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Influence of inflation pressure, speed, load and warm-up phase on rolling resistance of passenger car tyres

Master's thesis in Automotive Engineering

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ABSTRACT

The importance of improving vehicle energy efficiency has risen for modern day automobiles. It's even more vital for electric vehicles which have limited range. The driving range is an important consideration for any potential customer and is influenced by the vehicle's energy efficiency. The energy efficiency is governed by the vehicle's driving resistance forces. In a broad sense, the major contributors to the driving resistance force are the aerodynamic drag, inertial drag and rolling resistance. The rolling resistance accounts for a significant share of the driving resistance and has a direct impact on the fuel consumption and energy efficiency of vehicles. Michelin in their 2003 study '*The tyre: Rolling resistance and fuel savings*' estimate the average contribution of the tyre's rolling resistance towards the total resistance to movement varies between 20% and 30%. The present-day industry standard to evaluate a tyre's rolling resistance is the rolling resistance coefficient (RRc) measured using the ISO 28580 standard in the EU. This method is a single point test and does not account for the variation in the operating parameters such as the tyre's inflation pressure, speed and the load on the tyre. It also does not include the contribution of the warm-up phase of the rolling resistance which has a significant impact on the energy efficiency of tyres. This impact is especially pronounced for short distance travel during which the tyre does not completely warm up.

This thesis work investigated the influence of variation in the inflation pressure, speed and load on the rolling resistance and energy consumption of free rolling passenger car tyres. It also investigated the additional contribution due to the warm-up phase and how this varied with pressure, speed and load for different tyres. The RRc shows a negative correlation with change in inflation pressure and load and a positive correlation with change in speed. The magnitude of change in the RRc due to pressure change serves as a conservative approximation of the corresponding change in the tyre's energy consumption. The same cannot be applied to the influence of speed and load variation however. This is primarily due to their influence on the contribution of the warm-up phase towards the energy consumption of the tyre. This additional contribution was found to be between 25 - 30 % for short driven distances of 5 km and reduced to 2.5 % at 100 km as compared to the respective steady-state values. This additional contribution was found to correlate positively with an increase in the speed and load levels. Through these findings it was concluded that the consideration of the warm-up phase for estimating the energy efficiency of tires is warranted, especially in the context of short distance travel.

Keywords: Rolling resistance, warm-up phase, inflation pressure, speed, load, energy loss.

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NOMENCLATURE

ABBREVIATIONS

RRc	Rolling resistance coefficient	N/kN
RRf	Rolling resistance force	N
ANOVA	Analysis of variance	
DoE	Design of experiments	
ISO	International Organization for Standardization	
LI	Load index	

PREFIXES

$\Delta E_{220-250}$	Change in energy consumption between 220 and 250 kPa	Wh/km
$\Delta E_{250-280}$	Change in energy consumption between 250 and 280 kPa	Wh/km
ΔE_{3-6}	Change in energy consumption between 3 and 6 kN	Wh/km
ΔE_{40-80}	Change in energy consumption between 40 and 80 kmph	Wh/km
$\Delta E_{6-9.2}$	Change in energy consumption between 6 and 9.2 kN	Wh/km
ΔE_{80-130}	Change in energy consumption between 80 and 130 kmph	Wh/km
$\Delta F_{z,3-6kN}$	Change in normal load from 3 to 6 kN	N
$\Delta F_{z,6-9.2kN}$	Change in normal load from 6 to 9.2 kN	N
$\Delta P_{220-250kPa}$	Change in pressure from 220 to 250 kPa	kPa
$\Delta P_{250-280kPa}$	Change in pressure from 250 to 280 kPa	kPa
$\Delta RRc_{220-250}$	Change in RRc between 220 and 250 kPa	N/kN
$\Delta RRc_{250-280}$	Change in RRc between 250 and 280 kPa	N/kN
ΔRRc_{3-6kN}	Change in RRc between 3 and 6 kN	N/kN
ΔRRc_{40-80}	Change in RRc between 40 and 80 kmph	N/kN
$\Delta RRc_{6-9.2kN}$	Change in RRc between 6 and 9.2 kN	N/kN
ΔRRc_{80-130}	Change in RRc between 80 and 130 kmph	N/kN

NOMENCLATURE

ΔT	Difference between initial and final temperature	$^{\circ}C$
ΔT_f	Change in final temperature	$^{\circ}C$
$\Delta V_{40-80km/h}$	Change in speed from 40 to 80 kmph	km/h
$\Delta V_{80-130km/h}$	Change in speed from 80 to 130 kmph	km/h
Δx	Eccentricity	mm
λ	Scaling factor	
E	Energy loss	kWh
F_t	Tyre spindle force	N
F_x	Longitudinal force	N
F_z	Normal force	N
F_{pl}	Parasitic loss	N
F_{z0}	ISO normal force	N
L	Load	N
P	Power	W
P_i	Inflation pressure	kPa
P_{i0}	ISO inflation pressure	N
R	Free radius of tyre	m
r_L	Loaded radius of tyre	m
RRc_{ss}	Steady-state rolling resistance coefficient	N/kN
T	Temperature	$^{\circ}C$
T_f	Final temperature at the end of test	$^{\circ}C$
t_{amb}	Ambient temperature	$^{\circ}C$
V_0	ISO velocity	m/s
V_x	Velocity	m/s

Contents

List of Figures

List of Tables

1 Introduction

The 21^{st} century is witnessing a substantial transformation in regards to automotive mobility. With 'electric' and 'sustainable' being focal points in the mission statement of many major automotive companies, improving energy efficiency and adopting electrification are evidently the significant courses of action in realizing this mission. This is pushing OEM's to stretch the bounds of energy efficiency in the vehicles they manufacture. The energy efficiency of vehicles is linked directly to the driving resistance forces and the rolling resistance loss in vehicles is a significant factor contributing to vehicle driving resistance forces [1].

1.1 Background

The rolling resistance is defined as the energy consumed by the tyre per unit distance covered [2]. This rolling resistance accounts for up to 20% of fuel consumption from cars and 30 to 40% from trucks, while comparing it to the other resistive forces that have to be overcome by the vehicle [3]. In the context of electric vehicles, a generally higher drive-train efficiency as compared to conventional vehicles increases the contribution of rolling resistance to the total energy consumption. This coupled with the limited range of present-day electric vehicles makes a strong case to quantify and possibly reduce the losses due to the rolling resistance of tyres. Consequentially, an accurate estimation of this loss is important to understand its true contribution to energy efficiency.

ISO 28580, ISO 18164, SAE J1269, SAE 2452, etc. are the commonly used industry standards for measuring and comparing the rolling resistance of tyres. Out of this, the ISO 28580 standard [4] is currently used throughout the EU to measure the rolling resistance of passenger car, truck and bus tyres using a standardized measurement on a drum tester under specific ambient and test conditions. This standard provides a way of meaningfully comparing the rolling resistance of tyres across different manufacturers and classifications. This method however is not best suited for understanding the entire impact of rolling resistance on the energy efficiency of tyres in real world driving, since the rolling resistance measured using this standard is done at steady state and fixed operating conditions. The author in [5] discusses that the rolling loss of tyres measured in the laboratory under steady-state, free-rolling conditions does not adequately represent the varied circumstances a tyre is likely to encounter on the road. Additionally, using the steady-state rolling resistance value can result in inaccurately calculated energy consumption of the tyre, as the rolling resistance is almost 20% higher at the beginning of the test and then reduces until it reaches its steady-state value after 20-30 minutes [1]. This is due to the 'warm-up' phase of the rolling resistance, which is one of the important aspects discussed in this work. This brings about the need to evaluate the contribution of rolling resistance beyond just its ISO value, which would help better quantify the actual energy efficiency of tyres.

1.2 Purpose

This thesis work intends to understand the spread of the rolling resistance of tyres due to variation in the inflation pressure, speed and load with respect to the ISO specified conditions. This work also aims to analyse the impact of the 'warm-up' phase of the rolling resistance on the energy efficiency of tyres. This will help assess how important it is to account for the warm-up phase of the rolling resistance when evaluating the energy efficiency of tyres and whether the steady state rolling resistance could be used as a conservative approximation for said purpose.

1.3 Deliverables

- A study of the spread of rolling resistance of different class of tyres and the correlation between rolling resistance and the variation in inflation pressure, speed and load.

- Analysis of the warm-up phase of the rolling resistance and its impact on the energy efficiency of tyres.

- Measurement of the tyre temperature and the analysis of its correlation with variation in inflation pressure, speed and load.

1.4 Delimitation

For this thesis work the delimitations that were applicable are as follows:

- The rolling resistance measurements performed for this thesis have been done using a laboratory drum tester with a smooth steel surface and for free rolling tyres in accordance with the ISO 28580 standard.

- The effect of driving manoeuvres (ex. acceleration, braking, cornering, etc.), variation in road surface condition and wheel geometry (ex. toe, camber, etc.) on the rolling resistance is not a focus of this thesis. The measurements and analysis is done at a tyre level as opposed to a micro-level.

- The measurements and analysis is done for only EU All-season (A/S) and Summer (S) category tyres. Winter (W) category tyres have not been considered in the sample set for the analysis.

- The tyre temperature analysis is focused on studying the correlation between the measured temperature and the influence of speed, pressure and load. It does not focus on investigating the variation in the measured temperature at different regions of the tyre.

- Rolling resistance is a core attribute of the tyre along with other attributes such as comfort, NVH, durability, wet grip etc. This study does not discuss about the other attributes or the attribute balancing for tyres.

2 Literature

This section includes the literature reviewed for the purpose of understanding what rolling resistance of tyres is and its impact on energy consumption as well as how it is influenced by various parameters. The different tyre parameters and attributes are discussed in brief in addition to the method used to measure the rolling resistance of tyres.

2.1 What is Rolling Resistance?

The resistance to the motion of a vehicle is generally attributed to the forces opposing the motion of the vehicle, known as the driving resistance forces. These forces can be condensed broadly into aerodynamic drag F_{AD}, rolling resistance F_{RR}, acceleration (inertial) force F_{ACC} and slope (gradient) F_{RG}. The total force as a sum of all these forces can be expressed as [6]:

$$F_{Total} = F_{AD} + F_{RR} + F_{ACC} + F_{RG} \tag{2.1}$$

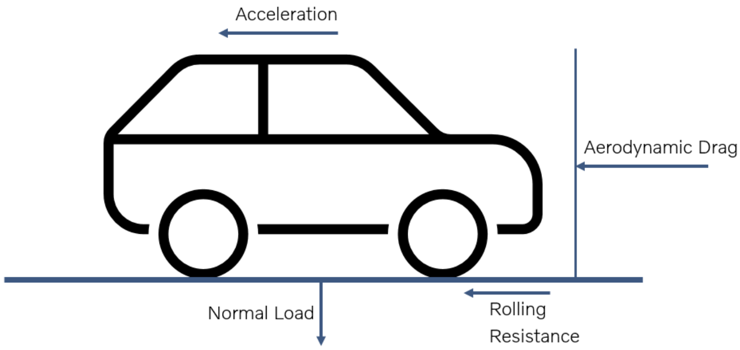


Figure 2.1: Driving resistance forces affecting a vehicle in motion [6]

The rolling resistance forces F_{RR} are mainly attributed to the loss due to tyres and the tyre-road interaction, but also include a contribution from the driveline of the vehicle which includes driveshafts, bearing losses, etc. The interpretation of rolling resistance can be done with the help of the definitions provided by multiple sources:

- The energy consumed by a tyre per unit of distance traveled is known as rolling resistance. The visco-elasticity of the materials used to construct tyres is the primary source of energy dissipation. When visco-elastic materials are deformed, they lose energy in the form of heat. As a result of the energy lost, a force opposes the rotation of the tyre [2].

- Both the tyre and the road are subjected to deformation in the contact patch when the tyre spins. Because the road is significantly stiffer, its deformation can be neglected. However, the tyre is elastic and as the tyre rotates, additional material from the tyre enters the contact patch.The energy spent in deforming the tyre material is not totally recovered when the material returns to its normal shape due to the internal damping of the tyre material. This energy loss is represented by a force acting on the tyres termed rolling resistance, which opposes the vehicle's speed. [7]

The definitions above suggest that rolling resistance can be understood as the energy loss of the tyre due to the visco-elasticity of the tyre compound. The energy loss is manifested through the rolling resistance force F_{RR}, which is influenced by the normal load acting on the tyre and the coefficient of rolling resistance, which can be expressed as:

$$F_{RR} = C_{RR} \cdot F_Z \tag{2.2}$$

where, F_Z is the normal load on the tyre
C_{RR} is the rolling resistance coefficient
F_{RR} is the rolling resistance force.

The coefficient of rolling resistance C_{RR} is a dimensionless quantity, although it is expressed in units of $\frac{kg}{tonne}$ or $\frac{N}{kN}$. It represents the effects of the complicated and interdependent physical properties of tyre and ground [8]. While other resistances to the vehicle act only under certain conditions of motion, rolling resistance is present from the instance the wheels begin to turn. Thomas D. Gillespie in his book 'Fundamentals of Vehicle Dynamics' defines at least seven mechanisms responsible for rolling resistance [8]:

1. Energy loss due to deflection of the tyre sidewall near the contact area.
2. Energy loss due to deflection of the tread elements.
3. Scrubbing in the contact patch.
4. Tyre slip in the longitudinal and lateral directions.
5. Deflection of the road surface.
6. Air drag on the inside and outside of the tyre.
7. Energy loss on bumps.

This can be considered as one of the ways to define the factors influencing rolling resistance of tyres.

Another way of explaining the effect of rolling resistance of tyres involves the loss of energy due to tyre deformation resulting in a non-symmetric distribution of the tyre normal force over the contact patch. The tyre is considered as a series of independent springs and as the tyre rotates, the difference in the force of compression and expansion of the springs represents the viscous dissipation of energy in the tyre. This dissipation causes the net resultant normal force to act at the front of the contact patch (of a rotating tyre), which subsequently results in a moment opposing the rotation of the tyre [7].

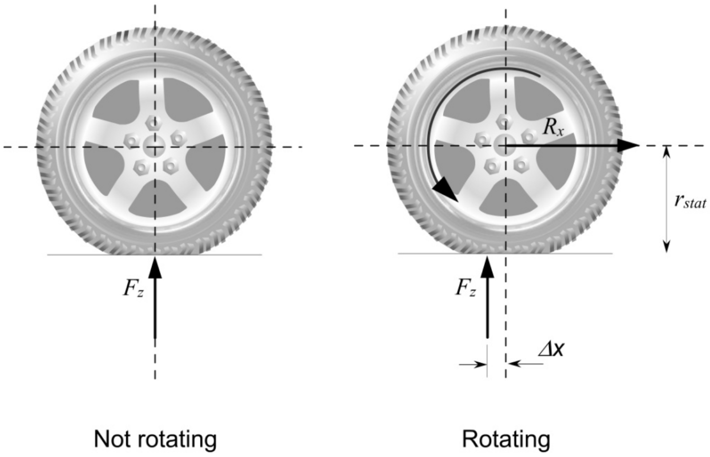


Figure 2.2: Resultant tyre normal force due to rotation [7].

In figure 2.2, the left image represents the resultant tyre normal force acting along the center of the contact patch as a result of symmetric force distribution when the tyre is not rotating. The image on the right shows an (anti-clockwise) rotating tyre which generates a resultant tyre normal force F_Z not along the center of the contact patch, which subsequently leads to a moment acting about the center of the tyre (in a clockwise direction) opposing the rotation of the tyre. This opposing moment (whose magnitude is given by the product of F_Z and the eccentricity Δx) can be characterized as the 'rolling resistance' of a tyre.

2.2 Tyre parameters and influence on rolling resistance

This section aims to briefly explain what tyre design parameters, specifications, attributes and operating parameters are and their effect on rolling resistance.

2.2.1 Tyre design parameters

Considering the tyre representation shown in figure 2.3 with the specifications: 245/50 R19 XL 100H.

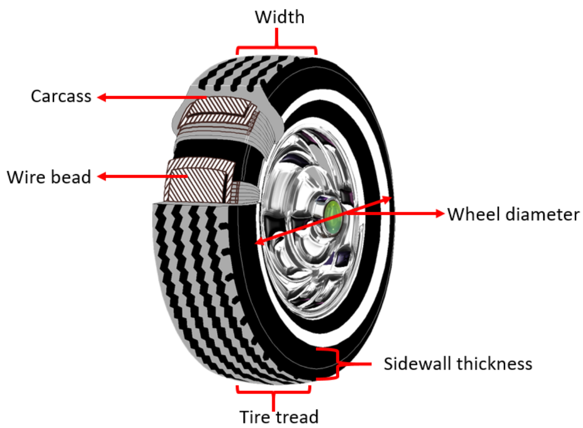


Figure 2.3: Tyre design parameters [9]

i **Construction**: This refers to the physical construction of the tyre. Most commonly tyres are made from rubber plies with inner edges wrapped with a wire bead as seen in figure 2.3. The tyre's sidewalls are built of a separate rubber compound. They are then hardened together in a mould to construct a single tyre unit.

ii **Compound**: The compound represents the type of rubber used in the construction of tyres. Softer tyre compounds wear faster and generally have higher rolling resistance but provide good grip. Harder tyre compounds wear slower and have lower rolling resistance but provide less grip comparatively. Modern tyre developments have progressed to have tyres with soft compounds as well as low rolling resistance. According to a German study, replacing the carbon black in tyres by silica shows a reduction in the CO_2 emissions and increases fuel efficiency [13].

iii **Tyre tread and pattern**: Tread is the thick layer of rubber compound wrapped around the outside of the tyre carcass to protect it from damage caused due to ground irregularities and wear as seen in figure 2.3. It serves the purpose of reducing the aqua-planing of summer tyres or assists in the penetration of gravel/snow for off-road/winter tyres with the help of blocks and sipes. The grooves in the tread assist in channeling water away from the trailing side of the contact patch between the road and the tyre. It also provides grip during acceleration, braking and steering. The general types of tread patterns and their benefits are listed in table 3.1.

Table 2.1: Types of tyre tread patterns and their benefits

Tread Pattern	Benefits
Symmetrical	Low rolling resistance and provides good directional stability
Directional	Good handling in mud and snow conditions. Provides good grip at high speeds.
Asymmetric	Provides good handling and high stability while cornering. Provides good grip in wet conditions.

2.2.2 Tyre specifications

Tyre specifications majorly comprise tyre width, aspect ratio, diameter, load index, speed index, tyre family etc.

i **Tyre width**: It is the lateral distance between one end of the sidewall to the other end. It is most commonly presented in 'mm'. In figure 2.3, '245' represents the width of the tyre in mm.

ii **Aspect ratio**: The ratio of the height of the tyre's cross-section to its width. The sidewall thickness increases with an increase in aspect ratio. In figure 2.3, '50' denotes the aspect ratio of the tyre.

$$Aspect\ Ratio\ (AR)\ =\ \frac{Height}{Tyre\ width} * 100 \tag{2.3}$$

iii **Wheel diameter**: The radial size of the wheel rim. It is represented in inches.

iv **Load index**: It is the maximum load that the tyre can withstand when inflated. Load index varies between 70 to 126 for passenger car tyres. In the example 2.3, '100' represents the load index which corresponds to 800 kg of maximum load capacity.

v **Speed index**: This rating indicates the tyre's ability to withstand the maximum load while traveling at the specified maximum speed. In the example 2.3, 'H' represents a max speed of level of 210 kmph.

vi **RRc class**: It is the fuel efficiency class that is labeled based on the *RRc* value of the tyre. It varies between A to E with A-class being the most fuel efficient and E being the least. The EU defined range of the *RRc* for each class is shown table 2.2:

Table 2.2: EU RRc class [10]

Fuel efficiency class	RRc [N/kN]
A	≤ 6.5
B	$6.6 \leq$ RRc ≤ 7.7
C	$7.8 \leq$ RRc ≤ 9.0
D	$9.1 \leq$ RRc ≤ 10.5
E	RRc ≥ 10.6

vii **Tyre family**: This represents the type of tyres that have different properties based on conditions they are intended to be used in. Some broad classification categories include weather, road condition, performance, etc.

Table 2.3: Different types of tyre family

Type	**Benefit**	**Limitation**
All-season	Provide good comfort and handling and can be used in both dry and wet conditions.	Not best suited for maximum performance of the vehicle.
Summer performance	Provide very good grip to utilize full performance of the vehicle	They wear faster due to their softer compound and water channeling is not as good due to tightly spaced treads.
Off-road	Provide more traction in rough conditions and also resist punctures and tears due to deeper tread blocks.	They have high road noise and are not great in wet conditions.
Touring	Provided very good comfort, handling and are reliable.	Performance is not as great at high speed cornering and braking.

'Snow' tyres are a major tyre family in the weather category however have not been included in table 2.3. This family has multiple sub-classes such as studded, unstudded, nordic, etc. each having very different properties which makes it difficult to present a general benefit and limitation for the entire family of snow tyres.

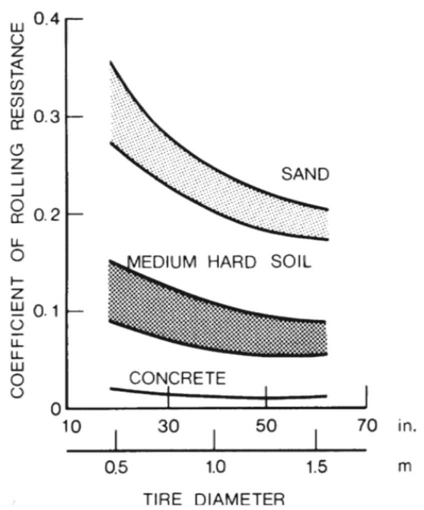


Figure 2.4: Change in RRc due to change in tyre diameter for different road surfaces [11].

Rolling resistance depends on the tyre's specifications such as the outer diameter, aspect ratio, tread depth, etc. In [2] Michelin discuss the impact of tyre outer diameter on rolling resistance. Increasing the tyre outer (rolling) diameter by 1 cm results in a reduction of the rolling resistance by about 1% [2]. This is due to the less severe bending of the tyre when entering and leaving the contact patch. The tyre outer (rolling) diameter can be increased by increasing the wheel size or the tyre sidewall height. Increasing the tyre size also affects the other attributes such as NVH and handling. To keep the loading capacity (determined by the load index) the same while increasing the outer diameter of the tyre, the rim size needs to be increased and sidewall height should be decreased. This however may result in reduced comfort and resistance to road irregularities. Vertical deformation for the same contact patch length decreases with an increase in tyre size, which means less transition of the radius on edges of the contact patch resulting in less bending of the tyre tread region and lower hysteresis loss for larger diameter tyres [12]. Figure 2.4 shows the change in rolling resistance coefficient due to change in the tyre diameter for different road conditions. This is seen from the experimental data presented by Wong in [11]. It is observed that the hard concrete surface shows the least rolling resistance coefficient, followed by medium and hard soil. The highest coefficient is observed for sand. However, the decreasing trend of RRc with increasing tyre diameter is seen across all surface types [11].

2.2.3 Tyre attributes

i **Tyre wear**: It is a reduction of the tread depth across the tyre width or it is the loss of rubber material due to rolling and sliding contact of tyres with the road resulting in peeling off of the rubber.

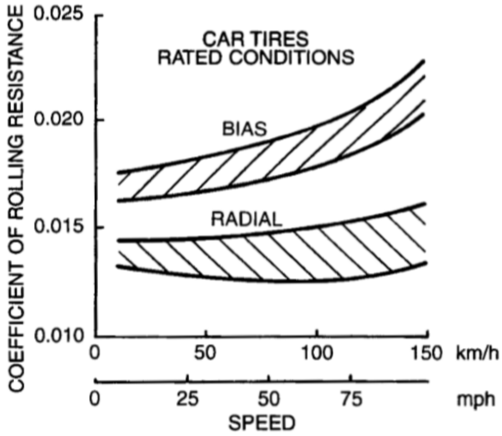
ii **Ageing**: Over time the material properties of a tyre deteriorate, resulting in a reduction in its performance and capabilities.

The authors in [13] discuss the tests performed at VTI for testing the road noise and rolling resistance change by wearing down the tyre tread in steps of 2mm with an initial tread depth of 8mm. The rolling resistance comparison between the 8mm tread depth and 2mm tread depth showed a reduction by about 20%. VTI also performed tests considering five different tyre sets which were aged artificially from their new condition and were tested against two surfaces; smooth-textured safety walk and rough-textured dressing conditions. The smooth-textured surface tests showed higher RRc values as compared to the rough-textured surface. The report also discusses that rolling resistance is reduced by up to 30% between a new unworn tyre and an older worn tyre.

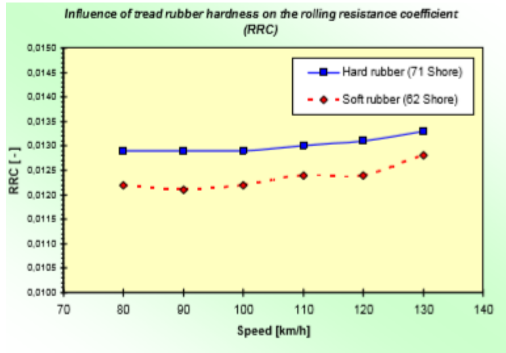
2.2.4 Tyre operating parameters

The impact of the operating parameters such as speed, normal load, inflation pressure, temperature and road surface on the rolling resistance is discussed in this section.

i **Speed**: If the tyres are run at a constant load and pressure, an increase in speed increases the aerodynamic drag and there is a development of strong vibrations at high speeds due to which the tyre deforms, leading to higher energy dissipation. Tests conducted by VTI show that the RRc change is very less $\sim 2\%$ with a change in speed ranging between 80-120 kmph [13]. The results discussed include two different drum surfaces with both showing a similar change in RRc due to change in speed.



(a) RRc change with change in speed for bias and radial ply tyres [11].

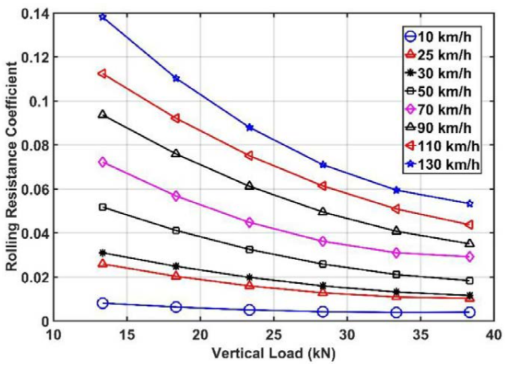


(b) RRc change with change in speed for hard and soft rubber tyres [13].

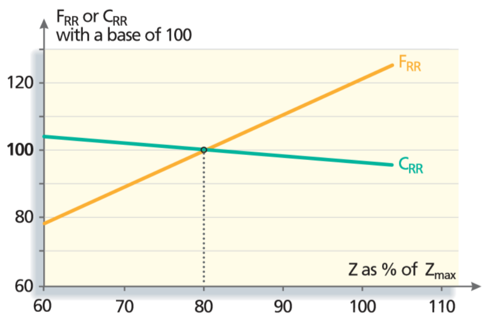
Figure 2.5: Influence of speed on RRc

Figure 2.5a shows the variation of RRc with speed for different type of tyre constructions. In the case of radial ply tyres, the increase in RRc is very less until 80-100 kmph, beyond which the increase is slightly higher. For bias ply tyres, RRc increases significantly with an increase in speed. Figure 2.5b shows the variation of RRc with speed for different compound tyres [13]. A trend similar to that of the radial tires in figure 2.5a is seen in this case for both hard and soft rubber tyres. In general, the rolling resistance coefficient shows an increasing trend with an increase in the speed but the magnitude of increment is affected by multiple factors.

ii **Normal load**: For a given pressure and speed, the rolling resistance coefficient decreases with an increase in the vertical load acting on the tyre. The RRc is expressed as $\frac{F_x}{F_Z}$. With an increase in load (F_Z), the interface force between the tire and drum (F_x) also increases, however not in the same proportion as the increase in F_Z. This results in an overall reduction of the RRc.



(a) RRc variation with load [14]



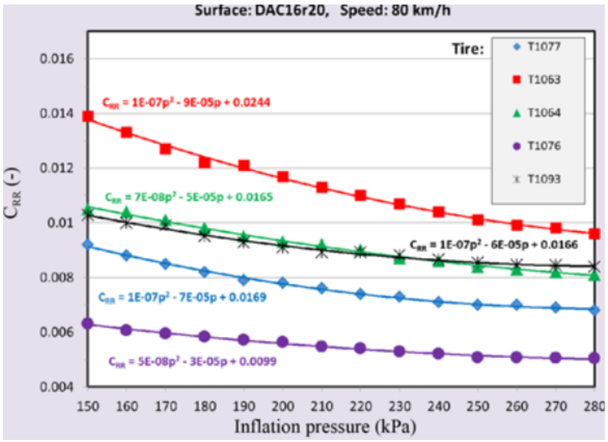
(b) RRc and RRf variation with load [2]

Figure 2.6: Influence of load on RRc

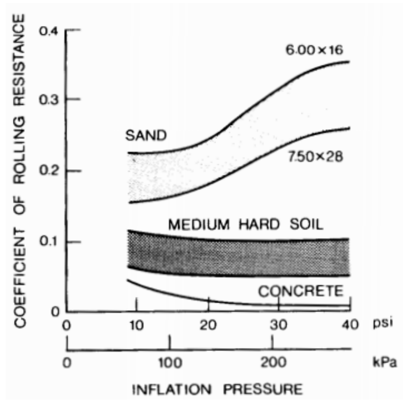
Figure 2.6a shows a decrease in RRc with an increase in the vertical load for different speeds. Michelin correlates this to the slight decrease in visco-elasticity due an increase in load, as the higher bending and shearing at high loads results in increased temperatures

[2]. The figure 2.6b by Michelin shows the variation of rolling resistance force (F_{RR}) and rolling resistance coefficient (C_{RR}) with vertical load [2].

iii **Inflation pressure**: At a given load and speed, the rolling resistance coefficient decreases with an increase in the tyre inflation pressure. The increase in pressure reduces the local deformation of the tyre (contact patch) hence reducing the hysteresis loss due to deformation.



(a) RRc variation with pressure for different tyres [15]



(b) RRc variation with pressure for different surfaces [11]

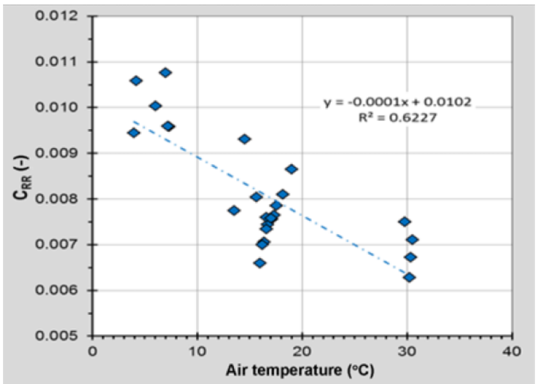
Figure 2.7: Influence of pressure on RRc

Figure 2.7a shows the influence of inflation pressure on rolling resistance coefficient at a load of 408 kg and a speed of 80 kmph for five different tyres [2]. The tyres have been tested on a replica of dense asphalt concrete. The results show that for all the different tyres, a decreasing trend of the RRc is seen with increasing inflation pressure but the magnitude of change is different for different tyres [15]. Figure 2.7b shows the influence of road surface and inflation pressure on the RRc. A decrease in the RRc is seen with an increase in inflation pressure when tested on the hard concrete surface. As the contact patch length decreases there is lesser deformation of rubber resulting in lower hysteresis losses. The decrease in RRc is more subtle in the case of medium-hard soil. However, on surfaces such as sand, the RRc is seen to increase with an increase in the inflation pressure [11]. This is probably because in the case of sand the local stiffness of the surface is less than that of the tyre especially at higher pressures, leading to a loss of traction between the tyre and the surface. The exact mechanism causing this would need to be explained using micro-surface effects.

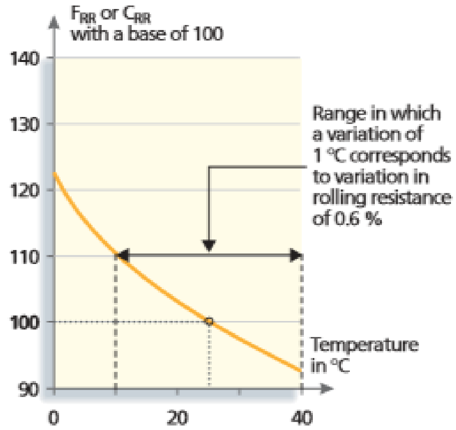
iv **Temperature**: Temperature is an important factor that affects the rolling resistance of tyres. The tyre's thermal condition are affected primarily by three different temperatures and in two phases:
(a) Ambient temperature (b) Pavement/road temperature (c) Tyre temperature.
The two phases of the tyre temperature are warm-up (evolution of temperature over time when operating from a cold start condition) and steady-state (the stabilized value of the tyre temperature over time after the warm-up has occurred). The latter is often observed during laboratory measurements using a drum tester but is not truly achieved

in real-world driving due to multiple transients such as driving manoeuvres, road surface variations, etc. affecting the thermal saturation of the tyre [16].

(a) Ambient temperature: It is the temperature of the environment surrounding the tyre. The influence of air temperature on the RRc is seen in figure 2.8:



(a) RRc variation with air temperature [16]

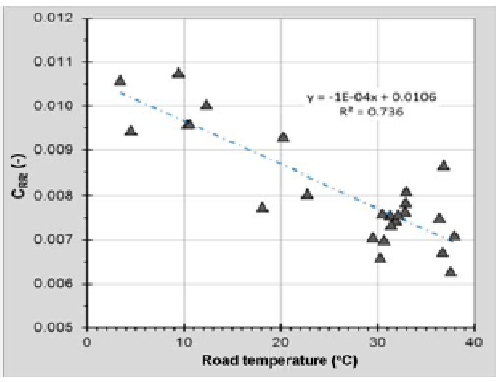


(b) RRc variation with air temperature [2]

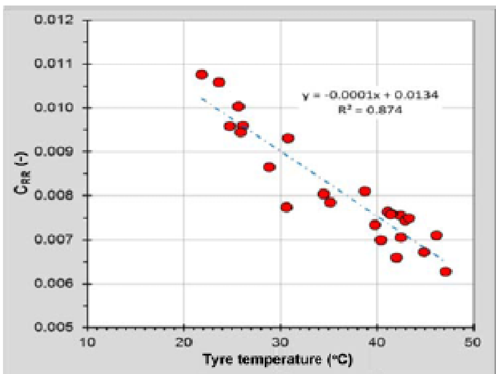
Figure 2.8: Influence of ambient temperature on RRc

In figure 2.8b Michelin discusses the effect of ambient temperature on rolling resistance [2]. Rolling resistance is low for higher ambient temperatures since the amount of energy dissipated by elastomers when subjected to repeated deformation decreases with an increase in the temperature. Higher the ambient temperature, the closer is the tyre's internal temperature to its upper limit.

(b) Pavement/road temperature: Temperature of the road surface or the pavement is influenced by the air temperature, solar radiation and wind. Influence of road temperature on RRc is shown in figure 2.9a. An increase in the road temperature will consequentially increase the tyre temperature hence reducing the RRc.



(a) Influence of road temperature on RRc [16]



(b) Influence of tyre temperature on RRc [16]

Figure 2.9: Influence of road and tyre temperature on RRc

(c) Tyre temperature: This refers to the actual temperature of the tyre. It differs at different parts (tyre tread, tyre sidewall, tyre shoulder, inflation air temperature etc.) of the tyre which makes it difficult to measure and generalise. It depends on many factors such as the interface force between the tyre-road interaction, the cooling effect by the surrounding air, road temperature etc. The influence of tyre temperature on RRc is as shown in figure 2.9b.

2.2.5 Warm-up of the tyre

Although this does not fall directly under the category of any tyre specification, attribute, design or operating parameter, the effect of the warm-up or warm-up phase on the rolling resistance of tyres is of paramount importance.

Thomas D. Gillespie in his book '*Fundamentals of Vehicle Dynamics*' [8] discusses that for short trips representative of much automotive travel, the tyres never warm up to benefit from the lowest possible levels of rolling resistance. As the tyre begins rolling from a cold condition, the temperature rise of the tyre results in a reduction of the rolling resistance. This effect is inherently linked to the hysteresis properties of the tyre rubber. In addition, the rise in tyre temperature also increases the inflation air temperature which reduces the rolling resistance. In the paper '*Transient Versus Steady-State Tire Rolling Loss Testing*' the author D.J. Schuring discusses that the average energy loss per unit distance (or average rolling loss) would be higher at the beginning since the tyre is cold and dissipates more energy [5]. The measurements performed by Ejsmont et al. [16] discuss the time evolution of the the temperature at different regions of the tyre, the pavement temperature and the rolling resistance coefficient (C_{RR}) of the tyre. The plots are seen in figure 2.10 in which the solid red curve representing the C_{RR} shows the time evolution of the tyre's rolling resistance coefficient. The reduction of the C_{RR} between t=0 and t=1500 seconds is due to the effect of the warm-up phase of the tyre.

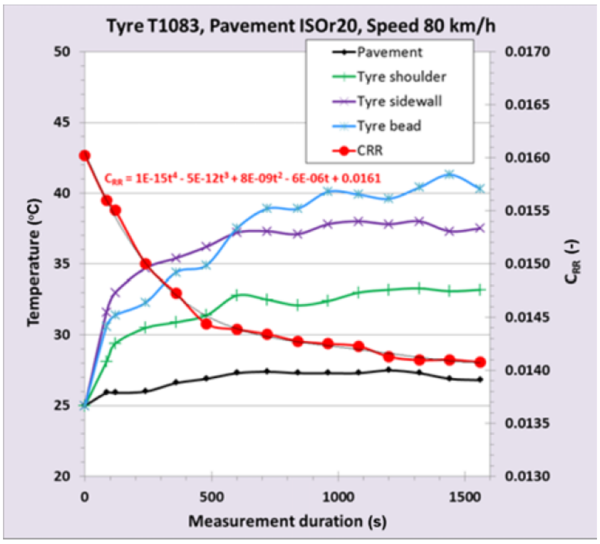


Figure 2.10: Variation of temperature at different parts of tyre [16]

2.3 Measuring Rolling Resistance

The ISO 28580 is a standard followed throughout the EU to measure the rolling resistance of tyres used in passenger cars, trucks and buses. There are other standards such as the ISO 18164, SAE J1269, SAE 2452, etc. that also measure the rolling resistance however with slight differences in procedural specifications and are followed in different regions of the world. The ISO 28580 standard is discussed in detail here as the rolling resistance data analysed in this thesis was measured based on the ISO 28580 standard.

2.3.1 ISO 28580

The International Standard ISO 28580 specifies the method for measuring the rolling resistance under controlled laboratory conditions for pneumatic tyres designed primarily for passenger cars, trucks and buses [4]. This does not apply to tyres intended for temporary use (ex. spare tyre). The ambient temperature for the test environment is specified as 25 °C, the tyre load as 80 % of the maximal load rated for the tyre (based on the Load Index rating of the tyre) and the test speed as 80 kmph. The pressure is specified as 2.1 bar and 2.5 bar for a standard-load (SL rated) and extra-load (XL rated) tyre respectively. The test tyre whose rolling resistance is to be measured is required warmed up for at least thirty minutes before the recording the actual measurement. The tyre is required to have the same temperature as the ambient temperature of the test environment (25^oC) and hence is required to be soaked in the test environment before being tested. If ambient temperature cannot be controlled and measurements at ambient temperatures other than 25^oC are to be done, only temperatures $\geq 20^oC$ and $\leq 30^oC$ are acceptable. The correction in the measured rolling resistance due to the temperature variation is made using the following equation [4]:

$$F_{r25} \;=\; F_r \cdot [1 + K_t(t_{amb} - 25)] \tag{2.4}$$

F_r is the rolling resistance force measured at the actual ambient temperature (in N).
F_{r25} is the equivalent rolling resistance force temperature corrected for 25^oC (in N).
t_{amb} is the ambient temperature (in ^oC).
K_t is the correction factor constant (= 0.008 for passenger car tyres).

The rolling resistance coefficient is then determined by ratio of the measured F_r and the normal load applied to the tyre. This coefficient serves as a way to compare the efficiency of different tyres based on the actual rolling resistance coefficient value as well as the rolling resistance class they lie in based on the class definitions shown in table 2.2.

2.3.2 MF and Rolling Resistance

The 'MAGIC FORMULA' tyre model is a semi-empirical tyre model used to calculate the steady-state tyre force and moment characteristics [17]. It is developed based on the 'Magic Formula' and has been widely adopted throughout the automotive industry over the past few decades for tyre modelling and vehicle handling simulations. In Michelin [2], the equation 2.5 is presented to adapt the rolling resistance for conditions deviating from the ISO rolling resistance test.

$$f_{rr} \;=\; f_{rr,ISO} \cdot \left(\frac{p_i}{p_{i.ISO}}\right)^{\alpha} \cdot \left(\frac{F_z}{F_{z.ISO}}\right)^{\beta} \tag{2.5}$$

where, f_{rr} is the rolling resistance coefficient, p_i is the tyre inflation pressure and F_z is the tyre vertical force. According to Michelin [2], $\alpha = -0.4$ and $\beta = 0.85$ are applicable for passenger car tyres. This equation has been slightly modified by the Magic Formula tyre model to include the effects of forward velocity dependence. The equation for the rolling resistance moment (not including the camber effects) given by Magic Formula is [18]:

$$M_y \;=\; -R_0 \cdot F_{z0} \cdot \lambda_{My} \left(q_{sy1} + q_{sy2}\frac{F_x}{F_{z0}} + q_{sy3}\left|\frac{V_x}{V_0}\right| + q_{sy4}\left(\frac{V_x}{V_0}\right)^4\right)\left(\frac{F_z}{F_{z0}}\right)^{q_{sy7}}\left(\frac{p_i}{p_{i0}}\right)^{q_{sy8}} \tag{2.6}$$

Using equation 2.6, the modelling of the steady-state rolling resistance force (F_x) with inflation pressure, load and velocity as presented by the Magic Formula can be seen in figure 2.11:

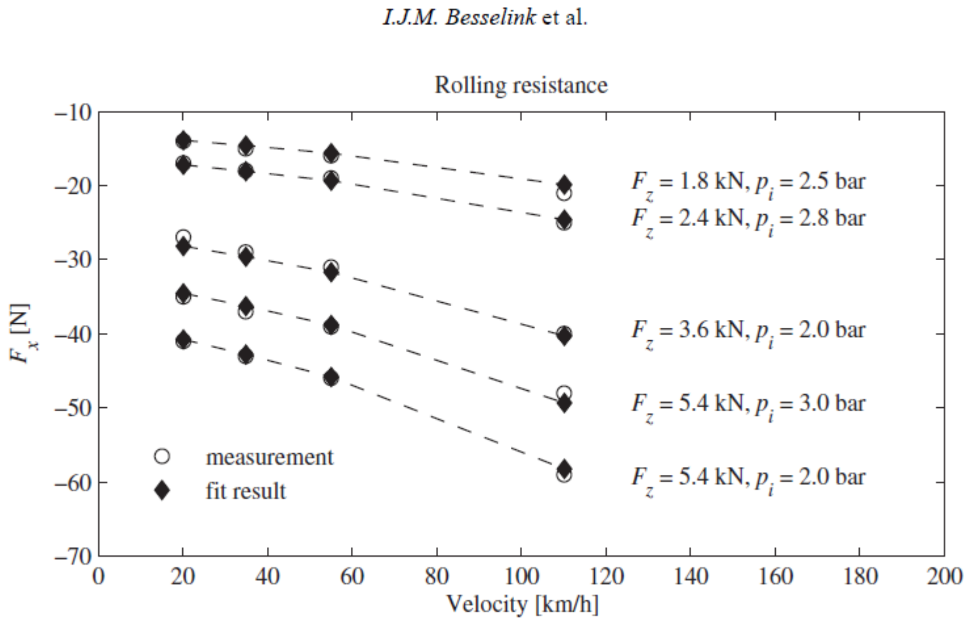


Figure 2.11: Rolling resistance force as a function of vertical force, inflation pressure and forward velocity [18].

The figure 2.11 represents the measurement and fit data of rolling resistance force (rolling resistance coefficient * load) for varying speeds (velocity), vertical loads (F_z), and inflation pressures (p_i). The circular markers in the background represent the measurement data and the solid diamond markers in the foreground connected by the dotted lines represent the fit data generated using equation 2.6.

3 Methodology

This section discusses the method of measuring the rolling resistance that has been used in this thesis with a brief description about the measurement equipment and procedure used to perform the rolling resistance measurements. In addition, the design of experiments that were used to study the influence of pressure, speed and load on the rolling resistance of tyres is discussed as well. The temperature measurements are discussed in the final part of this section.

3.1 Rolling Resistance Measurements

The rolling resistance measurements were performed in the PV-16 lab using the 'RIG-0455' machine located in the PV building at Volvo Cars, Gothenburg. The lab technicians in charge of performing the measurements were Jan-Evert Bäckström and Roger Andren.

3.1.1 Machine and Measurements

The 'RIG-0455' machine is a drum tester intended for measuring the rolling resistance of tyres based on the ISO-28580:2009 standard which specifies the method of measuring the rolling resistance of pneumatic tyres in a controlled laboratory environment [4]. The machine is shown in figure 3.1.

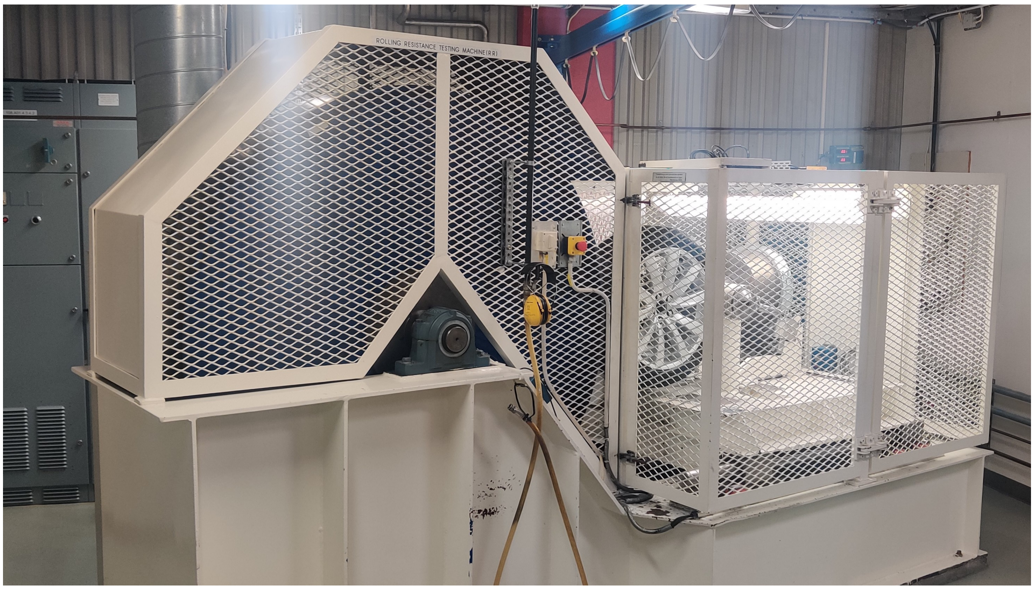


Figure 3.1: 'Rig-0455' rolling resistance measurement machine at Volvo Cars

According to the ISO standard, some of the principal test equipment and measurement requirements specified for measuring rolling resistance are as follows [4]:

- The diameter of the drum should be at least 1.7m with a smooth steel surface and the width of the drum should exceed the width of the tyre being tested.
- The measurement of load, alignment, control and instruments should be accurate.

- The ambient temperature should be maintained at 25°C. Measurements at temperatures other than this but between 20 and 30°C are allowed with a correction factor.

The measurement specifications of the RIG-0455 machine is listed in table 3.1.

Table 3.1: Specifications of the RR measurement machine at PV16 in Volvo

Data	**Value**
Drum diameter	1700 mm
Drum width	300 mm
Peripheral speed	0 - 150 kmph
Radial load	2 - 9 kN
Peripheral force at wheel axle	15 - 300 N
Peripheral drum momentum	300 p/rev
Tyre revolution	1 p/rev
Tyre pressure	0 - 500 kPa
Surrounding air temperature	20 - 25 °C
Tyre temperature	20 - 100 °C
Wheel radius	200 - 350 mm
Bearing friction	0 - 10 N
Toe-in-angle	0 ±2°C

The size of the drive unit to run the drum is designed such that the full target test speed (peripheral speed) is achieved within one minute. The tyre that is tested is rotated against the drum using an actuator that moves the sliding cradle. The counterweight of the wheel is set before the start of the test to achieve equilibrium.

The parameters of interest that are measured and/or controlled by the machine are **surface speed**, **radial force**, **peripheral force** and the **ambient temperature**. In addition to this the technician operating the machine also sets the target inflation pressure of the tyre before the test. The data is recorded by the machine for approximately thirty minutes, which is the duration listed in the ISO 28580:2009 standard for the warm up of passenger car tyres. The data is recorded at a frequency of 10Hz. The measurement accuracy of the machine for the various measured parameters is presented in table 3.2.

Table 3.2: Measurement accuracy of RIG-0455 [19]

Parameter	**Accuracy**
Radial Force	$\pm 10N$
Pressure	$\pm 1kPa$
Spindle force	$\pm 0.5N$
Friction torque	$\pm 0.5Nm$
Radius of tyre	$\pm 1mm$
Ambient temperature	$\pm 0.2°C$
Surface speed	$\pm 0.1kmph$

There ISO standard provides four different ways of measuring the rolling resistance force of tyres [4]:

1. **Force method**: In this method the rolling resistance force F_r is calculated using equation 3.1.

$$F_r = F_t \left(1 + \frac{r_L}{R}\right) - F_{pl} \tag{3.1}$$

where, F_t is the tyre spindle force [N]
F_{pl} are the parasitic losses [N] explained ahead
r_L is the distance from tyre axis to drum surface [m]
R is the test drum radius [m].

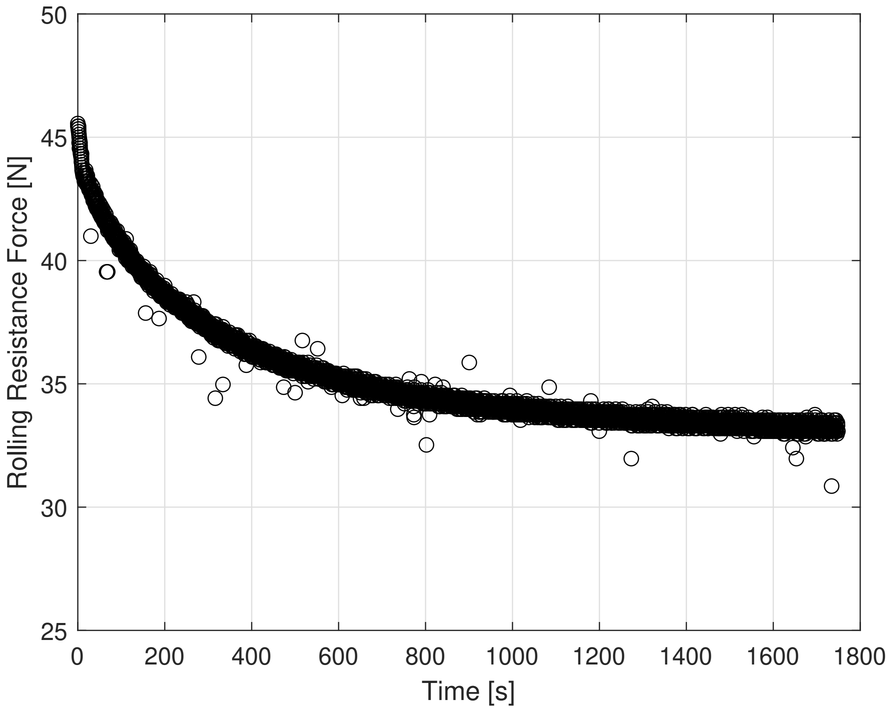


Figure 3.2: Raw data of the rolling resistance force measured by RIG-0455.

The RIG-0455 uses the force method to calculate the rolling resistance force at the tyre-drum interface, which represents the rolling loss of the tyre. This measured data has been used to calculate the rolling resistance coefficient or energy consumption for the analysis done in this thesis. A sample of the raw data measured by the machine over the duration of thirty minutes is seen in figure 3.2.

2. **Torque method**: The torque input at the test drum is measured in the torque method which is used to measure the rolling resistance force.

3. **Power method**: The rolling resistance force is calculated using the measured power input to the test drum.

4. **Deceleration method**: The rolling resistance is measured using the deceleration of the test drum and tyre assembly.

The procedures outlined in the ISO 28580 standard to be followed for measuring the rolling resistance are as follows [4]:

1. Thermal conditioning: The inflated tyre is placed in the thermal environment of the test environment for three hours to maintain thermal equilibrium.

2. Pressure adjustment: After thermal conditioning, the inflation pressure is adjusted to the test pressure and verified ten minutes after the adjustment is made.

3. Warm-up: The tyre is tested at the specified test conditions for the specified duration.

4. Measurement and recording: The important measurements recorded by the machine include the rolling resistance force, peripheral speed, normal load, rolling resistance coefficient (actual and temperature corrected), ambient temperature in addition to the other measurements.

The ISO 28580 standard mainly specifies the inflation pressure, speed, radial load and ambient temperature of the tyre as the test conditions to be controlled when measuring the rolling resistance of a free rolling tyre (apart from the measurement and machine specifications). Consequentially, machines such as the RIG-0455 designed based on the ISO 28580 standard are capable of controlling the target test speed and load levels of the tyre and are not deigned to vary the wheel geometry or torque input of the tyre. The measurement laboratory of RIG-0455 also does not have the capability to vary the ambient temperature. Hence the speed and load level controllability by the machine in addition to the technician's ability to control the initial inflation pressure is used as the basis for selecting the '**operating parameters**' and studying their influence on the rolling resistance of tyres.

3.1.2 Design of Experiments

To study the influence of any factor(s)/parameter(s) on a certain system variable or output, a 'Design of Experiments' (DoE) is a commonly used scientific method to assess the problem. This requires specifying the levels of variation of each parameter that are required to study that parameter's influence on the output. Additionally, the number of parameters whose influence is to be studied can be more than one, each with multiple levels of variation which affect the output. In the context of this thesis, the output is the rolling resistance of tyres and the parameters include the inflation pressure, speed and load on the tyre. Within Volvo Cars, work in this domain has been previously done and hence an internally created design of experiments (DoE) already exists. This was originally created by Hunor Szasz and later modified by Xin Li. The DoE used for this thesis was formulated based on this existing DoE within Volvo Cars, with slight modification in the specified load levels. The DoE studies pressure and load influence across three levels and the speed influence across four levels. A representative image of the DoE used is seen in figure 3.3.

Pressure levels	Speed levels	Load levels		
		3 kN	6 kN	9.2 kN
220 kPa	20 kmph			
	40 kmph			
	80 kmph			
	130 kmph			
250 kPa	20 kmph			
	40 kmph			
	80 kmph			
	130 kmph			
280 kPa	20 kmph			
	40 kmph			
	80 kmph			
	130 kmph			

Figure 3.3: DoE used for rolling resistance measurements

According to this DoE, the pressure varies across three levels; 220, 250 and 280 kPa, the load varies across three levels; 3, 6 and 9.2 kN and the speed varies across four levels; 20, 40, 80 and 130 kmph. The levels of each parameters are chosen with the following in consideration:

- To study the effect of variation of each parameter (pressure, speed and load) bidirectionally about the ISO standard specified value (discussed in section 2.3.1).
- To study the effect of a low to high level variation of each operating parameter on the rolling resistance.

The DoE in figure 3.3 is a full-factorial DoE which translates into a set of 36 test combinations ($3\ pressures * 3\ loads * 4\ speeds = 36\ tests$) for which the system output (rolling resistance, energy consumption etc.) is evaluated. These tests are performed for every tyre whose rolling resistance is measured. The tyres tested in this thesis include a combination of A, B and C (ISO) class tyres which are presented in table 3.3.

Table 3.3: Tyres used for rolling resistance measurements

Tyre	Radius (inch)	Size (Width/AR)	Load Index	EU RRc	EU RRc class
Tyre 1	20	245/40	99 XL	6.5	A
Tyre 2	20	255/45	105 XL	6.3	A
Tyre 3	19	235/50	103 XL	6.3	A
Tyre 4	19	235/55	105 XL	6.3	A
Tyre 5	19	235/55	105 XL	6.36	A
Tyre 6	19	235/45	99 XL	6.34	A
Tyre 7	19	235/50	103 XL	<6.4	A
Tyre 8	20	245/45	103 XL	7.3	B
Tyre 9	19	235/50	103 XL	7.7	B
Tyre 10	19	234/45	99 XL	8	C

Three identical samples of each tyre listed in table 3.3 were used to perform the measurements according to the DoE. This was done to ensure that each tested used was soaked at the ambient temperature and hence consecutive tests could be performed without having to wait for a tested tyre to cool down before testing for the next combination in the DoE. Also before recording the set of 36 measurements for each tyre according to the DoE, the RRc measurements at the ISO specified conditions were done for all the three (identical) samples of a tyre (ex. Tyre 1 in table 3.3). The recorded RRc of the three samples was averaged and used to establish the baseline RRc of that tyre when measured using the RIG-0455 machine. Subsequently a correction factor was used to compensate all further rolling resistance measurements done for that tyre. The correction factor is a ratio of the ISO RRc measured using RIG-0455 and the manufacturer provided ISO RRc value for that tyre. This was done to ensure the validity of the measurements performed using a non ISO-certified machine (RIG-0455). In addition to the tyres listed in table 3.3, the test data of some additional tyres that had been previously tested in Volvo Cars was also used for certain analysis done in this thesis.

3.2 Rolling Resistance Model

Volvo Cars has an in-house developed empirical data fitting tool which was used for processing and analyzing the raw measurement data received from the rolling resistance measurements [20][21]. This tool has been used in this thesis to study and evaluate the test data and investigate the influence of the operating parameters.

3.2.1 Warm-up fitting

The raw data of the rolling resistance measurements obtained from the machine was seen in figure 3.2. The warm-up sub-routine of the fitting tool generates a curve-fit for the raw data using a least-squares estimate. The data is fitted to a function which is derived using a general first order response which is represented by equation 3.2.

$$y = a + b \cdot e^{-cx} \tag{3.2}$$

where in this context, y is the rolling resistance
a,b,c are the fit parameters according to the test data.
and x is the measurement duration.

The curve fit is generated using the 'lsqcurvefit' function in Matlab, which is a regression fit function that uses least squares to reduce the data offset and find the best fit for a given dataset. The figure 3.4 shows the raw data measurements as well as the curve-fit generated by the fitting tool. The black dots represent the raw data and the red curve represents the curve fit of the corresponding raw data.

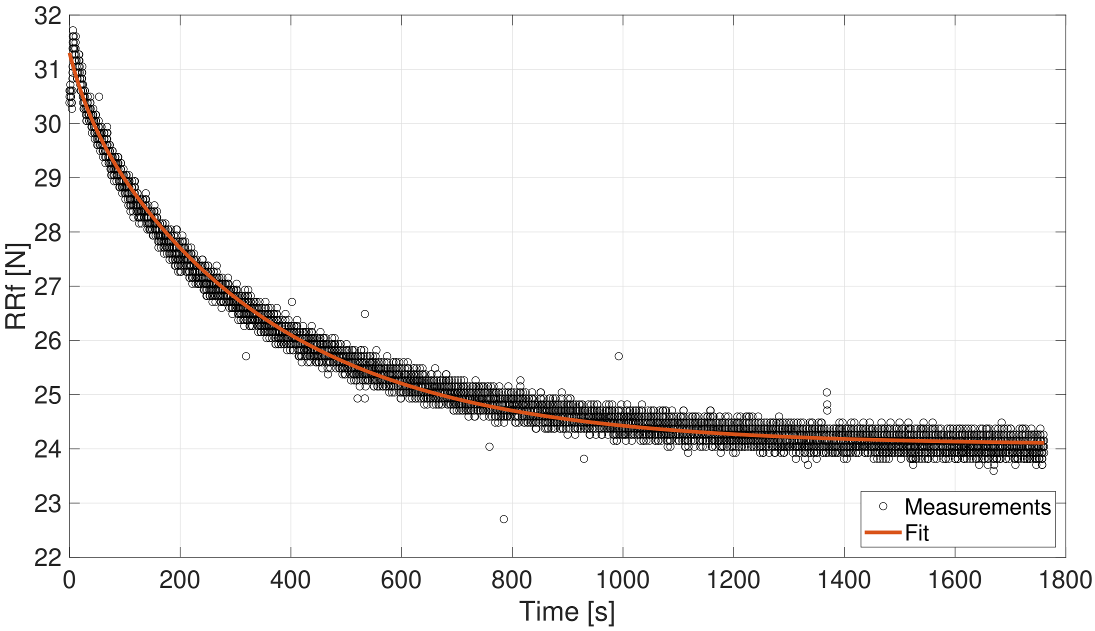


Figure 3.4: Curve-fit output generated by the fitting tool developed in-house by Volvo Cars

The steady-state rolling resistance coefficient (RRc_{ss}) is then calculated as ratio of the rolling resistance force at saturation and the normal load applied to the tyre. Each test combination (out of 36) in the DoE generates a unique set of raw data, curve-fit and corresponding steady-state RRc.

3.2.2 Steady-state fitting

The other part of the fitting tool generates a fit of the steady-state RRc based on the Magic Formula. The stabilized RRc values from each of the 36 tests are used to generate a fit of the steady-state rolling resistances for a given tyre.

The steady-state RRc fit is based on empirical equation of the Magic Formula from [18], which is shown in equation 3.3.

$$M_y = -R_0 F_{z0} \lambda_{My} \left\{ q_{sy1} + q_{sy2} \frac{F_x}{F_{z0}} + q_{sy3} \frac{V_x}{V_{ref}} + q_{sy4} \left(\frac{V_x}{V_{ref}} \right)^4 \right\} \left(\frac{F_z}{F_{z0}} \right)^{q_{sy7}} \left(\frac{P_i}{P_{i0}} \right)^{q_{sy8}} \tag{3.3}$$

where, M_y is the rolling resistance moment of the tyre [Nm].
R_0 is the free radius of the tyre [m].
F_{z0}, V_{ref} and P_{i0} are the reference load [N], reference speed [m/s] and reference pressure [kPa] respectively.
F_z, V_x and P_i are the test load [N], test speed [m/s] and test pressure [kPa] respectively.
λ_{My} is the scaling factor for rolling resistance.
$q_{syi};\ i = 1, 2, 3, 4, 7, 8$ are the fit parameters.

Figure 3.5 shows the steady-state rolling resistance moment curve-fit generated using the fitting tool developed by Volvo Cars.

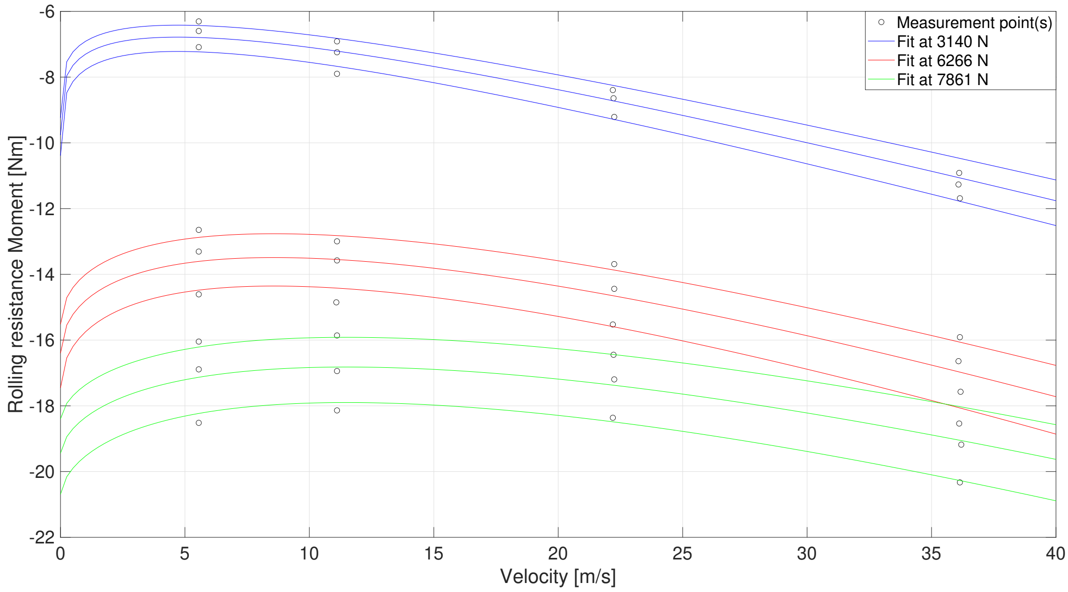


Figure 3.5: Steady state rolling resistance moment curve-fit generated by the fitting tool.

The curve-fit is expressed as the rolling resistance moment (Nm) instead of rolling resistance force or coefficient, as this is the standard representation of the empirical fit in the Magic Formula as seen in equation 3.3. The negative sign represents the loss of energy in the form of a moment in the standard representation. This can easily be translated into the rolling resistance force or coefficient as well.

Each individual curve in the figure 3.5 represents a unique load and pressure case. The top three curves (in blue) represent all pressure cases for the low load case. The highest blue curve represents the lowest pressure case. The red curves in the middle represent the middle load level case and the lower green curves represent the high load level case. The varying velocity is along the x-axis. The dots represent the measured stabilized rolling resistance moments for each of the 36 test cases in the DoE. The curves represent the to those measurement data points generated using equation 3.3 as the fitting function. The recorded steady-state RRc values are used for analysis however the entire fit seen in figure 3.5 is not directly used for any analysis.

3.2.3 Energy loss study

The contribution of the measured rolling resistance is most significant when evaluating the energy consumption (or energy loss) of the tyre. The energy loss for all the test cases in the DoE is evaluated to study the trend and influence of the variation in the operating parameters. Subsequently, the energy loss across the different class of tyres is compared. The calculation of energy loss is done using equations of fundamental physics:

$$P = RR_f \cdot v \tag{3.4}$$

where, P is the power or power loss [W] by the tyre due to its rolling resistance
v is the velocity [m/s] at which the tyre is free rolling
RR_f is the rolling resistance force [N] at the tyre-drum interface.

The energy loss is calculated as;

$$E = \int_0^t P \cdot dt * 2.77778 \cdot e^{-7} \tag{3.5}$$

where, E is the energy loss [kWh]
P is the power [W]
t is the time for which the enery loss is calculated [s]
$2.77778 \cdot e^{-7}$ is the numerical conversion factor for expressing the energy loss in kWh.

For a particular test the energy loss can be essentially evaluated in two ways, one considering the steady-state rolling resistance coefficient/force and the other considering the rolling resistance force/coefficient including the warm-up. The latter is of particular importance as this represents the contribution of the 'warm-up' phase, which is an integral part of the problem statement of this study. A graphical representation to illustrate what 'warm-up' means can be seen through the figure 3.6

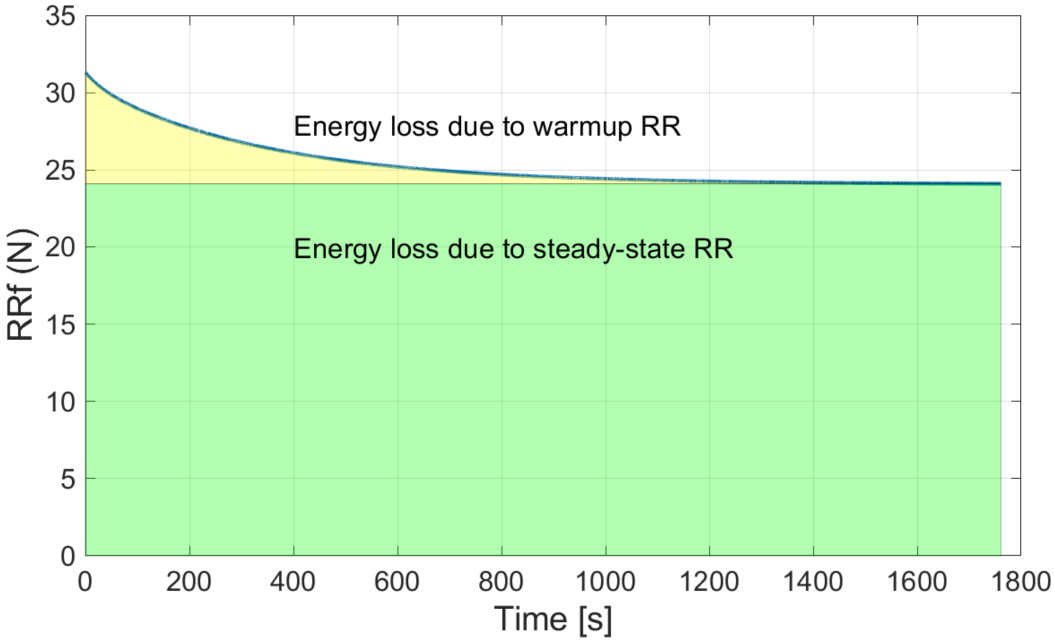


Figure 3.6: Warm-up and Steady-state energy loss

Actual energy loss: The energy loss calculated for the test from time 0 to T (any time of interest) using the time-evolving rolling resistance force values. The actual energy loss in the figure 3.6 is the sum of green and yellow shaded areas.
Steady-state energy loss: The green shaded area in the figure 3.6 shows the steady-state energy loss. It is the integral of steady-state power over time where steady-state rolling resistance force is used in the calculation of power.
Warm-up energy loss: Warm-up energy loss is represented by the yellow shaded region in the figure 3.6. It is the difference between the actual energy loss and the steady-state energy loss and can be attributed to the contribution of the warm-up phase of the tyre during the test.

The tyre's energy loss calculated as a function of time to analyze the influence of variation in operating parameters is slightly abstract since the energy loss correlated with time is not intuitive to assess. However, distance travelled by the tyre as a metric for assessing the energy loss seems more plausible as it can be easily associated with real-world driving. On average inter-city trips are usually for short distances varying between 5 to 50 km and hence using the distance travelled as a way of comparing the energy loss seems like a good approach.

The figure 3.7 shows the difference between the actual energy loss and the steady-state energy loss of the tyre estimated for different distances travelled. This highlights the contribution of the warm-up phase of the tyre for different distances.

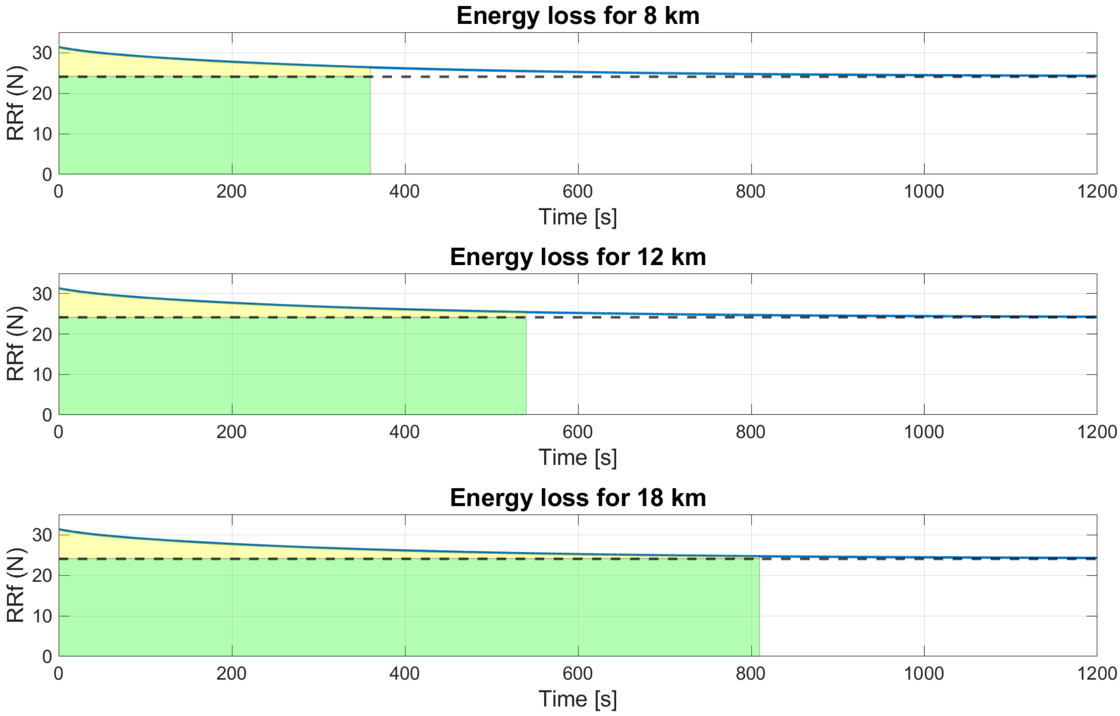


Figure 3.7: Energy loss for varying distance

In the three sub-plots in figure 3.7, the ratio between the yellow shaded region and the yellow + green shaded region reduces as the distance travelled increases (top to bottom). This indicates the decreasing contribution of the warm-up phase as the distance travelled by the tyre increases. The numerical values for the same are presented in table 3.4.

Table 3.4: Energy loss for varying distances

Distance	**E1 (kWh)**	**E2 (kWh)**	**% contribution due to warm-up**
8 km	0.1048	0.0866	21.06
12 km	0.1515	0.1298	16.77
18 km	0.2194	0.1948	12.63

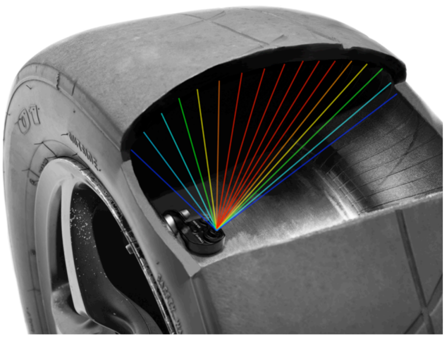
The table 3.4 contains the energy loss for varying distances. 'E1' is the energy loss including warm-up rolling resistance and 'E2' is the energy loss due to the steady-state rolling resistance. Both 'E1' and 'E2' are calculated using the equations 3.4 and 3.5. The difference between E1 and E2 is the additional energy loss due to the warm-up phase. The percentage contribution of this additional energy loss due to warm-up towards the total energy loss (E1) is shown in the last column in table 3.4. As the distance travelled increases the contribution of the energy loss due to warm-up decreases. However at shorter distances travelled, the warm-up phase has a significant contribution ($\approx$ 21% at 8 km) toward the total energy loss of the tyre.

3.3 Temperature Measurements

As discussed in the previous section under influence of temperature (iv), the significance of temperature on the tyre's rolling resistance is substantial. To explore this dimension, the possibility of using an external setup for measuring the tyre temperature along with the rolling resistance measurement was investigated. The RIG-0455 does not have the capability of integrating an external tyre temperature measurement system and hence the temperature measurement system needed to be a standalone setup with data logging capabilities. Multiple tyre temperature measurement suppliers were contacted for the requirement of a standalone temperature measurement system out of which the products from '**IZZE Racing**' [22] best suited the requirements and hence were used for the measurements.

The 'IZZE Racing' make sensors that were used in this thesis were of two types:

TTPMS (Tyre temperature and pressure measuring sensor): This is a wireless infrared sensor that is mounted on the inner surface of the wheel/rim in place of the pressure valve and measures the temperature of the inner tyre surface and inflation pressure of the tyre as shown in figure 3.8a. The temperature data is transmitted wirelessly to an external receiver which can be connected to a computer through a CAN interface.



(a) TTPMS sensor

(b) IRTS sensor

Figure 3.8: Tyre temperature measurement sensors [22].

IRTS (Infrared temperature sensor): This is also an infrared sensor that measures the temperature of the tyre's tread area over the external width of the tyre as shown in figure 3.8b. The sensor is wired and was connected to the computer using a 9 pin D-SUB connector on a CAN interface for our use. Both the sensors use IR to measure the inner or outer tyre surface temperatures. The sensors record the temperature across 16 different channels and in hexadecimal format. The collected data is then post-processed in MATLAB using a script that was developed by the authors.

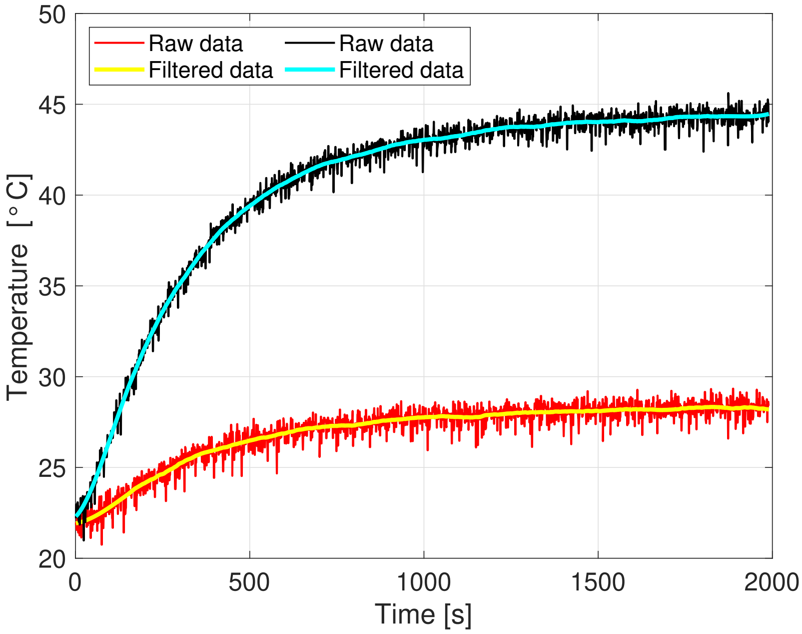


Figure 3.9: Raw data and filtered data from temperature sensors

For processing the temperature data, the hexadecimal data available on the sensor's CAN bus is converted into decimal values representing the measured temperature at a time instant using the conversion algorithm provided by the sensor manufacturer. The converted temperature raw data is post-processed in Matlab using the 'Savitzky-Golay' filter in the signal analyzer tool. Figure 3.9 represents the raw data and the filtered data for internal tyre temperature recorded for two test cases. The noisy red and black curves represent the raw data and the smooth yellow and blue curves represent the respective filtered data.

4 Analysis

This section presents the analysis performed during this thesis, which is majorly focused in two dimensions:

- The variation in the steady state rolling resistance due to the change in the inflation pressure, speed and load.
- The influence of change in inflation pressure, speed and load on the energy consumption of tyres including the contribution of the warm-up phase.

Both aspects of the analysis are discussed in detail in corresponding sections of this chapter.

4.1 Steady state rolling resistance

The analysis of the steady state rolling resistance coefficient (denoted by RRc_{ss} in this section) includes analyzing the influence of variation in the operating parameters; speed, inflation pressure and the normal load on the RRc_{ss} for different class of tyres. The steady state rolling resistance coefficient RRc_{ss} represents the stabilized RRc value, which is measured after the warm-up phase of the tyre has occurred. In the figure 3.4, the RRc value at the end of the test (a timestamp of approx. 1700-1800 s) can be considered as the steady state or stabilized RRc (RRc_{ss}) value for that particular test case. The influence of variation in operating parameters is studied with ISO rolling resistance class as the control parameter. This includes the A-class, B-class and C-class tyres for which we evaluate the impact of variation in each operating parameter on RRc_{ss}. The ISO RRc value (denoted by RRc_{ISO} henceforth) of a tyre is provided by the manufacturer/supplier and represents the RRc_{ss} value at the ISO specified test conditions: 80 kmph, 250 kPa and 0.8*LI load (these conditions are specifically applicable for 'XL' rated tyres, which are all the tyres used in this analysis).

Note: 'XL' refers to extra-loaded/reinforced tyres, which is a classification terminology based on the load capacity and used in the ISO definition of passenger car tyres. The other category in this classification is 'SL' or standard-loaded tyres. The ISO test conditions for measuring the rolling resistance differ in the level of pressure specified for XL rated-250 kPa and SL rated-210 kPa tyres.

Since the RRc_{ISO} is measured at a specific level of pressure, speed and load, the RRc_{ss} measured at any combination of pressure, speed and load other than the ISO specified level will result in a different value. This change in the level of the operating parameters is motivated by the variation that occurs in real world driving, in which it is impractical to drive at the ISO specified speed, pressure and load all the time. Consequentially, the validity of the RRc_{ISO} is not absolute in real world driving. Since the perceived efficiency of a tyre is based on its RRc_{ISO} value, it is of interest to understand how this efficiency is affected when the operating parameters deviate from the ISO specified value. Hence the change in the RRc_{ISO} due to a variation in operating parameters, the magnitude of change and its trend with each operating parameter is essentially what the focus of analysis in this section is.

The figure 4.1 shows the spread of the RRc_{ss} for the three different class of tyres; A-class, B-class and C-class. Each class represented by a unique colour (A-class: green, B-class: blue and C-class: red) consists of the data points of the RRc_{ss} values for two identical tyres (identical meaning both tyres have similar RRc_{ISO} values) from that class. The spread of RRc_{ss} for each individual tyre is represented by the data points along a given ordinate. These data points represent all the RRc_{ss} values recorded for all combinations of the operating parameter according to the DoE, which is shown in figure 3.3. A total of 27 RRc_{ss} data points for each tyre are presented along a given ordinate, corresponding to their absolute RRc value shown on the y-axis. For the analysis here, we consider the data set for each tyre consisting of the RRc_{ss} values recorded at three levels of inflation pressure, speed and load each. This is representative of the 'low', 'medium' and 'high' level of each parameter. The manufacturer provided RRc_{ISO} value of each tyre is also shown in the figure in each tyre's corresponding ordinate, represented by a black '•' marker. The horizontal dashed lines that are colour coded to each class of tyre represent the ISO rolling resistance class limits as defined by the ISO standard.

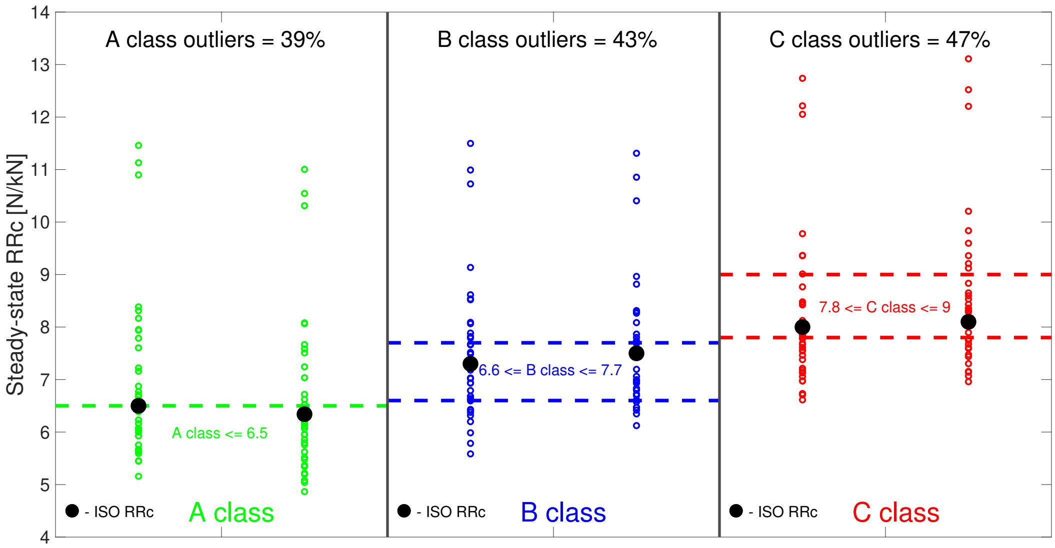


Figure 4.1: An illustration of the spread of the RRc_{ss} for three class of tyres, each class containing two tyres. Each point along an ordinate represents the RRc_{ss} measured at a certain combination of pressure, speed and load level according to the DoE.

The intent of this figure is to illustrate to the reader the spread of the RRc_{ss} of a tyre compared to its RRc_{ISO} value due to the variation in the operating parameters. The amount by which each operating parameter is varied w.r.t its ISO specified level will determine how large of a spread is observed, but the idea is to demonstrate a spread representative of 'real world' driving conditions. For instance, the RRc_{ISO} is measured at a speed of 80 kmph but in real world driving the speed can vary for example, anywhere between 0 kmph to 150 kmph (this speed range is not universal rather considered only for the sake of explanation), depending on multiple factors such as geographical region (part of the world), vehicle type (passenger car/sports car), driving environment (urban/motorway), etc. This means that the RRc_{ISO} value of that tyre which has been measured at 80 kmph speed is only truly accurate for when a vehicle with that tyre is being driven at 80 kmph, assuming the load and pressure are also maintained at the ISO level conditions. Hence the validity of the provided RRc_{ISO} value of a tyre is limited in real-world driving. The influence of each operating parameter (pressure, speed and load) on the RRc_{ss} is discussed individually in the subsequent parts of this section.

4.1.1 Influence of Pressure

The influence of inflation pressure on the RRc_{ss} is analysed here. By inflation pressure what is meant is the 'capped' or initial inflation pressure, which is set at the beginning of the rolling resistance measurement test as opposed to the regulated inflation pressure, which is controlled at a fixed level throughout the test. The rolling resistance measurements performed for this thesis work varied the initial inflation pressure level and the actual pressure throughout the test was not 'regulated' or controlled at a target level. This is relevant in the context of 'real world' applicability since the inflation pressure level is generally controlled/set before the start of a journey, and the effect of its level on the tyre's rolling resistance can be observed through the efficiency (fuel consumption in conventional vehicles) of the vehicle during the journey. It is uncommon to dynamically regulate the inflation pressure level during a journey. Vehicle OEM's often provide a recommended tyre inflation pressure to their customers to optimize the energy efficiency or NVH and comfort during driving (usually optimizing the pressure level for one attribute requires some degree of trade-off for the other).

The figure 4.2 shows the change in the RRc_{ss} with change in inflation pressure recorded at three levels of inflation pressure (220, 250 and 280 kPa) for the different class of tyres. The influence of pressure is observed at an operating speed of 80 kmph and at an avg. load of 6 kN for a set of 11 tyres.

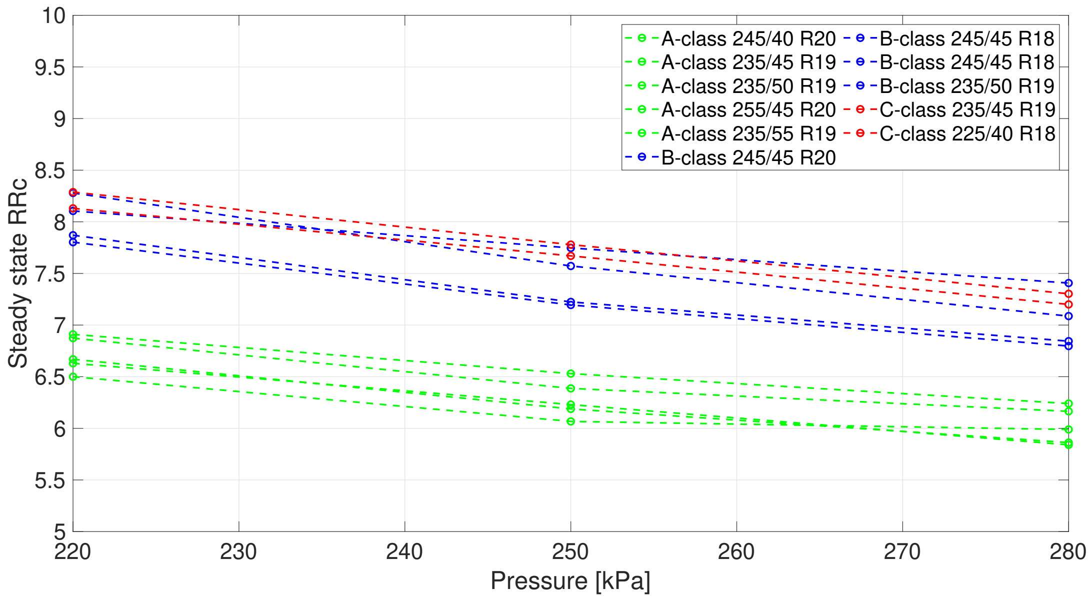


Figure 4.2: Influence of pressure on RRc_{ss} for different class of tyres at 80 kmph and 6 kN.

From the figure 4.2, the following is observed:

- With an increase in the inflation pressure the RRc_{ss} decreases. This observation is consistent across all class of tyres. As discussed in section 2.2.4 under the influence of pressure, an increase in inflation pressure reduces the contact patch of a rotating tyre reducing the area under deformation when contacting the ground or contact surface (test drum in our case), leading to a reduction in the rolling losses. Also, the increased pressure increases the mechanical stiffness of the tyre reducing the magnitude of deformation it experiences. This reduces the hysteresis losses of the tyre as it is being less deformed.

- There is a clear distinction in the RRc_{ss} levels between the A-class and the B and C-class tyres. At all pressure levels in the figure 4.4, the A-class tyres have lower RRc_{ss} values than the other two class of tyres. The distinction between the B and C class tyres is not very apparent.

The increase in inflation pressure reduces the RRc_{ss} of a tyre, which is favorable for the energy efficiency of the tyre (explained in the next sections), but in actual driving, it also has an impact on the ride, handling, performance and NVH attributes of the tyre, the analysis of which is not a part of this study, however is relevant to be pointed out to the reader. An increase in pressure for example might result in a degradation of the NVH and ride comfort quality of the vehicle, since a stiffer (high pressure) tyre will not conform well to the road surface irregularities as compared to a flexible (low pressure) tyre. The analysis of these cross-attribute influences have great depth and shall be left to future work in this subject. The improvement in energy efficiency of the tyre due to a reduction in RRc_{ss} can be theoretically understood through the equation 4.1:

$$F_x = RRc \cdot F_Z \qquad W = F_x \cdot d \tag{4.1}$$

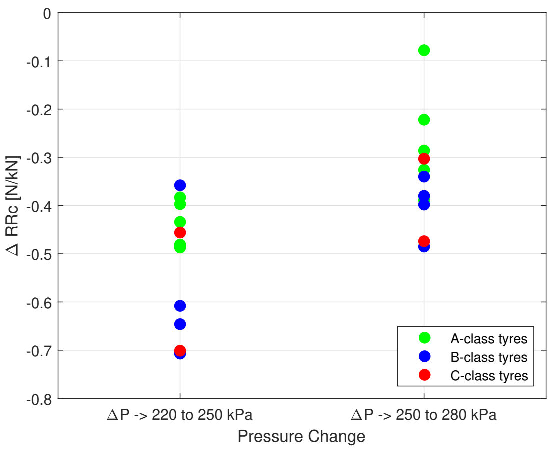
where 'W' represents the work done or energy consumed by the tyre for travelling a distance 'd'. Lower the 'RRc' or rolling resistance coefficient, lower the tangential force at the tyre-ground interface 'F_x' required to keep a free rolling tyre rotating at a given speed and load, resulting in lower energy consumed by the tyre.

However, this approach of calculating the energy consumption (or loss) by a tyre does not include the contribution of the warm-up phase of the rolling resistance, since we only use the steady state values of the RRc to calculate the energy consumption, and hence the influence of the pressure on RRc_{ss} cannot be directly extended to the complete energy efficiency of the tyre. This influence is analysed separately in the next sections which include the contribution of the warm-up phase/warm-up rolling resistance and also discuss in brief what it means.

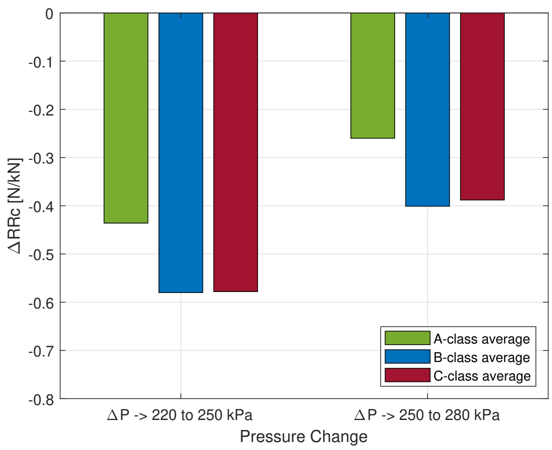
4.1.1.1 Main Effect

Knowing that an increase in inflation pressure reduces the RRc_{ss}, the impact across different class of tyres is studied to compare the sensitivity due to pressure change. We analyse the effect of only changing the pressure levels at a fixed load and speed level, to exclude any possible influence of the other operating parameters. This approach accounts for the 'main effect' of pressure on the RRc_{ss}.

For this analysis, a set of 11 tyres consisting a mix of A, B and C-class tyres are used. Most of the tyres chosen for the analysis have been tested during the tenure of this thesis, however some data of tyres that had been tested previously in Volvo Cars by engineers who initiated this study have also been included in the sample set to maintain an inclusion of all class of tyres. These are tyres used in various existing Volvo Cars models, and hence are suited to be analysed for the subject matter. A large proportion of the tyres included in the sample set are A-class tyres, since these are of particular interest due to their higher efficiency, which make them a popular choice to be used in most car models. It is also intriguing to understand the extent to which the efficiency of these tyres can be improved through the variation or change in the operating parameters. In figure 4.3, we compare the individual tyre and class average change in RRc_{ss} due to an increase in pressure. The class average helps quantify the influence into a singular value for each class of tyre, which can be conservatively approximated as the representative effect for that class of tyre.



(a) Individual tyre's change in RRc_{ss} due to pressure change from 220 to 250 kPa and 250 to 280 kPa



(b) Class-average change in RRc_{ss} due to pressure change from 220 to 250 kPa and 250 to 280 kPa

Figure 4.3: Individual tyre and class average change in RRc_{ss} due to pressure change

Figure 4.3a shows the change in the RRc_{ss} (or ΔRRc_{ss}) due to an increase in pressure from 220 to 250 kPa ($\Delta RRc_{220-250} = RRc_{ss,250} - RRc_{ss,220}$) and from 250 to 280 kPa ($\Delta RRc_{250-280} = RRc_{ss,280} - RRc_{ss,250}$). The RRc_{ss} value at 220kPa is considered as the reference RRc_{ss} value for calculating $\Delta RRc_{220-250}$ and the RRc_{ss} value at 250 kPa is the reference for calculating $\Delta RRc_{250-280}$. The figure 4.3b shows the class average change in RRc_{ss} due to an increase in the inflation pressure. The highest class avg. reduction in RRc_{ss} by a magnitude of 0.58 due to pressure change from 220 to 250 kPa is observed for the B-class tyres, whereas the highest class avg. reduction in RRc_{ss} by a magnitude of 0.4 due to pressure change from 250 to 280 kPa is also observed for the B-class tyres. Additionally, it is also observed that the effect of reduction in RRc_{ss} due to an increase in pressure reduces with an increase in absolute pressure level. This means that the reduction in RRc_{ss} due to pressure change from 250 to 280 kPa is less than the reduction in RRc_{ss} due to pressure change from 220 to 250 kPa, which is observed for all class of tyres. The class average results are shown in table 4.1.

Table 4.1: Class average reduction in RRc_{ss} due to pressure change at 80 kmph and 6 kN avg. load.

Tyre class	$\Delta RRc_{220-250}$	$\Delta RRc_{250-280}$
A-class avg	-0.436	-0.260
B-class avg.	-0.580	-0.401
C-class avg.	-0.578	-0.388

4.1.1.2 Interaction Effect

In section 4.1.1, we analyzed the effect of change in inflation pressure, which is the primary operating parameter in consideration. However it is also important to know if the other two operating parameters speed and load influence the effect that varying pressure has on the RRc_{ss}. The authors in [23] refer to this as the interaction effect between two variables when discussing the analysis of full factorials. This interaction is investigated to understand how changing the load or speed level (according to the DoE) will influence the changes in RRc observed due to the pressure change. In the previous section, the main effect of change in pressure is evaluated at a fixed load (6 kN) and a fixed speed (80 kmph) level.

To determine which interaction effect to evaluate, we perform an Analysis of Variance (ANOVA) of the full factorial of the RRc_{ss}, which is the all the 27 RRc_{ss} values recorded for a tyre according to the DoE. Through the ANOVA, we determine the statistical significance between the effects observed in the output due to two variables affecting the system. This is done using the 'p-value' indicator. A 'p-value' ≤ 0.05 means there's a less than 5% probability that the variance observed between two data sets is purely due to chance, meaning the two data sets are statistically significant. When we perform a full-factorial ANOVA based on the DoE which consists of a combination of 27 test conditions (variation of 3 levels of speed, pressure and speed each = 3^3 test cases) using the RRc_{ss} values as the output for each of the 27 combinations, we get a p-value for the following effects:

- **MAIN EFFECTS**
  1. Pressure
  2. Speed
  3. Load
- **INTERACTION EFFECTS**
  1. Pressure vs. Speed
  2. Pressure vs. Load
  3. Speed vs. Load

The ANOVA compares the variances due each of the effects shown above with the corresponding variances observed in the RRc_{ss} values, and calculates a p-value based on that. The p-value (probability value) indicates whether the two variances are statistically significant or not, and hence whether the two data sets are correlated. An example of the ANOVA of an A-class tyre can be seen in figure A.1. This ANOVA was performed using Mintab software. Performing the ANOVA of the full factorial DoE consisting of the RRc_{ss} as the output for the 11 tyres, it was observed that for 9 out of the 11 tyres the 'p-value' for the pressure vs. speed interaction effect was higher than 0.05. Based on this information, we interpret that statistically the there is very little influence of the variation in speed levels on the effect that pressure (or change in pressure) has on the RRc_{ss}. This holds good for the speed vs. pressure interaction effect as well, since the interaction is applicable to both parameters being considered as the primary parameter. To verify this interpretation, we tabulate the class-average difference in the RRc_{ss}

due to change in pressure (primary parameter here), observed at the different levels of speed (secondary parameter) and a load of 6 kN (fixed parameter). In the table 4.2, δ_{max} represents the maximum difference between the class average ΔRRc's at the three levels of speed for every class of tyre.

Table 4.2: Class average reduction in RRc_{ss} due to pressure change, observed at different levels of speed and 6 kN load. Each row represents the pressure vs. speed interaction effect observed for a class of tyre.

Tyre Class	$\Delta RRc_{220-250}$				$\Delta RRc_{250-280}$			
	40 kmph	**80 kmph**	**130 kmph**	$\lvert\delta_{max}\rvert$	**40 kmph**	**80 kmph**	**130kmph**	$\lvert\delta_{max}\rvert$
A-class avg.	-0.481	-0.436	-0.422	0.059	-0.248	-0.260	-0.286	0.038
B-class avg.	-0.583	-0.580	-0.559	0.024	-0.429	-0.401	-0.437	0.036
C-class avg.	-0.630	-0.578	-0.617	0.052	-0.487	-0.388	-0.354	0.133

From the table 4.2, we observe that except for the C-class avg. of $\Delta RRc_{250-280}$, the reduction in RRc_{ss} due to pressure change ($\Delta RRc_{220-250}$ and $\Delta RRc_{250-280}$) does not vary more than a maximum value of 0.059 between different levels of speeds. This value is small compared to the absolute RRc_{ss} values at each speed level. Meaning that in the table 4.2, at 6 kN of operating load an A-class tyre will have an avg. reduction of RRc by 0.4 +/- 0.06 due to an increase in pressure from 220 kPa to 250 kPa, regardless of which speed level (out of 40, 80 and 130 kmph) the tyre is operating at. The variation in the $\Delta RRc_{220-250}$ due the speed level is not more that 0.059. The difference between $\Delta RRc_{220-250} = 0.4$ and $\Delta RRc_{220-250} = 0.459$ can be disregarded conservatively, considering that precision of the RRc_{ISO} class limit values are limited to the first decimal. This would be the explicit interpretation of the statistical non-significance of pressure vs. speed interaction effect. The relatively higher variation between different speed levels for $\Delta RRc_{250-280}$ for the C-class tyres could be due to the fact that out of the 2 tyres that showed a p-value ≥ 0.05 for the pressure vs. speed interaction effect, one tyre was a C-class tyre, the effect of which is seen in the table 4.2. An explanation for why specifically this C-class tyre has a significance of the pressure vs. speed interaction effect on the variation of its RRc_{ss} is difficult to quantify. This is treated as statistical noise which is justified by the authors as: 9 out of 11 tyres did not show this effect (i.e., p-value ≥ 0.05 for the pressure vs. speed interaction effect) and one out of the two C-class tyres also did not show a p-value ≥ 0.05, limiting the possibility of this being a phenomenon specific to C-class tyres.

Hence the statistical non-significance of the pressure vs. speed interaction effect is considered to hold good conservatively, meaning the evaluation of only the interaction effect of pressure vs. load at a fixed level of speed is done, to determine the global ('main' + 'interaction') effect of change in pressure on RRc_{ss}.

Pressure vs. Load Interaction Effect:

Here the influence of different load levels on the effect of pressure (or change in pressure) on RRc_{ss} is discussed. The speed level is fixed at 80 kmph. The change in RRc_{ss} due to pressure change from 220 kPa to 250 kPa and from 250 kPa to 280 kPa at different levels of load is presented in table 4.3:

Table 4.3: Class average reduction in RRc_{ss} due to pressure vs. load interaction effect at 80 kmph. Increasing intensities of the blue and orange colors from left to right represent the positive effect of increasing load level on the ΔRRc_{ss} due to pressure change from 220 to 250 kPa and 250 to 280 kPa respectively.

Tyre Class	F_z = **3 kN**		F_z = **6 kN**		F_z = **9.2 kN**	
	$\Delta RRc_{220-250}$	$\Delta RRc_{250-280}$	$\Delta RRc_{220-250}$	$\Delta RRc_{250-280}$	$\Delta RRc_{220-250}$	$\Delta RRc_{250-280}$
A-class avg.	-0.351	-0.073	-0.436	-0.260	-0.439	-0.308
B-class avg.	-0.432	-0.269	-0.502	-0.360	-0.605	-0.409
C-class avg.	-0.393	-0.334	-0.456	-0.474	-0.569	-0.387

From the table 4.3, we observe that for the A-class and B-class tyres, the load level has a positive correlation with the avg. reduction in RRc_{ss} due to pressure change. This means that an increase in the absolute load level increases the Δ reduction of RRc_{ss} due to pressure change. To illustrate this, each ΔRRc_{ss} due to pressure change has been coloured with the same color and with increasing intensity of the color from left to right representative of the increasing load level. The $\Delta RRc_{220-250}$ has been represented by blue color and the intensity of the colour increases as we move from left to right. Similarly, $\Delta RRc_{250-280}$ has been represented by orange color and the intensity of the colour also increases as we move from left to right.

Note: The tyre sample set used for the analysis of the 'main effect' of pressure change in the previous section included the data of the tyres tested during this thesis as well as some tyres that had been tested in the past in Volvo Cars, which combined together formed a master sample set of 11 tyres. The 6 kN load level (middle load level) is consistent in the DoE's of both currently and previously tested tyres, however the higher and lower load levels are not the same. Hence for comparing the pressure vs. load interaction effect, the samples of tyres chosen out of master set of 11 tyres are limited to only those tyres which have the same high and low load levels as well. This results in a slightly different avg. reduction in ΔRRc_{ss} for the B-class and C-class tyres between tables 4.2 and 4.3.

For the C-class tyres however, the avg. reduction in RRc: $\Delta RRc_{250-280}$ at 9.2 kN load level does not follow the trend of the pressure vs. load interaction effect observed for the other class of tyres. Since the C-class avg. values presented in the table 4.3 have been obtained using only one C-class tyre which was tested at the same load levels as all the other tyres in the sample set, it is difficult to ascertain the exact cause of this deviation.

4.1.2 Influence of Speed

The the effect of change in speed on the RRc_{ss} is analysed here. The figure 4.4 shows the change in the RRc_{ss} with change in speed for the different class of tyres. This influence is observed at an inflation pressure of 250 kPa and an avg. operating load of 6 kN for a sample set of 11 tyres.

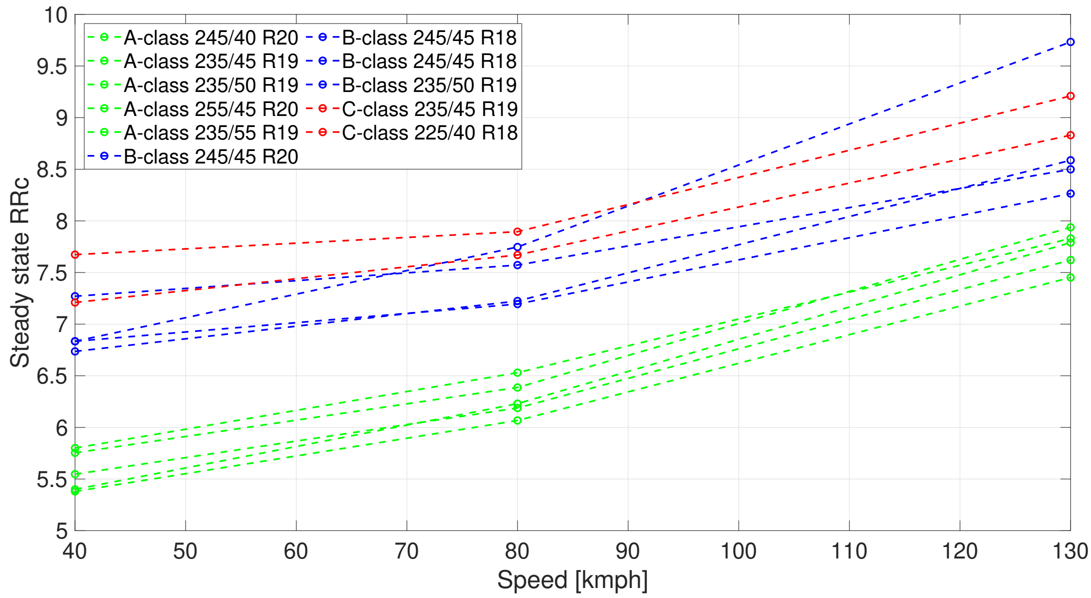


Figure 4.4: Influence of speed on RRc_{ss} for different class of tyres at 250 kPa and 6 kN.

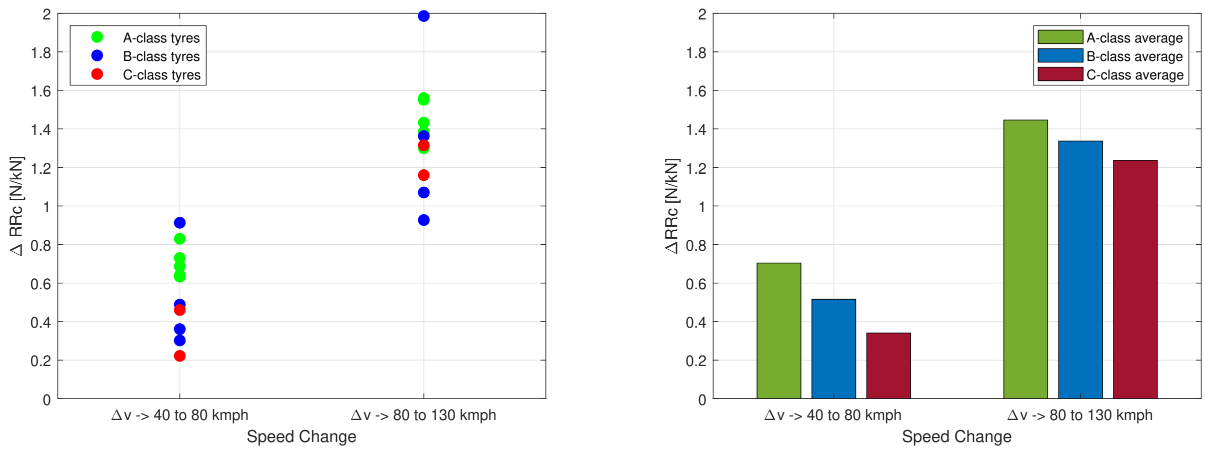
From the figure 4.4, the following can be observed:

- With an increase in speed, the RRc_{ss} increases. As discussed in section 2.2.4 under 'influence of speed', the increase in RRc_{ss} is more significant at higher speeds. The phenomena resulting in the increase in RRc at higher speeds is multi-dimensional, but can be attributed to the following major phenomena:
  - At higher speeds the rotating tyre experiences higher aerodynamic losses. This loss is proportional to the square of the speed and the effect increases exponentially with the absolute speed level. This effect is extrinsic to the tyre and does not depend on tyre's material properties, however it is certainly influenced by external attributes such as the shape of the tyre tread, wheel geometry and shape, etc. which influence the aerodynamics of the tyre.
  - Higher deformation frequencies at high speeds increases the hysteresis loss. This effect is discussed by the author in [5]. The propensity of tyre rubber to lose energy due to hysteresis increases with an increases in the frequency.
  - Higher speeds generate higher temperatures which reduces the tyre's visco-elastic losses reducing the hysteresis losses. Additionally, higher temperatures also increase the inflation pressure which reduces the rolling losses. This effect of high speeds counters the previous two effects.
- There is a clear distinction in the RRc_{ss} levels between the A-class and the B and C-class tyres. At all speed levels in the figure 4.4, the A-class tyres have distinctly lower RRc_{ss} values than the other two class of tyres. The distinction between the B and C-class tyres is not very apparent.

4.1.2.1 Main Effect

Knowing that an increase in speed increases the RRc_{ss}, the impact across different class of tyres is studied to compare the sensitivity of speed change. We analyse the effect of only changing the speed levels at a fixed load and pressure level, to disregard the influence of the other operating parameters. This influence is discussed in the next sub-section under 'Interaction Effect.

For this analysis, a sample set of 11 tyres consisting of a mix of A, B and C-class tyres are selected as was done for the analysis in section 4.1.1.1. In figure 4.5, the individual tyre and class average change in RRc_{ss} due to an increase in speed is presented:



(a) Individual tyre's change in RRc_{ss} due to speed change from 40 to 80 kmph and 80 to 130 kmph.

(b) Class-average change in RRc_{ss} due to speed change from 40 to 80 kmph and 80 to 130 kmph.

Figure 4.5: Individual tyre and class average change in RRc_{ss} due to speed change.

The figure 4.5a shows the change in RRc_{ss} (or ΔRRc_{ss}) due to increase in speed from 40 to 80 kmph ($\Delta RRc_{40-80} = RRc_{ss,80} - RRc_{ss,40}$) and from 80 to 130 kmph ($\Delta RRc_{80-130} = RRc_{ss,130} - RRc_{ss,80}$). The RRc_{ss} value at 40 kmph is considered as the reference RRc value for calculating ΔRRc_{40-80} and the RRc_{ss} value at 80 kmph is the reference for calculating ΔRRc_{80-130}. The figure 4.5b shows the class average change in RRc_{ss} due to increase in speed. The highest avg. increase in RRc_{ss} by a magnitude of 0.704 due to speed change from 40 to 80 kmph is seen for the A-class tyres and the highest avg. increase in RRc_{ss} by a magnitude of 1.45 due to speed change from 80 to 130 is also seen in the A-class tyres. The tabulated class average results are shown in table 4.4.

Table 4.4: Class average increase in RRc_{ss} due to speed change at 250 kPa and 6kN load. The highlighted row shows the highest class average increase in RRc_{ss}.

Tyre class	ΔRRc_{40-80}	ΔRRc_{80-130}
A-class avg.	0.704	1.446
B-class avg.	0.516	1.337
C-class avg.	0.341	1.237

From table 4.4, it is observed that the A-class tyres are the most sensitive to change in speed levels at 250 kPa pressure and 6 kN load.

4.1.2.2 Interaction Effect

The global influence of change in speed on the RRc_{ss} is analyzed along with the interaction effects due to the other operating parameters pressure and load. As discussed and explained in section 4.1.1.2, the ANOVA of the full factorial DoE was performed to determine the statistically significant interaction effects. The pressure vs. speed interaction effect was conservatively determined to be statistically not significant, which was verified through table 4.2. Hence, we evaluate only the speed vs.load interaction effect to analyze the global ('main' + 'interaction') effect of change in speed on the RRc_{ss}.

Speed vs. Load Interaction Effect:

The influence of changing load levels on the effect of speed (or change in speed) on RRc_{ss} is discussed here. The change in RRc_{ss} due to speed change from 40 kmph to 80 kmph and 80 kmph to 130 kmph at different levels of load is presented in table 4.5:

Table 4.5: Class average increase in RRc_{ss} due to speed change at different levels of load and 250 kPa pressure. Decreasing intensities of the blue and orange colors from left to right represent the negative effect of increasing load level on the ΔRRc_{ss} due to speed change from 40 to 80 kmph and 80 to 130 kmph respectively.

Tyre Class	F_z = **3 kN**		F_z = **6 kN**		F_z = **9.2 kN**	
	ΔRRc_{40-80}	ΔRRc_{80-130}	ΔRRc_{40-80}	ΔRRc_{80-130}	ΔRRc_{40-80}	ΔRRc_{80-130}
A-class avg.	1.452	2.742	0.704	1.446	0.341	0.898
B-class avg.	1.719	3.381	0.701	1.675	0.284	1.014
C-class avg.	1.599	2.833	0.460	1.160	-0.052	0.710

From the table 4.5, is is observed that the load level has a negative correlation with the avg. increase in RRc_{ss} due to speed change, as represented using the colour intensities. A possible reason of this interaction effect could be explained by the fact that higher load levels result in higher temperatures due to greater bending and shearing of the tyre's treads and sidewalls. This increase in temperature helps reduce the visco-elastic losses of the tyre as well as increase the inflation pressure which reduces the RRc_{ss}. Consequentially, the effect of increasing the load level opposes the primary effect of increasing the speed level. For the C-class tyre an increase of speed from 40 to 80 kmph at 9.2 kN load level results in a **reduction** of the RRc_{ss} by 0.052. This being interesting, however cannot be used to draw any inferences about the sensitivity of C-class tyres to speed changes at higher loads. This is primarily due to the low number of C-class tyre samples used for the avg. ΔRRc calculation and the magnitude of the change being very small relative to the absolute level of RRc_{ss} (which is 7.28 for that tyre at 40 kmph and 9.2 kN).

4.1.3 Influence of Load

The influence of load on the RRc_{ss} is analysed here. The figure 4.6 shows the change in the RRc_{ss} with change in load for the different class of tyres. This influence is observed at an inflation pressure of 250 kPa and at 80 kmph for a sample set of 9 tyres which have all been tested at the same load levels.

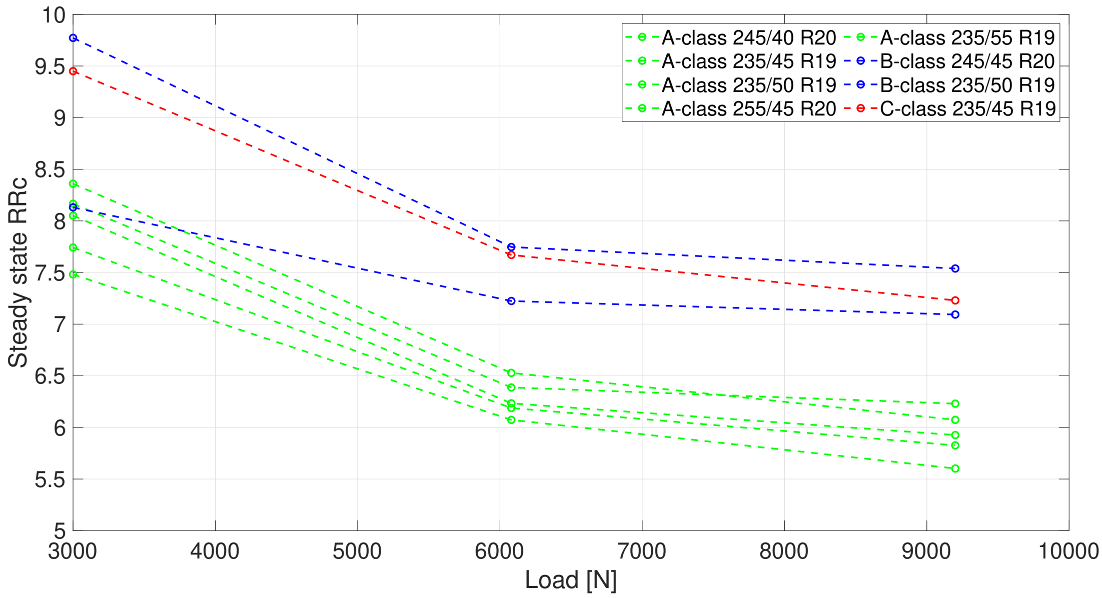


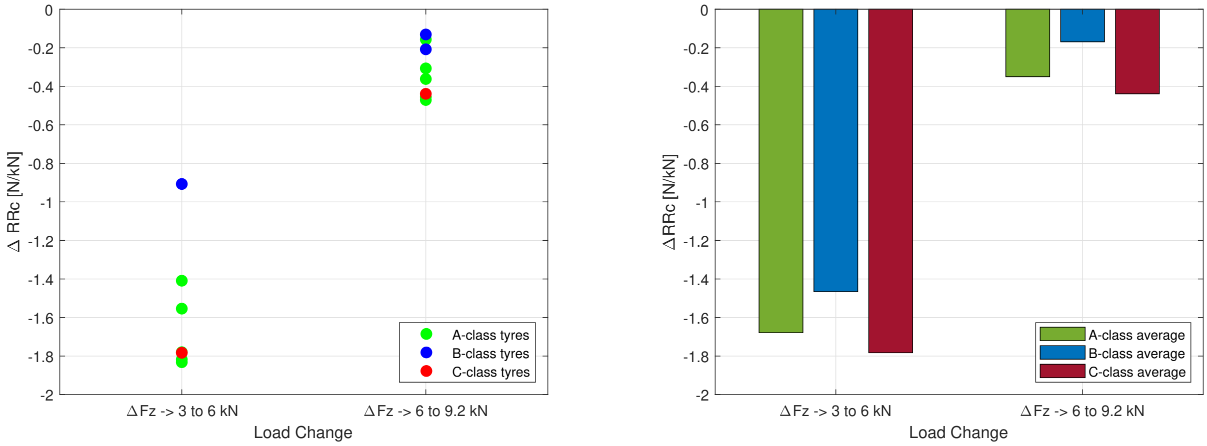
Figure 4.6: Influence of load on RRc_{ss} for different class of tyres at 250 kPa and 80 kmph.

From the figure 4.6, the following is observed:

- With an increase in load, the RRc_{ss} decreases as discussed in section 2.2.4 under 'influence of load'. A higher load level causes a greater deformation of the tyre, which increases the temperature. This increase in temperature decreases the visco-elasticity of the tyre, reducing the RRc_{ss} [2].
- There is a clear distinction in the RRc_{ss} levels between the A-class and the B and C-class tyres. At all load levels in the figure 4.6, the A-class tyres have distinctly lower RRc_{ss} values than the other two class of tyres.

4.1.3.1 Main Effect

The main effect due to load change in analyzed in a similar way as was done in the case for the pressure and speed influence. The effect of changing load levels at a fixed speed and pressure level is seen through figure 4.7.



(a) Individual tyre's change in RRc_{ss} due to load change from 3 to 6 kN and 6 to 9.2 kN.

(b) Class-average change in RRc_{ss} due to load change from 3 to 6 kN and 6 to 9.2 kN.

Figure 4.7: Individual tyre and class average change in RRc_{ss} due to load change

From the figure 4.7, the following is observed:

- The highest class avg. decrease in RRc_{ss} by a magnitude of 1.783 due to load change from 3 kN to 6 kN is seen for the C-class tyre and the highest class avg. decrease in RRc by a magnitude of 0.439 due to load change from 6 kN to 9.2 kN is also seen for the C-class tyre.
- The effect of decrease in the RRc_{ss} due to an increase in load reduces substantially with an increasing load level.

The class average results are shown in table 4.6.

$\Delta RRc_{3-6kN} = RRc_{ss,3kN}$ - $RRc_{ss,6kN}$ and $\Delta RRc_{6-9.2kN} = RRc_{ss,9.2kN}$ - $RRc_{ss,6kN}$.

Table 4.6: Class average reduction in RRc_{ss} due to load change at 250 kPa and 80 kmph. The highlighted row shows the highest class average reduction in RRc_{ss}.

Tyre class	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$
A-class avg.	-1.679	-0.350
B-class avg.	-1.446	-0.169
C-class avg.	-1.783	-0.439

From table 4.6 we observe that the C-class tyre shows the highest class average sensitivity in RRc_{ss} to changes in load although the distinction between the A-class and C-class average is subtle.

4.1.3.2 Interaction Effect

The interaction effects of both the load vs. pressure and load vs. speed were determined to be statistically significant based on the ANOVA performed, as was discussed in depth in section 4.1.1.2. Hence, the outcomes of both the aforementioned interaction effects are discussed below.

Load vs. Pressure Interaction Effect:

The change in RRc_{ss} due to load change from 3 kN to 6 kN and 6 kN to 9.2 kN at different levels of pressure is presented in table 4.7.

Table 4.7: Class average decrease in RRc_{ss} due to load change at different levels of pressure and 80 kmph speed. Increasing intensities of the orange color from left to right represent the positive effect of increasing pressure level on the ΔRRc_{ss} due to load change from 3 to 6 kN.

Tyre Class	P = 220 kPa		P = 250 kPa		P = 280 kPa	
	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$
A-class avg.	-1.580	-0.331	-1.679	-0.350	-1.852	-0.383
B-class avg.	-1.396	-0.172	-1.466	-0.169	-1.557	-0.203
C-class avg.	-1.719	-0.326	-1.783	-0.439	-1.922	-0.352

From the table 4.7 it is observed that the pressure level has a positive correlation with the avg. decrease in RRc_{ss} due to load change from 3 kN to 6 kN (ΔRRc_{3-6kN}). This is represented by the increasing orange color from left to right. No consistent trend is observed for the $\Delta RRc_{6-9.2kN}$ with the change in pressure levels for all class of tyres. However the magnitude of the $\Delta RRc_{6-9.2kN}$ is very similar at the different pressure levels for each class of tyre. This suggests that the effect load change has on the RRc_{ss} at high loads is strong enough to be unaffected by the effect of pressure on the RRc_{ss}.

Load vs. Speed Interaction Effect:
The change in RRc_{ss} due to load change from 3 kN to 6 kN and 6 kN to 9.2 kN at different levels of speed is presented in table 4.8.

Table 4.8: Class average decrease in RRc_{ss} due to load change at different levels of speed and 250 kPa pressure. Increasing intensities of the orange and blue colors from left to right represent the positive effect of increasing speed level on the ΔRRc_{ss} due to load change from 3 to 6 kN and 6 to 9.2 kN respectively.

Tyre Class	v = 40 kmph		v = 80 kmph		v = 130 kmph	
	Δrrc_{3-6kN}	$\Delta RRc_{6-9.2kN}$	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$	ΔRRc_{3-6kN}	$\Delta RRc_{6-9.2kN}$
A-class avg.	-0.754	0.030	-1.679	-0.350	-3.395	-0.883
B-class avg.	-0.447	0.248	-1.466	-0.169	-3.172	-0.830
C-class avg.	-0.644	0.073	-1.783	-0.439	-3.457	-0.887

From the table 4.8 it is observed that the speed level has a positive correlation with the avg. decrease in RRc_{ss} due to load change from 3 kN to 6 kN (ΔRRc_{3-6kN}) and 6 kN to 9.2 kN ($\Delta RRc_{6-9.2kN}$). Higher speed levels allow a greater reduction in RRc_{ss} due to load change. This interaction effect is in stark contrast to the speed vs. load interaction effect (considering speed as the primary operating parameter). The exact mirco-level phenomenon resulting in this effect is difficult to state, however a possible hypothesis with regards to the macro level effect would be that the increase in tyre temperature at higher loads coupled with the increase in temperature due to higher speeds dominates the combined effect of increases in hysteresis loss due to higher deformation frequencies as well as increased aerodynamic losses at higher speeds. Interestingly is is also observed that for the $\Delta RRc_{6-9.2kN}$ at 40 kmph speed level, there is a slight increase in the RRc_{ss} from 6 kN to 9.2 kN load (hence the positive sign of the values in that column), which is contrary to the 'main effect' of load on ΔRRc_{ss}. This suggests that the speed influence at low levels (40 kmph) counteracts and subdues the effect of load change from 6 to 9.2 kN.

4.2 Warm-up rolling resistance and energy efficiency

The previous section 4.1 dealt with the analysis of the influence of pressure, speed and load levels on the RRc_{ss}. As discussed in the introduction of the previous section, RRc_{ss} is the term that is usually correlated with the efficiency of a tyre however it does not present us with complete information regarding the energy consumption of the tyre and its true efficiency, especially for short distances travelled. This is due to the influence of the warm-up rolling resistance, which is the evolution of the tyre's rolling resistance before it reaches a stabilised value. The contribution of the warm-up rolling resistance is not accounted for in the RRc_{ss} value. This generates the need to evaluate the entire RRc evolution with time and not just the steady state value. Specifically, we evaluate the rolling resistance force ($RR_f = RRc \cdot F_z$) evolution which is easily interchanged with the energy consumption (or loss) of the tyre as was discussed in section 3.2.3.

To make the analysis and comparisons coherent w.r.t the driving impact, the energy consumption (or loss) as a function of the driven distance serves as a good way of expressing the energy efficiency of tyres. This translates into the average energy loss per km. This is because the effects of the warm-up phase are captured acutely in this representation. To expand on this, the accumulated tyre energy consumption (or loss) as a function of the distance travelled in the range of 5 to 100 km is plotted. This range of distance is chosen such that it is densely populated for short driven distance which accounts for most of the average short-distance and inter-city driving. The figure 4.8 shows the total energy loss (black curve) along the left y-axis and average energy loss per km (red curve) along the right y-axis as a function of the distance travelled.

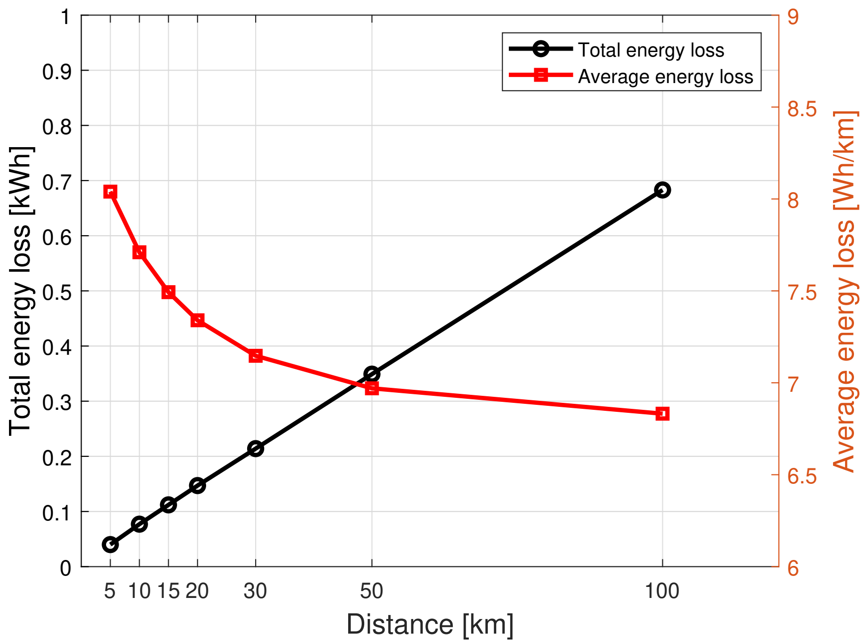


Figure 4.8: Total energy loss and average energy loss including warm-up phase contribution for varying distance travelled.

From the figure 4.8, the following can be observed:

- The total energy loss (black curve) increases with increasing distance travelled. This is consistent with the fact that the total energy loss will always increase with total distance travelled. Even though this energy includes the contribution of the warm-up phase, its effect is not perceptible directly.

- The average energy loss per km (red curve) is the ratio of the total energy loss to the distance travelled. It can be expressed as:

$$E_{avg} = \frac{E}{d} \tag{4.2}$$

E = Total energy loss for a distance of 'd' km (in kWh).
E_{avg} = Average energy loss for a distance of 'd' km (in Wh/km).
This is higher for shorter distances and reduces as the distance travelled increases, which is due to the reducing contribution of the warm-up phase as distance travelled increases. The author in [5] labels this as the 'average rolling loss' of the tyre.

The subsequent sections analyse the trends of the average energy loss due to change in the pressure, speed and load as well as how this influences the percentage contribution of the warm-up phase.

4.2.1 Influence of Pressure

To analyse the influence of pressure (or pressure change) on the average energy loss per km (E_{avg}) and warm-up rolling resistance, we include the contributions of both the main effect and the interaction effect of pressure.

4.2.1.1 Main Effect

The figure 4.9 shows the influence of pressure change on the E_{avg} for different class of tyres.

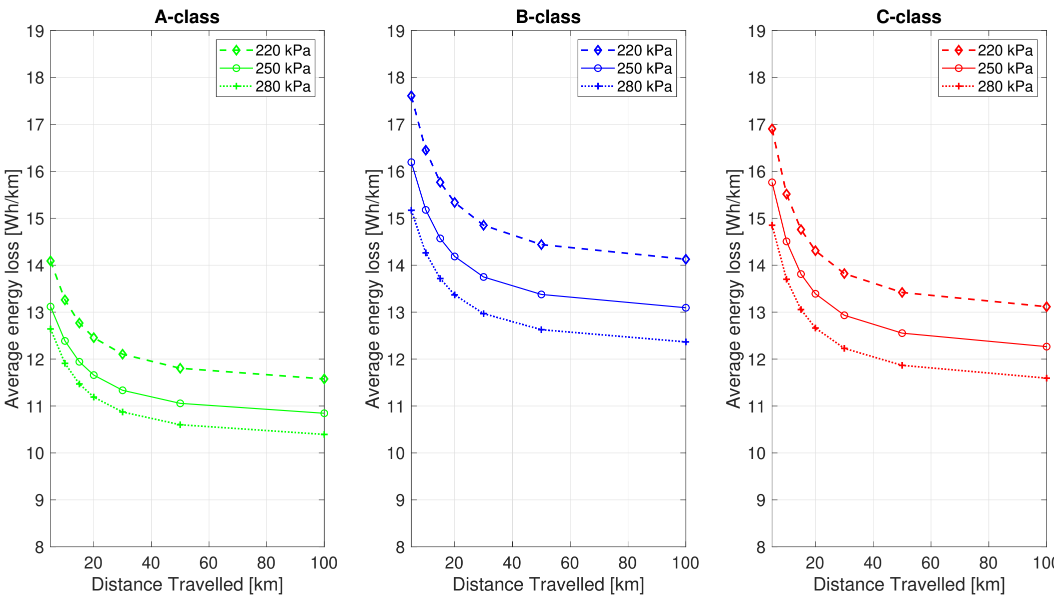


Figure 4.9: Influence of pressure on class-average E_{avg} for different class of tyres at 6 kN and 80 kmph. Each subplot represents the influence of pressure change on E_{avg} for a given class of tyre.

In the figure 4.9, each subplot shows the class-average E_{avg} at different pressure levels for a class of tyre. It is visibly evident that an increase in the absolute pressure level (220 to 250 to 280 kPa) reduces the E_{avg} for each class of tyre. This effect of pressure change on E_{avg} is consistent with the effect observed for the RRc_{ss} and can be explained with the same phenomena discussed in section 4.1.1. The amount of reduction in the energy loss would translate into the sensitivity of a certain class of tyre towards pressure change. The table 4.9 shows the reduction in the E_{avg} with an increase in pressure for the different class of tyres. In the table, '$\Delta E_{220-250}$' represents the difference in E_{avg} between 220 kPa and 250 kPa for each corresponding distance travelled ($\Delta E_{220-250} = E_{avg,250} - E_{avg,220}$). Similarly '$\Delta E_{250-280}$' represents the difference in E_{avg} between 250 kPa and 280 kPa for each corresponding distance travelled ($\Delta E_{250-280} = E_{avg,280} - E_{avg,250}$).

Table 4.9: Reduction in E_{avg} due to pressure change at 80 kmph and 6 kN for varying distances

Class	ΔE_{avg}	**5 km**	**10 km**	**15 km**	**20 km**	**30 km**	**50 km**	**100 km**
A-class	$\Delta E_{220-250}$	-0.97	-0.87	-0.83	-0.80	-0.77	-0.75	-073
	$\Delta E_{250-280}$	-0.48	-0.48	-0.47	-0.47	-0.46	-0.46	-0.45
B-class	$\Delta E_{220-250}$	-1.63	-1.48	-1.39	-1.33	-1.27	-1.22	-1.18
	$\Delta E_{250-280}$	-1.05	-0.94	-0.88	-0.85	-0.82	-0.79	-0.77
C-class	$\Delta E_{220-250}$	-1.14	-1.01	-0.95	-0.92	-0.89	-0.87	-0.85
	$\Delta E_{250-280}$	-0.91	-0.81	-0.76	-0.73	-0.70	-0.69	-0.67

Based on the figure 4.9 and table 4.9, the following is observed:

- The highest E_{avg} at all pressure levels is observed for the B-class tyres (highlighted in yellow). This is contrary to the expectations from the RRc_{ss}, for which the C-class tyres have the highest magnitude. This inconsistency is due to the contribution of the warm-up phase which gets accounted for in E_{avg} as opposed to RRc_{ss} and hence motivates this comparison.
- For an increase in the pressure from 220 to 250 kPa and 250 to 280 kPa, the highest reduction in E_{avg} is observed for the B-class tyres, followed by the C-class and A-class tyres. This is consistent with the corresponding pressure sensitivities observed for the RRc_{ss}.

4.2.1.2 Interaction Effect

The analysis of the interaction effects of speed and load on the influence of pressure followed the same approach as was done for the RRc_{ss} in section 4.1.1.2. The ANOVA of the energy consumption for a travelled distance of 50 km (which includes the contribution of the warm-up phase) presented the pressure vs. speed interaction effect to not be statistically significant. Hence, only the pressure vs. load interaction effect was considered. The class-average reduction in E_{avg} due to pressure change observed at 3 kN and 9.2 kN load level is shown in tables 4.10 and 4.11 respectively.

Table 4.10: Reduction in E_{avg} due to pressure change at 80 kmph and 3 kN for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	$\Delta E_{220-250}$	-0.41	-0.38	-0.36	-0.35	-0.34	-0.33	-0.32
	$\Delta E_{250-280}$	-0.11	-0.09	-0.08	-0.07	-0.06	-0.06	-0.05
B-class	$\Delta E_{220-250}$	-0.43	-0.41	-0.39	-0.39	-0.38	-0.37	-0.37
	$\Delta E_{250-280}$	-0.23	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22
C-class	$\Delta E_{220-250}$	-0.36	-0.34	-0.34	-0.33	-0.33	-0.33	-0.33
	$\Delta E_{250-280}$	-0.41	-0.37	-0.35	-0.33	-0.31	-0.30	-0.29

Table 4.11: Reduction in E_{avg} due to pressure change at 80 kmph and 9.2 kN for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	$\Delta E_{220-250}$	-1.54	-1.35	-1.27	-1.23	-1.19	-1.17	-1.15
	$\Delta E_{250-280}$	-0.92	-0.87	-0.85	-0.84	-0.82	-0.81	-0.81
B-class	$\Delta E_{220-250}$	-1.76	-1.55	-1.45	-1.41	-1.36	-1.33	-1.30
	$\Delta E_{250-280}$	-1.49	-1.32	-1.24	-1.18	-1.12	-1.08	-1.04
C-class	$\Delta E_{220-250}$	-1.82	-1.58	-1.50	-1.48	-1.46	-1.46	-1.46
	$\Delta E_{250-280}$	-1.37	-1.20	-1.13	-1.09	-1.05	-1.03	-1.01

Comparing the values in tables 4.9, 4.10 and 4.11, the following can be observed:

- An increase in the absolute load level has a positive correlation with the reduction in E_{avg} due to pressure increase.
- The effect of higher compression of the tread block at higher loads and the increased mechanical stiffness of the tread due to a higher pressure interact additively to reduce the hysteresis losses of the rubber compound.
- The highest class-avg. reduction in E_{avg} does not see a consistent trend at all load levels.

4.2.1.3 Contribution of the Warm-up Phase

As explained through figure 4.8, the contribution of the warm-up phase is significant for short travelled distances. This section helps to quantify this additional contribution in terms of percentage and also discuss the influence of change in pressure on this additional contribution.

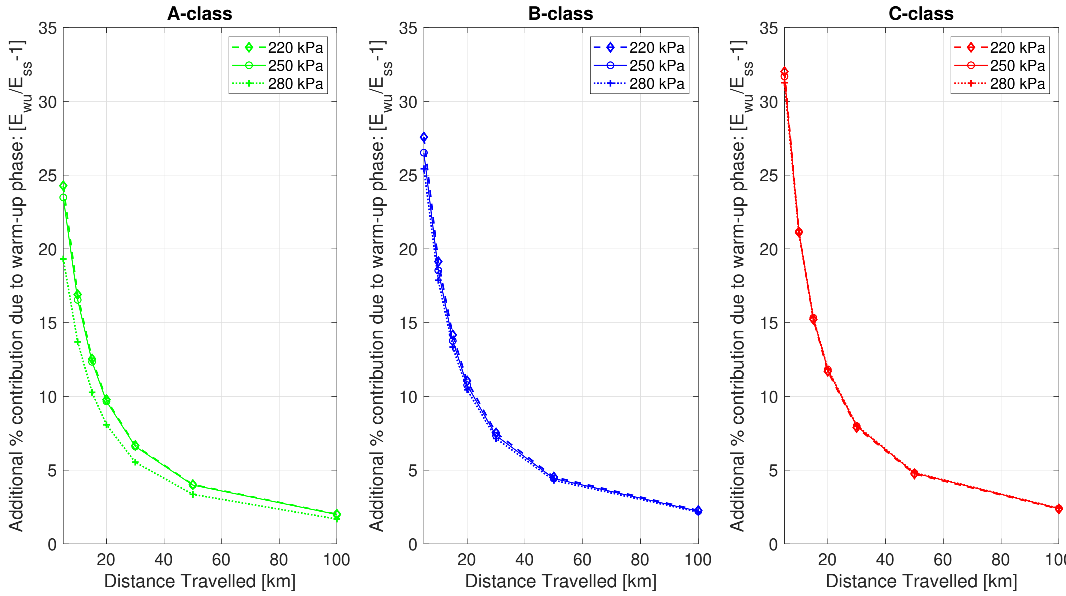


Figure 4.10: Contribution of the warm-up phase in additional percentage for varying pressure and different class of tyres

Each sub-plot in figure 4.10 shows the ratio the actual energy loss including warm-up and the steady-state energy loss expressed as a percentage. At lower distances the % contribution due to warm-up is high and reduces progressively with increasing distances. Based on figure 4.10 the following is observed:

- Depending on the class of tyre, the additional contribution of the warm-up phase varies between 33 % to 25 % at 5 km to 2.5 % at 100 km.
- The C-class tyres have the highest additional percentage contribution of the warm-up phase, followed by the B-class and A-class tyres.
- A change in pressure has almost no effect on the additional percentage contribution of the warm-up phase, as can be seen from each sub-figure in figure 4.10. This observation in interesting as it is seen that the pressure influences the absolute energy loss of the tyre but does not affect the contribution of the warm-up phase. The mechanics of the warm-up phase is correlated to thermal stability of the tyre which is discussed in the subsequent temperature analysis.

4.2.2 Influence of Speed

To analyse the influence of speed (or speed change) on the E_{avg} and warm-up rolling resistance of tyres, we include the contributions of both the main effect and the interaction effects of speed, as was done for the analysis of pressure.

4.2.2.1 Main Effect

The figure 4.11 shows the influence of speed change on the E_{avg} for different class of tyres.

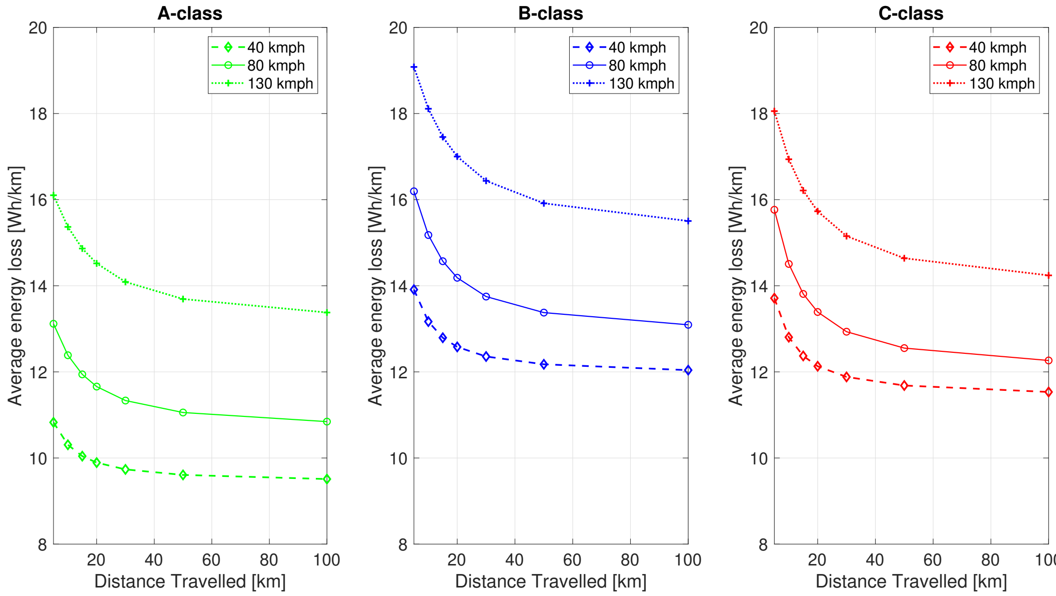


Figure 4.11: Influence of speed on class-average E_{avg} for different class of tyres at 6 kN and 250 kPa. Each subplot represents the influence of speed change on E_{avg} for a given class of tyre.

An increase in speed increases the E_{avg} for each class of tyre. This effect of speed is consistent with the effect observed for the RRc_{ss} and can be explained with the same phenomena discussed for the same. The magnitude of increase in the E_{avg} due to speed change translates into the sensitivity of each class of tyre. The table 4.12 shows the increase in E_{avg} with an increase in the speed level for different class of tyres. 'ΔE_{40-80}' represents the increase in E_{avg} due to speed change from 40 to 80 kmph ($\Delta E_{40-80} = E_{avg,80} - E_{avg,40}$) and similarly '$\Delta E_{80-130}$' represents the increase in E_{avg} due to speed change from 80 to 130 kmph ($\Delta E_{80-130} = E_{avg,130} - E_{avg,80}$).

Table 4.12: Increase in E_{avg} due to speed change at 250 kPa and 6kN for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	ΔE_{40-80}	2.3	2.1	1.9	1.8	1.6	1.4	1.3
	ΔE_{80-130}	3.0	3.0	2.9	2.9	2.8	2.6	2.5
B-class	ΔE_{40-80}	2.1	1.8	1.6	1.4	1.2	1.0	0.8
	ΔE_{80-130}	2.6	2.6	2.6	2.5	2.4	2.2	2.1
C-class	ΔE_{40-80}	2.1	1.7	1.4	1.3	1.0	0.9	0.7
	ΔE_{80-130}	2.3	2.4	2.4	2.3	2.2	2.1	2.0

Based on the figure 4.11 and table 4.12, the following is observed:

- The highest E_{avg} at all speed levels is observed for the B-class tyres (highlighted in yellow). This is contrary to the expectations from the RRc_{ss}, for which the C-class tyres have the highest magnitude. This inconsistency is due to the contribution of the warm-up phase which gets accounted for in E_{avg} as opposed to RRc_{ss} and hence motivates this comparison, as was observed in the main effect of pressure influence.
- For an increase in the speed level from 40 to 80 kmph and from 80 to 130 kmph, the highest reduction in E_{avg} is observed for the A-class tyres. This is consistent with the

corresponding speed change sensitivities observed for the RRc_{ss}.

4.2.2.2 Interaction Effect

The speed vs. load interaction effects are analysed which present us with the following observations:

- For a change in the speed level from 40 kmph to 80 kmph, the highest ΔE_{avg} for all class of tyres is observed at the 9.2 kN load level for distance travelled between 10 to 20 km. Beyond this distance, the energy loss/km due to speed increases is higher for the low load levels. The influence of the speed vs. load interaction effect on the E_{avg} due to speed change is most sensitive at high load levels for short distances travelled (up to 20 km). The effect of increased tread deformation magnitude and higher frequency losses interact additively at high load and speed levels.
- For a change of the speed level from 80 kmph to 130 kmph, the ΔE_{avg} does not show any consistent trend of the interaction effect among the different tyre classes.

A graphical illustration of the speed-load interaction effects discussed above can be seen in the figure A.2.

4.2.2.3 Contribution of the Warm-up Phase

This section discusses the additional contribution due to the warm-up phase and the effect of change in speed on the same.

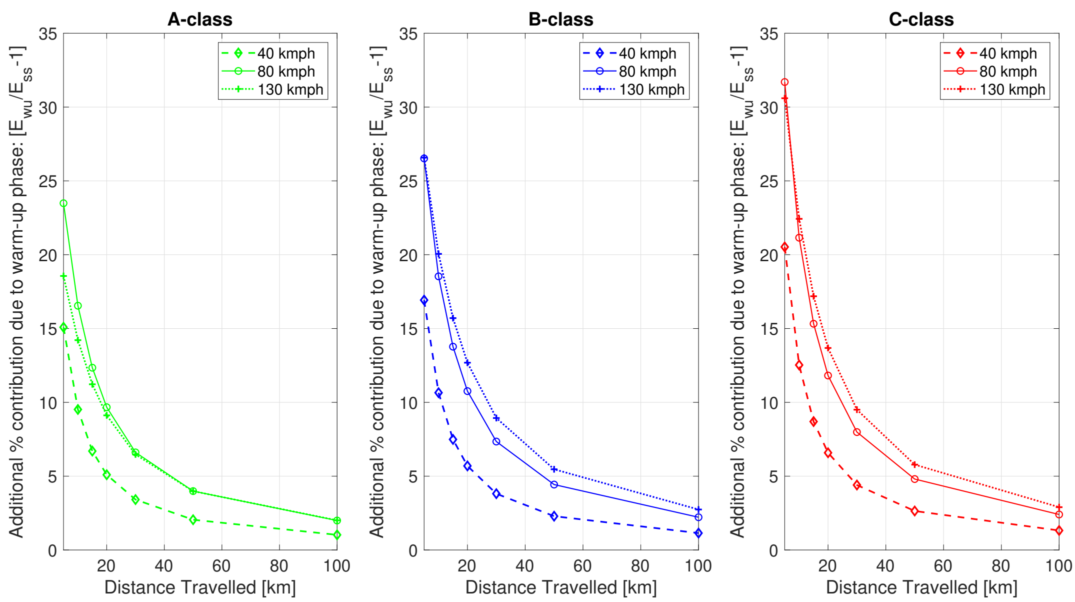


Figure 4.12: Contribution of the warm-up phase in additional percentage for varying speed and different class of tyres

The figure 4.12 shows the following:

- Depending on the class of tyre, the average additional contribution of the warm-up phase varies between 32% to 24 % at 5 km to 2.5 % at 100 km.
- The C-class tyres show the highest addition percentage contribution of the warm-up phase, followed by the B-class and A-class tyres.

- A change in speed has an effect on the warm-up phase at higher speed levels. An increase in the speed from 40 to 80 kmph increases the percentage contribution due to warm-up. The increase in speed accelerates the warm-up of the tyre and attains a higher thermal saturation due to a higher frequency of deformation, however the effect of aerodynamic drag counters this by increasing the rate of heat loss of the tyre to the surroundings.
- A further increase in speed from 80 to 130 kmph has little effect on the contribution of the warm-up phase. This suggests a possibility that at high speed levels, the effect of increase in the rate of heat build-up within the carcass is counteracted in comparable magnitude by the increase in rate of heat loss to the surroundings due to the aerodynamic effect. In summation, the increase in speed from 80 to 130 kmph has minimal effect on the percentage contribution of the warm-up phase.

4.2.3 Influence of Load

This section discusses influence of load (or change in load) on the warm-up phase and energy efficiency of tyres, which includes the 'main effect' and 'interaction effect' of load.

4.2.3.1 Main Effect

The figure 4.13 shows the influence of load change on the E_{avg} for different class of tyres.

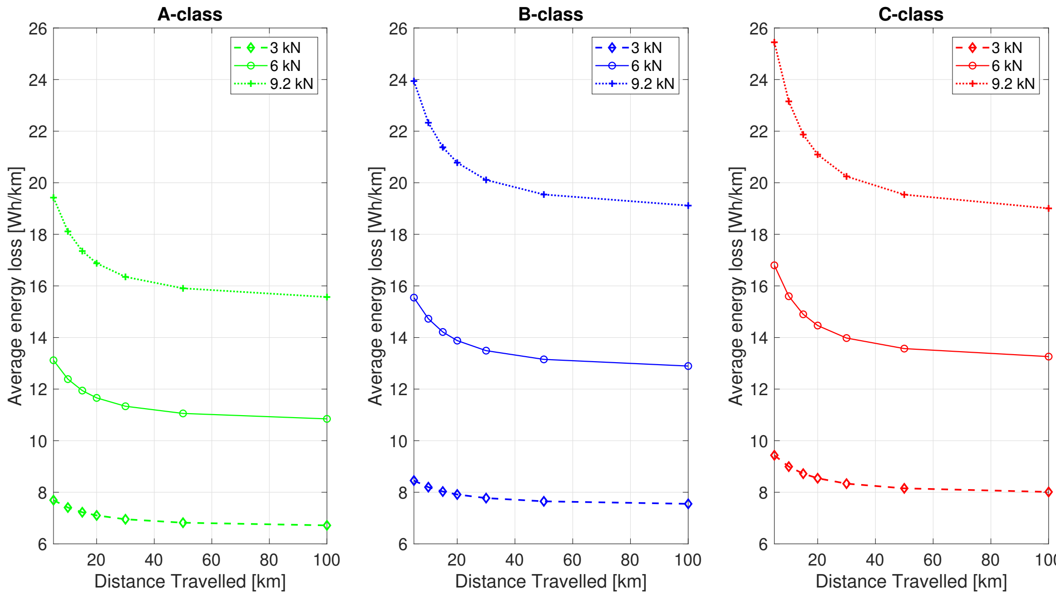


Figure 4.13: Influence of load on class-average E_{avg} for different class of tyres at 80 kmph and 250 kPa. Each subplot represents the influence of load change on E_{avg} for a given class of tyre.

An increase in load increases the E_{avg} for each class of tyre. This effect of load is contrary to the effect observed for the RRc_{ss}. The increasing load increases the absolute rolling resistance force (F_{RR}) which increases the E_{avg} however, the ratio of F_{RR} to F_Z reduces at higher loads as the increases in F_{RR} is proportionally less compared to the increase in F_Z. This concept is often applied in heavy vehicles with multiple axles. During part or low-load operations, some axles are lifted (not driven/rolled) from the ground so as to increase the acting load level on the non-lifted axles such that the net energy consumption of the vehicles is lower. To explain this through figure 4.13, consider the 3 kN and 6 kN E_{avg} curves of any class of tyres; if a load of 6 kN is to be carried by a vehicle it would be more efficient to utilise one tyre (loaded at 6 kN) to perform this as opposed to two tyres (each loaded at 3 kN). Even though the absolute E_{avg} at 6 kN is higher than that at 3 kN, two tyres loaded at 3 kN will have a higher combined E_{avg} than a single tyre loaded at 6 kN. This effect is what the reducing RRc_{ss} with increasing load signifies. The magnitude of increase in the E_{avg} due to load change translates into the sensitivity of each class of tyre. The following are the observations for the increase in E_{avg} due to load change:

- For any given load level, E_{avg} is the highest for the C-class tyres, followed by the B-class tyres and A-class tyres.
- The increase in E_{avg} is higher for an increase from 6 to 9.2 kN as compared to an increase from 3 to 6 kN suggesting the deformation of tyre treads and sidewalls increases non linearly with an increase in the load level.

4.2.3.2 Interaction Effect

The load vs. speed and the load vs. pressure interaction effects are analysed which present the following observations:

Load vs. Speed Interaction Effect: This interaction effect is complex to articulate accurately. Both load and speed individually have strong individual (main) effects on the E_{avg} of tyres due to a combination of physical phenomena affecting the outcome.

- For short driven distances, the increase in E_{avg} due to load change is higher at higher speed levels. However for longer distances, the 40 kmph (low) speed level has the highest increase in E_{avg}.
- This suggests that during the warm-up phase of the tyre which is more evident for short distances, the individual load and speed effects on E_{avg} interact additively. The mechanism causing this outcome for the load vs. speed interaction effect is difficult to reason purely with empirical data.

Load vs. Pressure Interaction Effect:

- For all class of tyres, the increase in E_{avg} due to load increase reduces with an increase in the absolute level of pressure. This means that for each class of tyre the highest E_{avg} is observed at 220 kPa pressure level suggesting the effects of load and pressure on E_{avg} interact additively.
- At any pressure, the C-class tyres have the highest additional energy loss, followed by the B-class and A-class tyres.

4.2.3.3 Contribution of the Warm-up Phase

This section discusses the additional contribution due to the warm-up phase and the effect of change in load on the same.

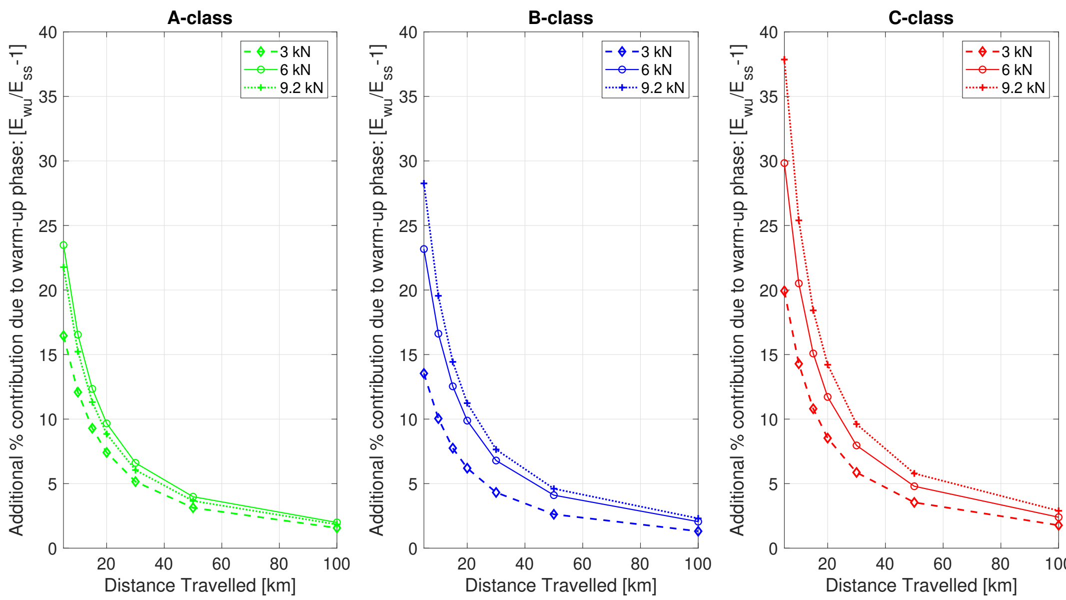


Figure 4.14: Contribution of the warm-up phase in additional percentage for varying load and different class of tyres

The figure 4.14 shows the following:

- Depending on the class of tyre, the average additional contribution of the warm-up phase varies between 38% to 25 % at 5 km to 2.5 % at 100 km.
- The C-class tyres show the highest addition percentage contribution of the warm-up phase, followed by the B-class and A-class tyres.
- A change in the load level has a positive correlation with E_{avg}.
- It is observed from figure 4.13 that at higher loads the E_{avg} curves have a steeper descent and higher reduction w.r.t the initial values. This suggests that the increase in temperature during the warm-up phase is faster at high load levels due to the excessive bending and shearing of the tread and sidewalls. This results in a greater percentage contribution due to the warm-up phase.

4.3 Intra-class variation

An aspect of interest is also the intra-class variation in the energy consumption for tyres that have identical or near identical RRc_{ISO} values. Tyres with identical RRc_{ISO} within the same ISO class are generally perceived as very similar if not indifferent in terms of efficiency. This section investigates the impact of warm-up rolling resistance on the variation in energy efficiency of tyres within a class. For the analysis, a set of three A-class tyres each with identical RRc_{ISO} values (= 6.3) and two B-class tyres with near identical RRc_{ISO} (7.4 and 7.5) are considered. The figure 4.15 shows the intra-class variation at 250 kPa, 80 kmph speed and 6 kN.

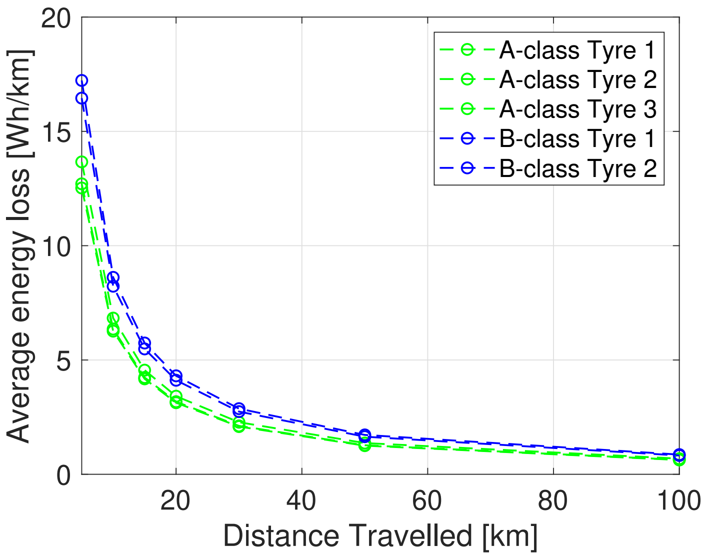


Figure 4.15: Intra-class variation in E_{avg} at 250 kPa pressure, 80 kmph speed and 6kN.

The intra-class variation between the three A-class and two B-class tyres is small compared to the absolute magnitude of E_{avg} however, it is present. This variation in the E_{avg} between the tyres within each respective class is further inspected for a change in pressure, speed and load. To distinguish this variation more clearly, the maximum delta or variation in E_{avg} within a class is graphed.

4.3.1 Influence of pressure

The maximum delta between the E_{avg} within each class at different levels of pressure is shown in figure 4.16.

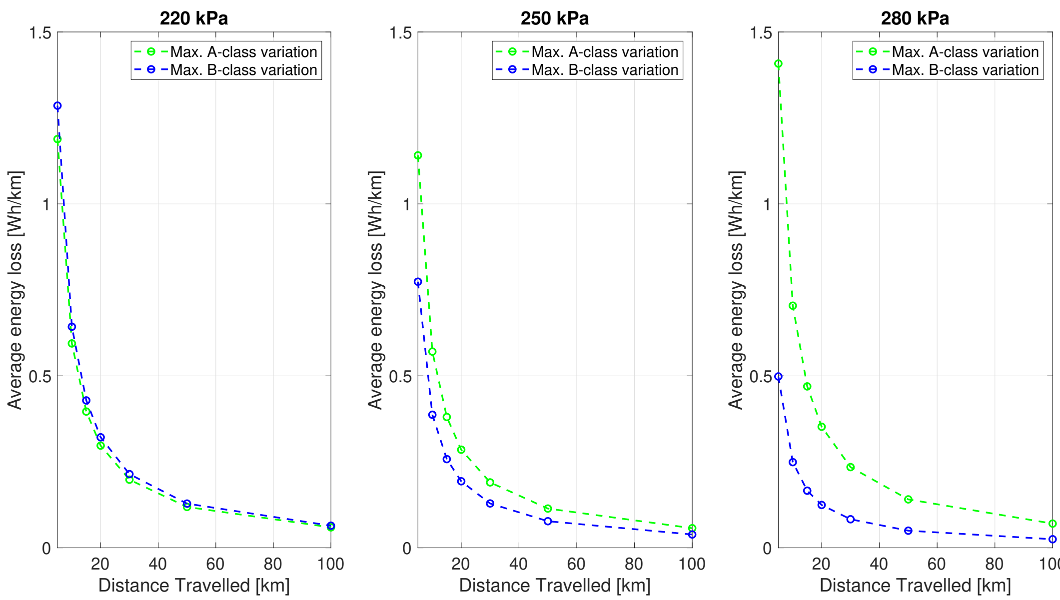


Figure 4.16: Maximum intra-class variation in E_{avg} for varying pressures at 80 kmph speed and 6 kN load.

The following is observed from the figure 4.16:

- The variation has a maximum value of **1.2 to 1.4** $\frac{Wh}{km}$ (depending on the pressure level) for **A-class** tyres. The highest variation is observed at 280 kPa pressure level.
- The variation has a maximum value of **0.5 to 1.3** $\frac{Wh}{km}$ (depending on the pressure level) for **B-class** tyres and the magnitude of variation decreases with an increase in the pressure level. The highest variation is observed at 220 kPa pressure level.

These variations observed can be attributed to the differences in the tyre design parameters, tyre specifications and tyre attributes which were briefly explained in section 2.2. The extent of this variation and the sensitivity of the variation to change in different design parameters, specifications and attributes between tyres with identical RRc_{ISO} is an extensive analysis in itself and is not explored in depth here.

4.3.2 Influence of speed

The maximum delta between the E_{avg} within each class at different levels of speed is shown in figure 4.17.

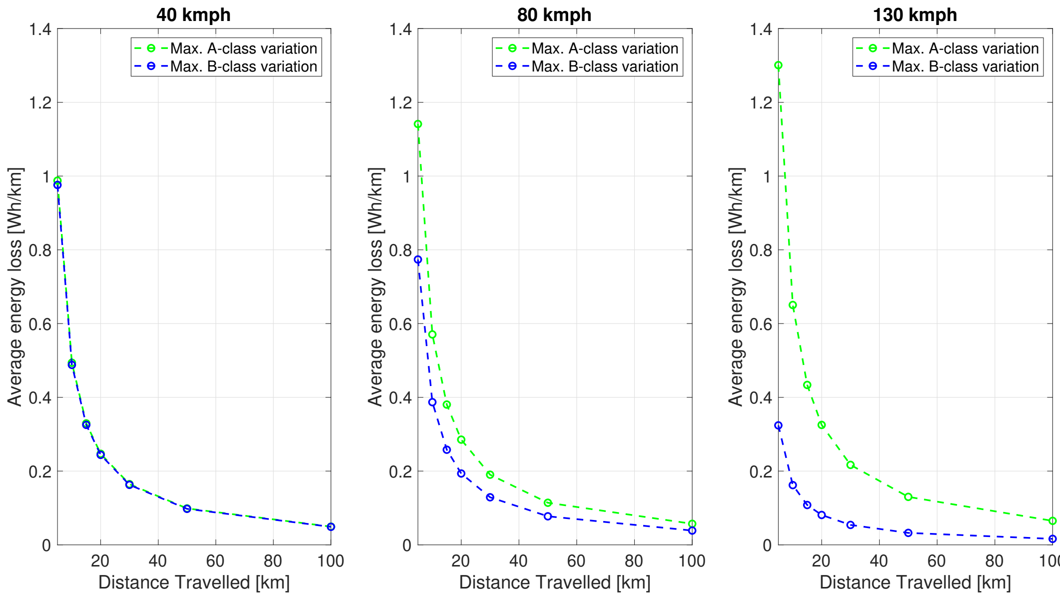


Figure 4.17: Maximum intra-class variance in E_{avg} for change in speed at 6 kN load and 250 kPa pressure

The observations from the figure 4.17 are as follows:

- For the **A-class** tyres, the variation in energy loss increases with an increase in the speed level (as seen across the three subplots). The variation has a maximum value of **1 to 1.3** $\frac{Wh}{km}$ (depending on the speed level) for **A-class** tyres.
- For the B-class tyres the variation decreases with an increase in speed level. The variation has a maximum value of **0.3 to 1** $\frac{Wh}{km}$ (depending on the speed level) for **B-class** tyres.

4.3.3 Influence of Load

The maximum delta between the E_{avg} within each class at different levels of load is shown in figure 4.18.

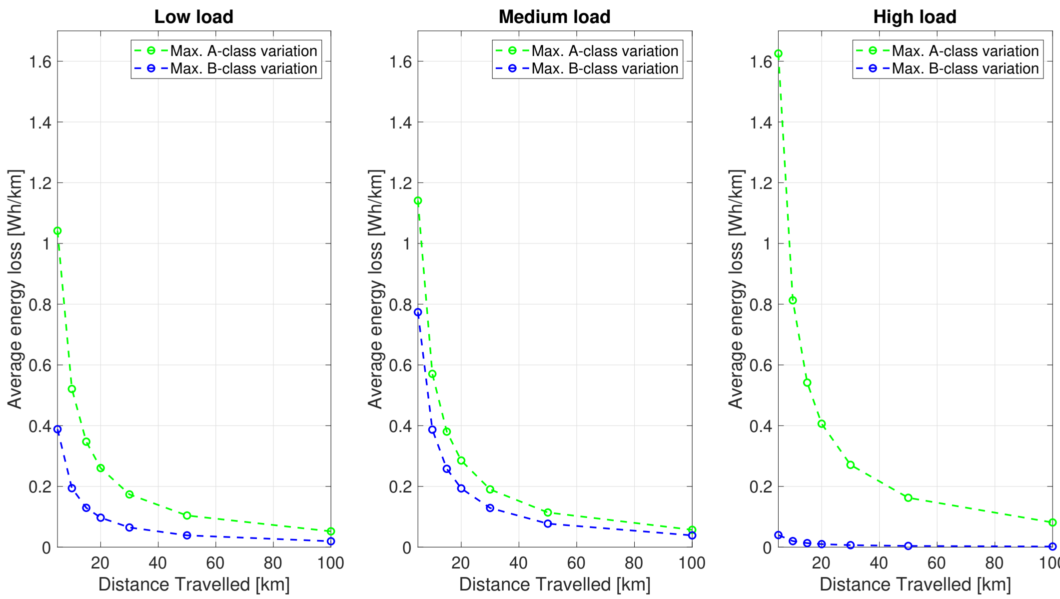


Figure 4.18: Maximum intra-class variance in E_{avg} for change in load at 80 kmph speed and 250 kPa pressure.

The observations from the figure 4.18 are as follows:

- For the **A-class** tyres, the variation increases with an increase in the load level (as seen across the three subplots). The variation has a maximum value between **1.05 to 1.85** $\frac{Wh}{km}$ (depending on the load level).
- For **B-class** tyres the variation has the highest magnitude at at the 6 kN (medium) load level. The variation has a maximum value between **0.05 to 0.8** $\frac{Wh}{km}$ (depending on the load level).

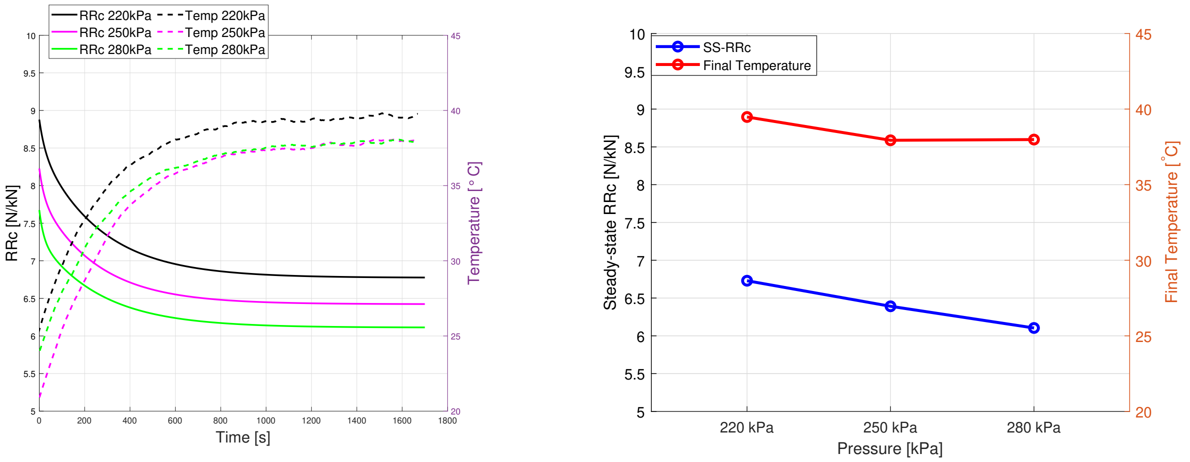
Summarising the observed intra-class variations for changes in pressure, speed and load, the intent is to make the reader aware that tyres with identical RRc_{ISO} indeed do have variations in the actual energy loss. The tyres used for these comparisons were similar sized tyres which suggests that the differences in E_{avg} could be attributed to the difference in manufacturer, tread pattern, tyre compound, wheel and/or tyre design, etc. The A-class tyres showed a higher intra-class variation than the B-class tyres however this cannot be considered as a general extension for all A-class tyres based on just this investigation as the variation is very specific to the tyres considered.

4.4 Temperature Analysis

In this section the analysis of the temperature measurements recorded are discussed. The influence of the variation in the operating parameters pressure, speed and load on the delta temperature ($\Delta T = T_i - T_f$) and final temperature (T_f) during the rolling resistance measurements is studied. The temperatures at the end of each test (T_f) is of particular interest for this analysis. An ANOVA of the final temperatures (T_f) and the difference between the initial and final temperature (ΔT) recorded for the test conditions according to the DoE is performed. This is done to determine the statistical significance of the variation of each operating parameter with the corresponding T_f and ΔT observed.

4.4.1 Influence of pressure

The influence of pressure on the final temperature shows a decreasing trend with an increase in pressure level. The contact patch area reduces at higher pressures, which reduces the amount of tyre contacting the surface. This suggests that the heat generating occurs over a smaller area at higher pressures, reducing the saturation temperature in turn. The slope of the temperature evolution with time at different pressures in figure 4.19(a) appear similar, further suggesting that a change in pressure does not influence rate of heat build up within the tyre carcass, rather only the amount of heat that is generated.



(a) Warm-up RRc and temperature for varying pressures

(b) Steady-state RRc and final temperature for varying pressures

Figure 4.19: Influence of varying pressure on RRc and temperature at 6 kN and 80 kmph

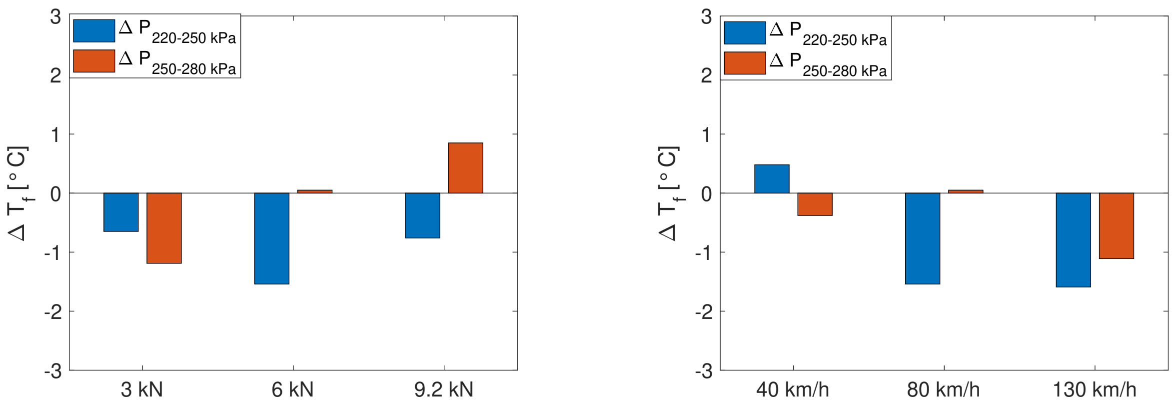
Figure 4.19(a) shows the evolution of RRc and the corresponding temperature over time for varying pressures. The color coded solid lines represent the RRc curves whereas the corresponding colored dashed lines represent the temperature build-up. Figure 4.19(b) shows the variation of RRc_{ss} and T_f for varying pressures from 220 kPa to 280 kPa at a load of 6 kN and 80 kmph speed. It is observed that T_f follows a trend similar to that of the RRc_{ss}.

From the table 4.13 it is observed that with increase in inflation pressure from 220 kPa to 250 kPa a dip in T_f by $1.54°C$ (3.9 %) is observed compared to the T_f at 220kPa. A further increase in the pressure from 250 kPa to 280 kPa shows a lesser increase in the T_f, by about 0.13% compared to T_f at 250 kPa.

Table 4.13: Change in T_f and ΔT due to pressure change

Pressure change [kPa]	$\Delta T_f °C$	% changeΔT_f
220 to 250	-1.54	-3.90
250 to 280	0.05	0.13

An ANOVA of the T_f and ΔT performed is presented in figure A.3. This gives us the information about the contribution of main effect and interaction effects due to change in pressure. The variation in the temperatures due to pressure change is 0.12% for T_f and 0.03% for ΔT. Also the p-value of the main effect of pressure change on the T_f and ΔT is ≥ 0.05 suggesting that the effect of pressure on the observed temperatures is not statistically significant. As for the interaction effects, the p-value observed for both pressure vs. load and pressure vs. speed interaction effects are ≥ 0.05, meaning the global influence of pressure variation on the final or delta temperature is not significant, or rather does not have a significant variance.



(a) Interaction effect of pressure vs. load on change in final temperature

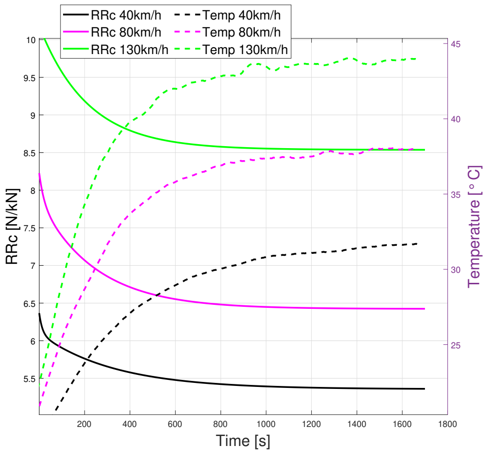
(b) Interaction effect of pressure vs. speed on change in final temperature

Figure 4.20: Interaction effect of pressure vs. load and pressure vs. speed on change in final temperature

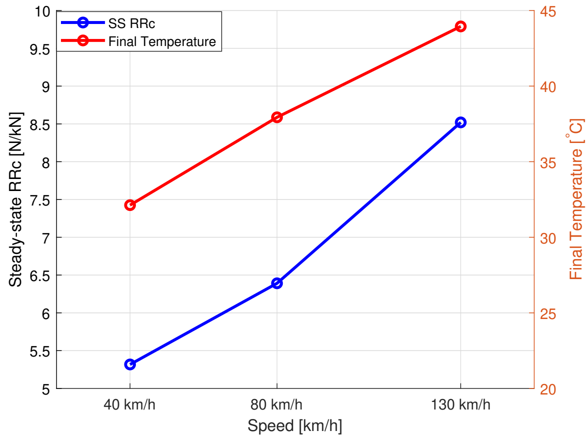
The figure 4.20 shows the interaction effects of pressure vs. load and pressure vs. speed on change in T_f. In figure 4.20(a) it is observed that for a change in pressure from 220 to 250 kPa at different load levels, the change in T_f varies between -0.8 to 0.8 $°C$. Similarly for change in pressure from 250 to 280 kPa at the different load levels, the change in T_f is between 0.8 to 1.2$°C$. The variations are small in comparison to the absolute magnitude of T_f. Similarly for the pressure vs. speed interaction effect in figure 4.20(b), for a change in pressure from 220 to 250 kPa at different speed levels, the change in T_f is within -2$°C$. For a change in pressure from 250 to 280 kPa the change in temperature is between -1.2 to 0.4$°C$.

4.4.2 Influence of speed

The influence of speed variation on T_f shows an increasing trend with an increase in the speed level. This can be explained by the increased deformation frequency at higher speeds which results in a faster build-up of the temperature and lesser time available for the tyre to lose heat to the surroundings.



(a) Warm-up RRc and temperature for varying speeds



(b) Steady-state RRc and final temperature for varying speeds

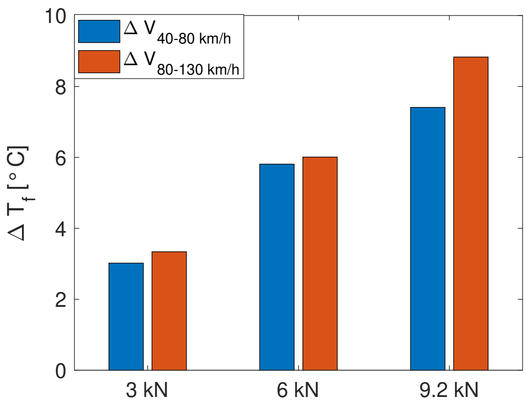
Figure 4.21: Influence of varying speed on RRc and temperature at 250kPa and 6 kN

The figure 4.21 shows the variation in the warm-up temperature (figure 4.21 a) and the T_f (figure 4.21 b) for different levels of speed. It is observed that T_f has a positive correlation with speed as well as with RRc_{ss}. The table 4.14 shows the increase in T_f due to speed change. Higher speeds witness a higher increase in T_f.

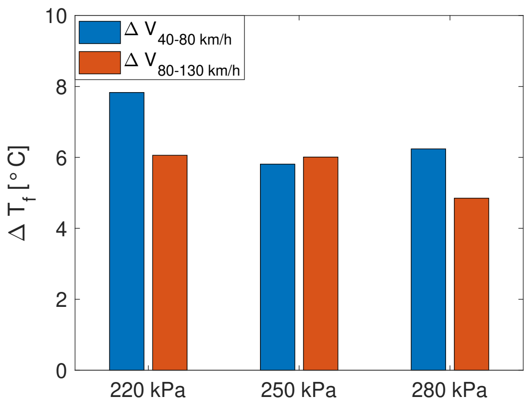
Table 4.14: Change in final temperature due to speed change

Speed[km/h]	$\Delta T_f °C$	**% change**ΔT_f
40-80	5.81	18.09
80-130	6.01	15.85

The variation in ΔT_f due to different load levels is between 4.4 and 5.5$°C$ and the variance in ΔT_f due to different pressure levels is between -2 to 1.2$°C$.



(a) Interaction effect of speed vs. load on final temperature



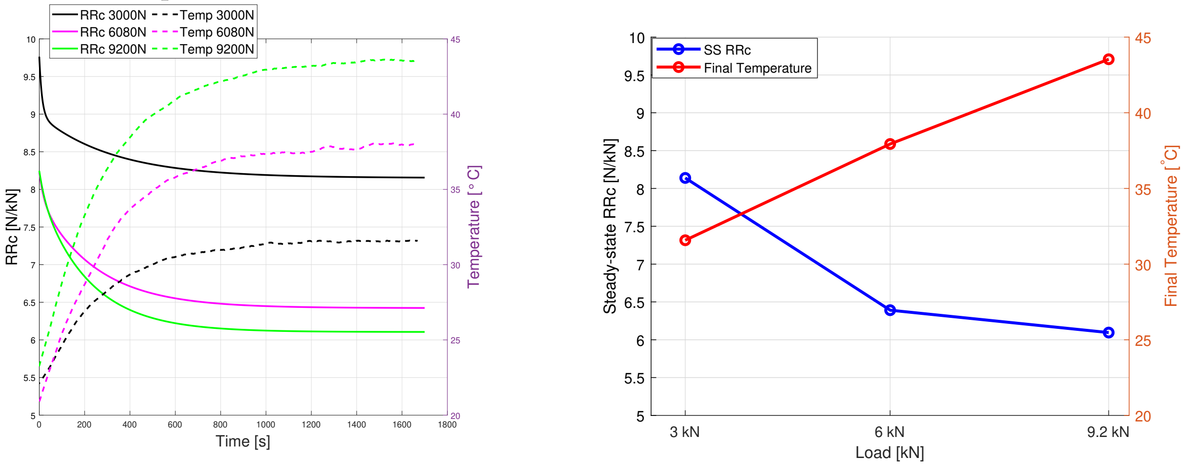
(b) Interaction effect of speed vs. pressure on final temperature

Figure 4.22: Interaction effect of speed vs.load and speed vs. pressure on change in final temperature

The ANOVA of the T_f based on the DoE showed the contribution of speed as 43.8% towards the variance observed in T_f. The results are presented in figure A.3.

4.4.3 Influence of load

The influence of load variation on T_f shows an increasing trend with an increase in the load level. Higher load levels result in a larger contact patch due to increased compression force as well as greater bending and shearing of the tread block and sidewalls. Both phenomena result in increased temperature levels.



(a) Warm-up RRc and temperature for varying loads

(b) Steady-state RRc and final temperature for varying loads

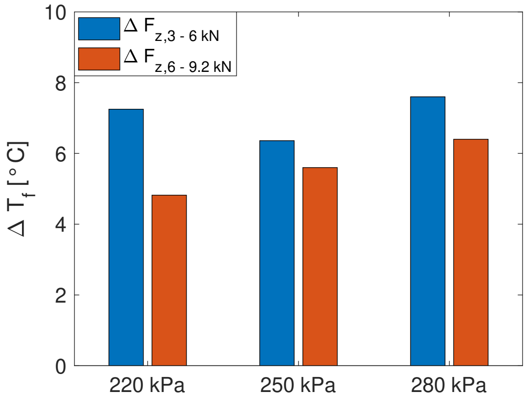
Figure 4.23: Influence of varying load on RRc and temperature at 250 kPa and 80 kmph

The figure 4.23 shows the variation in the warm-up temperature (figure 4.23 a) and T_f (figure 4.23 b) for different levels of load. It is observed from figure 4.23 that temperature has a positive correlation with change in load. The phenomena causing this has been discussed above. The table 4.15 shows the increase in T_f due to load change. It is observed that an increase in load from 3 kN to 6 kN increases the T_f by 6.3$°C$ (20%) compared to T_f at 3000N and a further increase in load from 6 kN to 9.2 kN increases the T_f by 14% compared to the T_f at 6 kN.

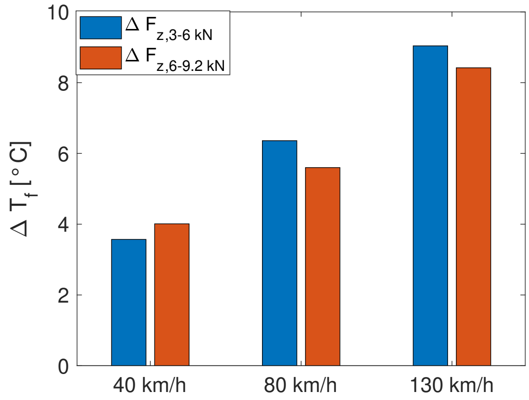
Table 4.15: Change in final temperature due to load change

Load [kN]	$\Delta T_f °C$	**% change**ΔT_f
3 - 6	6.36	20.14
6 - 9.2	5.60	14.77

The interaction effects of load vs. pressure and load vs. speed are compared in figure 4.24. For a change in pressure levels, the variation in ΔT_f due to load change is between 0.8 to 1.2 $°C$. For a change in the speed levels however, the variation in T_f due to load change is between 4.4 to 5.4 $°C$. The suggests a stronger influence of the speed effect on the influence of load on T_f.



(a) Interaction effect of load vs. pressure on change in final temperature



(b) Interaction effect of load vs. speed on change in final temperature

Figure 4.24: Interaction effect of load vs. pressure and load vs. speed on change in final temperature

The ANOVA of the T_f based on the DoE showed the contribution of load as 50.8% towards the variance observed in T_f. The results can be found in figure A.3.

5 Discussions

The discussions of the analysis of the RRc_{ss} and the energy consumption including contribution of the warm-up phase are presented in this section.

5.1 Steady State RRc

The influence of pressure, speed and load on the RRc_{ss} in terms of the correlation and magnitude of change is discussed individually for each operating parameter.

5.1.1 Influence of pressure

The influence of pressure presents a negative correlation with the RRc_{ss} which aligns with the literature. Out of the set of tyres analysed the highest class-average reduction in RRc_{ss} is observed for the B-class tyres. The reduction in RRc_{ss} is presented in table 5.1.

Table 5.1: Class avg. reduction in RRc_{ss} due to pressure change at 80 kmph and 6 kN load.

Tyre class	$\Delta RRc_{220-250}$	$\%\Delta RRc_{220-250}$	$\Delta RRc_{250-280}$	$\%\Delta RRc_{250-280}$
A-class avg.	-0.436	-6.5	-0.260	-4.2
B-class avg.	-0.580	-8.2	-0.401	-5.7
C-class avg.	-0.578	-6.9	-0.388	-5

The reduction in RRc_{ss} due to pressure change from 250 to 280 kPa is lesser than that for 220 to 250 kPa, which suggests that the magnitude of RRc_{ss} reduction is lower at higher pressure levels. The ANOVA of the RRc_{ss} based on the DoE presented the pressure vs. load interaction effect as statistically significant. The interaction effect results in a greater reduction in RRc_{ss} due to pressure change at higher load levels implying the effects of pressure and load interact additively on the RRc_{ss}.

5.1.2 Influence of speed

The influence of speed presents a positive correlation with the RRc_{ss} which aligns with the literature. The highest class-average increase in RRc_{ss} is observed for the A-class tyres. The increase in RRc_{ss} is presented in table 5.2:

Table 5.2: Class average increase in RRc_{ss} due to speed change at 250 kPa and 6kN load.

Tyre class	ΔRRc_{80-40}	$\%\Delta RRc_{80-40}$	ΔRRc_{130-80}	$\%\Delta RRc_{130-80}$
A-class avg.	0.704	12.7	1.446	23
B-class avg.	0.516	7.5	1.337	17.9
C-class avg.	0.341	4.6	1.237	15.9

The higher magnitude of increase in RRc_{ss} at higher speeds is due to a combination of the aerodynamic drag effects and the material loss properties. The RRc_{ss} and the corresponding final temperatures (T_f) both show a positive correlation with speed indicating a higher thermal saturation level at higher speed levels, which reduces the visco-elastic losses of the tyre. However the increases in the material deformation frequency coupled with the aerodynamic effects present a dominant effect at higher speeds resulting in a net increase of the RRc_{ss}. The effect of the aerodynamic losses at higher speeds has not been investigated in separation to the material losses but is assumed to be present since its contribution is included in the rolling resistance measurements recorded and is not compensated for. The speed vs. load interaction effect presents a lower increase in RRc_{ss} at higher load levels. This can be reasoned with the increase in temperature at higher loads which reduces the visco-elastic losses of the tyre. Since the aerodynamic effects at higher speeds are unaffected by the load level, the speed and load interact additively by increasing the saturation temperature level which results in a reduction of the magnitude of ΔRRc_{ss} at higher loads.

5.1.3 Influence of load

The influence of load presents a negative correlation with the RRc_{ss}. The highest class-average reduction in RRc_{ss} is observed for the C-class tyres. The reduction in RRc_{ss} due to load increase in shown in table 5.3:

Table 5.3: Class average reduction in RRc_{ss} due to load change at 250 kPa and 80 kmph

Tyre class	$\Delta RRc_{3kN-6kN}$	$\%\Delta RRc_{3kN-6kN}$	$\Delta RRc_{6kN-9.2kN}$	$\%\Delta RRc_{6kN-9.2kN}$
A-class avg.	-1.679	-21	-0.350	-5.6
B-class avg.	-1.446	-11.1	-0.169	-1.8
C-class avg.	-1.783	-18.9	-0.439	-5.7

The increase in T_f at higher loads reduces the visco-elastic losses of the rubber resulting in a reduction of the RRc_{ss}. The higher T_f at higher loads is caused due to the increased bending and shearing losses as suggested by literature. The interaction effects of both load vs. pressure and load vs. speed are of significance according to the ANOVA and have been analysed.

- **Load vs. pressure interaction effect:** Pressure has an additive influence on the effect of change in load from 3 to 6 kN. The reduction in RRc_{ss} increases with an increase in the pressure level for all class of tyres. For a change in load from 6 to 9 kN however, the absolute reduction in RRc_{ss} is marginal and hence a trend is not apparent. The C-class tyre is the most sensitive to the load vs. pressure interaction effect.

- **Load vs. speed interaction effect:** Speed does not have an additive influence on the main effect of load change. The reduction in RRc_{ss} due to load change increases with an increase in the absolute level of speed. At 80 and 130 kmph, C-class tyres are the most sensitive to load change and hence will benefit the most. Low speed (40 kmph) however does not adhere to the trend for load change of 6 to 9.2 kN, where interestingly an increase in RRc_{ss} is observed which is the only **anomaly** with regards to the 'main effect' of load change.

5.2 Warm up rolling resistance and energy efficiency

The results of the energy consumption and contribution due to the warm-up rolling resistance are discussed here. The influence of each operating parameter on the energy consumption is discussed individually and a comparison with the corresponding results of the steady state RRc is addressed as well.

5.2.1 Influence of pressure

The 'main effect' of the pressure influence shows a negative correlation with the average energy loss (E_{avg}). This is consistent with the influence of pressure change on the RRc_{ss}. The results for the reduction in E_{avg} due to pressure change are presented in table 5.4. The absolute reduction in E_{avg} along with the corresponding percentage reduction of E_{avg} is presented.

Table 5.4: Reduction in E_{avg} due to pressure change at 80 kmph and 6 kN for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	$\Delta_{220-250}$	-0.97	-0.87	-0.83	-0.80	-0.77	-0.75	-073
	$\Delta_{250-280}$	-0.48	-0.48	-0.47	-0.47	-0.46	-0.46	-0.45
B-class	$\Delta_{220-250}$	-1.63	-1.48	-1.39	-1.33	-1.27	-1.22	-1.18
	$\%\Delta_{220-250}$	-9.1	-8.8	-8.7	-8.6	-8.5	-8.4	-8.3
	$\Delta_{250-280}$	-1.05	-0.94	-0.88	-0.85	-0.82	-0.79	-0.77
	$\%\Delta_{250-280}$	-6.4	-6.2	-6.1	-6	-6	-5.9	-5.9
C-class	$\Delta_{220-250}$	-1.14	-1.01	-0.95	-0.92	-0.89	-0.87	-0.85
	$\Delta_{250-280}$	-0.91	-0.81	-0.76	-0.73	-0.70	-0.69	-0.67

Comparing the results between RRc_{ss} (table 5.1) and E_{avg} (table 5.4), both show the B-class tyres as most sensitive to pressure increase. The RRc_{ss} shows a reduction of 8.2 % and 5.7 % for increase in pressure from 220 to 250 kPa ($\Delta_{220-250}$) and 250 to 280 kPa ($\Delta_{250-280}$) respectively. For the E_{avg} reduction however, a percentage change starting from 9.1 % and 6.4 % (at 5 km distance travelled) for the corresponding pressure changes is observed, which reduces to 8.3 % and 5.9 % respectively. The latter values are closer in magnitude to the changes observed in $\%\Delta RRc_{ss}$ reduction. Also of interest is the fact that the highest E_{avg} observed was for the B-class tyres whereas the highest RRc_{ss} was for the C-class tyres. This indicates that just the RRc_{ss} alone is not a good measure for evaluating the energy efficiency of tyres and the effect of the warm-up phase on the energy efficiency is of importance.

The additional contribution due to the warm-up phase is between 33% and 25% at 5 km driven distance and reduces to 2.5 % at 100 km. The change in pressure has almost no influence on the additional contribution of the warm-up phase. This is correlated to the very small change in T_f as well as similar temperature evolution curves at different levels of pressure.

5.2.2 Influence of speed

The 'main effect' of the speed influence shows a positive correlation with the E_{avg}. This effect is consistent with that observed for the RRc_{ss}. The results for the increase in E_{avg} due to speed change are shown in the table 5.5. The absolute increase of E_{avg} along with the corresponding percentage increase of E_{avg} is presented.

Table 5.5: Increase in E_{avg} with change in speed at 250 kPa and 6 kN for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	Δ_{40-80}	2.3	2.1	1.9	1.8	1.6	1.4	1.3
	$\%\Delta_{40-80}$	21	20	19	18	16	15	14
	Δ_{80-130}	3.0	3.0	2.9	2.9	2.8	2.6	2.5
	$\%\Delta_{80-130}$	25	24	24	24	24	24	23
B-class	Δ_{40-80}	2.1	1.8	1.6	1.4	1.2	1.0	0.8
	Δ_{80-130}	2.6	2.6	2.6	2.5	2.4	2.2	2.1
C-class	Δ_{40-80}	2.1	1.7	1.4	1.3	1.0	0.9	0.7
	Δ_{80-130}	2.3	2.4	2.4	2.3	2.2	2.1	2.0

Comparing the results between RRc_{ss} (table 5.2) and E_{avg} (table 5.5), both show the A-class tyres as most sensitive to speed increase. The RRc_{ss} shows an increase of 12.7 % and 23 % for increase in speed from 40 to 80 kmph (Δ_{40-80}) and 80 to 130 kmph (Δ_{80-130}) respectively. For the E_{avg} increase however, a percentage increase starting with 21 % and 25 % for the corresponding speed changes is seen, which reduces to 14 % and 23 % respectively. The latter are closer in magnitude to the changes observed in $\%\Delta RRc_{ss}$ reduction.

The additional contribution due to the warm-up phase is between 32 % to 24 % at 5 km driven distance and reduces to 2.5 % at 100 km. A change in speed increases the percentage contribution of the warm-up phase. The change between higher speed levels (80 kmph and 130 kmph) is lesser than that between low and high speed levels. This suggests a correlation between the increase in T_f and the increase in percentage contribution at higher speeds.

5.2.3 Influence of load

The 'main effect' of the load influence shows a positive correlation with the E_{avg}. This effect is in contrast to that observed for the RRc_{ss} trend with load change. The results for the increase in E_{avg} due to load change are presented in the table 5.6.

Table 5.6: Increase in E_{avg} due to load change at 250 kPa and 80 kmph for varying distances

Class	ΔE_{avg}	5 km	10 km	15 km	20 km	30 km	50 km	100 km
A-class	Δ_{3-6}	5.42	4.98	4.72	4.56	4.38	4.24	4.13
	$\Delta_{6-9.2}$	6.31	5.73	5.41	5.22	5.02	4.85	4.72
B-class	Δ_{3-6}	7.09	6.53	6.19	5.97	5.72	5.50	5.34
	$\Delta_{6-9.2}$	8.40	7.60	7.16	6.90	6.62	6.39	6.22
C-class	Δ_{3-6}	7.37	6.61	6.18	5.92	5.64	5.42	5.25
	$\Delta_{6-9.2}$	8.65	7.55	6.97	6.63	6.27	5.97	5.75

An increase in the load level increase the E_{avg}. No consistent trend of a most sensitive tyre class is observed. A correlation between the effects of RRc_{ss} and E_{avg} is not apparent. A lower load level certainly has a lower E_{avg} however the RRc_{ss} is much higher as compared to a higher load level. The interpretation of the combined effects of the RRc_{ss} load trend and E_{avg} load trend is explained in section 4.2.3.

The additional contribution due to the warm-up phase is between 38 % to 25 % at 5 km driven distance and reduces to 2.5 % at 100 km. A change in load increases the percentage contribution of the warm-up phase. The change between higher load levels (6 kN and 9.2 kN) is lesser than that between low and high load levels. A correlation between the increase in T_f and the increase in percentage contribution at higher speeds can be suggested for the load influence as well.

5.3 Tyre Temperature

The findings of the tyre temperature variation observed due to changes in the operating parameters are discussed in brief.

5.3.1 Influence of pressure

An increase in the pressure reduces the contact patch area resulting in lower T_f at higher pressures. Variation in pressure has the least effect on the change in T_f observed which is $<$ 2°C in total between the different pressure levels at 6kN and 80 kmph. These observations correlated with the ANOVA of the T_f suggest that pressure variation has no significant effect on the T_f variation and percentage contribution due to warm-up.

5.3.2 Influence of speed

An increase in the deformation frequency of the contact patch at higher speeds results in increased heat generation rate in the tyre, resulting in increased T_f at higher speeds. The variation of speed shows a maximum increase in T_f by 6°C. Change in speed accounts for almost 44 % of the variance observed in the T_f based on the results of the ANOVA, which suggest that speed has a strong influence on the tyre temperature.

5.3.3 Influence of load

An increase in the load level increases the deformation and consequentially the contact area, resulting in more heat generation due to increased friction between the tyre and contact surface. Variation in load shows a maximum increase of T_f by 5-7°C at 80 kmph and 250 kPa. The load variation accounts for about 50 % of the variance observed in the T_f suggesting that load has a strong influence on the tyre temperature.

6 Conclusions

This work investigated the influence of operating parameters; inflation pressure, speed and load variation on the steady state rolling resistance coefficient (RRc_{ss}), the energy consumption in terms of average energy loss per km (E_{avg}) and the additional contribution of the warm-up phase for A-class, B-class and C-class tyres. The rolling resistance measurements of tyres done based on the ISO 28580 protocol were used for the analysis. The DoE for the rolling resistance measurements involved a 3-level variation of each operating parameter which was used to analyse the influence of that parameter.

Inflation pressure and load both have a negative correlation with the RRc_{ss}. Speed has a positive correlation with the RRc_{ss}.

- An increase in pressure results in a reduction of the RRc_{ss} which is beneficial for energy efficiency. Difference in the corresponding percentage reduction of RRc_{ss} and E_{avg} due to pressure change is small. This is because a change in pressure does not have a significant impact on the additional contribution due to the warm-up phase. Changes in the RRc_{ss} value due to pressure change can be used as a conservative approximation of the corresponding reduction in E_{avg}.
- An increase in speed results in an increase of the RRc_{ss} and E_{avg}. Difference in the corresponding percentage increase of RRc_{ss} and E_{avg} due to speed change is significant for short distances and hence the changes in RRc_{ss} cannot be used as an approximation of the corresponding change in E_{avg}. The additional contribution due to warm-up is strongly influenced by change in speed, more so for a change from a low to high speed level (40 to 80 kmph). This correlates to the observed disparity between the corresponding changes in RRc_{ss} and E_{avg} due to speed change.
- An increase in load results in a decrease of the RRc_{ss} and an increase in the E_{avg}. The change in the RRc_{ss} due to load change cannot be used for approximating the corresponding magnitude of change in the E_{avg}. The additional contribution due to warm-up phase is strongly influenced by change in load.

The actual energy loss including the warm-up phase is not well represented by the corresponding steady state RRc's and hence should be considered on its own merit. The tyre's class-average sensitivity of the RRc_{ss} due to change in speed, load and pressure is in correlation with the corresponding sensitivities of the E_{avg}. For short travelled distances the additional contribution due to the warm-up phase towards energy consumption is significant and the E_{avg} is almost 25 to 30 % higher than the corresponding steady state values. With an increase in the travelled distance up to 100 km, this difference reduces to approximately 2.5 %. This additional contribution of the warm-up phase is influenced due to changes in speed and load with a positive correlation with both as discussed above. These findings warrant the consideration of the warm-up phase and actual E_{avg} over just the corresponding RRc_{ss} when evaluating the energy efficiency of passenger car tyres, especially for short driven distances such as inter-city driving during which the warm-up phase has a significant contribution.

7 Future Work

- The rolling resistance measurements performed during this thesis were done in a laboratory environment which did not allow a variation in the ambient temperature. The ambient temperature in the laboratory was between 20-25°C (unregulated). However the primary effect of variation in the ambient temperature on rolling resistance and its secondary effect on the influence of pressure, speed and load on rolling resistance is of interest in regards to real-world applicability and would serve as an crucial dimension to explore as an extension of the work done in this thesis.

- This work focused primarily on the investigation of the energy efficiency aspect of tyres due to the influence of pressure, speed and load. However, changing these operating parameters also has an effect on the other tyre attribute such as NVH, performance, comfort and stability, etc. which was not investigated in this work. This would serve as an interesting future dimension to be added to this investigation which could help shed light on the implications of the ideal energy efficiency targets on other tyre attributes.

- The control parameter of the tyre that was considered to study the influence of pressure, speed and load was the ISO rolling resistance class. In addition to this, other control parameters such as the tyre sizing, construction, tread pattern, family, manufacturer, etc. can be considered as the next set of control parameters to investigate how the influence of warm-up phase and the energy efficiency changes with regards to them. This could be expanded on the intra-class variation which was briefly discussed in this thesis work.

- All the rolling resistance measurements performed in this thesis were done for free rolling tyres as is specified by the ISO 28580 protocol. The influence of the variation in pressure, speed and load on driven (powered) wheels with a torque input was not studied, however would be interesting to be analyzed as well.

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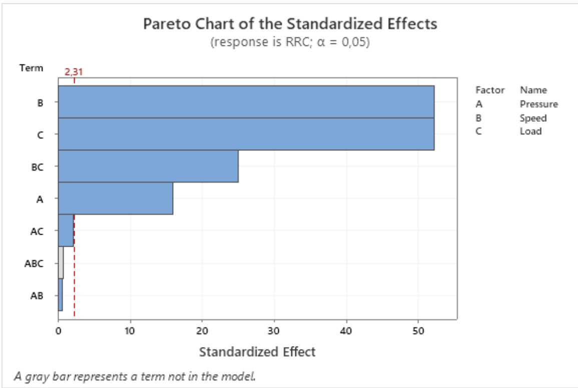
A Appendix

A.1 Steady state RRc

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	18	83,5469	4,6415	586,32	0,00000
Linear	6	73,1248	12,1875	1539,55	0,00000
Pressure	2	2,8140	1,4070	177,74	0,00000
Speed	2	38,9323	19,4661	2459,00	0,00000
Load	2	31,3785	15,6892	1981,90	0,00000
2-Way Interactions	12	10,4221	0,8685	109,71	0,00000
Pressure*Speed	4	0,0247	0,0062	0,78	0,56840
Pressure*Load	4	0,1144	0,0286	3,61	0,05759
Speed*Load	4	10,2830	2,5707	324,74	0,00000
Error	8	0,0633	0,0079		
Total	26	83,6103			

(a) ANOVA of full factorial DoE for an A-class tire



(b) Pareto chart of standardized effects

Figure A.1: Statistical model of steady state RRc variance for an A-class tire.

A.2 Energy consumption and warm-up contribution

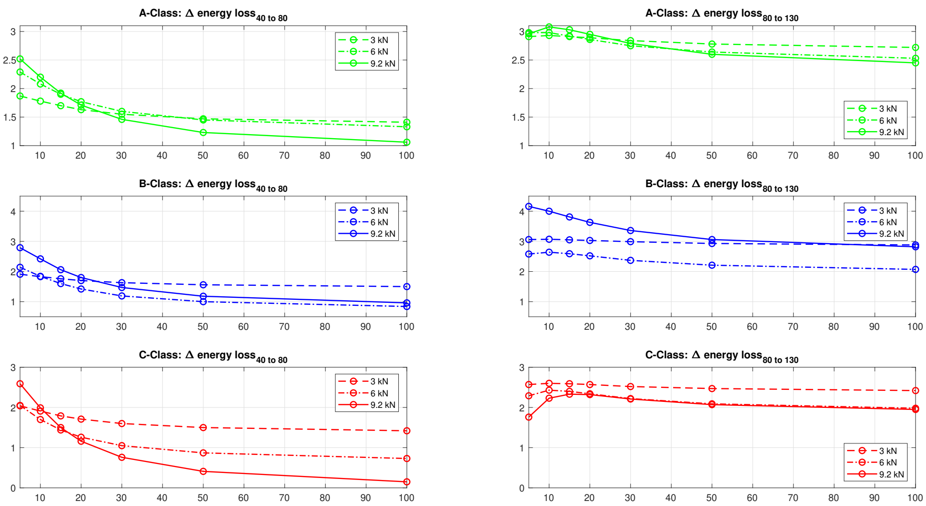


Figure A.2: Class-avg. energy loss due to speed vs. load interaction effect

A.3 Influence on temperature

Analysis of Variance - Final Temperature			
Source	DF	Contribution	P-Value
Model	18	99,58%	0,000
Linear	6	94,77%	0,000
Pressure	2	0,12%	0,354
Speed	2	43,78%	0,000
Load	2	50,86%	0,000
2-Way Interactions	12	4,82%	0,004
Pressure*Speed	4	0,14%	0,642
Pressure*Load	4	0,13%	0,666
Speed*Load	4	4,56%	0,000
Error	8	0,42%	
Total	26	100,00%	

(a) ANOVA of the final temperature based on the full factorial DoE.

Analysis of Variance - Delta Temp			
Source	DF	Contribution	P-Value
Model	18	99,14%	0,000
Linear	6	95,72%	0,000
Pressure	2	0,03%	0,868
Speed	2	48,27%	0,000
Load	2	47,42%	0,000
2-Way Interactions	12	3,42%	0,086
Pressure*Speed	4	0,36%	0,533
Pressure*Load	4	0,20%	0,762
Speed*Load	4	2,86%	0,012
Error	8	0,86%	
Total	26	100,00%	

(b) ANOVA of the change in temperature based on the full factorial DoE.

Figure A.3: ANOVA of measured final and delta temperature

Pressure [kPa]	speed[kmph]	Load[N]	T_i [°C]	T_f [°C]	delta_T [°C]	RRc
220	40	3000	22,197	28,238	6,041	5,899
		6080	18,665	31,645	12,980	5,573
		9200	22,082	36,474	14,392	5,572
	80	3000	23,467	32,226	8,759	8,131
		6080	25,305	39,478	14,173	6,729
		9200	23,717	44,303	20,585	6,084
	130	3000	20,612	34,591	13,979	12,191
		6080	23,808	45,534	21,726	8,211
		9200	23,230	52,817	29,587	7,888
250	40	3000	21,696	28,557	6,861	5,894
		6080	22,660	32,125	9,465	5,317
		9200	22,561	36,133	13,572	5,362
	80	3000	22,091	31,576	9,485	8,139
		6080	20,789	37,937	17,148	6,391
		9200	23,184	43,538	20,354	6,095
	130	3000	20,462	34,913	14,451	11,990
		6080	22,298	43,949	21,651	8,520
		9200	23,472	52,367	28,895	7,460
280	40	3000	23,119	28,827	5,708	5,829
		6080	21,194	31,748	10,554	5,003
		9200	21,513	36,589	15,077	5,075
	80	3000	20,090	30,384	10,294	8,109
		6080	23,835	37,984	14,150	6,104
		9200	25,116	44,388	19,272	5,835
	130	3000	21,673	36,269	14,596	12,117
		6080	21,298	42,838	21,539	8,917
		9200	22,423	51,090	28,667	7,218

Figure A.4: Final and delta temperature data (TTPMS sensor) for the test conditions according to the DoE.

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