

Parametric analysis of various design factors on characteristic performance of Non-Pneumatic Tyres

Ahmad Naveed¹, Muhammad Ali Saqib^{1*}, and Moiz Bin Azeem¹

¹ Department of Mechanical Engineering, University of Engineering & Technology, 54890 Lahore, Pakistan

Abstract. Non-pneumatic tires (NPTs) have emerged as a promising alternative to conventional pneumatic tires. In this study, a systematic parametric analysis was conducted to assess the influence of various design factors, including cell size, cell wall thickness, cell round radius, and spoke band thickness on the performance of NPTs. The Taguchi method, in conjunction with ANOVA, was employed to leverage the design of experiments (DOE) approach for identifying optimal settings for the examined factors. This investigation on sets revealed that both cell size and cell round radius have a significant impact on the mechanical performance of NPT. Specifically, cell size was shown to significantly affect the deformation and strain, with respective contributions of 48.74% and 45.16%. Meanwhile, cell round radius exhibited a substantial impact on the von Mises stress and strain energy, with respective contributions of 44.02% and 45.30%. Moreover, spoke band thickness was observed to significantly influence the mass of airless tires, with a contribution of 44.75%. The findings of this study furnish valuable insights into the design and optimization of NPTs for diverse applications.

1 Introduction

Pneumatic tires have been in use for over a century, with the first patent for a pneumatic tire being issued in 1846. However, it wasn't until the late 19th century that pneumatic tires began to be widely used on vehicles. Despite their many advantages, one of the main disadvantages of pneumatic tires is the risk of flat tires. Pneumatic tires can develop a flat tire due to punctures, leaks, or other types of damage. This can be inconvenient and can also be dangerous if it occurs while driving. Pneumatic tires are also affected by environmental factors. They are sensitive to extreme temperatures, particularly hot and cold weather, which can affect their performance and lifespan [1].

* Corresponding author : alisaqib11223@gmail.com

Non-pneumatic tires (NPTs) do not use air as a means of support. Instead, they rely on the mechanical properties of their structure to bear the load and provide traction, causing them to gain increasing attention in recent years due to their potential to improve the performance and efficiency of vehicles [2]. As compared to standard Pneumatic tires, NPTs do not suffer from punctures and do not require frequent air pressure checks, which can reduce maintenance costs and downtime. In addition, NPTs can offer improved ride comfort, better handling, and enhanced traction, especially in challenging terrain [3, 4].

Despite these benefits, the design of NPTs is a complex process, and the effect of various design factors on their characteristics and performance is not well understood [5, 6]. The studies found that design parameters of the spokes, including the initial elastic modulus and thickness of the honeycomb cell-wall and the cell angle, significantly affect the natural frequencies of identified in-plane and out-of-plane vibration modes in airless tires [7]. The optimized structure of the airless tire demonstrates significantly improved radial stiffness and antisymmetric pure longitudinal sliding characteristics, resulting in less vibration during braking and improved safety [8]. Jin et al. [9] contributed by investigating the dynamic parameters of a rolling honeycomb wheel in terms of the rolling resistance, tread stress, and stresses and deformations of the spokes. The wheel with a narrower cell angle resulted in a decreased rolling resistance, which was attributable to its significantly lower spoke deformation and mass. Jackowski et al. [10] evaluated the energy consumption of a pneumatic and non-pneumatic tire selected for size and application by empirically assessing the rolling resistance of each. Veeramurthy et al. [11] investigated the influence of geometric and material characteristics on the overall performance of non-pneumatic tire components. In particular, the optimization of NPTs for different application scenarios requires a thorough understanding of the trade-offs between different performance metrics such as load-carrying capacity, stiffness, lateral stability, energy absorption, and ride comfort [12].

To address this gap in knowledge, a parametric analysis was conducted to investigate the influence of different design parameters on the performance of NPTs. The parameters considered in the study included the Cell size, Cell wall thickness, Cell round radius and Spoke band Thickness. The objectives of the study were to:

1. Identify the key design factors that influence the performance of NPTs.
2. Understand the trade-offs between different performance metrics.
3. Provide guidance for the design and optimization of NPTs for different application scenarios.

Influence of parameters is studied by Taguchi method. It is based on the idea that quality of a product or process can be improved by designing experiments that systematically vary the input parameters (called "control factors") and measuring the output responses. It is a standardized fractional design strategy that enables the identification of nearly ideal circumstances and the relative relevance of each design aspect in a computationally efficient way using factorial parametric effects [13]. Taguchi technique has been extensively used to uncover near-optimal product designs or processes incorporating several parameters, particularly when there are no major interactions between the design components. The goal is to identify the optimal combination of control factor levels that will produce the desired output response with the highest quality and the least variation. ANOVA (analysis of variance) is often used in conjunction with Taguchi to analyse the data collected from experiments. By comparing the variance within the groups to the variance between the groups, it can determine whether the differences in the mean responses are due to chance or whether they are statistically significant.[14] Allowing you to determine whether the control factor levels have significant effect on the output response.

All of these approaches provide valuable insights to study parameters and effects and design a sustainable and durable NPT.

2 Methodology

The methodology is composed of deep literature review from previous work on Pneumatic as well as non-Pneumatic tires to design some sample models which can be used to determine contribution of each design parameter on tire characteristics for it to has lower value of Mass, Stress, Strain, Deformation and a higher value of Strain Energy. Following assumptions were made while designing this model:

1. Linear isotropic stress-strain behaviour is assumed for tire material.
2. Tire model is assumed to have smooth tread pattern to avoid excessive computational time and effort.
3. Contact surface is assumed to be frictionless.

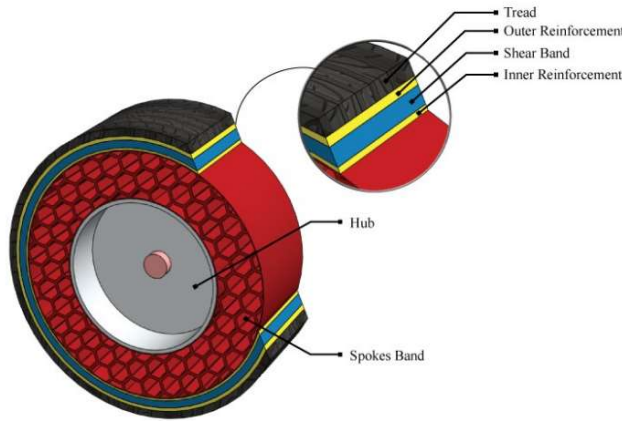


Figure 1: Structure of NPT

The NPT designed is made up of an Aluminium Hub in centre as shown in Figure 1. with a radius of 316mm and width of 215mm. Honeycomb Spokes and Shear band are made up of thermoplastic polyurethane (TPU). TPU material has both elasticity and stiffness at the same time [15, 16], having isotropic elasticity with shear modulus of 10 MPa. A uniform honeycomb structure, with cell of equal length and width is used (refer to Figure 2). The honeycomb structure is able to support a large amount of weight while still being lightweight [17]. Another advantage is its flexibility, as the structure can be customized to suit the specific needs of different vehicles and applications [18]. Additionally, the honeycomb structure is resistant to compression and deformation, which helps to maintain the tire's shape and performance over time [9, 19].

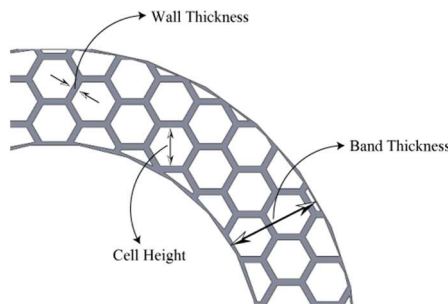


Figure 2: Design Parameters

Shear beam having a thickness of 10.2 mm almost deforms completely due to shear as it reduces the impact of the change of spokes shape especially in contact pressure distribution [20]. It is sandwiched between two layers of inner and outer steel rings, made up of steel with 1 and 0.75mm thickness respectively. These inextensible steel membranes are also called reinforcements due to their higher strength, higher circumference stiffness and low radial bending stiffness, preventing shear band from buckling [21]. Tread is made up of rubber, with a thickness of 2mm. The material properties (by default in Ansys material library) are listed in Table 1:

Table 1: Material Properties

Material	Density (kg/m ³)	Young Modulus (MPa)	Poisson's ratio	Shear Modulus (MPa)
Polyurethane	1265	32	0.49	10.7
Stainless Steel	7800	210 x 10 ³	0.31	8.01 x 10 ⁴
Aluminum alloy	2770	71 x 10 ³	0.33	2.6 x 10 ⁴
Rubber	1000	11.9	0.49	3.9

The simulation of tire models has made considerable use of Finite Element (FE) Analysis because of its capacity to resolve complex structural behaviours combining the nonlinearity of a material and its geometry [22]. The creation of 2D or 3D models, which will be the first step in the simulation process, is a critical component of any product design or improvement. These geometrical drawings represent and replicate the actual design details that can be used to validate the model in simulation and thus play an important role in product development [23]. Software used to design sample tires are SOLIDWORKS and CREO PARAMETRIC. Simulations are carried out using Finite Element method on ANSYS 2022. Evaluation is the process of systematically assessing resources and intended results in order to appropriately analyse design and FEA attributes. The default mesh size for target element i.e., 5e-2 m was used, with a total 15180 number of nodes, and 72190 number of elements.

By comparing responses in terms of spokes peak local stress and overall vertical deflection with reported data under identical normal loads, the validity of models with material properties and nominal dimensions was established. Initially six different sets of varying cell size and cell wall thickness were modelled and analysed, with their masses kept almost constant. Following that, numerical experiments were performed with various combinations of design parameters based on the Taguchi L16 orthogonal array to efficiently evaluate the main effect of each factor in each of the wheel response measures. As a result, the findings are discussed in order to provide design guidance for non-pneumatic tires.

Initially, six different sets of honeycomb tires are modelled with spokes band outer radius of 233mm. At this stage, no cell round radius is considered. Following that, each wheel component was assembled using the surface-to-surface tie formulation or shared nodes. Following dimensions (Table 2) are being followed for six samples, provided the mass in each of them is constant:

Table 2: Dimensions of sets bearing same mass

Samples	Cell Dimensions (mm)	Cell wall thickness (mm)
Case 1	55*55	6.6
Case 2	50*50	6
Case 3	45*45	5.4
Case 4	40*40	4.8
Case 5	35*35	4.2
Case 6	30*30	3.6

Because the Wheel Hub serves as a fixed support member for the wheel, it was completely constrained. It holds the inner surface of the wheel hub together. These are analysed on ANSYS at different load values of 500N, 1000N, 1500N and 2000N.

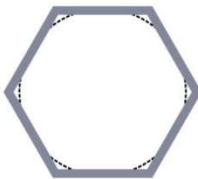


Figure 3: Round Radius

For the NPW with a specific wheel width and materials, the primary design factors that influence the mass, stress, strain, deformation and strain energy of the honeycomb wheel include the honeycomb cell-wall thickness, honeycomb cell size, round radius and honeycomb spokes band thickness. The concept of round cell radius corners is introduced, which refers to design feature where the corners of a cellular structure are rounded, rather than sharp (Figure 3). This feature is intended to reduce stress concentrations at the corners, can increase the overall strength and durability of the structure by reducing stress concentration and improving fatigue resistance. Results for previous values predicted suitable sets, which can we used for further calculations. Their values supposed for calculations are in (Table 3):

Table 3 : Ranges of parameters

Level	Cell Wall thickness (mm)	Cell Size(mm)	Round Radius (mm)	Shear Band Thickness (mm)
1	35	4.2	2	233
2	40	4.8	4	243
3	45	5.4	6	253
4	50	6	8	263

3 Results and Discussion

The mechanical performance of airless tire samples is simulated in Ansys (Figure 4). The focus is on determining the Von Mises stress, strain, deformation, and strain energy of the NPT samples under different loading conditions, allowing a detailed analysis of the behaviour of NPT and provide insight into how changes in design parameters can affect the overall performance of airless tires.

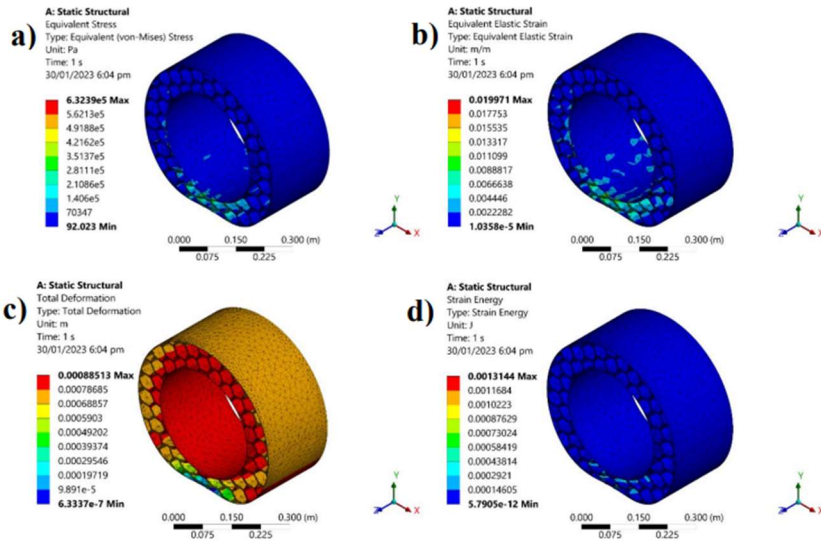


Figure 4: Simulating sample CASE 1 for (a) Von-Mises Stress (b) Equivalent Strain (c) Total Deformation (d) Strain Energy

The simulation results demonstrated a trend in the behaviour of NPT samples varying in cell sizes and spoke band thicknesses under equal variable loads ranging from 500N to 2000N. Sets with a specific ratio between cell size and spoke band thickness showed better performance in terms of stress, strain, deformation, and strain energy. This suggests that the size of the cells and the thickness of the spoke bands play an important role in the overall mechanical performance of airless tires.

Sets 1 and 6, which had comparatively much bigger or much smaller cell sizes, were found to be less suitable as compared to the other four sets as shown in Figure 5. This highlights the importance of finding a balance between the cell size and spoke band thickness to achieve optimal performance. If the cell size is too big or too small, it can result in a decrease in performance and lead to a higher stress, strain, deformation, and strain energy.

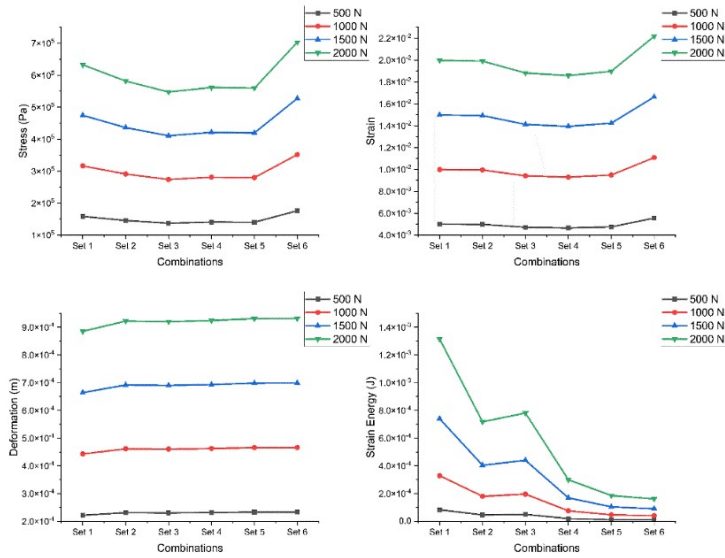


Figure 5: Trends of Stress, Strain, Deformation, and Strain Energy for six different load sets.

3.1 Design of experiments using Taguchi method:

The Taguchi method, which employs orthogonal arrays for efficient experimental designs, represents the average effect of two levels of a design factor while taking into account variations in all other design factors. The results of ANOVA of main effects that resulted were used to determine the relative significance of each design factor for a specific performance measure. To perform ANOVA on the S/N ratio in a Taguchi experiment, the experimenter would first set up the experiment using an orthogonal array to systematically test the various factors and levels. The S/N ratio would then be measured for each experimental condition, and the data would be analysed using ANOVA to determine whether the differences in the S/N ratio are statistically significant.

If the differences are found to be statistically significant, the experimenter can then use the ANOVA results to identify which factors have the greatest impact on the S/N ratio, and to determine the optimal combination of factors for the best performance. Table 4 shows an initial formulation of a L16 orthogonal array using the six two-level factors design.

Table 4: Taguchi L16 array

L16 Orthogonal Array	Cell Size (mm)	Cell Wall thickness (mm)	Round Radius (mm)	Shear Band Thickness (mm)
Set 1	35	4.2	2	233
Set 2	35	4.8	4	243
Set 3	35	5.4	6	253
Set 4	35	6	8	263
Set 5	40	4.2	4	253
Set 6	40	4.8	2	263
Set 7	40	5.4	8	233
Set 8	40	6	6	243
Set 9	45	4.2	6	263

Set 10	45	4.8	8	253
Set 11	45	5.4	2	243
Set 12	45	6	4	233
Set 13	50	4.2	8	243
Set 14	50	4.8	6	233
Set 15	50	5.4	4	263
Set 16	50	6	2	253

3.2 Influences of selected design parameters on wheel responses:

The proper selection of tire size with correct weight-to-axle power ratio is critical in the design and efficient operation of wheeled vehicles. For a vehicle designed to operate at a specific speed range, the weight-to-axle power ratio must be within a certain range in order to maintain a specific level of conversion efficiency [24]. Usually, mass of tire is considered to be less in order to achieve better fuel average, provided the durability and structural integrity is not compromised.

Figure 6 presents the main effects plots for Signal-to-Noise (S/N) ratios for the mass of the non-pneumatic tires (NPTs) at different levels of four design factors. It can be concluded that the spoke band thickness is the most influential factor on the mass of NPTs, followed by cell wall thickness, cell size, and cell round radius.

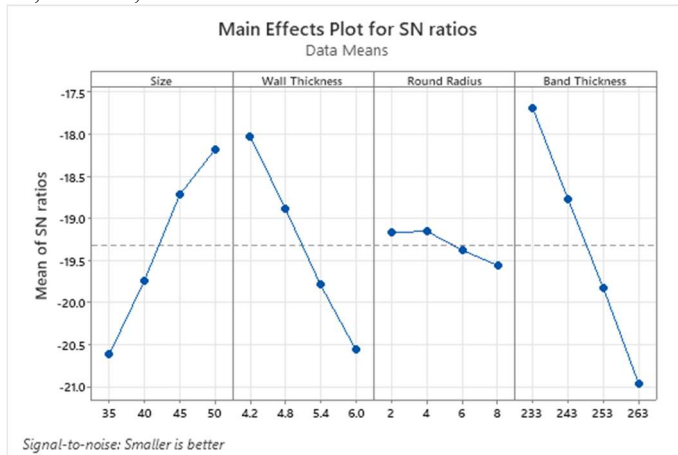


Figure 6: S/N ratio plot for Mass:

The airless tire becomes less responsive to the rider's input as the spoke band thickness increases, because of inappropriate increase in mass. As a result, traction and braking performance are reduced. From the given set of data, it was calculated that a tire with larger cell size (50mm), smaller cell wall thickness (4.2mm), smaller round radius (2mm) and smaller band thickness (233mm) is the one with minimum amount of mass. Percentage contributions are shown in Table 5.

Table 5: ANOVA for S/N ratio of Mass

Source	DF	Seq SS	Adj SS	Adj MS	F	P%
Size	3	14.0394	14.0394	4.67980	537.75	26.73%
Wall Thickness	3	14.5084	14.5084	4.83613	555.72	27.62%

Round Radius	3	0.4388	0.4388	0.14626	16.81	0.83%
Band Thickness	3	23.5051	23.5051	7.83504	900.32	44.75%
Residual Error	3	0.0261	0.0261	0.00870		
Total	15	52.5178				

Von-Mises stresses experienced by NPT is due to the load applied on it. If the von Mises stress in an airless tire exceeds the material's yield strength, the tire will start to permanently deform, which can lead to a reduction in its load-carrying capacity and its durability [25]. In extreme cases, the tire can fail and experience a complete structural collapse [26]. Significant variations also occur in critical situations, particularly oversteering in situations with rapid variations. A tire with larger stress values may yield or fracture with a desired amount of load. Main effect plots for Signal-to-noise ratio for Stress are shown in Figure 7:

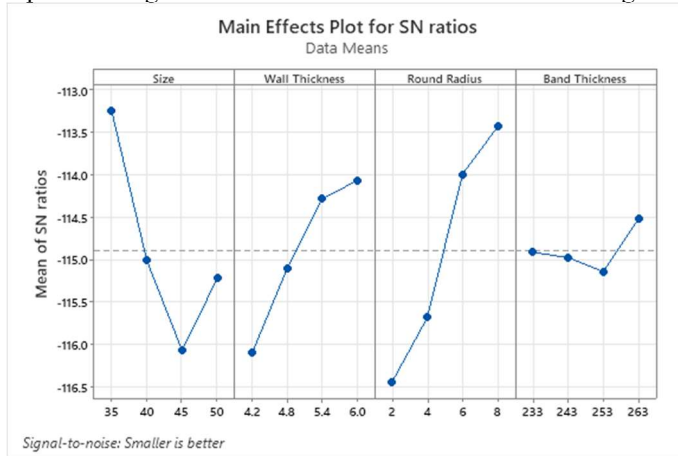


Figure 7: S/N ratio plot for Stress

Following samples were being tested, it was found that round radius was the major contributor for tire’s mass. On the other hand, spoke band thickness is the least contributor in tire’s stress. From the given set of data, it was calculated that a tire with smaller cell size (35mm), smaller cell wall thickness (6mm), larger round radius (8mm) and moderate spoke band thickness (263mm is good in this case) is the one with minimum amount of von-mises stress. Analysis of Variance (ANOVA) for signal-to-noise ratio of stress is shown in Table 6:

Table 6: ANOVA for S/N ratio of Stress

Source	DF	Seq SS	Adj SS	Adj MS	F	P%
Size	3	16.8830	16.8830	5.6277	6.80	31.10%
Wall Thickness	3	10.1778	10.1778	3.3926	4.10	18.75%
Round Radius	3	23.8914	23.8914	7.9638	9.63	44.02%
Band Thickness	3	0.8393	0.8393	0.2798	0.34	1.54%
Residual Error	3	2.4815	2.4815	0.8272		
Total	15	54.2730				

Strain is a measure of the deformation of a material as it is subjected to load. In an airless tire, strain occurs as the tire is subjected to loads and deformation during use. Excessive strain

can lead to a reduction in the load-carrying capacity and durability of the airless tire. In airless tires, the strain distribution affects the overall performance of the tire, including ride comfort, durability, and road handling [27]. To optimize the performance of the airless tire, designers need to consider the strain distribution in the tire under different loading conditions and to develop a design that will minimize the strain while still ensuring adequate load-carrying capacity and durability. Main effect plots for Signal-to-noise ratio for Strain are shown in Figure 8:

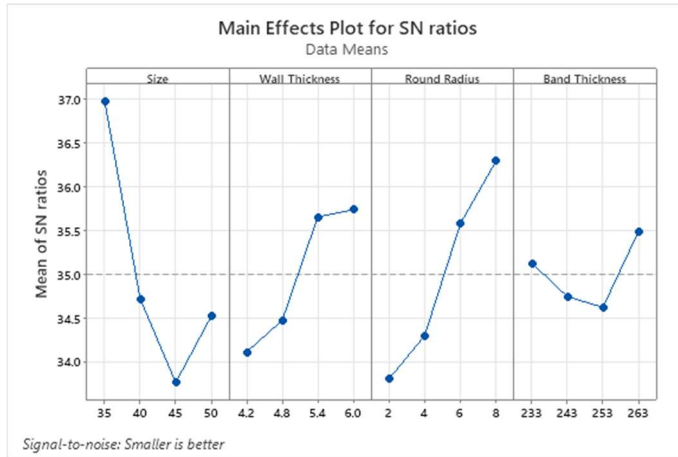


Figure 8: S/N ratio plot for Strain

From the given set of data, it was calculated that a tire with smaller cell size (35mm), smaller cell wall thickness (4.2mm), smaller round radius (2mm) and smaller band thickness (253mm) is the one with minimum amount of strain. The S/N ratio for band thickness is predicting that strain is comparatively higher for first and last value of thickness, which shows that the actual value of strain energy is also highly influenced by other design parameters. Analysis of Variance (ANOVA) for signal-to-noise ratio of Strain is shown in Table 7:

Table 7: ANOVA for S/N ratio of Strain

Source	DF	Seq SS	Adj SS	Adj MS	F	P%
Size	3	23.013	23.013	7.6710	10.82	45.16%
Wall Thickness	3	8.157	8.157	2.7190	3.84	16.01%
Round Radius	3	15.812	15.812	5.2707	7.44	31.03%
Band Thickness	3	1.839	1.839	0.6130	0.86	3.60%
Residual Error	3	2.127	2.127	0.7088		
Total	15	50.948				

Deformation is due to stress in tire due to applied loadings. A larger value of deformation means that stress is showing larger deflection for small loadings. Hence smaller the deformation behavior of tire is also heavily influenced by local structures and their spatial arrangements.[26, 28, 29]. Main effect plots for Signal-to-noise ratio for Deformation are shown in Figure 9:

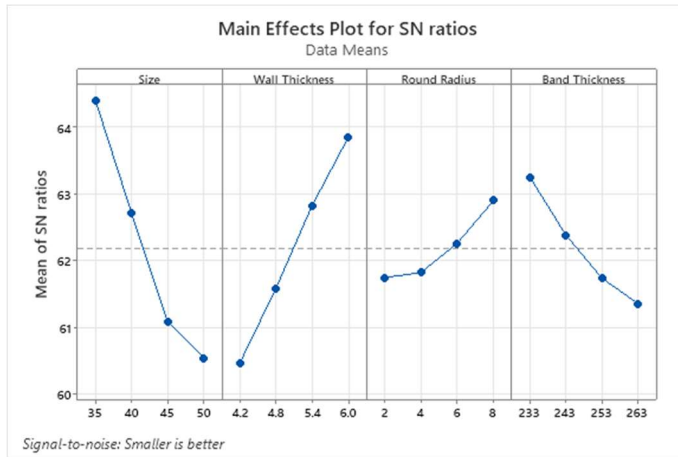


Figure 9: S/N ratio plot for Deformation

Following samples were being tested, it was found that cell size was the major contributor for tire’s deformation (Rank 1). On the other hand, round radius is the least contributor in tire’s stress (Rank 4). From the given set of data, it was calculated that a tire with cell size 35mm, cell wall thickness 6mm, round radius 8mm and spoke band thickness 233mm is the one with minimum amount of deformation. Percentage contributions are shown in Figure 13. Analysis of Variance (ANOVA) for signal-to-noise ratio of Deformation is shown in Table 8:

Table 8: ANOVA for S/N ratio of Deformation

Source	DF	Seq SS	Adj SS	Adj MS	F	P%
Size	3	36.4207	36.4207	12.1402	53.00	48.74%
Wall Thickness	3	25.9432	25.9432	8.6477	37.75	34.72%
Round Radius	3	3.3740	3.3740	1.1247	4.91	4.51%
Band Thickness	3	8.2882	8.2882	2.7627	12.06	11.09%
Residual Error	3	0.6872	0.6872	0.2291		
Total	15	74.7133				

The amount of strain energy stored in an airless tire will depend on the tire's material properties, its design and construction, and the loads and deformation it experiences. For example, an airless tire made of a highly elastic material may be able to store more strain energy than a tire made of a less elastic material. Similarly, an airless tire with a thicker cross-section or a more robust internal structure may be able to store more strain energy than a tire with a thinner cross-section or a weaker internal structure.

A tire with a high capacity for storing strain energy may be able to withstand larger loads and deformation without failing, which can improve the tire's service life [30]. On the other hand, a tire with a low capacity for storing strain energy may be more prone to failure under heavy loads or severe deformation, which can limit its useful life. Main effect plots for Signal-to-noise ratio for Strain Energy are shown in Figure 10:

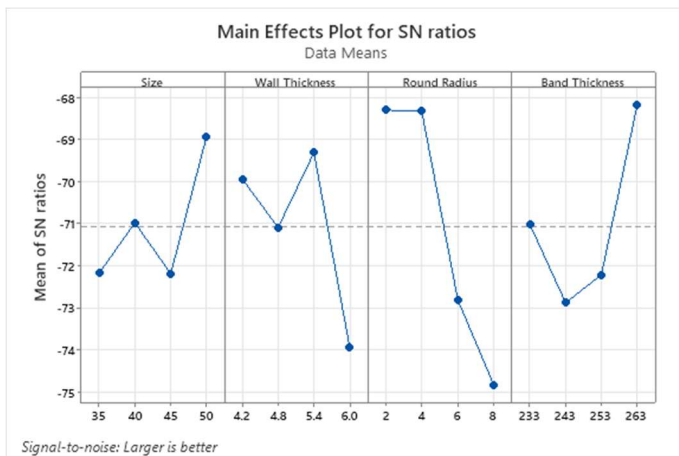


Figure 10: S/N ratio plot for Strain Energy

Following samples were being tested, it was found that round radius was the major contributor for tire’s deformation (Rank 1). On the other hand, cell size is considered to be the least contributor in tire’s strain energy (Rank 4). From the given set of data, it was calculated that a tire with cell size 35mm, cell wall thickness 2mm, round radius 2mm and spoke band thickness 263mm is the one with maximum amount of strain energy. Analysis of Variance (ANOVA) for signal-to-noise ratio of Strain Energy is shown in Table 9:

Table 9: ANOVA for S/N ratio of Strain Energy

Source	DF	Seq SS	Adj SS	Adj MS	F	P%
Size	3	28.25	28.25	9.416	1.07	9.83%
Wall Thickness	3	50.44	50.44	16.812	1.91	17.54%
Round Radius	3	130.12	130.12	43.375	4.93	45.30%
Band Thickness	3	51.98	51.98	17.325	1.97	18.09%
Residual Error	3	26.40	26.40	8.801		
Total	15	287.19				

4 Conclusion

The study of the effect of various design parameters on factors such as Von-Mises’s stress and deformation is necessary in order to design a durable tire. The results of this research demonstrate that by carefully considering the interplay between these factors, it is possible to design a tire that is able to withstand the rigors of daily use and maintain its performance over time. These factors are being influenced by parameters as:

1. Spoke band thickness is the major contributor in NPT’s mass.
2. Round radius is the major contributor in NPT’s stress as well as strain energy.
3. Cell size is the major contributor in NPT’s strain as well as deformation.

The study also highlighted that the selection of the right design parameters is crucial for the tire to perform well under different loading conditions, highlighting the importance of considering the durability of tires and the need for continued research to develop long-lasting tire designs that can meet the demands of modern transportation.

5 References

1. Pottinger, M.G., J.D. Walter, and J.D. Eagleburger, *A Commented Synopsis of the Report of the Committee for the National Tire Efficiency Study*. Tire Science and Technology, 2007. **35**(2): p. 70-93.
2. Sassi, S., M. Ebrahemi, and M. Al-Mozien, *New design of flat-proof non-pneumatic tire*. Int J Mech Syst Eng, 2016. **2**: p. 114.
3. Proddaturi, A., *Robust parameter design and finite element analysis for a non-pneumatic tire with low vibration*. 2009, Clemson University.
4. Bras, B. and A. Cobert, *Life-cycle environmental impact of Michelin Tweel® tire for passenger vehicles*. SAE international journal of passenger cars-mechanical systems, 2011. **4**(2011-01-0093): p. 32-43.
5. Deng, Y., et al., *A comprehensive review on non-pneumatic tyre research*. Materials & Design, 2023: p. 111742.
6. Karohika, I.M.G., et al. *Development of airless tires: A review*. in *AIP Conference Proceedings*. 2023. AIP Publishing LLC.
7. Zheng, Z., S. Rakheja, and R. Sedaghati, *Modal properties of honeycomb wheels: A parametric analysis using response surface method*. European Journal of Mechanics-A/Solids, 2023. **97**: p. 104842.
8. Zhu, L., et al., *Test and Simulation Study on the Static Load and Pure Longitudinal Slip Characteristics of Non-Pneumatic Tire*. Machines, 2023. **11**(1): p. 86.
9. Jin, X., et al., *Investigation on the static and dynamic behaviors of non-pneumatic tires with honeycomb spokes*. Composite Structures, 2018. **187**: p. 27-35.
10. Jackowski, J., M. Wiczorek, and M. Żmuda, *Energy consumption estimation of non-pneumatic tire and pneumatic tire during rolling*. Journal of KONES, 2018. **25**(1): p. 159-168.
11. Veeramurthy, M., et al., *Optimisation of geometry and material properties of a non-pneumatic tyre for reducing rolling resistance*. International Journal of Vehicle Design, 2014. **66**(2): p. 193-216.
12. Ku, L., et al., *Numerical analysis of steady-state mechanical characteristics of the flexible spoke non-pneumatic tire under multiple working conditions*. Journal of Terramechanics, 2023. **106**: p. 35-45.
13. Roy, R.K., *A primer on the Taguchi method*. 2010: Society of Manufacturing Engineers.
14. Payne, R., et al., *A Guide to ANOVA and Design in GenStat*. VSN International, Hemphstead, UK, 2008.
15. Ramadhani, M., M.I.P. Hidayat, and M. Gefin. *Optimization of airless tire strength in balance bike with airless tire geometry design variations using finite element methods*. in *AIP Conference Proceedings*. 2021. AIP Publishing LLC.
16. Wang, J., et al., *Research of TPU materials for 3D printing aiming at non-pneumatic tires by FDM method*. Polymers, 2020. **12**(11): p. 2492.
17. Sarma, S.R., et al. *Modelling and analysis of intelligent tyre alternatives for better performance*. in *Journal of Physics: Conference Series*. 2022. IOP Publishing.
18. Jafferson, J. and H. Sharma, *Design of 3D printable airless tyres using NTopology*. Materials Today: Proceedings, 2021. **46**: p. 1147-1160.
19. Ju, J., et al. *Design of honeycomb meta-materials for high shear flexure*. in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 2009.
20. Aboul-Yazid, A., et al., *EFFECT OF SPOKES STRUCTURES ON CHARACTERISTICS PERFORMANCE OF NON-PNEUMATIC TIRES*. International Journal of Automotive & Mechanical Engineering, 2015. **11**.

21. Phromjan, J. and C. Suvanjumrat. *The modification of steel belt layer of airless tire for finite element analysis*. in *IOP Conference Series: Materials Science and Engineering*. 2020. IOP Publishing.
22. Tönük, E. and Y.S. Ünlüsoy, *Prediction of automobile tire cornering force characteristics by finite element modeling and analysis*. *Computers & Structures*, 2001. **79**(13): p. 1219-1232.
23. Genovese, A., et al., *Static and dynamic analysis of non-pneumatic tires based on experimental and numerical methods*. *Applied Sciences*, 2021. **11**(23): p. 11232.
24. Sharma, A.K. and K. Pandey, *Matching tyre size to weight, speed and power available for maximising pulling ability of agricultural tractors*. *Journal of terramechanics*, 2001. **38**(2): p. 89-97.
25. Porcel, A., M. Basset, and G. Gissinger, *Car stability detection from tyre stresses*. *IFAC Proceedings Volumes*, 2004. **37**(22): p. 577-582.
26. Ali, M., M. Maarif, and A. Hussain, *Design and structural analysis of non-pneumatic tyres for different structures of polyurethane spokes*. *Journal of Engineering and Applied Science*, 2022. **69**(1): p. 38.
27. Miyata, T., et al., *Nanoscale stress distribution in silica-nanoparticle-filled rubber as observed by transmission electron microscopy: Implications for tire application*. *ACS Applied Nano Materials*, 2021. **4**(5): p. 4452-4461.
28. Gao, X., et al., *Modeling and experimental study of tire deformation characteristics under high-speed rolling condition*. *Polymer Testing*, 2021. **99**: p. 107052.
29. Mathew, N.J., D.K. Sahoo, and E.M. Chakravarthy. *Design and static analysis of airless tyre to reduce deformation*. in *IOP Conference Series: Materials Science and Engineering*. 2017. IOP Publishing.
30. Bae, J.-J., et al., *Calculation of the structural stiffness of run-flat and regular tires by considering strain energy*. *International Journal of Automotive Technology*, 2019. **20**: p. 979-987.