**Mechatronics and Intelligent Transportation Systems**
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# Enhanced Vehicle Performance through Nonlinear Finite Element Analysis of Tyre-Soil Interaction

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**Received:** 08-15-2023 **Revised:** 09-16-2023 **Accepted:** 09-24-2023

**Citation:** F. Aliramezani and Tashi, "Enhanced vehicle performance through nonlinear finite element analysis of tyre-soil interaction," *Mechatron. Intell Transp. Syst.*, vol. 2, no. 3, pp. 158–168, 2023. https://doi.org/10.56578/mits020304.

**Abstract:** In this investigation, critical insights into the complex interactions between tyres and soil are explored through the utilization of nonlinear finite element analysis (FEA), bearing significant implications for vehicle dynamics, safety, and performance. Maximal shear stress values, identified through shear stress analyses, reveal a peak of 8.4 MPa in the tyre-road contact region and an approximately uniform shear stress of 1.703 MPa in alternative areas, laying the foundation for advancements in tyre design optimisation. It was demonstrated that tyre designs necessitate optimisation to specific ground materials to fulfil essential traction requirements and preclude sinking. For interfaces involving soil and neoprene rubber, the contact status at the mid-section zone was observed to be in a sticking condition, transitioning to sliding as the observation point moved away from the centre. The research highlighted that through nonlinear analysis, accurate predictions of tyre behaviour under fluctuating loads can be achieved, thereby aiding in the formulation of designs for more fuel-efficient tyres and enhanced wet-weather handling. However, the study recognises the constraints imposed by simplifications within the tyre model, omission of dynamic behavioural factors, and assumptions regarding unvarying friction coefficients. While the analysis was confined to particular material models and validation was executed primarily via numerical simulations, findings affirm that strategic application of nonlinear FEA elucidates pivotal factors in tyre-soil interaction, propelling the establishment of safer and more performance-oriented vehicle models.

**Keywords:** Nonlinear finite element analysis (FEA); Vehicle dynamics; Performance analysis; ANSYS simulation; Tyre deformation; Frictional stress; Material properties

## 1 Introduction

Tires, recognised as the pivotal linkage between a vehicle and the road surface, have been identified as significantly influencing vehicle performance, handling, and safety due to their sole position as the point of direct contact between the vehicle and the road [1–3]. Upon commencement of a vehicular journey, a complex amalgamation of forces and moments converges upon the tires, embodying the epitome of vehicle dynamics and control technologies. Within the intricate realm of tire mechanics, numerous properties, each bearing impact upon tire performance, have been brought to light, necessitating a comprehensive exploration.

An attribute such as tire vertical rigidity, determined by the ratio of vertical force to vertical displacement, has been revealed to exert influence over ride comfort and vertical vibration characteristics [4–6]. Rubber, indispensable to tire construction and noted for its complexity, has been reported to be susceptible to deterioration under suboptimal conditions, and its incompressible nature has been observed to pose modelling challenges when utilising conventional finite element methods. Accommodation of the non-linear behaviour of rubber has been achieved through the implementation of strain energy functions, with the selection between Neo-Hookean and Mooney-Rivlin contingent upon the complexity of the application [7–13].

In the sphere of tire-soil interaction analysis, scrupulous reviews of research contributions have unveiled critical aspects of tire behaviour under assorted conditions. An analysis of stress and strain distribution in essential tire regions, such as breaker edges and carcass turn-up edges, has proffered insights into premature tire design failures [14].

Sokolov's work, in which a meticulous analysis of tire stress concentrations was conducted, and failure locations were adroitly predicted through FET simulations embracing bulk isotropic components, commands attention [15]. The criticality of tension and stress concentration in transition zones, separating tread or casing, and potentially serving as heralds to early fatigue-related tire failures, was illuminated through this research. Wang et al. [16] integrated experimental data with FEA, delving deeper into complex stress and strain dynamics along the bond line between fresh tread and casing in retreaded tires.

The introduction of a concept of cause-based analysis by Tighe et al. [17] spotlighted road roughness and lubrication as pivotal factors, with lubrication comprising elements such as water film, ice, and snow, serving as intermediaries between the tire and the road. A correlation between a decrease in tire grip force, friction, and compromised vehicle stability underscored the paramountcy of understanding these elements.

The term "lubricant" is herein defined to include elements such as water film, ice, and snow, recognised as agents mediating the interaction between the tyre and the road surface. It has been established that an understanding of these factors is imperative, as diminished tyre grip force and friction have been correlated with compromised vehicle stability. A journey into tyre design, undertaken by Erdogan et al. [18], utilised finite elements to craft acceleration profiles, encompassing lateral, tangential, and radial accelerations. Experimental outcomes were employed to validate simulations of acceleration profiles, further facilitating the estimation of slip angles and assessment of tyre-road friction coefficients. While showcasing potential, improvements, particularly concerning the utilisation of advanced FET algorithms for enhanced simulation accuracy and the incorporation of strain sensors for noise-resistant outcomes, are acknowledged. Notably, Micro-Electro-Mechanical Systems (MEMS) accelerometers, albeit with a higher cost, present advantages over strain sensors under specific contexts.

Lugner et al. [19] emphasized the pivotal role of tyre modeling techniques for understanding physical characteristics of tyres and ameliorating performance. Distinct modeling methods, each designed with specific research objectives such as examining static and dynamic behaviours, dependability, or durability, have emerged. Examples such as Tire and SWIFT, which have been employed in commercial contexts, serve to illustrate the applicability of such models. Nevertheless, simulating the dynamics of a rolling tyre with realism continues to pose a challenge, prompting ongoing research endeavours [20].

Invaluable insights have been provided by the research of Bolarinwa and Olatunbosun [21–23], anchored in a tyre properties study from the University of Birmingham, utilizing the finite element program ABAQUS. Through the employment of 3D solid components, derived from a 2D cross-section tyre profile, comprehensive analyses were enabled via their FET model. A comparison between AEC tri-axial tyre test rig studies and computed steady-state tyre performance during cornering illuminated the influence of relaxation length on transient tyre behaviour in the presence of preload. However, limitations were encountered, predominantly arising from inaccuracies in data regarding tyre composite geometry and viscoelastic material properties.

In the domain of off-road vehicular mobility, especially in the context of Sports Utility Vehicles (SUVs) engineered for rugged terrains, a palpable research gap exists, characterized by a lack of thorough investigations into the dynamics of tyre-soil interaction amid the myriad challenges presented by varying soil types. The pursuit of optimal traction and stability on such terrains remains in its infancy, necessitating an intricate understanding of the mechanics underpinning tyre-soil interaction.

The selection of tyres for off-road SUVs has been identified as a crucial element, serving a pivotal role in the assurance of vehicular stability and safety. Specialised tyres, beyond shouldering vehicular weight and absorbing shock, seek to guarantee a seamless and secure journey. They become a critical point upon which functions such as acceleration, deceleration, and steering are hinged. However, challenges arise when these tyres encounter off-road environments, characterized by diverse soil types, whereby the complexities of tyre-soil interaction become prominently observable. An enhanced traction on terrains, notably sandy soils, necessitates an intricate balance between tyre adaptability and the dynamic relationship established between the tyre and terrain.

This investigation posits a pressing need for a comprehensive analysis of stresses, penetration depths, and varied contact parameters via FEA simulations of tyre and terrain interaction. The objective is to elucidate these dynamics under both stationary conditions and during vehicular motion. A hypothesis was formulated, suggesting that a scrupulous exploration of tyre-soil interaction, facilitated by advanced FEA simulations, has the potential to forge transformative insights into the mechanics of off-road driving, revolutionising off-road tyre design and performance in the process.

Within the scope of this investigation, numerous research questions, each probing into the complex domain of tyre-soil interaction within off-road driving contexts, were explored. Firstly, the capabilities of Creo design software were assessed in the quest to optimise designs of off-road tyres and terrain surfaces, deploying advanced computer-aided design (CAD) techniques. Subsequently, mechanics of tyre-soil interaction were scrutinised, unraveling principles governing force distribution during stationary conditions, and specifically when specialised tyre and soil models were applied. Progressing into dynamic scenarios during vehicular motion, an endeavour was made to comprehend the forces determining tyre penetration and sliding dynamics. Lastly, the impact of various tyre materials, such as neoprene rubber, Mooney Rivlin, and Yeoh 3rd order material, on tyre-soil interaction and off-road performance was evaluated, aiming to shed light on material-specific advantages within challenging off-road terrains [18].

The aforementioned objectives guiding this study are:

(1) To harness the capabilities of Creo design software in the development of optimised off-road tyre and terrain surface designs, employing advanced CAD techniques.

(2) To undertake a meticulous exploration of the mechanics of tyre-soil interaction under stationary conditions, utilising specialised tyre and soil models, and elucidating principles governing force distribution.

(3) To investigate dynamic forces during vehicular motion, including tyre penetration and sliding dynamics, thereby deepening the understanding of off-road driving mechanics.

(4) To assess the impact of various tyre materials, including neoprene rubber, Mooney Rivlin, and Yeoh 3rd order material, on tyre-soil interaction and off-road performance, illuminating material-specific advantages within challenging off-road environments [24].

In essence, this study seeks to bridge the existing knowledge gap, pioneer advancements in the comprehension of tyre-soil interaction, and pave the path towards innovative developments in off-road tyre design and performance.

## 2 Methodology

This section elucidates the systematic approach and simulation methodology, meticulously configured to explore the multifaceted interactions within the domain of tyre-soil interaction. A logical sequence is followed, initiating with a succinct approach overview, progressing into detailed model development, and ultimately engrossing a comprehensive exploration of simulations.

### 2.1 CAD Model Development

Intricate CAD models, both for the tyre and the ground, were crafted, commencing with the skilled utilisation of Creo design software [25]. Versatile tools, notably "revolve" and "thicken", were employed to sculpt these pivotal components with precision, assuring both clarity and detail. Individual components were modeled meticulously and independently, with distinct characteristics and requisites acknowledged. Subsequently, these detailed components were seamlessly converged within the assembly module, forming an integrated system, showcased in Figure 1, and primed for rigorous FEA simulations [26]. The melding of cutting-edge software and scrupulous design intricacies forged the methodology's foundation, enabling a comprehensive exploration of tyre-soil interaction.

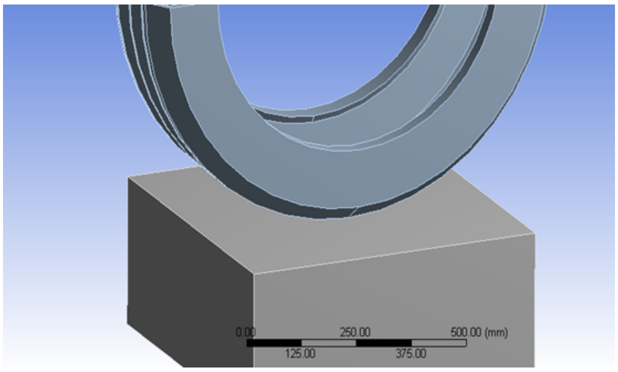


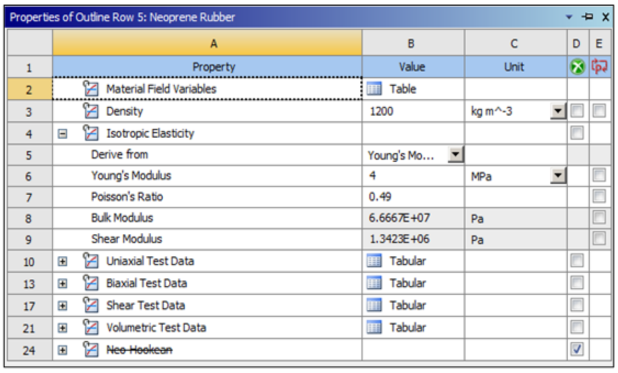
**Figure 1.** Assembly of tyre and ground

### 2.2 Material Selection

Derived from insights gleaned from extensive literature and prevailing material definitions, an encompassing simulation of nonlinear contact analysis between a tyre and a road surface was sought to be conducted. The widely-acknowledged cam clay model was adopted for the soil, aiming to accurately emulate its complex behaviour [27]. In parallel, neoprene was elected as the material for the tyre, thereby establishing a foundation for an in-depth analysis of the multifaceted interplay between the tyre and the road surface. The properties of the selected materials are delineated in Figures 2 and 3.

### 2.3 Model Examination and Optimization

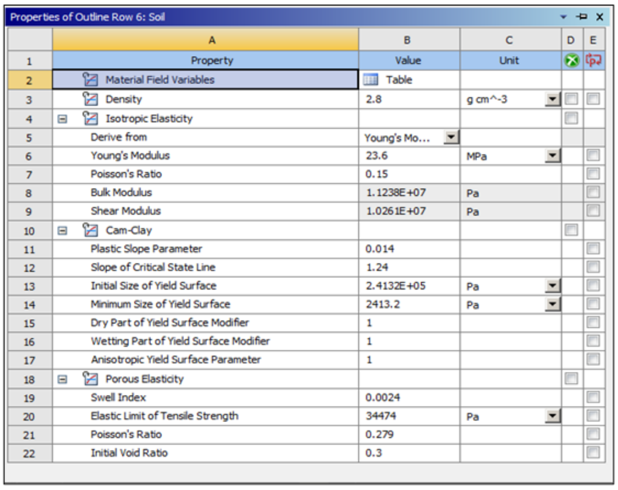
Upon importation of the CAD model into ANSYS Design Modeler, meticulous scrutiny was executed to safeguard geometric integrity. Attention was directed towards the identification and rectification of aberrations, such as sharp edges and surface irregularities, to optimise model accuracy. Subsequently, the model was deliberately bisected along its central plane, a step taken to streamline simulations, enhancing efficiency and precision, as depicted in Figure 4.



Properties of Outline Row 5: Neoprene Rubber

|  | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit |  |  |
| 2 | Material Field Variables | Table |  |  |  |
| 3 | Density | 1200 | kg m^-3 | ☐ | ☐ |
| 4 | ⊟ Isotropic Elasticity |  |  | ☐ |  |
| 5 | Derive from | Young's Mo... |  |  |  |
| 6 | Young's Modulus | 4 | MPa |  | ☐ |
| 7 | Poisson's Ratio | 0.49 |  |  | ☐ |
| 8 | Bulk Modulus | 6.6667E+07 | Pa |  | ☐ |
| 9 | Shear Modulus | 1.3423E+06 | Pa |  | ☐ |
| 10 | ⊞ Uniaxial Test Data | Tabular |  | ☐ |  |
| 13 | ⊞ Biaxial Test Data | Tabular |  | ☐ |  |
| 17 | ⊞ Shear Test Data | Tabular |  | ☐ |  |
| 21 | ⊞ Volumetric Test Data | Tabular |  | ☐ |  |
| 24 | ⊞ ~~Neo-Hookean~~ |  |  | ☑ |  |

**Figure 2.** Neoprene rubber model



Properties of Outline Row 6: Soil

|  | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit |  |  |
| 2 | Material Field Variables | Table |  |  |  |
| 3 | Density | 2.8 | g cm^-3 | ☐ | ☐ |
| 4 | ⊟ Isotropic Elasticity |  |  | ☐ |  |
| 5 | Derive from | Young's Mo... |  |  |  |
| 6 | Young's Modulus | 23.6 | MPa |  | ☐ |
| 7 | Poisson's Ratio | 0.15 |  |  | ☐ |
| 8 | Bulk Modulus | 1.1238E+07 | Pa |  | ☐ |
| 9 | Shear Modulus | 1.0261E+07 | Pa |  | ☐ |
| 10 | ⊟ Cam-Clay |  |  | ☐ |  |
| 11 | Plastic Slope Parameter | 0.014 |  |  | ☐ |
| 12 | Slope of Critical State Line | 1.24 |  |  | ☐ |
| 13 | Initial Size of Yield Surface | 2.4132E+05 | Pa |  | ☐ |
| 14 | Minimum Size of Yield Surface | 2413.2 | Pa |  | ☐ |
| 15 | Dry Part of Yield Surface Modifier | 1 |  |  | ☐ |
| 16 | Wetting Part of Yield Surface Modifier | 1 |  |  | ☐ |
| 17 | Anisotropic Yield Surface Parameter | 1 |  |  | ☐ |
| 18 | ⊟ Porous Elasticity |  |  | ☐ |  |
| 19 | Swell Index | 0.0024 |  |  | ☐ |
| 20 | Elastic Limit of Tensile Strength | 34474 | Pa |  | ☐ |
| 21 | Poisson's Ratio | 0.279 |  |  | ☐ |
| 22 | Initial Void Ratio | 0.3 |  |  | ☐ |

**Figure 3.** Soil material properties

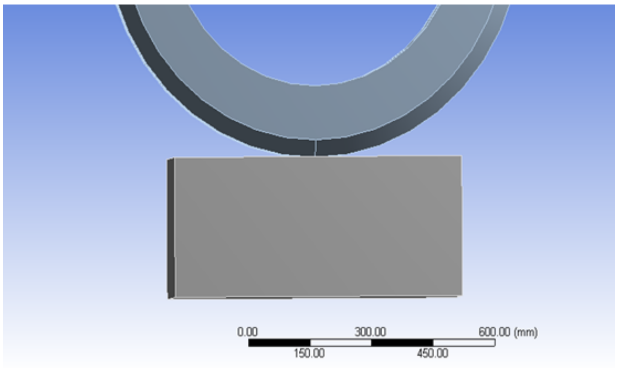


**Figure 4.** CAD model of tyre and ground

## 2.4 Mesh Generation

In the modelling process of the tyre, elements were systematically segregated, transitioning from coarser to finer sizes from the periphery to the central region. Employing a growth rate of 1.2 and a transition ratio of 0.272, a harmonious balance between computational efficiency and precision was achieved, culminating in a mesh comprised of 1911 elements and 11148 nodes. Such a comprehensive mesh adeptly encapsulates the intricate behaviours of the tyre. The meshed model of the tyre and ground is illustrated in Figure 5.

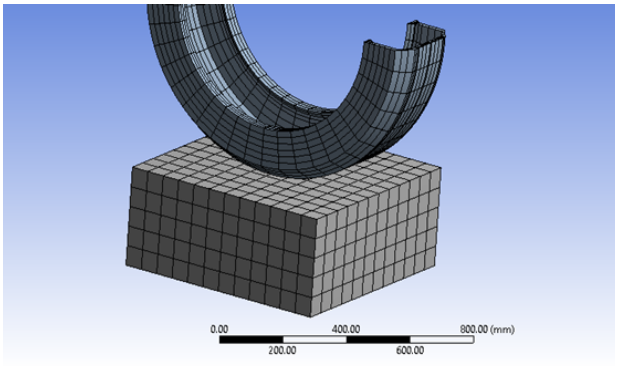


**Figure 5.** Meshed model of tyre and ground

### 2.5 Boundary Conditions

Within the soil domain, stability was ensured by firmly anchoring the bottom face through a static boundary condition. Concurrently, an exact pressure of 25 psi was applied to the inner surface of the tyre, simulating real-world conditions and facilitating an analytical exploration of the tyre's response, as demonstrated in Figure 6.

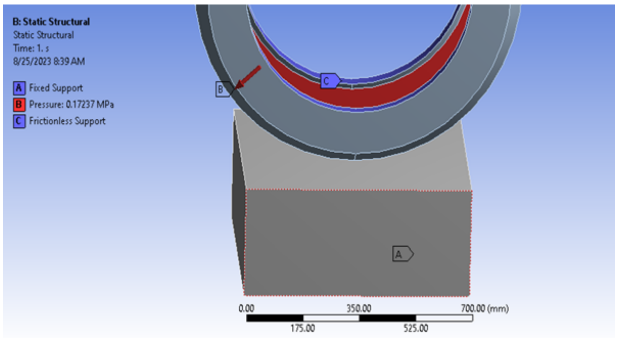


**Figure 6.** Loads and boundary condition

## 3 Results and Discussion

In the analyses' initial phase, the tyre was characterised by neoprene rubber, and Cam clay soil properties were utilised for ground simulation. The ANSYS library served as the source for neoprene rubber material properties, facilitating the application of precise and standardised parameters, thereby aligning with a commitment to accuracy and rigor [27].

The grid independence test, executed upon neoprene rubber, was paramount in substantiating the robustness and precision of the FEA simulations. This evaluative procedure systematically altered the quantity of elements within the mesh, whilst monitoring resultant shear stress values to validate grid independence. Elaboration on the various elements investigated and their respective shear stress values, pinpointing the mesh density that optimally balances computational efficiency and result accuracy, is provided in Table 1.

**Table 1.** Grid independence test data for neoprene rubber

| Number of Elements | Shear Stress |
|---|---|
| 1911 | 8.32 |
| 2258 | 8.38 |
| 2335 | 8.4 |

Illumination on the tyre-ground interface was obtained through the shear stress plot (Figure 7). The highest shear stress, quantified as 8.4 megapascals (MPa), was unveiled at the contact region, signalling intense mechanical interactions. Conversely, in alternate areas, shear stress maintained uniformity, approximately 1.703 MPa, harmonising with well-established literature and thus, validating the employed methodology [28].

The finite element evaluation yielded contact statuses, vividly illustrated in Figure 8, disclosing a sticking behaviour within the central zone and a transition to sliding in outward areas, revealing the tyre-road interface's dynamic nature. The discerned sticking behaviour in the central zone of the tyre-ground interface indicates that this region is subject to higher friction and superior grip, potentially fortifying vehicle stability and handling. In contrast, the outward transition to sliding behaviour suggests diminished grip, which may influence traction and control, particularly during manoeuvres.

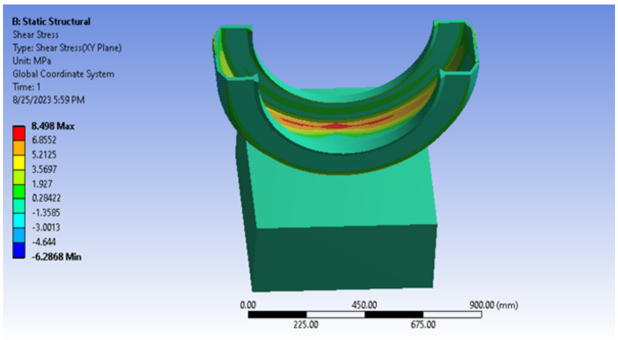


**Figure 7.** Shear stress distribution on neoprene rubber

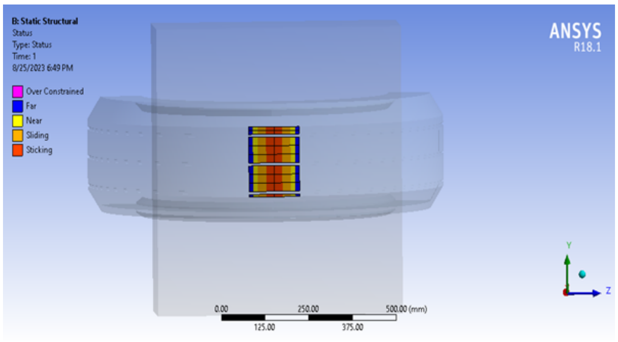


**Figure 8.** Status of tyre-ground contact

The elucidation of frictional stress distribution was achieved through the analysis presented in Figure 9, where higher frictional stress was identified in corner regions (3.42 MPa), contrasting markedly with the central area (1.71 MPa). Such findings serve to illuminate the nuanced behaviour inherent to tyre-road interactions.

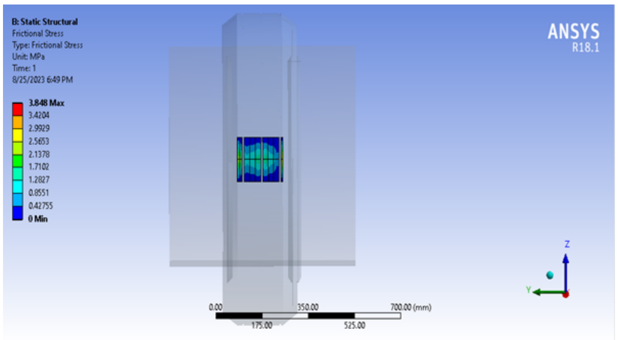


**Figure 9.** Frictional stress distribution

In Figure 10, a discernible disparity in tyre penetration was observed, with a peak of 0.024 mm documented at the corner region of the Cam Clay soil, and the nadir of penetration occurring within the central region.

Further finite element analyses, which employed hyper-elastic materials and are depicted in Figures 11 and 12, brought forth an unconverged solution (Figure 13) that revealed a notable tyre deformation of 48 mm and ground deformation of 5.24 mm under certain conditions, thereby warranting additional exploration.

The unconverged solution, relating to tyre penetration deformation and presented in Figure 13, originates from the interplay between Drucker-Prager (DP) soil properties and the Mooney Rivlin elastomer. A significant tyre deformation of 48 millimeters (mm) was evident, paralleled by a ground deformation—manifesting as tyre sinking—approximating 5.24 mm.

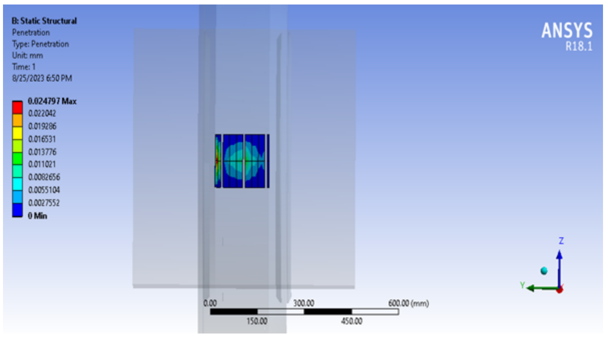
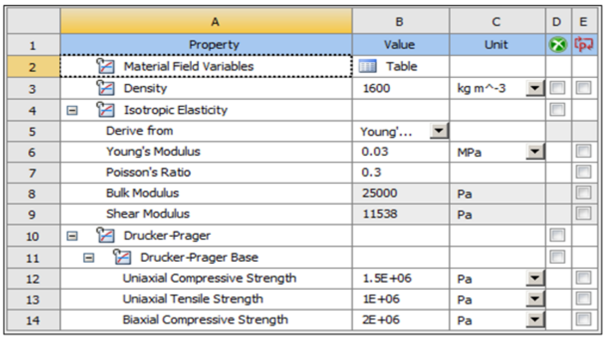
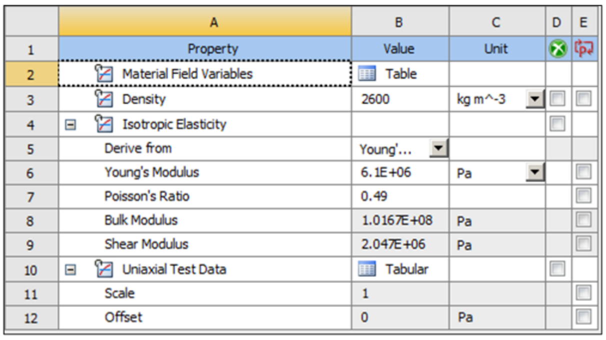


**Figure 10.** Tyre penetration



| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 1600 | kg m^-3 | ☐ | ☐ |
| 4 | ⊟ Isotropic Elasticity | | | ☐ | |
| 5 | Derive from | Young'... | | | |
| 6 | Young's Modulus | 0.03 | MPa | | ☐ |
| 7 | Poisson's Ratio | 0.3 | | | ☐ |
| 8 | Bulk Modulus | 25000 | Pa | | ☐ |
| 9 | Shear Modulus | 11538 | Pa | | ☐ |
| 10 | ⊟ Drucker-Prager | | | ☐ | |
| 11 | ⊟ Drucker-Prager Base | | | ☐ | |
| 12 | Uniaxial Compressive Strength | 1.5E+06 | Pa | | ☐ |
| 13 | Uniaxial Tensile Strength | 1E+06 | Pa | | ☐ |
| 14 | Biaxial Compressive Strength | 2E+06 | Pa | | ☐ |

**Figure 11.** Substance characteristics of the soil



| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 2600 | kg m^-3 | ☐ | ☐ |
| 4 | ⊟ Isotropic Elasticity | | | ☐ | |
| 5 | Derive from | Young'... | | | |
| 6 | Young's Modulus | 6.1E+06 | Pa | | ☐ |
| 7 | Poisson's Ratio | 0.49 | | | ☐ |
| 8 | Bulk Modulus | 1.0167E+08 | Pa | | ☐ |
| 9 | Shear Modulus | 2.047E+06 | Pa | | ☐ |
| 10 | ⊟ Uniaxial Test Data | Tabular | | ☐ | |
| 11 | Scale | 1 | | | ☐ |
| 12 | Offset | 0 | Pa | | ☐ |

**Figure 12.** Mooney rivlintyre properties

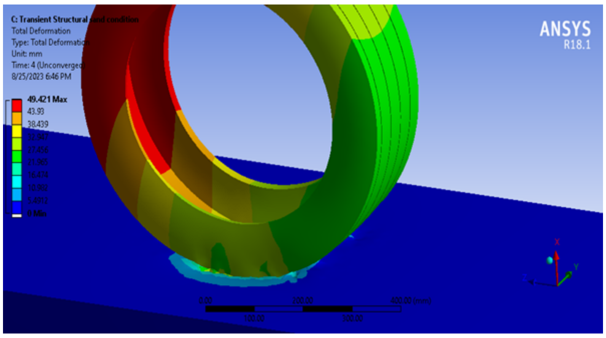
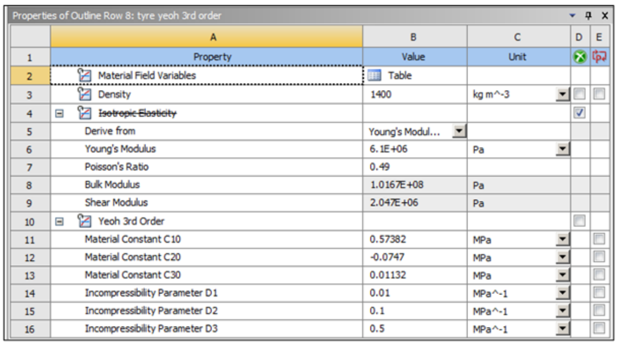


**Figure 13.** Tyre penetration on ground

In the finite element analysis, certain parameters were established: an internal tyre pressure of 35 pounds per square inch (psi) and a rotational velocity of 10 revolutions per minute (rpm), with the application of DP soil properties. The material properties of the tyre were defined adhering to the Yeoh 3rd order model, as depicted in Figure 14. This configuration set the stage for a meticulous analysis of tyre-soil interaction under the aforementioned conditions.



Properties of Outline Row 8: tyre yeoh 3rd order

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 1400 | kg m^-3 | ☐ | ☐ |
| 4 | ~~Isotropic Elasticity~~ | | | ☑ | |
| 5 | Derive from | Young's Modul... | | | |
| 6 | Young's Modulus | 6.1E+06 | Pa | | |
| 7 | Poisson's Ratio | 0.49 | | | |
| 8 | Bulk Modulus | 1.0167E+08 | Pa | | |
| 9 | Shear Modulus | 2.047E+06 | Pa | | |
| 10 | Yeoh 3rd Order | | | ☐ | |
| 11 | Material Constant C10 | 0.57382 | MPa | | ☐ |
| 12 | Material Constant C20 | -0.0747 | MPa | | ☐ |
| 13 | Material Constant C30 | 0.01132 | MPa | | ☐ |
| 14 | Incompressibility Parameter D1 | 0.01 | MPa^-1 | | ☐ |
| 15 | Incompressibility Parameter D2 | 0.1 | MPa^-1 | | ☐ |
| 16 | Incompressibility Parameter D3 | 0.5 | MPa^-1 | | ☐ |

**Figure 14.** Yeoh 3rd order material properties

Under variant parameters, an unconverged solution (Figure 15) evidenced a total deformation of 15.1 mm at the tyre's outer regions, exerting an impact on the ground as indicated. Furthermore, Figure 16 showcases the shear stress distribution, revealing a maximum shear stress at the contact region, amounting to 0.010612 MPa.

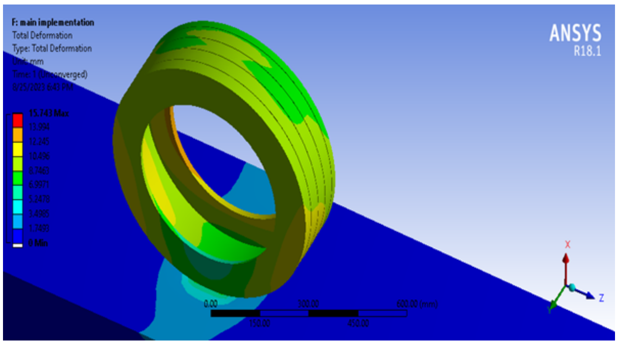


**Figure 15.** Total deformation (Un-converged solution)

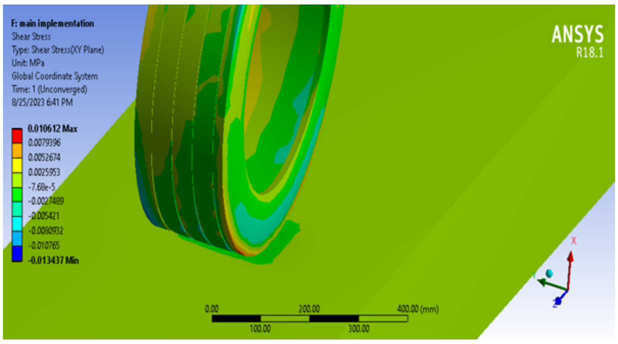


**Figure 16.** Generated shear stress on tyre

The shear stress distribution across the contact zone is illustrated in Figure 16. In the contact region, a shear stress of approximately 0.010612 MPa is registered, thereby underscoring the intensity of forces within this pivotal interface. Contrastingly, at the tyre corner, a shear stress measurement of 0.0027 MPa is recorded.

Visualised in Figure 17 is the contact state; a predominant sticking is observed within the contact zone, while sliding behaviour is exhibited at the corners, contributing to the tyre sinking into the ground. A subsequent friction analysis, depicted in Figure 18, reveals the apex of friction, precisely located at the tyre-ground contact point, registering at 0.665 MPa and further illustrated in Figure 19.

These findings serve to augment understanding related to the complexities of tyre-soil interactions, thereby establishing a foundation for the optimisation of tyre design, with implications for enhancing both vehicle performance and safety. It is imperative to note that further investigation is necessitated for the interpretation of sticking/sliding results, tyre penetration, Mooney-Rivlin deformation, and unconverged solutions. Although results are harmonious with extant knowledge, validation against physical tests presents itself as a plausible future research trajectory.

A notable disparity in tyre penetration between the corner and central regions has been identified. Such discrepancy is postulated to stem from variations in ground compaction, tyre design, and load distribution, illuminating the criticality of considering local soil conditions in the design of tyres tailored for specific applications. The considerably elevated deformation, observed in conjunction with the Mooney-Rivlin elastomer, could be attributed to its material properties, which might diverge from actual tyre behaviour. For the enhancement of realism, a refinement of material properties and contemplation of more accurate hyperelastic models may be requisite.

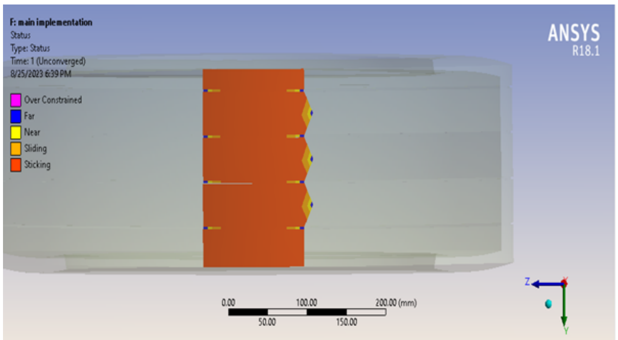


**Figure 17.** Tyre contact status

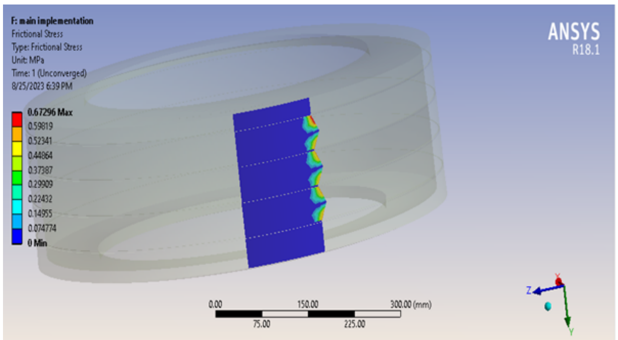


**Figure 18.** Frictional stress on tyre

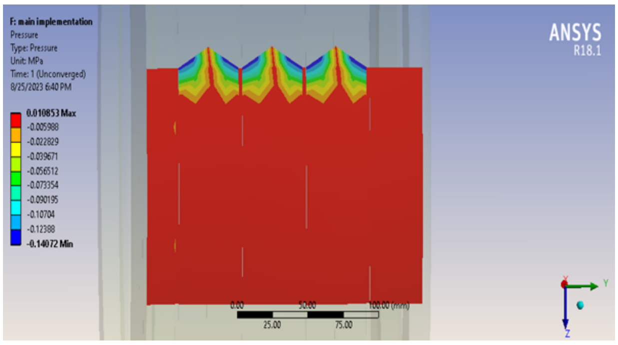


**Figure 19.** Pressure on tyre (Un-converged solution)

## 4 Conclusion and Future Scope

An exploration into nonlinear contact analysis, utilising ANSYS FEA software, has permitted a detailed examination of the nuanced interaction between tyre and road. Outcomes from this research spotlight the instrumental role of ground material in the dynamic interaction with the vehicle, wherein the chosen substrate is demonstrated to substantively influence pivotal parameters, including frictional stress, tyre deformation, and the degree of tyre sinking [29, 30]. Salient insights into the impacts of ground material on tyre behaviour, with direct ramifications for tyre design and vehicle performance, constitute the principal findings of this investigation. Additionally, novel contributions have been proffered, expanding current comprehension of tyre behaviour amid diverse soil conditions.

From a practical standpoint, the findings of this study harbour significant implications for tyre design and the optimisation of performance. The incorporation of ground material characteristics into tyre design permits engineers to augment traction, obviate sinking, and consequently engineer vehicles that are both safer and more efficient. While the insights rendered by this study are valuable, it is paramount to acknowledge its limitations, which encompass simplifications in the tyre model and assumptions pertaining to constant friction coefficients. Forthcoming endeavours in this domain should pivot towards the refinement of tyre models, the integration of shear stress considerations, exploration into variable friction coefficients, and investigations into different tread widths. To effect comprehensive validation, field testing should be contemplated.

This research elucidates the paramount influence of ground material on tyre behaviour, underlining the imperative for a customised approach to tyre design. It provides a substantive contribution to the collective understanding of tyre-soil interaction and has tangible applications in elevating vehicle safety and performance. The path ahead for research ought to forge towards the continued refinement of models and validation of findings through experimental means, thereby fostering advances in tyre design and the optimisation of road safety.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflilict of Interest

The authors declare that they have no conflicts of interest.

## References

[1] J. D. Zhuang, *Modern Vehicle Tyre Technology*. Beijing Institute of Technology Press, Beijing, 2001.

[2] H. B. Pacejka, "Basic tire modeling considerations," *Tire and Vehicle Dynamics*, pp. 59–85, 2012. https://doi.org/10.1016/B978-0-08-097016-5.00002-4

[3] M. H. R. Ghoreyshi, "A state of the art review of the finite element modelling of rolling tyres," *Iran. Polym. J.*, vol. 17, no. 8, pp. 571–597, 2008.

[4] "Faq," BayTires. https://www.baytires.com/faq

[5] M. F. Mendoza-Petit, D. Garcia-Pozuelo, V. Diaz, and M. Garrosa, "Characterization of the loss of grip condition in the strain-based intelligent tire at severe maneuvers," *Mech. Syst. Signal Process.*, vol. 168, p. 108586, 2022. https://doi.org/10.1016/j.ymssp.2021.108586

[6] C. Becker and S. Els, "Agricultural tyre stiffness change as a function of tyre wear," *J. Terramech.*, vol. 102, pp. 1–15, 2022. https://doi.org/10.1016/j.jterra.2022.04.001

[7] P. Sun, G. Feng, S. Zhou, C. Qiu, and J. Fan, "Experimental analysis of radial tire stiffness and grounding characteristics," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 677, no. 2, p. 022111, 2019. https://doi.org/10.1088/1757-899X/677/2/022111

[8] M. Dudziak, A. Lewandowski, and K. J. Waluś, "Static tests the stiffness of car tires," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 776, no. 1, p. 012071, 2020. https://doi.org/10.1088/1757-899X/776/1/012071

[9] P. Kaushik, "Unleashing the power of multi-agent deep learning: Cyber-attack detection in IoT," *Int. J. Glob. Acad. Sci. Res.*, vol. 2, no. 2, pp. 23–45, 2023. https://doi.org/10.55938/ijgasr.v2i2.46

[10] Y. Hirata, H. Kondo, and Y. Ozawa, "12 - Natural rubber (NR) for the tyre industry," *Chemistry, Manufacture and Applications of Natural Rubber*, pp. 325–352, 2014. https://doi.org/10.1533/9780857096913.2.325

[11] A. P. Evdokimov, "Nonlinear properties of rubber-cord shells of tire-type pneumatic clutches," *Chem. Pet. Eng.*, vol. 55, no. 11–12, pp. 1016–1022, 2020. https://doi.org/10.1007/s10556-020-00729-4

[12] W. A. A. S. Premarathna, J. A. S. C. Jayasinghe, K. K. Wijesundara, P. Gamage, R. R. M. S. K. Ranatunga, and C. D. Senanayake, "Investigation of design and performance improvements on solid resilient tires through numerical simulation," *Eng. Fail. Anal.*, vol. 128, p. 105618, 2021. https://doi.org/10.1016/j.engfailanal.2021.105618

[13] J. Hyttinen, R. Österlöf, L. Drugge, and J. Jerrelind, "Constitutive rubber model suitable for rolling resistance simulations of truck tyres," *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, vol. 237, no. 1, pp. 174–192, 2023. https://doi.org/10.1177/09544070221074108

[14] C. L. Chow and C. W. Woo, "The effect of inflation pressure and vehicle loading on the sidewall of a radial tire," *Exp. Mech.*, vol. 21, no. 10, pp. 379–385, 1981. https://doi.org/10.1007/BF02324799

[15] S. L. Sokolov, "Calculation of the stress-strain state of pneumatic tires by the finite element method," *J. Mach. Manuf. Reliab.*, vol. 36, no. 1, pp. 45–49, 2007. https://doi.org/10.3103/S1052618807010098

[16] T. M. Wang, I. M. Daniel, and K. Huang, "Stress analysis of tire sections," *Tire Sci. Technol.*, vol. 24, no. 4, pp. 349–366, 1996. https://doi.org/10.2346/1.2137527

[17] S. Tighe, N. Li, L. C. Falls, and R. Haas, "Incorporating road safety into pavement management," *Transp. Res. Rec.: J. Transp. Res. Board*, vol. 1699, no. 1, pp. 1–10, 2000. https://doi.org/10.3141/1699-01

[18] G. Erdogan, S. Hong, F. Borrelli, and K. Hedrick, "Tire sensors for the measurement of slip angle and friction coefficient and their use in stability control systems," *SAE Int. J. Passeng. Cars - Mech. Syst.*, vol. 4, no. 1, pp. 44–58, 2011. https://doi.org/10.4271/2011-01-0095

[19] P. Lugner, H. Pacejka, and M. Plöchl, "Recent advances in tyre models and testing procedures," *Veh. Syst. Dyn.*, vol. 43, no. 6-7, pp. 413–426, 2005. https://doi.org/10.1080/00423110500158858

[20] A. Agarwal and L. Mthembu, "Structural analysis and optimization of heavy vehicle chassis using aluminium P100/6061 Al and Al GA 7-230 MMC," *Processes*, vol. 10, no. 2, p. 320, 2022. https://doi.org/10.3390/pr10020320

[21] E. Bolarinwa and O. Olatunbosun, "A study of tyre cornering behaviour using a finite element model," in *WCCM VI Conference*, Beijing, China, 2004.

[22] O. A. Olatunbosun and O. Bolarinwa, "FE simulation of the effect of tire design parameters on lateral forces and moments," *Tire Sci. Technol.*, vol. 32, no. 3, pp. 146–163, 2004. https://doi.org/10.2346/1.2186779

[23] E. O. Bolarinwa and O. A. Olatunbosun, "Finite element simulation of the tyre burst test," *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, vol. 218, no. 11, pp. 1251–1258, 2004. https://doi.org/10.1243/0954407042580075

[24] M. Namjoo and H. Golbakhshi, "An efficient design tool based on FEM for evaluating effects of components properties and operating conditions on interaction of tire with rigid road," *J. Cent. South Univ.*, vol. 22, no. 1, pp. 189–195, 2015. https://doi.org/10.1007/s11771-015-2509-7

[25] A. Agarwal and L. Mthembu, "Investigation of dynamic factors in different sections of HVC by static and free vibration modal analysis," *Ann. Chim. - Sci. Mat.*, vol. 46, no. 2, pp. 75–84, 2022. https://doi.org/10.18280/acsm.460203

[26] A. Agarwal and L. Mthembu, "FE design analysis and optimization of heavy-duty truck chassis using sparse grid initialization technique," *Mater. Today Proc.*, vol. 60, no. P3, pp. 2084–2092, 2022. https://doi.org/10.1016/j.matpr.2022.01.471

[27] ANSYS. https://www.ansys.com/academic

[28] R. Moser and J. G. Lightner, "Using three-dimensional digital imaging correlation techniques to validate tire finite-element model," *Exp. Tech.*, vol. 31, no. 4, pp. 29–36, 2007. https://doi.org/10.1111/j.1747-1567.2007.00157.x

[29] K. Kabe and M. Koishi, "Tire cornering simulation using finite element analysis," *J. Appl. Polym. Sci.*, vol. 78, no. 8, pp. 1566–1572, 2000. https://doi.org/10.1002/1097-4628(20001121)78:8⟨1566::AID-APP140⟩3.0.CO;2-I

[30] J. R. Ellis, *Vehicle Handling Dynamics*. Mechanical Engineering Publications, London, 1994.