model development
c) Examine if model can be parametrised using measurement results
d) Include effects of tyre temperature and wheel angles in the model
e) Parametrise and validate with measurement results
f) Investigate model to verify if it is usable to examine how vehicle settings affect RR

Figure 2. Overview of the project goals.

The long-term goal for the PhD work is to add changes in wheel angles to this developed model, that will enable investigation of how vehicle settings influence RR. Such a model is then intended to optimise wheel angle settings to reduce RR in different driving conditions without compromising safety and performance.

The research goals are divided into tasks. The tasks of creating a method hypothesis and developing the measurement method are completed within this licentiate thesis. A large part of the task to create a model hypothesis and develop and parametrise the simulation model is also finished. The research method used to achieve these tasks has been threefold. First, a literature study was carried out, as the basis for **Paper A**, while the research for **Paper B** was mainly conducted through experimental laboratory tests. Finally, in **Paper C**, model development simulations and experimental tests were used in the last task included in this licentiate thesis.

Although the tasks included in this thesis are finished, several planned tasks remain for the research work leading to the PhD thesis.

1.2 Limitations

The developed test method and model focuses on passenger car tyres. Another limitation is that few tyres and temperature levels have been tested or simulated.

The ambient air temperature in the test facility is also a limitation since it cannot always be kept constant due to changes in the outside air temperature. The variations in ambient air temperature will affect both the tyre temperature and RR.

1.3 Thesis outline

After the introduction, this thesis commences with a description of a standardised RR measurement on a test drum, according to ISO 28580. After that, the VTI tyre test facility, used for flat track RR measurements in **Paper B** and **Paper C,** is described. The details of the proposed methodology can be found in **Paper B** and **Paper C**. Then a summary of the literature describing the relationships between tyre temperature and RR is provided. A more in-depth description can be found in **Paper A**.

The chapter that follows is focused on modelling; it starts with some general notes and continues with a description of the Brush tyre model, which is proposed to be combined with the RR model presented in **Paper C**. The final chapters provide a summary of the appended papers, some concluding remarks, and suggestions for future works.

2 Rolling resistance measurements

2.1 Measurements on a test drum

The most common test equipment for RR measurements is a test drum (Figure 3). The tyre is fixed against the drum with a set wheel load, while the drum is rotating with a set test speed, and the resistance the tyre exerts on the drum is measured.

Figure 3. A standardised test drum. Courtesy of Volvo Cars.

There are four standardised RR measurement methods [10]–[13]. An overview of them is included in **Paper A**. In this section, the ISO 28580 standard, the most commonly used in Europe, is described in more detail. The advantage of this measurement method is its high repeatability, and it is generally used to compare the RR of different tyres against each other. General requirements for tests, according to this standard, can be found in Table 1**Fel! Hittar inte referenskälla.**.

Table 1. Requirements for RR measurements of passenger car tyres according to ISO 28580.

Test drum diameter	≥1.7 m
Ambient air temperature	25 ⁰C ± 5 ⁰C
Test speed	80 km/h
Test load	80 % of maximum load capacity

The required capped inflation pressure is 210 kPa for standard load or light load tyres. For reinforced or extra load tyres the inflation pressure is increased to 250 kPa. Before the test is started, the tyres shall be conditioned in the test environment for at least 3 hours. Then the capped pressure can be set. Afterwards the test drum starts running, the tyre shall run for 30 minutes on the test drum or until it reaches steady state RR, before the measurement can start. Following the ISO 28580 standard, RR measurements can be performed according to either the force, torque, power, or deceleration method.

The force method measures the force acting on the tyre spindle. This method is precise at an ideal contact angle but sensitive to angle misalignment [14]. The torque method is less sensitive to misalignment compared to the force method. It measures the torque input on the drum that is required to maintain the test speed. The power method measures the input power to the drum. Lastly, the deceleration method is the only method where the tyre speed is not kept constant. Instead, the deceleration of the unloaded tyre and the drum are measured.

A drum measurement includes parasitic losses in the measured RR. The parasitic losses originate from equipment losses, such as bearing and aerodynamic losses. To subtract these losses, a skim measurement is performed to attain them. For the force, torque and power method, the skim measurement is performed as a RR measurement using the minimum wheel load, which still can maintain the tyre contact with the drum without slip. For the deceleration skim test, the tyre is removed from the drum, and the deceleration of both the drum and the tyre is measured. The RR is then calculated from the measurements. When the force method is used, the RR, F_{RR}, will be as follows:

$$F_{RR} = F_D \left(1 + \frac{r_T}{r_D} \right) - F_{pl} \qquad (1)$$

where F_D is the force measured during the RR measurement, r_T and r_D are the tyre and drum diameters respectively, and F_{pl} is the calculated parasitic loss. The repeatability of the measured, F_{RR}, is

6

dependent on a controlled ambient air temperature. For example, if the ambient air temperature deviates from 25 ºC, but remains within limits in Table 2**Fel! Hittar inte referenskälla.**, the measured RR can be used if it is adjusted according to the following:

$$F_{RR25} = F_{RR}[1 + K_t(t_{amb} - 25)] \qquad (2)$$

where K_t is a temperature constant, which is set to 0.008 for passenger car tyres, and t_{amb} is the measured ambient air temperature. The ambient air temperature, together with the other operating conditions, sets the tyre temperature for a steady state measurement such as ISO 28580. This approach results in a repeatable tyre temperature.

This drum steady state tyre temperature is high compared to both a steady state temperature on a flat surface [15] and the tyre temperatures generally achieved during driving. This will be further discussed in Section 2.3.

The tyre temperature is an important operating condition for RR. Neither ISO 28580 nor the other standardised methods can be applied to study temperature influence on RR, since these standards require testing at steady state, implying a fixed tyre temperature. Furthermore, the test drum curvature increases the RR and the tyre steady state temperature compared to a flat surface test (see **Paper A**).

2.2 Measurements on a moving ground equipment

The main advantage of using a flat track test equipment for RR measurements is that the curvature effects in a drum test can be avoided. These curvature effects influence both the RR and the tyre temperature. The VTI tyre test facility also has the advantage that different road surfaces can be used, and the tyre measurement temperature can be chosen.

The VTI tyre test facility is used for the experimental work in **Paper B** and **Paper C**. The VTI test equipment consists of a rig that holds the tyre in place and presses it toward the ground with a specific wheel load (Figure 4 - 5) [16]. The ground beneath the tyre is a large metal beam that can move at speeds up to 30 km/h. This beam is 54 m long and 0.6 m wide and runs on a 130 m long test track, see Figure

5. The metal beam is usually launched in the forward direction during a measurement. However, it can also be run in the backward direction but then the test speed is fixed to 1.7 km/h.

A low maximum speed, 30 km/h, together with the short measurement time, which prevents steady state measurements, are the main disadvantages associated with using this measurement equipment. The forces between the tyre and its moving ground are measured with a force sensor.
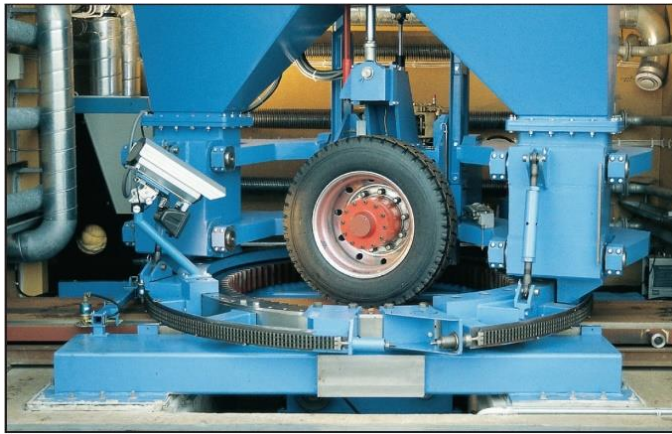

Figure 4. VTI tyre test facility. The blue fixture holds the tyre while the metal beam runs beneath it.
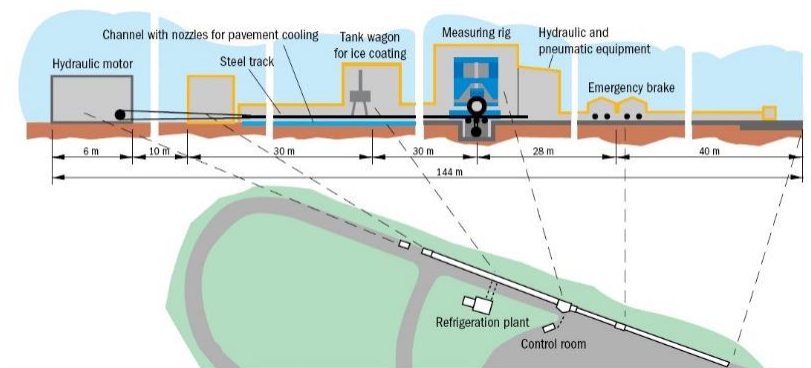

Figure 5. Overview of the VTI tyre test facility.

The force sensor measures the lateral, longitudinal and vertical forces that act on the tyre. The sensor is piezo-electrical, providing exact dynamic measurement results, while the force tends to drift in static measurements. The accuracy of the longitudinal force was measured to ±0.2 N (**Paper B**). The drift in measured force is not relevant for large forces, such as brake forces, but must be accounted for and compensated in RR measurements since the forces are relatively small.

The wheel load on the tyre during the measurement can be varied between 100 N and 100 kN. The tyre angle can also be adjusted to enable measurement with a camber angle of ±10⁰ and a slip angle of -30⁰ to 90⁰. Brakes can also be applied with a brake force of up to 70 kN.

The facility can be used to measure most pneumatic tyres, ranging from truck tyres via passenger car tyres to bike tyres. The moving ground surface can be steel, ice, and wet/dry asphalt. To launch the beam, a winch connected to electrohydraulic accumulators is used. These accumulators require a few minutes to load. When the test is started, the beam accelerates, runs a short distance at the test speed and is then slowed to a standstill by the test track braking system.

The tyre needs to be heated if the requested test temperature exceeds ambient air temperature. The test equipment can heat the tyre, by running it against a cylinder (Figure 6). The heating procedure must be stopped before loading the accumulators. This implies that a heated tyre cannot be tested in a steady state condition since it will cool down slightly before the test. To achieve a uniformly heated tyre another heating procedure, such as tyre warming bags, can be used instead. The warming bag would not give rise to the temperature gradients that exist in a rolling tyre, but the absence of temperature gradients could contribute to a more repeatable RR.

Figure 6. Heating a tyre in the VTI tyre test facility. Only the central cylinder is used for heating. The other two cylinders are there to support the beam under the wheel load from the blue test rig.

The VTI tyre test facility has been used in the development of the RR measurement procedure described in **Paper B**, and this procedure is used for the measurements in **Paper C**.

2.3 Tyre temperature effects

As concluded in **Paper A**, tyre temperature and RR strongly influence each other In RR measurements, the tyre temperature must be repeatable to achieve high repeatability. In standardised tests this is generally achieved through performing the tests at steady state RR, which corresponds to a steady state tyre temperature. A repeatable steady state is achieved through standardising the magnitude of the relevant test parameters. However, the steady state tyre temperature is equipment dependent and is often higher than the tyre temperatures achieved in real driving conditions. Therefore, to understand RR at tyre temperatures comparable to those in real driving conditions, the RR needs to be measured at temperatures other than the steady state temperature.

RR measurements at non steady state temperatures require accurate measurements of the tyre temperature. If the RR can be related to a tyre temperature, variations in measured RR due to differences in tyre temperature can be distinguished from the random errors inherent in the measurement. The tyre temperature varies over the tyre geometry, through the tyre rubber thickness and the tyre width, along the tread pattern and between different tyre parts [17]. The tyre temperature measurement shall provide sufficient data to enable an estimation of the tyre temperature in the tyre parts, which mostly affects the RR. This can be done for example through thermocouples placed in holes in the tyre rubber [15].

In this work, a non-destructive temperature measurement method is chosen, since it gives a good temperature measurement without damaging the tyres. The temperature sensors (Figure 7), further described in **Paper B**, measure the tyre surface temperature; one sensor measures the inside surface of the tyre and the other one measures the outside surface.

Figure 7. Temperature sensors. Left: outside infrared tyre temperature sensor. Right: inside tyre temperature and pressure measurement system [18]

The inside surface can be divided into the inside tread surface (section beneath the tread) and the inside sidewall surface. The temperature of these surfaces and the inflation pressure are measured with a tyre temperature and pressure measurement system. This inside sensor has 16 temperature channels. The sensor channels cover the inside tread surface and part of the sidewall area, where the portion of

the channels that measures the inside tread surface depends on the tyre width. On a wider tyre, a larger share of the channels measures the inside tread surface, and the measured part of the sidewall is smaller. The temperature of the sidewall is lower than the temperature of the inside tread surface. This is expected since the largest part of the RR originates from the tread [19].

The outside tyre tread surface temperature is measured with an infrared tyre temperature sensor. The outside sensor also has 16 temperature channels, which enable the identification of the temperatures of thin slices of the tyre width. The temperature variation between the channels (Figure 8), is a coarse image of the tyre temperature distribution. The peaks correspond to the tyre grooves and each line corresponds to an individual measurement.
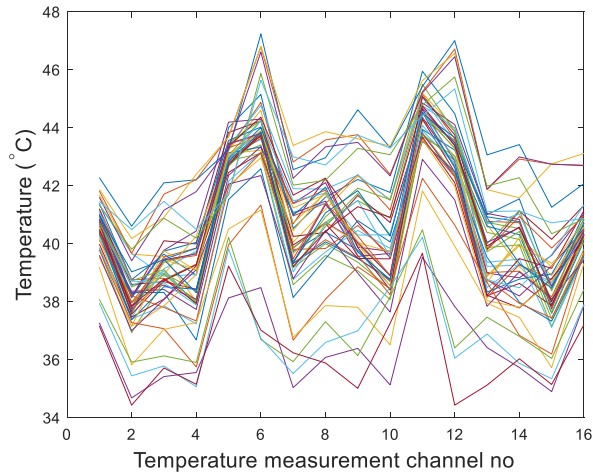
Figure 8. Tyre temperature variation between different measurement channels, measured with the outside temperature sensor.

Comparing RR at different tyre temperatures would be facilitated if a single tyre temperature could be used instead of the tyre temperature distribution. Such a temperature is defined in the measurement procedure in **Paper B.** The chosen temperature is considered as a single temperature due to the inside tread and the outside groove temperature becoming almost identical at the time of

the measurement. Therefore, the average of these two temperatures is defined as the tyre tread temperature.

The accuracy of the sensors depends both on tyre material properties, such as emissivity, and random error. The contribution of the error, which depends on tyre material properties, is found to be constant for each tyre and can therefore be ignored for comparisons between different measurements on the same tyre. Furthermore, the inflation pressure measurements are less noisy than the corresponding temperature measurements. This lower noise level is utilised in the developed measurement method. The tyre is heated to a temperature slightly above the desired test temperature by running on a cylinder, until the tyre inflation pressure reaches the set heat-up-level. Then the tyre is allowed to cool down. At the end of the cooling, the temperature in the tread area, from the tyre inside carcass surface to the outside tread surface, is almost uniform. Next the RR is measured. A more detailed description of the proposed and evaluated measurement method is found in **Paper B**.

During cool-down, the estimated temperature of the enclosed air within the tyre changes slightly slower than the tyre temperature at the tread area. This estimated air temperature is calculated from the inflation pressure, based on the assumption that the enclosed air follows the ideal gas law. This difference in cool down rate between the tyre tread temperature and the estimated air temperature, requires that tyre temperature and inflation pressure are treated as two separate variables. Since both variables have a significant influence on the RR, both variables shall be repeatable.

This separation between inflation pressure and tyre temperature is not found in steady state measurements, where an unambiguous relationship between tyre temperature and inflation pressure exists for the same operating conditions. However, the steady state temperature of the tyre is affected by the ambient air temperature which is not sufficiently controlled in the VTI test facility. One method to achieve both a repeatable inflation pressure and a repeatable tyre temperature, is to perform the tests at regulated pressure, where the pressure is kept constant during the entire measurement procedure. Using regulated pressure would simplify the measurement procedure since it would

suffice to maintain a repeatable tyre temperature to gain a repeatable RR. Regulated pressure could, however, not be used with the available equipment.

Due to this, the measurements are performed at capped pressure. The pressure is set before the test commences and the amount of air within the tyre is kept constant during the measurement. Since the different cooling rates are found to be repeatable, a constant cooling time gives a repeatable relationship between the tyre temperature and inflation pressure during a measurement series. To keep the cooling time constant and achieve the same measurement settings, a temperature indicator is used to indicate the time for the heat-up termination and another for the measurement initiation. These two times are marked as vertical lines in Figure 9.

The inflation pressure is chosen to be used for the temperature indicators, both the heat-up and measurement level, instead of the tyre temperature, due to its less noisy behaviour. However, a different choice of temperature indicator settings results in different RR levels. According to the measurement method described in **Paper B**, proper tyre temperature and inflation pressure values must be chosen to perform relevant RR measurements with this equipment.
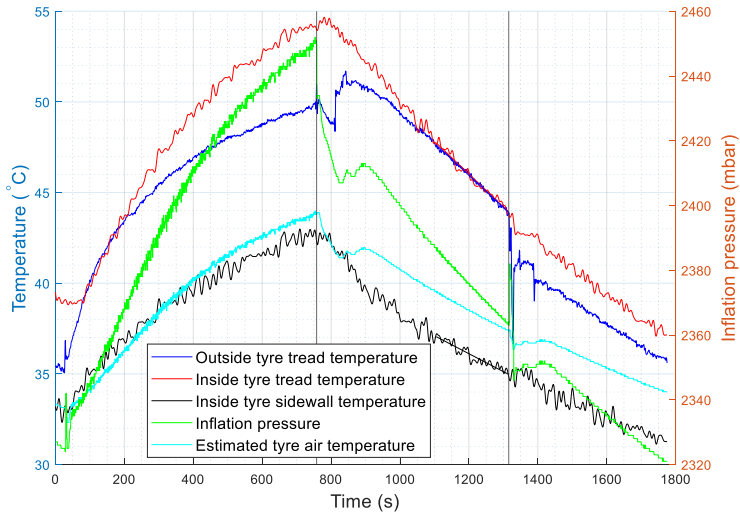

Figure 9. Changes in temperature and inflation pressure during heating, cooling, and RR measurement.

These measurements will also be affected by the ambient air temperature. Though, the impact of ambient air temperature is larger for steady state RR measurements, it has an influence on the tyre temperature in RR measurements performed according to the method developed in **Paper B**.

The cooling time, from the heat-up to the measurement level is affected by the ambient air temperature. If the ambient air temperature increases, the cooling time will also increase since the temperature difference between the tyre and the ambient air is reduced. This increase in cooling time will affect the relationship between the inflation pressure and tyre temperature, and since a fixed inflation pressure is used in all measurements, the tyre temperature will vary. The result is a reversed relationship between tyre temperature and ambient air temperature. An increase in ambient air temperature causes a slight decrease in the tyre measurement temperature due to the increased cooling time. This can be compared to a steady state measurement, where a higher ambient air temperature results in a higher measurement tyre temperature.

Besides the RR and ambient air, the tyre temperature is also affected by the ground temperature where the effect of the ground temperature is more than the effect of the ambient air temperature [16]. However, in measurements using the VTI tyre test facility, described in Section 2.2, the time the tyre is in contact with the ground is too short for the road temperature to affect the tyre temperature. At the same time, it is shown that variations in ambient air temperature directly affected the tyre temperature.

If the tyre temperature and inflation pressure at relevant operating conditions are known, the corresponding RR can be measured at the VTI tyre test facility. Hence an investigation was performed to determine the tyre temperatures and inflation pressure at different real driving conditions. The measurements were performed in Sweden during early spring. Three road types were used, motorway, rural road and city road. The tyre temperature for a class A tyre was found to vary between 16° - 36°C for the inside tread surface and between 15° - 29°C for the outside tread surface, under different driving conditions [20]. The tyre temperature and speed from one of these driven test

rounds on motorway at ambient air temperature 13°C and road temperature 14°C is shown in Figure 10. The car is front wheel driven and the driving torque on the front tyres increases the temperature of those tyres in comparison to the free rolling rear tyres. Furthermore, the temperature of the right front tyre is higher than the temperature of the left one. This temperature difference is caused by the crossfall of the road. Counter steering the crossfall will lead to different slip angles on the left and right side due to the toe angle settings and cause a difference in tyre temperature.
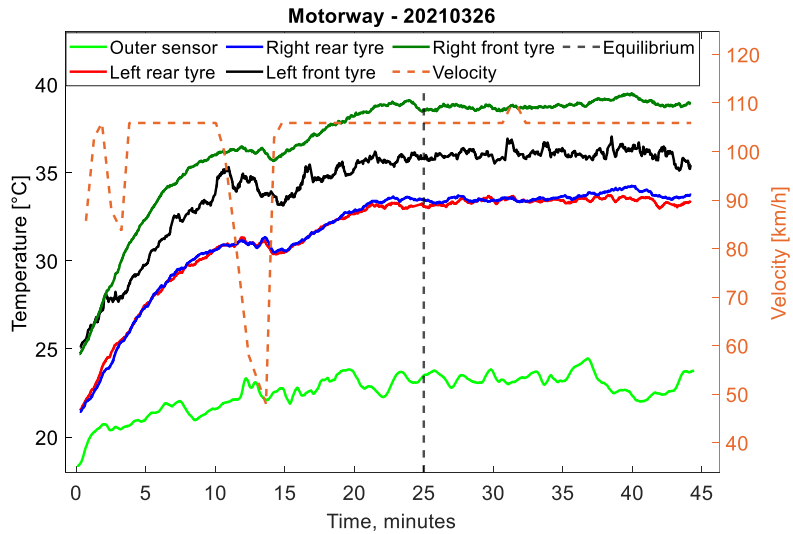
Figure 10. Example of tyre temperatures in traffic.

The tyre temperatures in traffic can be compared to the corresponding inside and outside tyre temperature for an identical tyre at steady state on a test drum, at standardised test conditions, was found to be approximately 44°C and 30°C. The difference in tyre tread temperature between drum measurements and real driving conditions implies that the RR measured in a drum test will deviate from the RR in many real driving conditions. The RR at different driving conditions should be further examined.

16

3   Modelling

There are three kinds of tyre models: physical, empirical and semi-empirical. A physical tyre model is theory based, built on equations governed by physical processes in the tyre and properties of the constituent materials. These equations govern the different tyre properties and their influence on each other. To simulate the RR of a specific tyre, the material properties of the tyre are used to parametrise the model, and the parameters contain information about these material properties. A well-known physical model is the Finite Element Method (FEM) model. In FEM simulations, the tyre is divided into small segments that influence each other. Their mutual influence on each other is governed by the physical properties and constituent material of the tyre.

In contrast to a physical model, an empirical model relies on measurement results instead of building on theoretical relationships. The model equations are parametrised using measurements performed at different set test conditions. These parameters have no physical meaning but are chosen to make the tyre simulation fit the measurement values. The most well-known empirical tyre model is the Magic formula [21]. However, this formula does not model the RR but can be used to model side force, brake force or self-aligning torque.

A semi-empirical model is a combination of the physical and empirical model. The governing equations of the model are based on physical processes, but loosely, compared to a physical model. The model is parametrised by measuring the requested properties, such as the RR. The parameters have physical meaning, but the parameter values are set to fit the measurement results, not an intrinsic material property of the tyre. One example of a semi-empirical model is a parametrised brush tyre model.

3.1 Brush tyre model

The brush tyre model is a simple physical model. The original brush tyre model simulates a tyre as a line of small brushes (or bristles) on a disc (Figure 11). The disc can deform normal to the plane to create a contact patch, while the bristles, modelled as linear springs can deform or bend in the plane. The forces acting on each bristle are calculated, and the resultant force acting on the tyre is defined as the combination of the forces from all individual bristles. This model can be used to calculate longitudinal and lateral tyre forces and includes the effect of slip and slip angles [22].

The brush tyre model has been extended to increase accuracy or enable calculations of different tyre properties [23]–[25]. For example, several lines of bristles can be used instead of one [24], which enables the inclusion of camber angle effects into the brush model.
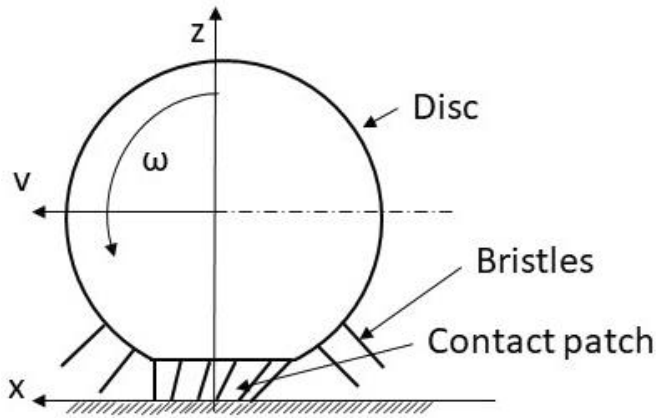
Figure 11. The brush tyre model.

To fulfil the goals of this work, a RR model is developed. This RR model shall be simple and feasible to include into the brush tyre model to enable vehicle dynamics simulation with a comprehensive tyre model. One advantage of a simple model, such as the brush model, is the low number of parameters that need to be set. This can be compared to an FEM-model where a large number of required parameters makes it difficult to properly model a tyre without all the

manufacturer's material data. Another advantage of this model is its relatively small requirement for computational power.

When extended with the RRM described in Section 3.2, the brush tyre model can be viewed as semi-empirical, since it intends to use experimental results for the parametrisation of the model.

3.2 Rolling resistance model

This section introduces a RR model compatible with the brush tyre model. The model is inspired by Davari and Conte [24], [25] and is described in detail in **Paper C**.

The properties of the linear bristles in the numerical brush tyre model can be improved by including the proposed RRM, which contributes with a vertical deformation of the bristles. Bristles in the model differs from the bristles in a brush tyre model since they cannot bend in either longitudinal or lateral direction, only compress or relax in vertical direction, as shown in Figure 12. However, the RRM has a comprehensive rubber model, which improves the modelling of the material properties of the tyre. This rubber model is divided into a viscoelastic part and an internal friction part, as shown in Figure 13,
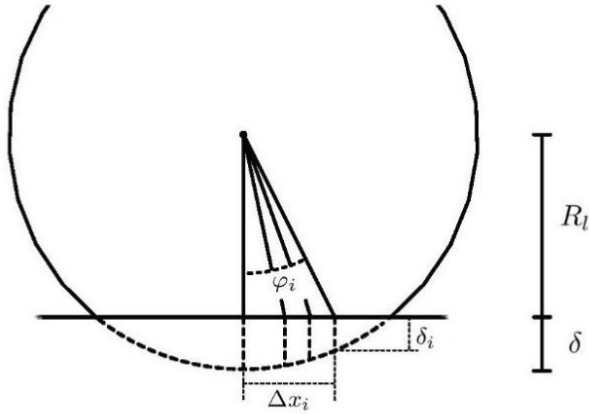

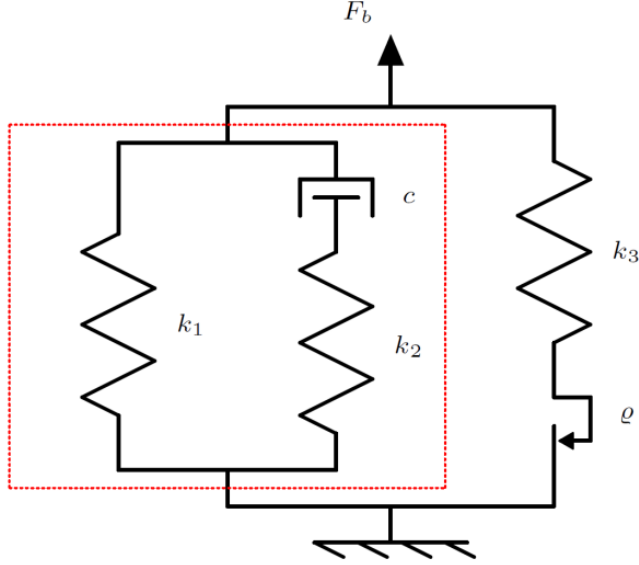Figure 12. Bristle deformation behaviour in RRM.

Figure 13. The RRM, used in **Paper C**, where the red frame contains the viscoelastic Zener model next to the Masing model on the right.

The viscoelastic force is modelled using a Zener model [26], as shown within the red frame in Figure 13. A viscoelastic material combines viscous and elastic properties. Where the viscous behaviour is simulated by a spring and a damper in series. This model reproduces the materials viscous properties which causes its polymer chains to rearrange under an applied stress. When the stress is removed, the material will eventually fully recover to its initial state. This elastic behaviour of the material is simulated by a single spring. The combination of these two elements, as seen in the Zener model, reproduces the stress-strain in a viscoelastic material well.

A tyre is generally exposed to a dynamic load during driving. The ratio between the resulting stress and strain is called the complex modulus. This modulus consists of a real part, the storage modulus and an imaginary part, the loss modulus. While the storage modulus is a measure of the part of the deformation energy which is regained after relaxation, the loss modulus measures the energy lost in a deformation cycle. The ratio between these moduli, is the loss factor

which measures the percentage of energy lost in a deformation cycle. Both the loss factor and the loss modulus can be used to estimate the RR. The loss modulus and loss factor from the Zener model, together with the RR can be seen in Figure 14, using the cold class B tyre parameters from **Paper C**.

RR is increasing with speed until it reaches a maximum level at 120 Hz, which is equivalent to a tyre speed of 200 km/h. This corresponds well with what has been reported in the literature, that the structural deformations responsible for rolling resistance generally occurs within 10 – 150 Hz [27]. The RR increase rate is very high at low speed but decreases as the speed increases. It should be highlighted that these plots are based on the Zener model which does not capture the effect of standing waves on RR. These waves emerge at speeds around 120 km/h or higher [27] and cause the total RR to continue to increase with speed also at higher speeds when the RR from the structural deformations decreases.
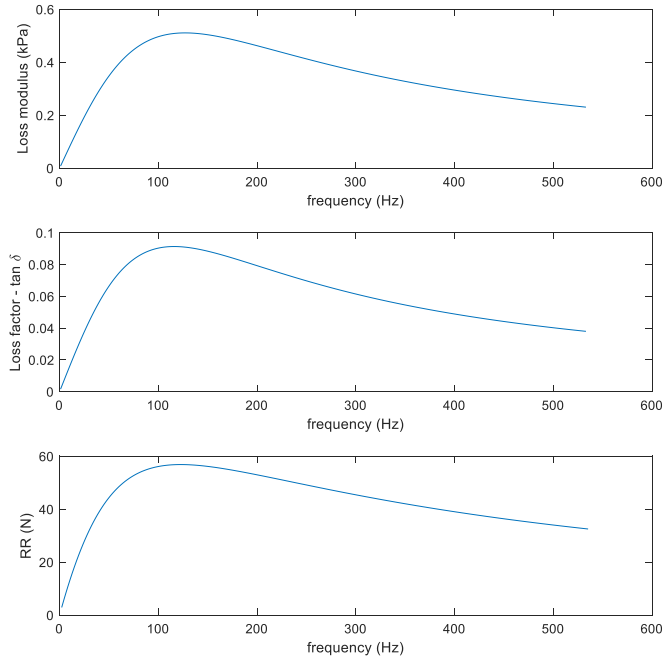

Figure 14. Storage modulus, loss factor and rolling resistance at different frequencies, calculated with the Zener model.

The Masing model, seen next to the red frame in Figure 13, represents the internal friction of the tyre material [25] and aims to reproduce the Payne effect. The Payne effect describes nonlinear elastic stress-strain behaviour in rubber, which contain a filler material. According to the Payne effect, the stiffness of the tyre is reduced at increased strain as the rubber is exposed to small dynamic strains [28]. The Masing model, which simulates this effect, consists of one Jenkins element in **Paper C**. More Jenkins elements give a more accurate representation of the Payne effect but also make the model and the parametrisation more complex. Figure 15 shows the difference in friction force between using one or five Jenkins elements. It is notable that the difference in RR between one or five Jenkins element is only a few percent if the model parameters are optimised according to **Paper C**.
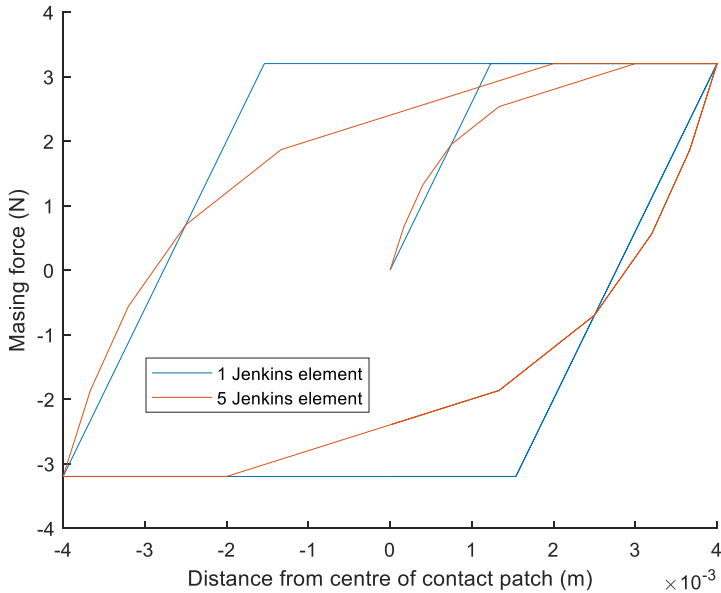

Figure 15.Comparison of the force-deformation relationship for Masing models with one or five Jenkins elements.

4 Summary of appended papers

Paper A: "Rolling resistance and its relation to operating conditions – a literature review"

L. Ydrefors, M. Hjort, S. Kharrazi, J. Jerrelind and A. Stensson Trigell. Published in Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol 235, issue 12:2931-2948 (2021)

This paper is a literature review focusing on three aspects of RR: its definition, the relationship between RR and its operating conditions; and finally, different techniques to measure RR. The aim of the paper is to give an overview of the influential operating conditions and their effect on RR.

The definition of RR is not completely consistent in the literature. The most commonly used definition today, found in ISO 28580, states that RR is "loss of energy (or energy consumed) per unit of distance travelled" [10]. This definition works well in drum tests, which is the context it was written for. It is, however, not as stringent as the traditional definition stated by Schuring. He defined RR as "the mechanical energy converted into heat by a tire moving for a unit distance on the roadway" [4].

The tyre operating conditions have a large effect on the RR of a tyre. These operating conditions are inflation pressure, temperature, surface curvature, load, road surface, speed, torque and slip, toe and camber angles. The effect of an increased inflation pressure or tyre temperature will be a decreased RR. This effect is also noticeable for quite small changes unlike the effect of surface curvature, where the curvature must be large enough to influence the RR, which is the case for drum tests. The RR measured on a drum will generally be about 10 % higher than the equivalent values on a flat surface. The influence from the road surface is more complex, but a smoother road would generally result in a lower RR. An increase in the wheel load, the speed, the applied torque, and the camber or slip angles of the tyre also increases the RR.

The presented RR measurement techniques are divided into field and laboratory measurements. The field measurement techniques are trailer measurements, coastdown and fuel consumption measurements. The most common laboratory measurement technique is drum measurements, used, for example, to compare the RR of different tyres. This measurement technique is the only one with governing standards [10]–[13]. The other laboratory techniques are rolling belt, commonly known as flat track, moving ground and moving rig equipment.

The main scientific contributions from this paper are highlighting the need for a harmonised definition of RR, as well as the value of further research regarding the effect of different operating conditions such as torque, wheel angles or tyre temperature during driving.

Paper B: "Development of a method for measuring rolling resistance at different tyre temperatures"

L. Ydrefors, M. Hjort, S. Kharrazi, J. Jerrelind and A. Stensson Trigell, Proceedings from IAVSD'21, St Petersburg, Russia.

The goal of the work presented in this paper is the development of a RR measurement procedure, as presented in the research goals in Section 1.1. In this paper, the creation of a hypothesis, the method development and the evaluation of a RR measurement method usable for measurements at different tyre temperatures with a moving ground equipment is presented. The equipment uses piezoelectric sensors to measure the lateral, vertical and longitudinal forces on the tyre. The longitudinal measured force gives the RR but also includes two sources of error originating from the equipment, which must be measured and subtracted from the longitudinal force to attain the RR. The accuracy of the longitudinal force measurement is investigated and found to be ±0.2 N, which is sufficient for RR tests.

RR is a temperature dependent property, and generally the tyre needs to be heated to reach the requested test temperature. The tyre is heated and then allowed to cool down making the tread temperature almost uniform. Next, the RR measurement is made. The standard deviation for 29 temperature adjusted measurements is 0.44 N for

heated tyres, while the temperature effect on the RR coefficient was approximately 1.7 % / °C.

The measurement results for both the heated and unheated tyre using the developed measurement method are found to be approximately 10% less than the drum measurement results from Bergier's study, which was conducted under similar operating conditions using the same tyre model [29]. This difference is expected when comparing the results from measurements on drums with measurements on flat surface test equipment.

The main scientific contribution of this paper is the development of a measurement method which is shown to be useful for measuring RR at different tyre temperatures.

Paper C: "Parametrisation of extended brush model for rolling resistance simulations"

L. Ydrefors, M. Åsenius, H. Jansson, S. Kharrazi, M. Hjort and J. Åslund. Submitted for publication.

This paper aims to create and parametrise a model for RR, which can be used in a complete vehicle dynamic model, as presented in the research goals in Section 1.1.

This paper describes a RR model, aimed to extend the brush tyre model. The model is based on the Masing and Zener models, which simulates the material properties of the tyre in a comprehensive way.

This model has been parametrised with RR measurement results from the VTI tyre test facility using the method described in **Paper B**.

The model gives a good fit for the relationship between the measured and modelled RR-deformation relationship. However, the relationship between the wheel load and the tyre deformation is not accurately described, and there is a need for further development of the model.

The main scientific contribution of this paper is that a RR model that can be used with a numeric brush model was created, parametrised, and evaluated.

5 Scientific contributions

The main scientific contributions of this work are as follows:

- Performed an extensive literature review that provided an overview of the operating conditions shown to influence the RR, including how they are affected by choice of measurement technique. (**Paper A**)
- Identified potential research gaps within the research field, such as the effect of wheel angles or torque on RR or the effect on RR of the difference in tyre temperature between a test on a laboratory equipment and actual driving. (**Paper A**)
- Highlighted the need for a harmonised RR definition. (**Paper A**)
- Developed a new method for RR measurement at different non steady state temperatures, on a flat track equipment. (**Paper B**)
- Investigated the relationship between inflation pressure and tyre temperature during cooling, which affects measurements performed at non steady state conditions (**Paper B**).
- Started the work towards a mathematical RR model which can be parametrised by tyre measurement data to be used in future vehicle dynamics simulations as well as investigating different wheel settings. (**Paper C**)
- Showed that the RR model gave a good fit between the measured and modelled RR-deformation relationship. (**Paper C**)

6   Concluding remarks

Tyre temperature is an important test condition that highly affects the RR. Today, most measurements are made on test drums at steady state, resulting in a controlled, repeatable tyre temperature. However, this temperature is generally higher than the temperature of tyres in traffic. To examine the effect of the tyre temperature relevant for traffic, the RR should be measured at repeatable controlled conditions at different tyre temperatures.

Such a RR measurement method has been established in this work. The method can be used at different tyre temperatures. The temperature and RR are repeatable provided that the tyre cooling time is kept constant. This is to maintain the same tyre temperature-inflation pressure relationship for the measurement.

Maintaining the tyre temperature-inflation pressure relationship is important since this measurement method uses capped pressure. For capped pressure, the pressure is set before the test commences and the amount of air within the tyre is kept constant during the measurement. Using regulated pressure, where the pressure is kept constant during the entire measurement procedure, would remove the requirement to use a constant cooling time and simplify the handling of the tyre temperature-inflation pressure relationship. Regulated pressure could, however, not be used with the available equipment.

The model developed and parametrised in **Paper C** is a RR model, compatible with the brush tyre model. The parametrisation of the model gives a good fit for the relationship between the RR and tyre deformation; however, the description of the relationship between the wheel load and the tyre deformation deviates from the measurement results. This deviation will also affect the RR coefficient.

The proposed measurement method and the developed model build a good platform for future deeper investigations of rolling resistance and its connection to tyre temperature.

7 Recommendations to future works

The ambition regarding future work concerns both the measurement and modelling of RR. The remaining measurement tasks are to compare the measurement results from a test drum, certified according to ISO 25280, with measurement results from the VTI tyre test facility using the measurement method developed in **Paper B** for the same tyre temperature and inflation pressure. This comparison aims to learn how these measurement methods correlate with each other, and how this correlation is affected by temperature variations.

The first objective related to the RRM is to implement the model developed in **Paper C** into a brush model and to investigate if the model can be adjusted to better capture the relationship between the tyre deformation and the wheel load. The next goal is to include the temperature dependence of the tyre and the effect of wheel angles in the model. Finally, if this extended model is parametrised, it will be a good basis to examine possibilities to reduce RR through adjustments in the vehicle settings for the tyre.

Another interesting topic is the relationship between tyre temperature and wear. For example, if critical temperatures linked to wear tyre transitions can be found.

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