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Rolling Resistance Estimation for PCR Tyre Design Using the Finite Element Method

Sutisna Nanang Ali

Abstract

This study presents rolling resistance estimation in the design process of passenger car radial (PCR) tyre by using finite element method. The rolling resistance coefficient of tyres has been becoming one of main requirements within the regulation in many countries as it is related to the level of allowable exhaust gas emission generated by vehicle. Therefore, the tyre being designed must be digitally simulated using finite element method before the tyre is manufactured to provide a high confident level and avoid unnecessary cost related to failure physical product testing. The simulation firstly computes the deformation of several alternative designs of tyres under certain loading, and then the value of deformation force in each tyre component during deformation took place is calculated. The total force of deformation is considered as energy loss or hysteresis loss resulted in tyre rolling resistance. The experiment was carried out on three different tyre designs: two grooves, three grooves, and four grooves. The four groove tyre design gave the smallest rolling resistance coefficient (RRC). Finally, the simulation was continued to compare different crown radius of the tyres and the result shows that the largest crown radius generates the lowest rolling resistance.

Keywords: rolling resistance, PCR tyre, design, hysteresis loss, finite element method

1. Introduction

Passenger car radial (PCR) tyre is one of the most widely used tyres and is designed to follow the international standard and the regulation in the country where the tyre is being used. The recent regulation mainly concerns with the reduction the source of pollution and safety, such as rolling resistance, rolling noise, and wet grip. This study discusses the finite element simulation of tyre in order to design PCR tyre having low rolling resistance coefficient that lead to a low energy consumption tyre.

The energy consumption of vehicle to some extent is contributed by tyres. According to International Council on Clean Transportation [1], improving tyre energy efficiency will reduce fuel consumption by 3 to 5% which will reduce greenhouse gas emission by more than 100 million metric ton annually. Therefore, a low rolling resistance tyre is highly required to reduce the gas emission produce by vehicles.

Tyre rolling resistance is defined as the energy consumed per unit travel distance when the tyre rolls under load [2]. Therefore, lower energy use of vehicle can be obtained by using low rolling resistance tyre.

Tyre design process includes conceptual design, benchmarking, detail design, and design review and analysis. During design review and analysis phase, a simulation was conducted to estimate the value of rolling resistance coefficient. In this simulation, a finite element model was built by using Abaqus software to simulate the tyre deformation and calculate a complete energy loss absorbed by the deformation of rolling tyre under certain load and speed. The hysteresis energy loss was calculated using a user defined subroutine written in Python and is used as Abaqus plug-in.

2. Rolling resistance

Tyre rolling resistance requirement was outlined in United Nation Economic Commission for Europe (UNECE) regulation No. 117 Revision 2, together with rolling sound emission and adhesion on wet surface (wet grip). The country applying this Regulation may refuse to allow the sale or entry into service of a PCR tyre (C1 Class) which does not meet the stage 1 rolling resistance requirements from 1 November 2014 and the stage 2 rolling resistance requirements from 1 November 2018 [3].

However, different countries have different policies regarding implementation standard, date and rating. European Union implements tyre labeling requirement since 2012, where the label states the rating of Rolling Resistance Coefficient, Rolling Sound Emission, and Wet Grip. Gulf Cooperation Council implement GSO standard tyre labeling starting 2014, mandatory for rolling resistance and wet grip.

2.1 Rolling resistance coefficient

UNECE Regulation No. 117–2 defines Rolling Resistance F_r as loss of energy (or energy consumed) per unit of distance traveled, and Rolling Resistance coefficient C_r as ratio of the rolling resistance to the load on the tyre (**Table 1**).

As stated by Tonachel [4], rolling resistance occurs as tyres deform during rotation. The load within the rubber material and rebar that construct the tyre are deformed and the loss of energy during these repeated deformations is then dissipated in the form of heat. The dissipation of energy in radial tyre occurs on crown is estimated about 70%, on sidewall 15%, and bead area 15% [5].

Standard rolling resistance		
	Stage 1	Stage 2
Tyre class	Max value (N/kN)	Max value (N/kN)
C1	12.0	10.5
C2	10.5	9.0
C3	8	6.5
For snow tyres, the limits shall be increased by 1 N/kN.		

Table 1.
Standard RR coefficient based on ECE R117–2.

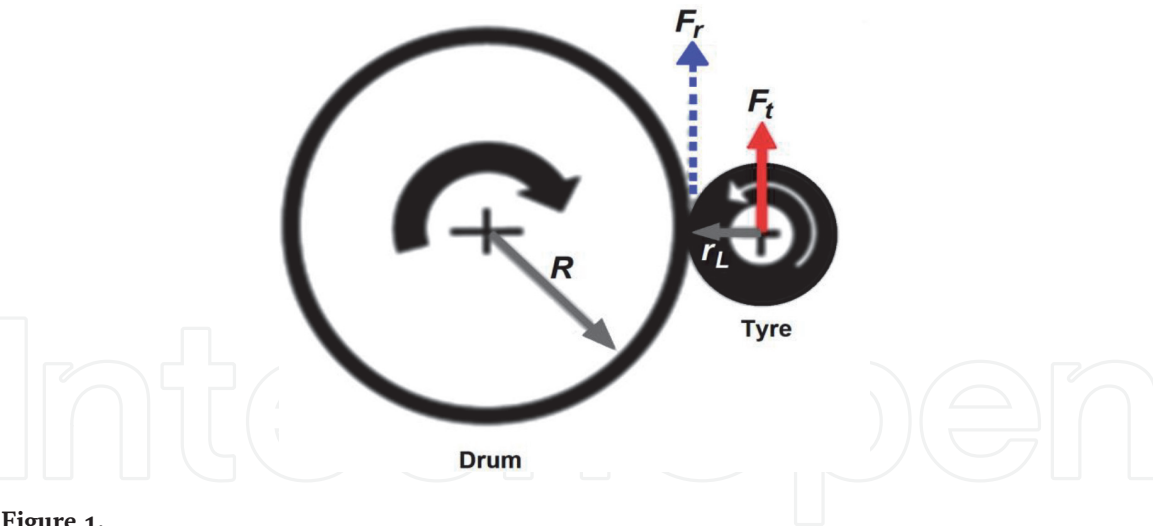


Figure 1.
Rolling resistance test method [6].

Therefore, the research was focused on the crown area. The simulation was done on crown initial radius and the stiffness of tread to study their effect on rolling resistance coefficient C_r .

2.2 Rolling resistance measurement

In this research, the rolling resistance test was conducted according to ISO 28580, i.e. using force measurement method (**Figure 1**). In this method, the tyre and drum wheel assembly is forced toward a drum wheel with the skim load F_{pl} , and the reaction force at the axle of tyre and drum wheel assembly F_t is then measured. The rolling resistance F_r at the contact of tyre and drum can be calculated using the following equation:

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

where F_r Rolling Resistance (N)
 F_t Measured force at the spindle (N)
 r_L Tyre radius (m)
 R Drum wheel radius (1.7 m)
 F_{pl} Skim load (N)

3. Design methodology

Tyre design consists of several phases, including conceptual design, benchmarking, detail design, design review and analysis. Design review and analysis phase is important to ensure that the final product will be in accordance with the required performance as designed. One of the processes in this phase is doing simulation by using finite element method with the following steps [7]:

1. Define target performance
2. Tyre Simulation using FEA
3. Validation of FEA simulation result

3.1 Target Performance

The tyre being designed is PCR tyre with size of 175/65 R14, should have maximum Rolling Resistance Coefficient of 8.5 N/kN and good cornering stability.

3.2 Tyre simulation using FEA

The Finite Element Method is used to analyze the rolling resistance of PCR tyre, consisting of two steps:

1. Tyre simulation was performed using commercial finite element software Abaqus. The simulation consists of several steps as follows:
 - a. FE tyre modeling, using axisymmetric modeling method.
 - b. Define material properties and material modeling.
 - c. Static footprint simulation and Radial stiffness.
2. Energy dissipation and rolling resistance were evaluated by using internally developed python code. The code extracts the strain energy results of the model and the same is post processed with viscous material data. The dissipation energy is calculated based on the strain energy function of Yeoh’s model by taking the product of elastic strain energy and the loss tangent of materials. Computation of Tyre rolling resistance with its respective compounds developed for their applications, performed by considering different crown radius and radial stiffness.

3.2.1 Axisymmetric modeling

To model a tyre in Abaqus we use a cross section area of the tyre drawing and, imported as IGES file, this modeling technique is well known as axisymmetric modeling. All tyre component and their material properties are defined in this step. The tyre components that construct the tyre includes tread, base, wing, inner liner, side wall, apex, rim cushion, bead, JLB (join less belt), belt, and ply, are shown **Figure 2** and made up from four different types of materials and these are rubber compounds, textile fabrics, steel cords and bead wire.

The tyre model in Abaqus consists of two part partition: Carcass and Cord. Carcass and Cord partition were meshed separately, which are modeled in half axisymmetric model and then mirrored, become a complete assembly. In case the tread need to be included in the simulation, for instance to evaluate footprint, the

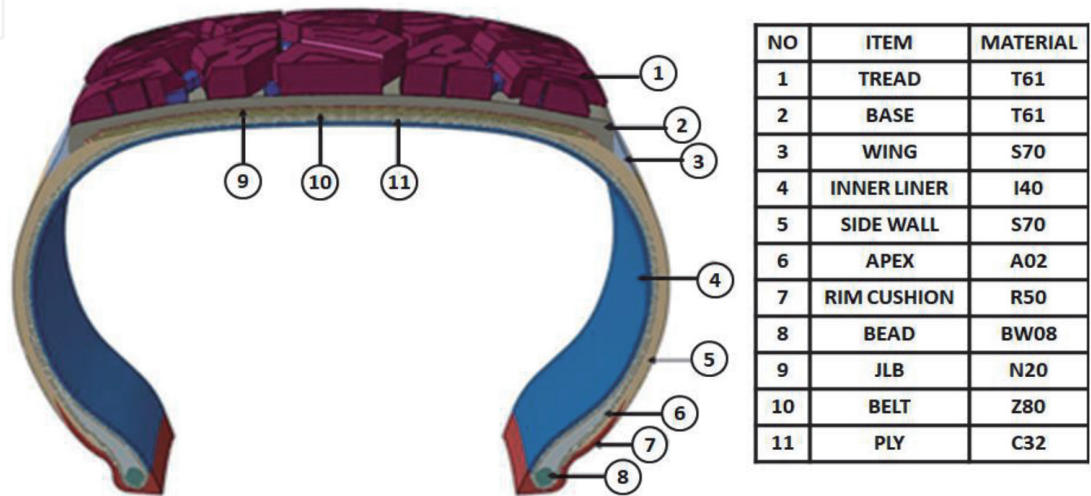


Figure 2.
Sample of Tyre components [7].

tread is meshed separately in addition to Carcass and Cord. Tread meshing need to be carefully done so that the nodes on tread and carcass will be matched perfectly. Later on the rim part is included in the assembly. The axisymmetric model of the tyre after meshing is illustrated in **Figure 3**.

The next steps are defining the mounting, creating constraints, defining boundary conditions, and loading (pressure) prior to running axisymetry function in Abaqus to form a full tyre. **Figure 4** illustrate the axisymmetric tyre with pressure and a full round of the axisymmetric tyre model.

3.2.2 Material properties and modeling

Material properties need to be input into Abaqus during this simulation step, each component should have the following material property data including hardness, density, stress, strain, Young’s modulus, mu, Kappa, C10, and D1. **Table 2** exhibits the full material properties of all tyre components under study.

A model that represents the stress–strain relationship of the material is needed in finite element analyses of rubber components. There are several material models available In Abaqus to describe the mechanical behavior of rubber. The model to be

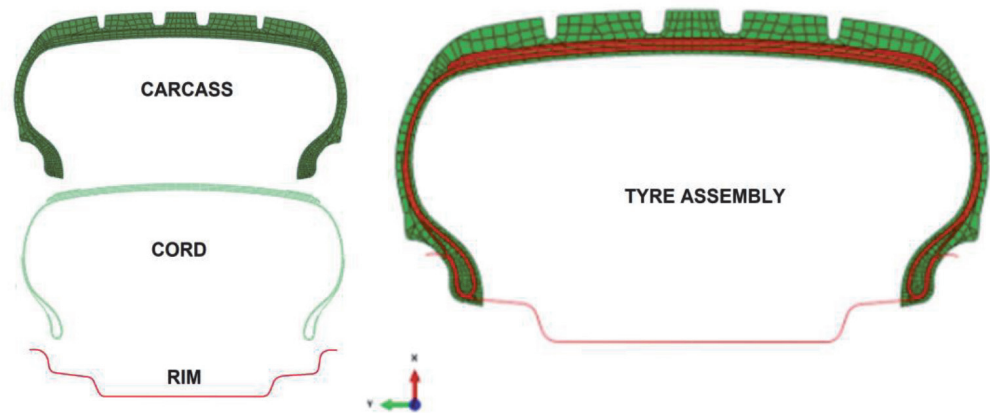


Figure 3.
Tyre meshing of axisymmetric model in Abaqus [7].

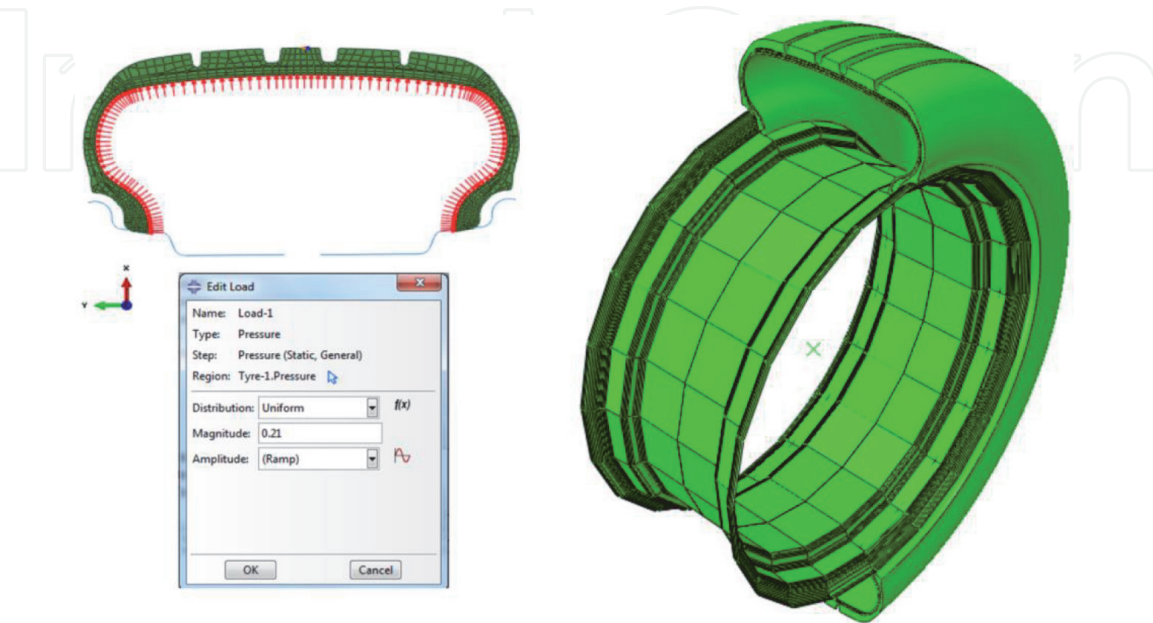


Figure 4.
Pressurized axisymmetric (left) and full axisymmetric Tyre model (right).

used in the analyses depends on several factors such as availability of experimental data, strain range, and complexity of loading.

Each tyre component shows different deformation response under external loading. Rubber exhibits non linear deformation and almost incompressible response, while fabric cords and steel wire withstand most both tension and compressions loads and therefore produce small strain. For rubber, hyper-elastic material models are used to describe high deformation. In this study, Yeoh’s model was chosen to define hyperelastic property of rubber materials and Marlow model for reinforcements such as fabric and steel cords. Bead was modeled as an elastic material.

The Yeoh material model had a cubic form with only I_1 dependence and is applicable to purely incompressible materials. The strain energy density for Yeoh model is written as

$$W = \sum_{i=1}^3 C_i(I_1 - 3)^i \tag{2}$$

where C_i are material constants. C_i quantity is 0.5 of the initial shear modulus.

The reason for using the Yeoh’s model in the rubber material model, despite the fact that Abaqus supports other material models like Neo-Hookean and Mooney-Rivlin, because it is capable of predicting different deformation modes using data from a simple deformation mode like uni-axial tension test. A review by Wei et al. [8] found that most of material models are determined based on the polynomial expression of strain energy function. Although Mooney-Rivlin energy density function has been widely applied for tyre dynamic properties analysis, the function has a limitation that it could not be accurately applied to large deformation problems of the rubber material. Neo-Hookean material model also has a limitation that the coefficients derived from uni-axial deformation tests are not suitable to describe other deformation modes. In order to determine the parameters of rubber hyperelastic property, most of the material models need to combine three deformation tests (uni-axial, biaxial tension and pure shear), which is recognized as a complex and time consuming procedure.

No	Properties	Tread	Under tread	Wing	Inner liner	Side wall	Apex	Rim cushion	Bead	Belt	Ply
1	Hardness	74.00	74.00	62.67	67	59	89	73	82	71	69
2	Density	1.16	1.16	1.09	1.221	1.088	1.163	1.162	1.289	1.182	1.114
3	Stress, Mpa	0.95	0.95	0.49	0.78	0.50	2.00	1.09	1.53	0.84	0.96
4	Strain, %	0.16	0.16	0.16	0.17	0.15	0.17	0.16	0.16	0.16	0.17
5	Young’s modulus	5.94	5.94	3.06	4.68	3.27	12.04	6.78	9.42	5.36	5.73
6	Poisson ratio	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
7	mu	1.99	1.99	1.03	1.57	1.10	4.04	2.28	3.16	1.80	1.92
8	Kappa	99.01	99.01	50.94	77.97	54.47	200.60	113.02	156.95	89.26	95.53
9	C10	1.00	1.00	0.51	0.78	0.55	2.02	1.14	1.58	0.90	0.96
10	D1	0.02	0.02	0.04	0.03	0.04	0.01	0.02	0.01	0.02	0.02

Table 2.
Material properties.

3.2.3 Footprint and radial stiffness analysis

After completing the axisymmetric tyre modeling, the next step is the simulation of tyre under static loading. From this simulation there are two analyses can be further performed: footprint analysis and radial stiffness analysis. For footprint analysis, the load needs to be applied on the tyre to represent the normal load according to the specified load index of the tyre. **Figure 5** shows the tyre under static loading and its respective footprint result.

For designing a new PCR tyre, there are three different tyre were taken for benchmark. The tyre being simulated is of the size 175/65 R14 and were inflated at 2.1 bar (30.5 psi) with various loads of 100 kg, 150 kg, and 200 kg using three types of tyre, called tyre A, tyre B, and tyre C. Tyre A has two grooves, tyre B has three grooves, and tyre C has four grooves.

To obtain more accurate footprint result, the full tyre with tread was modeled so that the contact pressure distribution on the tread which in contact with the road can be evaluated. **Figure 6** exhibits the footprint comparison of these three tyres.

In Abaqus, footprint simulation is performed under static loading and needs several input files for defining geometry, boundary condition, sequence and load of tyre and rim. The result of Abaqus footprint analysis as it is shown in **Figure 6**, suggests that the tyre having two grooves shows the largest contact area at shoulder. Large contact area on shoulder indicates better cornering stability.

The second simulation result is about radial stiffness of the tyre. The radial stiffness mainly depends on sidewall stiffness and affects the transversal bending of tyre. This transversal bending causes the tyre to lose its height by certain value, from initial radius R becomes deflected radius R_{def} , as shown in **Figure 7**.

The R_{def} resulted from simulation of two groove tyre is the largest (see **Table 3**), that means that its radial stiffness is also the largest. Larger radial stiffness gives more cornering stability.

By looking at footprint and radial stiffness, the two groove tyre indicates a better cornering stability compared to the other tyre types.

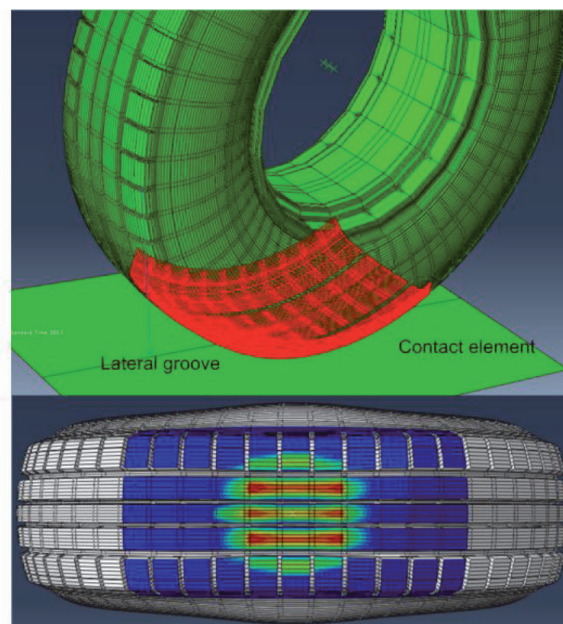


Figure 5.
Footprint simulation under static loading.

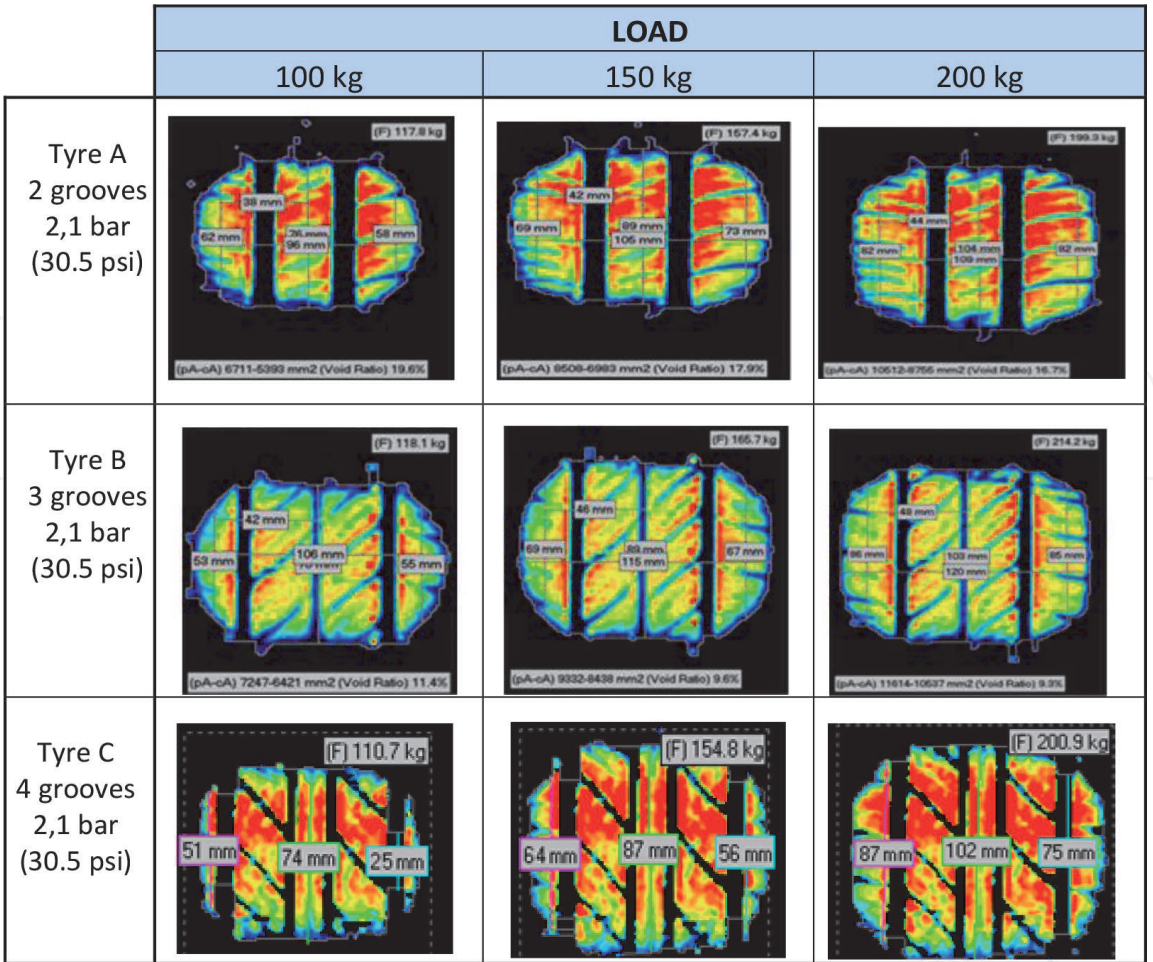


Figure 6.
Footprint comparison of benchmark tyres [7].

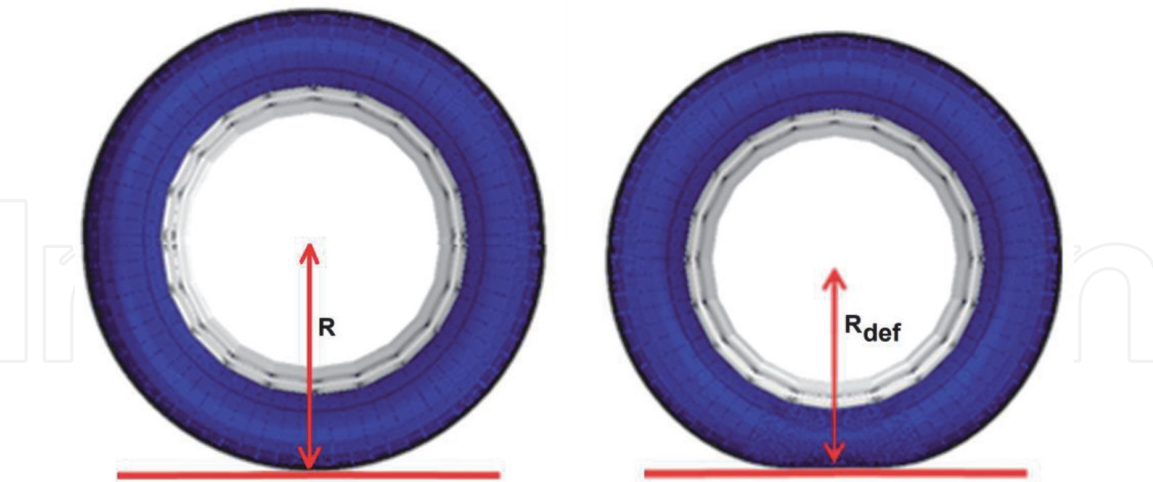


Figure 7.
Tyre deformation.

	2 Groove tyre	3 Groove tyre	4 Groove tyre
R deflection	269.06 mm	268.75 mm	268.54 mm
R initial	291.5 mm		

Table 3.
Value of Tyre radius during deflection.

3.3 Rolling resistance analysis

Rolling resistance force in tyre is mainly generated by friction force, drag force, and hysteresis loss. This study will only discuss rolling resistance force generated by hysteresis loss inside the rubber and cord. The analysis was performed in two main steps, those are static tyre simulation (footprint and radial stiffness) and calculation of strain energy loss to find rolling resistance force.

With review of a number of tyre rolling resistance simulations, it is found that rolling resistance calculation is based on the strain energy loss during a traveled distance. Aldhufairi et al. [9] used a script of Abaqus to extract the 3D tyre model data as input and an analytical rigid road drum with a straight and smooth surface was added to the model, equivalent to that used in the experiment, due to the limitation of the testing machine the travel speed was limited to 30 km/h. Ghosh et al. [10] suggested a method that implements a steady state rolling simulation using Abaqus software to obtained the strain energy and principal strains, together with the loss factors (Tan δ) of the material obtained separately in the laboratory, are used to estimate the energy dissipation of a rolling tyre through post processing. The internal code was developed to perform such a task.

Lind [11] suggested three sequential steps for solving the rolling resistance model; inflation, footprint and rolling. The last rolling step was performed using a dynamic solver setting where the center node was moved in the x-direction with a prescribed acceleration up to a target speed. The rolling resistance was from the FE-simulation result computed in two different ways. The first method uses the contact forces from each node multiplied with its distance from the wheel centre; the second method uses the reaction forces from the constrained middle node and computes the rolling resistance. The result presented for the material model and for the rolling resistance does not aim toward representing any specific tyre rubber compound or tyre.

While the others used FE tyre model without tread, Cho et al. [12] Included the tread in FE tyre model. The hysteretic loss during one revolution was computed with the maximum principal value of the half-amplitudes of six strain components, and the temperature distribution of tyre was obtained by the steady-state heat transfer analysis. The static tyre deformation analysis is performed by ABAQUS/Standard in the deformation module and the strain and stress results are input into the in-house dissipation module where the hysteretic loss, rolling resistance and heat generation rate are computed.

In this study, the footprint analysis was carried out with patterned tyre model and for rolling resistance simulation used tyre model without pattern for the sake of computing time. However, the accuracy is a little sacrificed but still acceptable i.e. 6.2% error as describe in the Section 3.4.

The rolling resistance analysis was based on hysteresis of rubber and cord where the phase of stress lags behind the strain as it is shown in **Figure 8**. The hysteretic loss ΔW per unit volume during a period $T_c = 2\pi/\omega$ is:

$$\Delta W = \int_0^{T_c} \sigma(\tau) \frac{d\varepsilon(\tau)}{d\tau} d\tau = \int_0^{T_c} \sigma_0 \varepsilon_0 \sin(\omega\tau + \delta) \cos(\omega\tau) d\tau = \pi \sigma_0 \varepsilon_0 \sin \delta \quad (3)$$

where σ_0 and ε_0 being the stress and strain amplitudes and ω being the excitation frequency.

In engineering application, as suggested by Cho et.al [9] 3D viscoelastic bodies are subjected to more complicated multi-axial cyclic excitations, so the time histories of strains and stresses are neither one-dimensional nor sinusoidal.

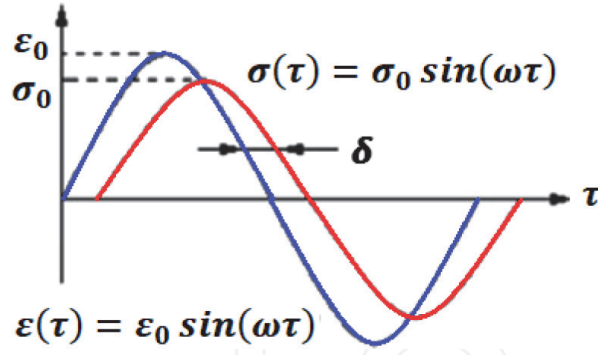


Figure 8.
Stress - strain phase.

Therefore, the hysteretic loss is expressed in a generalized form:

$$\Delta W = \int_0^{T_c} \sigma_{ij}(\tau) \frac{d\varepsilon_{ij}(\tau)}{d(\tau)} d\tau \quad (4)$$

The hysteretic loss can be converted to the heat generation, and the heat generation rate Q per unit volume during a cycle is:

$$Q = \frac{\Delta W}{T_c} = \frac{1}{T_c} \int_0^{T_c} \sigma_{ij}(\tau) \frac{d\varepsilon_{ij}(\tau)}{d(\tau)} d\tau \quad (5)$$

In order to calculate the energy loss during deformation, curve interpolation and FFT function were developed. Abaqus python contains NumPy which can do FFT. A python scripting is used to read signal curve, perform the FFT and create a new curve, i.e. amplitude vs. frequency, for plotting in Abaqus.

```
def interpolation(curve):
    myCurve = []
    i = 0
    n = len(curve)
    myCurve.append(0.0, curve[0])
    while i < n:
        myCurve.append(myAngle[i], curve[i])
        i = (i + 1)
    myCurve.append(360.0, curve[-1])
    i = 0
    n = len(myCurve)
    NewCurve = []
    while i < (n - 1):
        angle_A = (myAngle[i + 1][1] - myAngle[i][1]) /
                  (myAngle[i + 1][0] - myAngle[i][0])
        yo = myAngle[i][1]
        xo = myAngle[i][0]
        j = myAngle[i][0]
        while j < myAngle[(i + 1)][0]:
            newAngle.append(yo + (angle_A * (j - xo)))
            j = (j + delta)
        i = (i + 1)
    if i == (n - 1) and newAngle.append(myAngle[i][1]):
        pass
```

```

return newAngle
def fourier(sigma, epsilon):
    FFT1 = 2 * abs(fft.fft(sigma)) / len(sigma)
    FFT2 = 2 * abs(fft.fft(epsilon)) / len(epsilon)
    k = 0
    total = 0
    while k < (len(FFT1) / 2):
        total = total + (FFT1[k] * FFT2[k]) * k
        k = k + 1
    return total

```

The input for sigma and epsilon are the interpolated stress and the interpolated strain respectively.

In a rolling tyre, the rubber compounds exhibit the complicated 3D dynamic viscoelastic deformation. The strains and stresses are constituted in terms of the complex modulus $G^* = G' + iG''$. In this case, G' is called the storage modulus and G'' is the loss modulus. The complex modulus is a function of the strain amplitude ϵ_o , frequency f , and temperature T . The correlation between storage and loss modulus in terms of the phase difference δ as follows:

$$\tan \delta = \frac{G''}{G'} \text{ and } G'' = G' \sin \delta \quad (6)$$

In Abaqus simulation the complex modulus G^* can be obtained by extracting axisymmetric element data and therefore the heat dissipation from energy loss G'' can be calculated by multiplying G' and $\sin \delta$, and in terms of Python coding is written as follows:

$$\text{heat_dissipation} = \text{energy} * \sin(\text{tand}) \quad (7)$$

Where energy is extracted from previous axisymmetric simulation element data and tand is from input data.

The rolling resistance force generated by the hysteretic loss is computed as the total hysteretic loss of the rolling tyre during one revolution divided by the traveling distance of tyre during the same period of time, hence:

$$F_{RR} = \frac{W}{2\pi r} \quad (8)$$

where $W = \int_{\Omega} \Delta W dV$

r = effective radius of tyre

Ω = material volume of tyre

Rolling resistance coefficient C_r is the indication of how large the rolling resistance is for a given load upon which it is rolling and is calculated by:

$$C_r = \frac{\text{Total force (N)} \times 1000}{\text{Load (N)}} \text{ N/kN} \quad (9)$$

Total force is meant the sum of force caused by hysteresis loss in each tyre component material.

To analyze the force produced by tyre component materials, a Python code was developed as plugin in Abaqus software. The process of analyzing the rolling resistance is describe in the following steps and is shown in **Figure 9**.

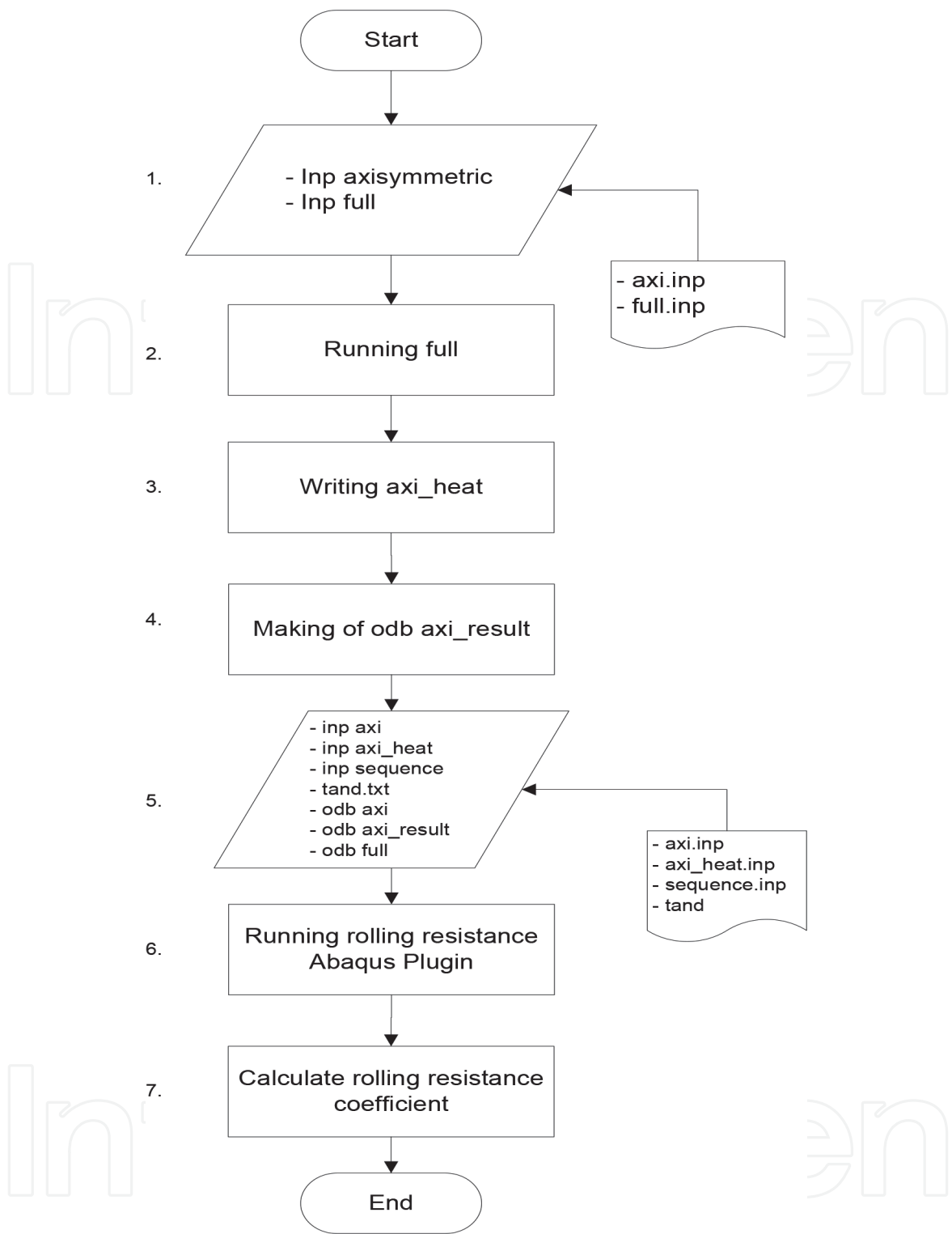


Figure 9.
Rolling resistance analysis process using Abaqus plugin.

1. Prepare input files, i.e.:
 - Axisymmetric input file (axi.inp)
 - Full tyre input file (full.inp)
2. Running full tyre model simulation in Abaqus using the input files in step 1 in command prompt with the following command:
Abaqus job = full oldjob = axi cpus = 4

3. Writing axi_heat input file:

- Copy axi, inp and rename it to axi_heat.inp
- Change the tyre element type from cgax into dcax
- Delete input of tyre_coord and rim
- Delete all properties in each material and replace with:
*conductivity: 0.2
- Delete all existing steps and boundary conditions and replace with steps and boundary conditions necessary for rolling resistance simulation

4. Copy axi.odb and rename it into axi_result.odb

5. Input data needed for running rolling resistance simulation:

a. Input files:

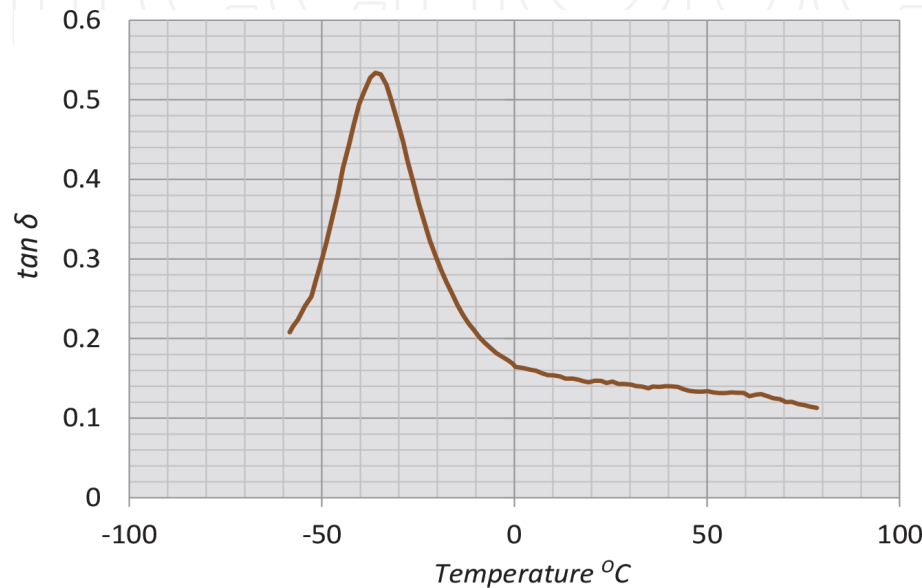
- axi.inp
- axi-heat.inp
- sequence.inp

b. Odb files:

- axi. Odb
- axi_result.odb
- full.odb

c. Tan delta data: tand.txt.

Below is tan- δ example of tread compound.



6. Running rolling resistance calculation using Abaqus plugin after specifying the required data as mentioned in step 5 in the pop up menu and other information needed for running the simulation such as:

- Select how energy is interpolated from coordinate element to bulk elements
- Define speed of tyre [km/h]
- Define error limit for heat transfer [%]
- Define interpolation parameter [deg]
- Define parameter for tyre radius calculation.

7. After completing the calculation the output data will be presented in axi_RR_result file (see **Figure 10**), and the Rolling Resistance Coefficient (C_r) is then calculated using equation (9):

$$C_r = \frac{\text{Total force (N)} \times 1000}{\text{Load (N)}} \text{ N/kN}$$

The example of the simulation result is shown below:
Results:

Force produced by material I40 is 2.08360116975 N

Force produced by material A02 is 1.29144915874 N

Force produced by material T61 is 18.8669933222 N

Force produced by material BW08 is 0.0 N

Force produced by material T61 is 1.67943517041 N

Force produced by material Z80 is 1.13411378677 N

Force produced by material S70 is 0.41902012456 N

Force produced by material S70 is 3.82462665603 N

Force produced by material R50 is 1.72655457713 N

Force produced by material N20 is 0.883588825178 N

Force produced by material C32 is 1.62535580812 N

Total force is 33.5347385989 N

Since load index of the tyre is 82, the maximum tyre load is equal to 475 kg.

According to ETRTO standard, the tyre load for rolling resistance calculation is 80%

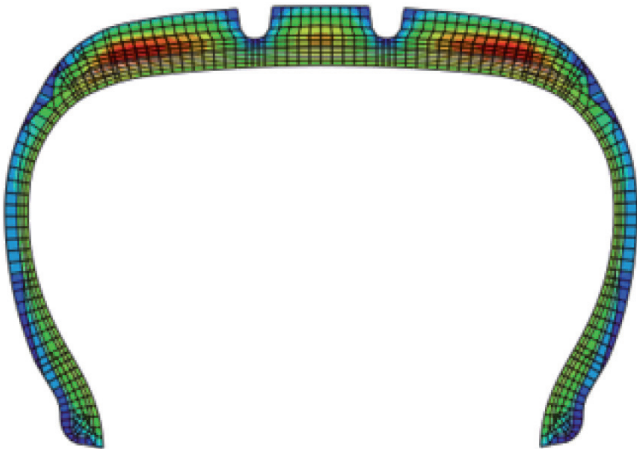
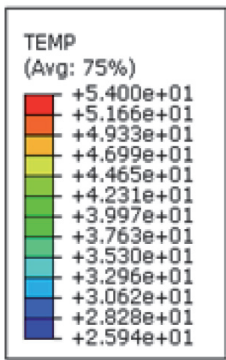


Figure 10.
Temperature distribution of 2 groove tyre.

of maximum load which is 380 kg or 3728 N, and then the rolling resistance coefficient is equal to:

$$C_r = \frac{33.5347 \times 1000}{3728} = 9 \text{ N/kN}$$

Using the same calculation for tyre B and C, we obtain the following result:
tyre A produces $C_r = 9 \text{ N/kN}$
tyre B produces $C_r = 8.77 \text{ N/kN}$
tyre C produces $C_r = 8.4 \text{ N/kN}$

3.4 Validation of rolling resistance simulation result

The rolling resistance simulation result obtained from an Abaqus plugin code need to be validated by comparing the result with the actual test result. The actual test has been carried out using 14 different tyres that has been tested on RR machine conducted by certified bodies, such as TUV, and the results are compared with the RR result from simulation, as shown in **Figure 11**.

In average, the simulation result is higher than the actual testing result by 0.46 or 6.2%.

3.5 Rolling resistance on different radial stiffness and crown radius

The radial stiffness of tyre significantly affects the rolling resistance. **Table 4** shows that smaller stiffness of sidewall (indicated by higher R deflection) resulted in higher rolling resistance. This phenomenon explain that to deform a higher stiffness material needs more energy, meaning that the energy loss is higher and eventually the rolling resistance is also higher.

Tyre tread contour has a great influence on rolling resistance. To study this, the simulation was performed on three tyres with different crown radiuses, i.e.:

- Tyre A: R1 = 250 mm and R2 = 150 mm,
- Tyre B: R1 = 550 mm and R2 = 300 mm, and
- Tyre C: R1 = 900 mm and R2 = 300 mm, as it is shown in **Figure 12**.

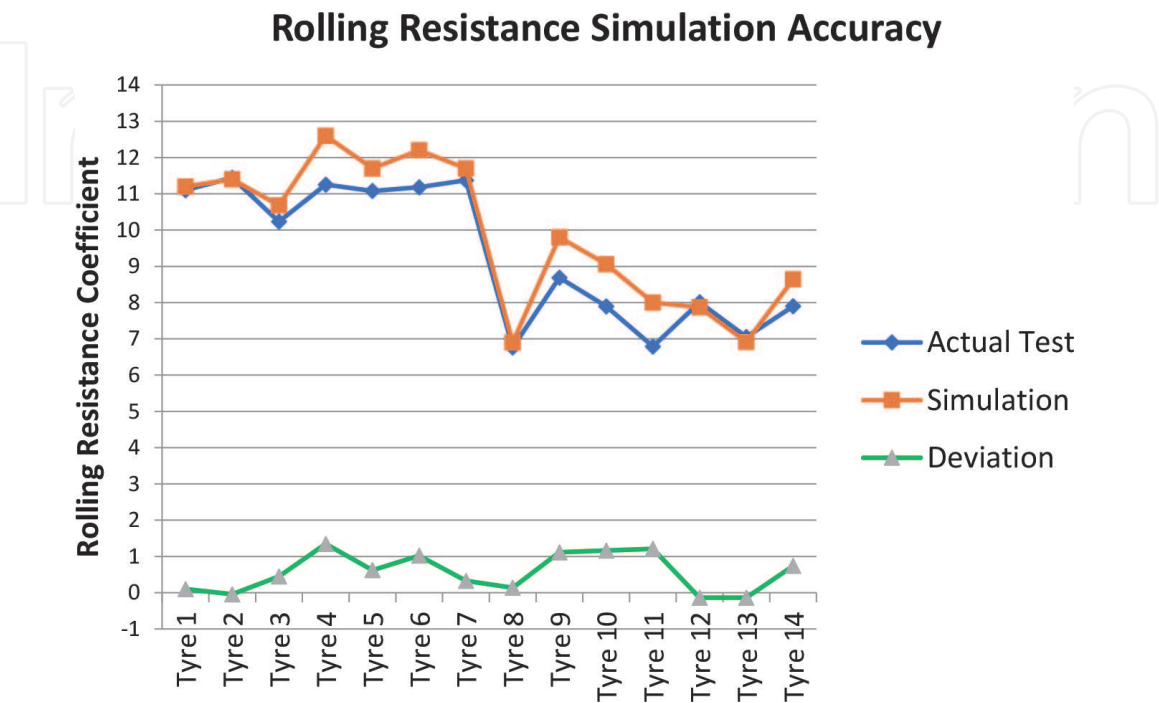


Figure 11.
Rolling resistance coefficient test result.

	2 groove tyre	3 groove tyre	4 groove tyre
R deflection	269.06 mm	268.75 mm	268.54 mm
Rolling resistance coef.	9 N/kN	8.77 N/kN	8.4 N/kN

Table 4.
Correlation between radial stiffness and rolling resistance.

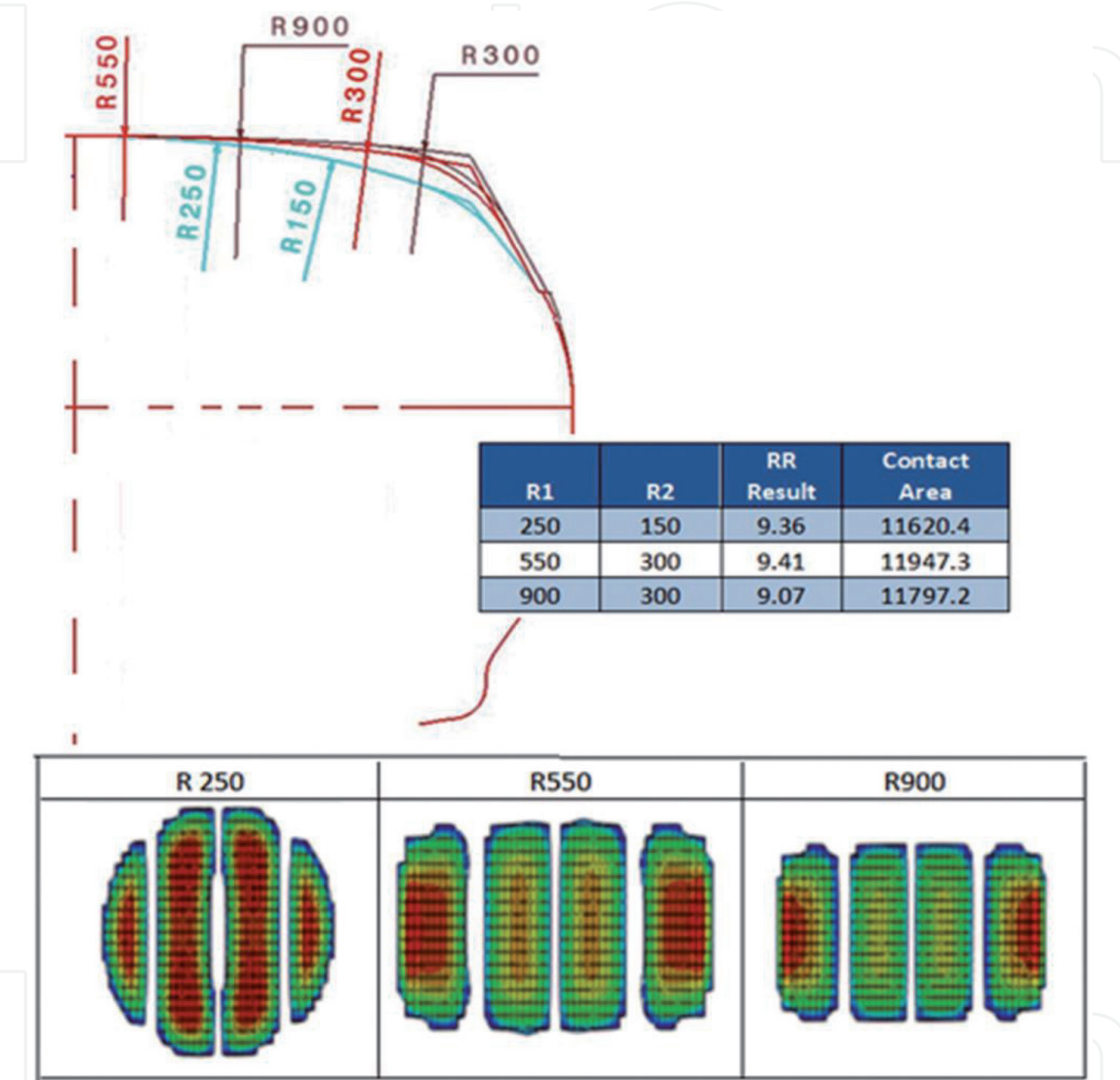


Figure 12.
Crown radius relation with footprint and rolling resistance [7].

4. Conclusion

During the PCR tyre design and development, there is several tyre performance parameters need to be considered, including rolling resistance, wet adhesion, noise, and cornering stability. In this study, a Finite Element simulation was carried out to perform prediction of rolling resistance and cornering stability.

The simulation was performed in two stages: steady state rolling simulation using Abaqus build in function and rolling resistance calculation using internally developed Python code as Abaqus plugin.

The validation was done by comparing the simulation result and actual test on RR machine and the average discrepancy of C_r is 0.46 or 6.2%. In addition, the RR

plugin only need between 10 and 15 minutes to run, it is very short compared to pre processing time.

The simulation result suggests that the best estimated rolling resistance is four groove tyre with crown radiuses of $R1 = 900$ mm and $R2 = 300$ mm. However, two grooves tyre provides larger shoulder contact area which in turn gives better cornering stability, but has rolling resistance coefficient of 9 N/kN.

Considering that the rolling resistance coefficient (Cr) of two groove tyre is within the allowable value for stage 2 requirement of UNECE regulation No. 117-2 (the maximum Cr is 10 N/kN), so the suggested PCR tyre should have the following specification to meet the performance target: low rolling resistance and good cornering stability:


- Two grooves
- Crown radius $R1 = 900$ mm and $R2 = 300$ mm

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