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Rolling Resistance and Noise Estimation for Product Design and Development of Eco-Tyre using Finite Element and Numerical Method

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Abstract. Design and development of tyre must adhere to international standard and particular regulation of destination countries.Currently, more and more countries in Europe, America, Middle East, and Asia have concern on eco-friendly tyre and implement regulation to ensure that tyres sold in the country compliance with the regulation. The regulation mainly governs the level of allowable air pollution caused by the use of fossil fuel and noise generated by passing by vehicle. Therefore, design and development of eco-friendly tyre need to pass certain rolling resistance and noise level test. To ensure the tyre that is being designed comply with the regulation, a simulation process need to be carried out before the real tyre is produced and tested. This research is aimed to conduct a finite element analysis to get simulated rolling resistance coefficient and numerical analysis to obtain estimated pass-by noise level.

Keyword:Eco-Tyre, Rolling Resistance, Noise, Product Design and Development.

1. Introduction

Eco-friendly tyres (often called as eco-tyre)are designed to fulfill the current trend of global products in reducing the source of pollution, mainly from exhaust gas emission and rolling noise. This paper discusses the design of eco-tyre with focuses on simulation of rolling resistance and rolling noiseto obtain a low energy consumption and low noise tyre.

The use of energy in vehicle is significantly contributed by tyres. The reduction of fuel consumption can be obtained by improving tyre energy efficiency. The existing capabilities could improve the efficiency that is resulted in reduction of fuel consumption by 3 to 5% which in turn reducing green house gas emission, according to International Council on Clean Transportation[1], by more than 100 million metric ton annually.In this regard, the benefits can be achieved by designinglow rolling resistance tyres.

Hall and Moreland define tire rolling resistance as "theenergy consumed per unit travel distance when the tire rolls under load."[2]Vehicle fuel consumption affected by tyre rolling resistance, therefore energy savings can be achieved by lowering rolling resistance of tyre.

During design and development stage, the estimated value of rolling resistance can be obtained by employing finite element model built by using ABAQUS. Then a complete energy loss of tyre deformation analysis is performed using HETVAL subroutine in ABAQUS.

Other characteristic of eco-tyre is having low rolling noise, i.e the noise generated mainly by mechanical impact of blocks of tyre tread continuously hiting the road surface. The shape, size,

arrangement, and sequence of blocksare significant factors in generating the noise. The estimated noise can be obtained by performing numerial simulation using Silentroll software on different design of tread blocks. The best result of simulation then be selected and used as a master model for developing tyre mould.

2. Tyre Regulation

There are different policies amongs countries in implementing tyre standard and rating. European Union implements the standard since 2012, mandatory for rolling resistance, wet grip, and noise. US seems to follow EU while Japan and Korea apply voluntary program for rolling resistance and noise. On the other hand in Middle East, Gulf Cooperation Council implement GSO standard tyre labeling starting 2014, mandatory for rolling resistance and wet grip.

United Nation Economic Commission for Europe (UNECE) regulation No. 117-2 outlines the standard for passenger car (C1 class) for stage 2 implementation (effective from November 2016) as follows:[3]

Tabel 1. Standard RR Coefficient, Noise, and Wet grip based on ECE R117-2

Rolling Resistance Coef.		Noise		Wet Grip	
Tire Class	Max Value(N/kN)	Section width	Limit dB (A)	Cathegory of use	Wet grip index
C1	10.5	Less than 185	70	snow tyre with speed <160 km/h	0.9
		185 - 245	71	snow tyre with speed >160 km/h	1.0
		245 - 275	72	normal (road type) tyre	1.1
		Over 275	74		

2.1 Rolling Resistance

Tonachel[4]identified that rolling resistance occurs as tires deformduring rotation. The area of the tire thatis deformed is subjected to load within therubber material that construct tyre. The loss of energyduring these repeated deformationsis then dissipated in the formof heat.

In addition, LaClair[5] stated that the dissipation of energy in radial tyre is estimated as follows: crown: 70%, sidewall: 15%, and bead area: 15%.
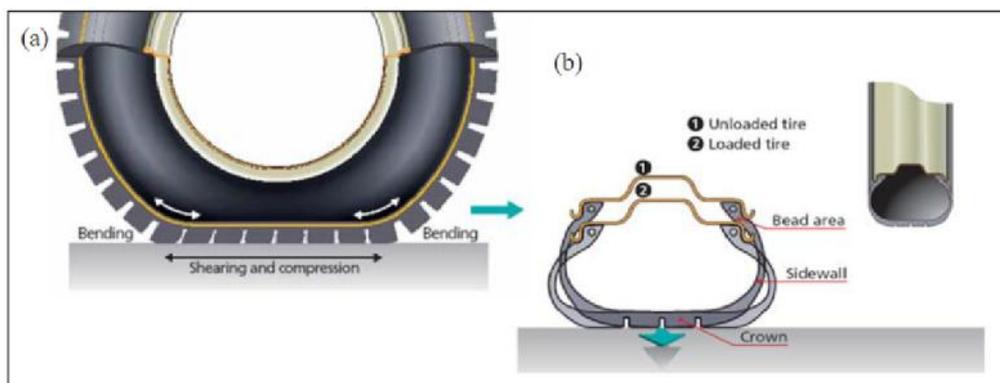

Figure 1. (a) Logitudinal bending and (b) transverse bending of tire[5]

Based on the figure 1, there two main areas of interest of this research: deformation in crown and sidewall area. The crown initial radius and the stiffness of sidewall will be studied to determine the targeted rolling resistance coefficient.

2.2 Rolling Resistance Measurement

There are two methods of rolling resistance test according to ISO 28580: force and torque measurement method. In force measurement method, the machine measures a reaction force at the axle of tyre and drum wheel assembly (F_t). In ISO 28580, the rolling resistance Fr at the contact of tyre and drum is calculated as follows:

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

where:

- F_r : Rolling Resistance

- Ft : Measured force at the spindle

- rL : Tire radius

- R : Drum wheel radius

- F_{pl}: skim load
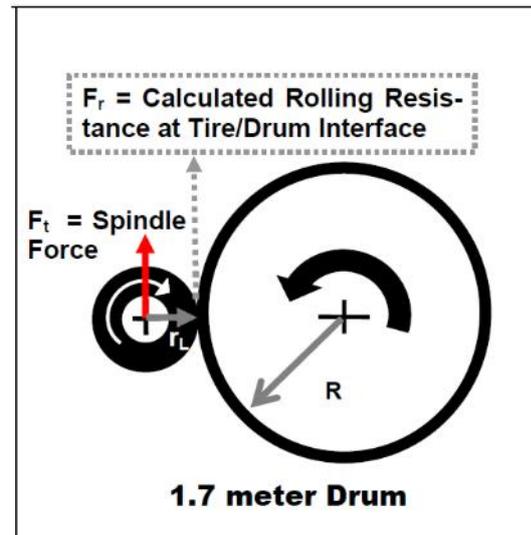
Figure 2. Force Method Rolling Resistance Test[6]

2.3 Tyre Noise

Tyre rolling noise is generated from the continuous contact of the tyres tread and road. According to Iwao and Yamazaki [7] tyre noise is 30.3% of the total noise generated by a passenger car. Kuijpers [8]as cited by Setiawan et. all [9]stated that tyre rolling noise can be categorized in two main factors:

- Mechanical
    – Radial and tangential vibrations
    – Sidewall vibrations
    – Stick-slip
    – Adhesion stick-snap

- Aerodynamic
    – Cavity resonance in tyre tube
    – Air-pumping
    – Air resonant radiation
    – Pipe resonance
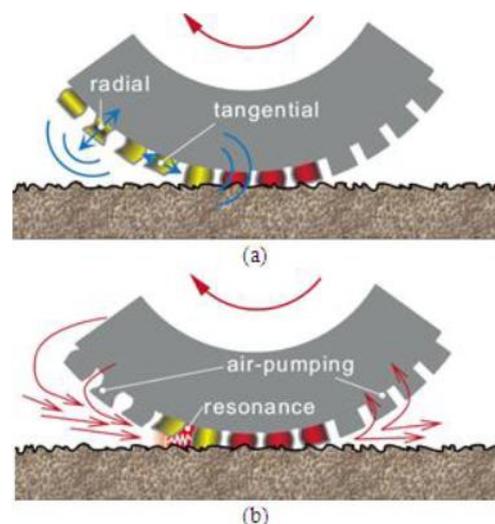
Figure 3. Noise generation mechanism: a) mechanical factors and b) aerodynamical factors.[8]

The mechanical type tyre noise mainly generated from the impact of tread block that continuously hit the road. The magnitude of noise of this type depends on block size, void area, non skid depth, and the angle of groove. This research will study the variation of groove angle and width of groove on shoulder area because the load is mostly supported by the shoulder.

3. Design and Development Methodology

3.1 Design Target

The tyre is designed for LCGC (Low Cost Green Car) with the following target:

– Size 175/65 R14
– Rolling Resistance Coef. Maximum 8.0
– Noise level 70 db(A)
– Cornering stability

3.2 Axisymetri Modeling

The first step of ABAQUS tyre modeling is axisymetri modeling. In this step, all tyre component and material properties need to be inputed. Figure 4 shows components that construct the tyre and figure 5 shows axisymetri model of the tyre after meshing.

NO	NOTE	MATERIAL
1	TREAD	T62 or T611
2	BASE	T62 or T611
3	WING	S70
4	INNERLINER	L40
5	SIDEWALL	S70
6	APEX	A02A
7	RIM CUSHION	R50
8	BEAD	BW089
9	JLB	N20
10	BELT	Z80
11	PLY	C32
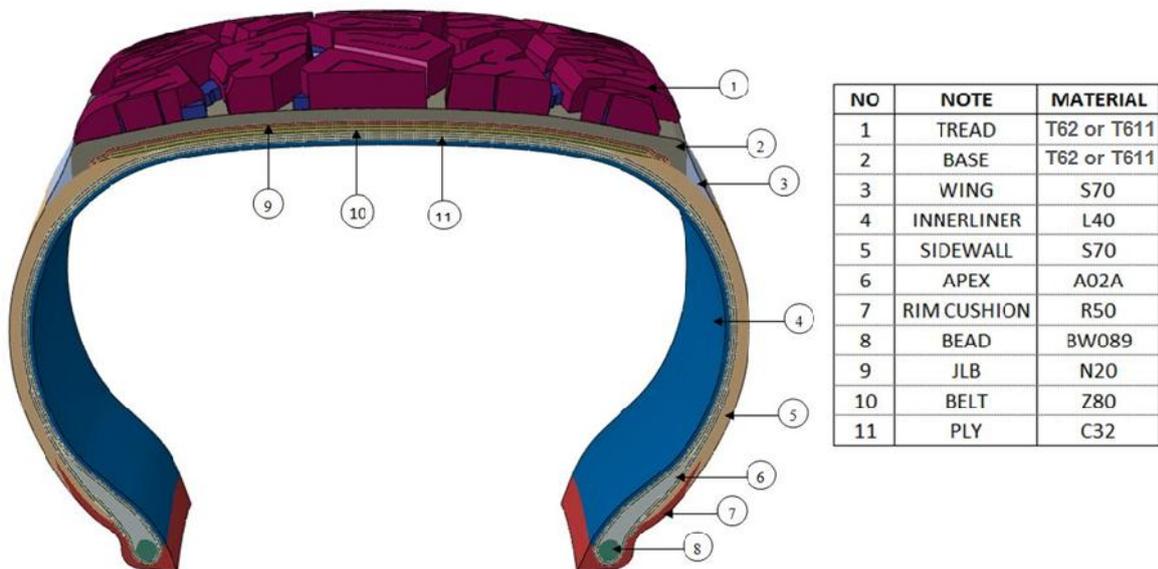
Figure 4. Tire construction components
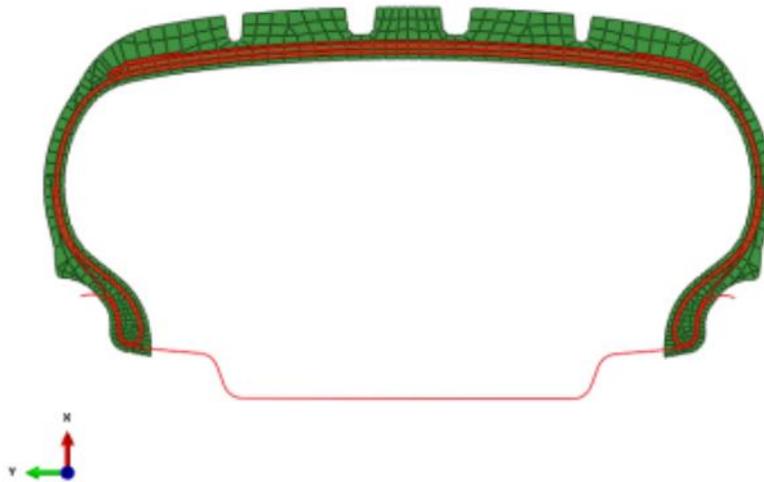
Figure 5. Axisymetry model in ABAQUS

3.3Footprint Analysis

There are three different tyres as reference: tyre A, tyre B, and tyre C. The tyre size is 175/65 R14 and were inflated at 2.1 bar with various loads of 100 kg, 150 kg, and 200 kg.

	LOAD		
	100 kg	150 kg	200 kg
Tyre A 2 grooves 2,1 bar (30.5 psi)			
Tyre B 3 grooves 2,1 bar (30.5 psi)			
Tyre C 4 grooves 2,1 bar (30.5 psi)			

Figure 6. Footprint comparison of benchmark tyres

The footprint of reference tyres are developed using finite element method on ABAQUS. Our interest are analyzing contact area and void ratio.

Based on the ABAQUS foot print analysis, the 2 grooves design having the biggest contact area at shoulder during low load (100 kg). Even at a narrow tread width, the contact area at shoulder are much wider compared to 3 grooves. Since the contact area on shoulder is bigger, the stability durimg cornering is better. Therefore, according to design target of having stability during cornering, the proposed tyre design should have 2 grooves.

3.4Crown Radius Analysis

There are three different crown radius being studied: R900, R550, and R250 as shown in figure 7. Each of design are analyzed based on contact area and rolling resistance result fromABAQUS.The bigger the crown radius the smaller the rolling resistance.



R1	R2	RR Result	Contact Area
250	150	9.36	11620.4
550	300	9.41	11947.3
900	300	9.07	11797.2
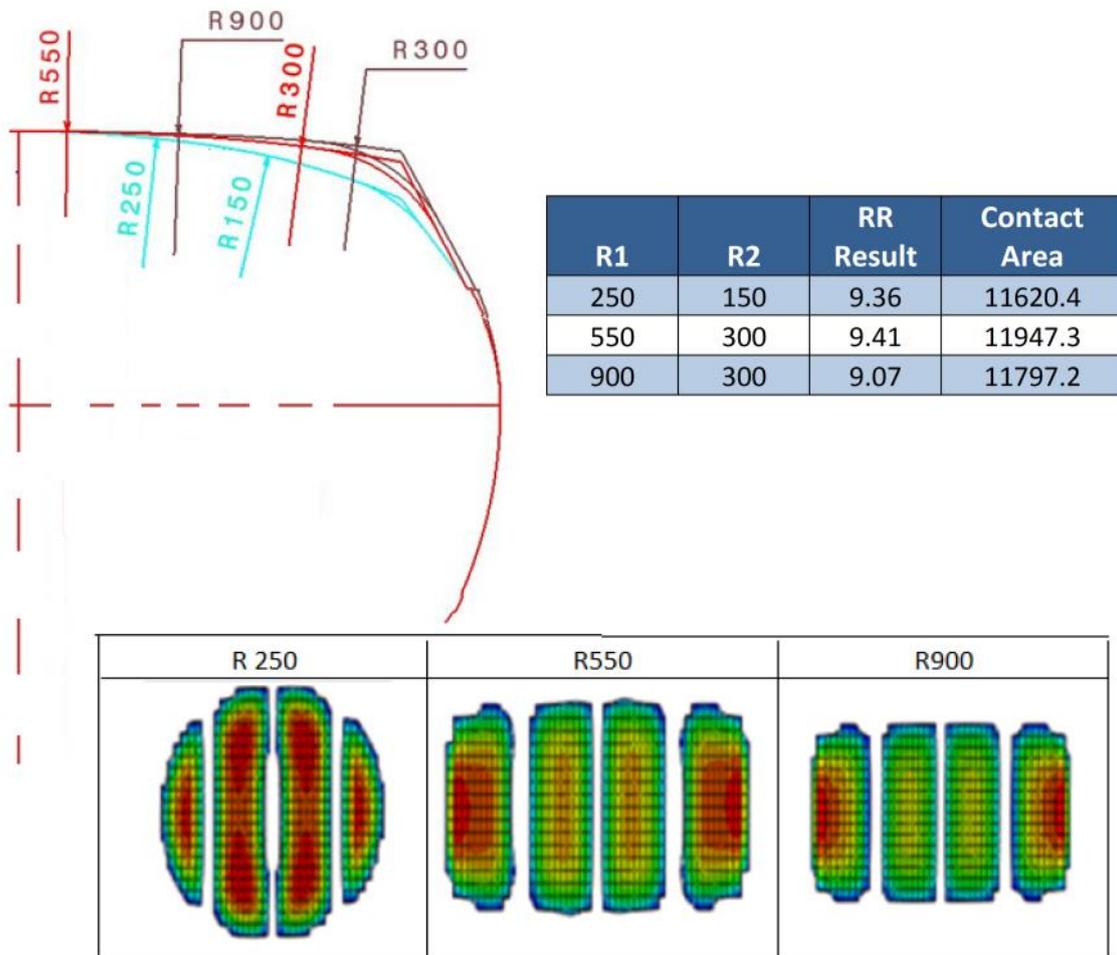
Figure 7. Crown radius relation with footprint and rolling resistance

3.5Radial stiffness Analysis

As it has been discussed earlier, the transversal bending of tyre is affected by radial stiffness that mainly depends on sidewall stiffness. This transversal bending causing the tyre loosing its heigh by certain value, from initial R become R deflection.
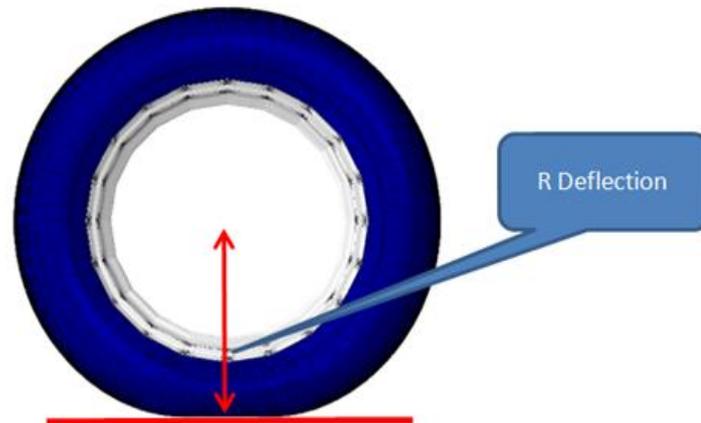
Figure 8. The tyre deflection changes R value to R deflection

Table 2 shows that smaller stiffness of sidewall (indicated by higher R deflection) resulted in higher rolling resistance. This phenomenon explain thatto deform a higher stiffness material needs more energy, meaning that the energy loss is higher and eventually the rolling resistance is also higher.

Table 2. Corelation between radial stiffness and rolling resistance

	2 Grooves	**3 Grooves**	**4 Grooves**
R deflection	269.06	268.75	268.54
Rolling Resistance Coef.	9	8.77	8.4

3.6Rolling Resistance Analysis

Based on benchmark tyres, three different tyres are under study: 2 grooves, 3 grooves, and 4 grooves tyres, all of the same size: 175/65 R14 82T with the following specification:

- – Section width   : 175 mm
- – Aspect ratio   : 65%
- – Wheel diameter   : 14 Inch
- – Load Index   : 82 (max 475 kg)
- – Speed symbol   : T (max 190 km/h)

2 Grooves

Results:

Force produced by material L41 is 2.08360116975N
Force produced by material A02A is 1.29144915874N
Force produced by material SC50 is 0.0N
Force produced by material T406H is 18.8669933222N
Force produced by material BW120 is 0.0N
Force produced by material T667B is 1.67943517041N
Force produced by material PC108 is 0.0N
Force produced by material Z80 is 1.13411378677N
Force produced by material NB90 is 0.0N
Force produced by material S71 is 0.41902012456N
Force produced by material S70 is 3.82462665603N
Force produced by material R50 is 1.72655457713N
Force produced by material N20 is 0.883588825178N
Force produced by material C32 is 1.62535580812N

Total force is 33.5347385989N
RRC = 9

3 Grooves

Results:

Force produced by material L41 is 2.15404391108N
Force produced by material A02A is 1.2687640233N
Force produced by material SC50 is 0.0N
Force produced by material T406H is 18.2630714183N
Force produced by material BW120 is 0.0N
Force produced by material T667B is 1.37219615074N
Force produced by material PC108 is 0.0N
Force produced by material Z80 is 1.11952948003N
Force produced by material NB90 is 0.0N
Force produced by material S71 is 0.47496454888N
Force produced by material S70 is 3.95690634128N
Force produced by material R50 is 1.67306575397N
Force produced by material N20 is 0.812599277529N
Force produced by material C32 is 1.6256442313N

Total force is 32.7207851364N
RRC = 8.77

4 Grooves

Results:

Force produced by material L41 is 2.10928413129N
Force produced by material A02A is 1.28980757869N
Force produced by material SC50 is 0.0N
Force produced by material T406H is 16.0070713797N
Force produced by material BW120 is 0.0N
Force produced by material T667B is 2.1240658482N
Force produced by material PC108 is 0.0N
Force produced by material Z80 is 1.30575082534N
Force produced by material NB90 is 0.0N
Force produced by material S71 is 0.440561389785N
Force produced by material S70 is 3.82348693223N
Force produced by material R50 is 1.69978529966N
Force produced by material N20 is 0.918398703379N
Force produced by material C32 is 1.66901782269N

Total force is 31.387229911N
RRC = 8.4

Figure 9. Rolling Resistance coefficient (RRc) of different tyres under study

3.7 Noise Analysis

Tyre noise is greatly affected by block shape, size, and void ratio which are the result of existence of grooves and sipes. In this study, the variation of shoulder groove angle and groove width will be simulated to obntained the best tyre noise. From figure 10 we notice that the best noise is achieved at shoulder groove angle 8°and groove width of 0.6 mm.

Noise Analysis Result	
Speed (km/h)	80
Load (kg)	380
Groove Depth (mm)	8.2
Sequence	2-1-1-2-4-3-1-3-5-2-1-1-2-2-4-5-3-2-1-1-3-4-4-5-3-1-1-2-1-2-3-4-5-1-1
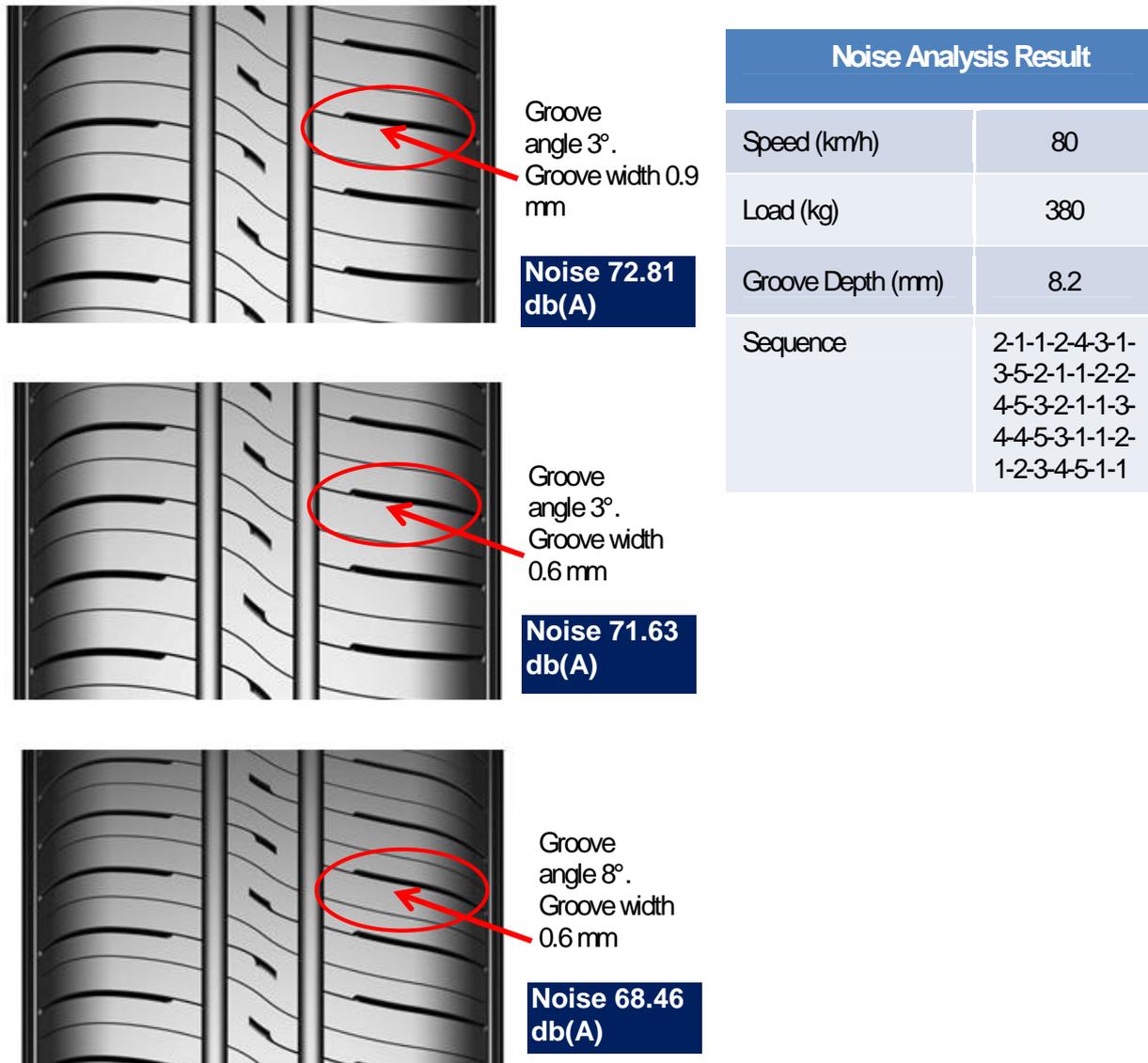
Figure 10. Noise simulation using SilentRoll on different shoulder groove parameters

4. Conclusion

Table 3 summarize the simulation result, in most cases it always need to compromise to achieve the design target. In our case, there is a choice either to use 2 groove or 4 groove tyre. The consideration should be taken on identifying which parameter is fixed and which one can be improved.

Table 3. Simulation result

Best Stability (large shoulder Contact Area)	2 groove tyre
Best Crown Radius	900 mm
Best Rolling Resistance	4 groove tyre

Therefore according to design target, 2 groove tyre is selected for having large shoulder contact area that give better stability (being fixed parameters because once the mould is made then it can not be changed). However, there is a way to improve rolling resistance by improving the tread compound as we notice from simulation result, the largest rolling resistance force comes from tread material (T406H).

In addition, the lowest noise is achieved on 2 groove tyre with 8º of shoulder groove angle and 0.6 mm groove width. Therefore the proposed tyre design specification is as follows:

- Number of main groove : 2
- Crown radius   : 900 mm
- Shoulder groove angle : 8º
- Shoulder groove width : 0.6 mm
- Tread compound   : need further research for lower rolling resistance compound

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