Traffic & Transportation

Numerical Simulation of Vehicle Tyre under Various Load Conditions and Its Effect on Road Traffic Safety

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ABSTRACT

The main objective of the transport reliability and maintenance analysis is to improve the understanding of accidents through incident investigations. This research focuses on composite pneumatic tyres used in transportation engineering and presents both theoretical and experimental studies. The finite element method used for numerical simulation combined with pre-experimental measurements based on optimisation by material vibration response is presented for tyre material modelling. Piezoelectric vibration test was used for the pre-experimental test of the tyre quarters. The simulation results indicate that the pneumatic tyre with the recommended air pressure inflation shows the least amount of deformation. In comparison, pneumatic tyres with recommended and reduced air pressure inflation of 0.25, 0.5 and 0.75 bar are under research. Additionally, it was established that, when subjected to external forces that exceed the tyre's maximum weight capacity, as determined by the manufacturer, the tyre exhibits significant stiffening and internal stress. The research suggests that this methodology can be used to obtain a realistic model of vehicle tyre dynamic processes and assess the impact on road traffic safety with different inflation pressures and loads.

KEYWORDS

finite element method; composite; tyre; road safety; blast effect; numerical simulation.

1. INTRODUCTION

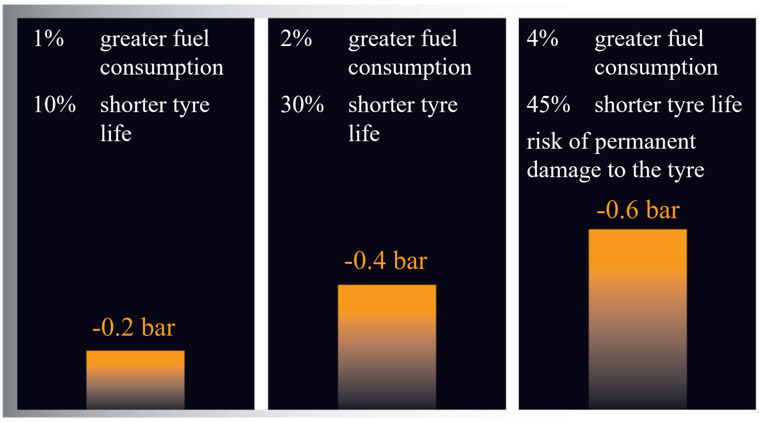
As the automotive industry has developed, vehicles have become the primary means of land transportation and travel. This is due to the widespread availability of road networks, low travel costs, and convenient and flexible travel options, as evidenced by the growing number of registered vehicles and the increasing annual miles travelled [1]. Despite the expected rise in road traffic accidents and fatalities with the growing use of personal vehicles, data from the United Nations Economic Commission (UNEC) [2] show that this trend is decreasing globally. However, road traffic accidents remain one of the leading causes of death for all age groups, according to the World Health Organization (WHO) [3]. On the other hand, statistics from the UNEC show that the Baltic States have some of the largest decreases (in the top 10 countries) in road traffic fatalities in Europe and North America from 2009 to 2019 (*Figure 1a*). A study [4] projects that between 2015 and 2030, losses from road traffic accidents (RTAs) could reach up to $1.8 trillion in costs, including hospitalisation and loss of labour. The COVID-19 pandemic in 2020 resulted in varying lockdown restrictions across EU countries, leading to a reduction in vehicle traffic. At the same time according to [5], there are different risk factors in different countries (for example – the highest number of road traffic accidents occurred in the Czech Republic; the highest number of fatalities occurred in Poland; the lowest number of road traffic accidents and casualties occurred in Slovakia) but one of the following factors that influenced the statistic is a technical malfunction of the vehicle. However, the impact on RTAs was not as straightforward, with only a minor decrease in RTAs observed in different organizations' statistics.

The goal of these statistics is to determine if new technologies, methods, and regulations can help reduce or prevent RTAs. Research in the transportation sector aimed at improving driver and pedestrian safety remains relevant, according to [6]. According to [7], nearly half of the RTAs are related to tyre problems, many of which result from punctures or blowouts, especially in electric vehicles which carry a 30% heavier load due to their own mass [8]. Vehicle tyres are the only point of contact between the vehicle and the road surface [9], so their condition has a significant impact on the stability and safety of the vehicle, especially in the case of flat tyres. The main causes of tyre blowouts are severe surface wear and abnormal tyre pressure, which are most likely to occur during high-speed driving or sudden braking, according to [10]. Maintaining proper tyre inflation pressure improves vehicle handling and braking, fuel efficiency and tyre life, as shown in [11]. In research [12] it is reported that a tyre pressure that is less than 0.6 bars below the recommended pressure leads to 4% higher fuel consumption, 45% shorter tyre life, and an increased risk of permanent tyre damage. Further details can be seen in *Figure 1b*. Furthermore, concerning the experiments carried out in reference [13], it is demonstrated unequivocally that adhering to the principle of maintaining nominal tyre pressure is essential for the safe operation of vehicles. Both low and high tyre pressures, in comparison to the recommended nominal pressure set by tyre manufacturers, result in extended braking distances across various road conditions. It is important to highlight that the research review presented in [13] reveals that a staggering 40% of the tested vehicles exhibited significantly low tyre pressures.

The implementation of tyre pressure monitoring systems (TPMS) in vehicles has become increasingly common [14], as driving with tyres that have too high or too low inflation pressure is similarly dangerous to driving with tyres at risk of blowout [15]. Many countries are considering making it mandatory for all vehicles to have a TPMS sensor installed on each wheel [16].

	Country	Changes in %
1.	Iceland	-65
2.	Belarus	-62
3.	Turkmenistan	-57
4.	Luxembourg	-54
5.	Greece	-53
6.	Lithuania	-50
7.	Norway	-49
8.	Latvia	-48
9.	Estonia	-47
10.	Switzerland	-46

a) Ten largest percentage decreases in road traffic fatalities in 2009–2019 by [2]



b) Risks of under inflation air pressure in a tyre, based on [11]

Figure 1 – Charts from the review part of research

The pneumatic tyre is made up of several structural components that are combined and vulcanised during the production process [17, 18]. These components can be made of rubber or rubber-based composites, as shown in *Figure 2*. The development of the tyre structure involves conducting experiments to assess its stability and reliability. Numerical modelling, using techniques such as the finite element method, is a more efficient and cost-effective alternative to experimental testing, according to [19, 20]. Therefore, careful consideration must be taken in developing an accurate numerical model.

To optimise tyre design and performance, the factors affecting the tyre's friction with the road surface and its local blast resistance must be thoroughly studied in the design stage. Consideration must be given to the loads during operation and material behaviour in a single task, according to [21−23]. As a result, tyre material behaviour should also be investigated. The study of tyre material under load can help improve the tyre's blast resistance, as stated in [24−26]. Optimisation of the tyre's structure through material combination can be achieved using the finite element method and algorithms such as genetic algorithms, according to [27]. Moreover, [28] recommends careful attention be given to material simulations through different methods, taking into account the frequency response of the material. Hence, experimental research combined with

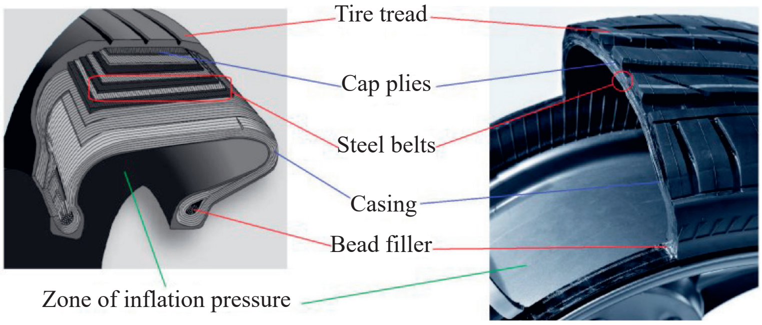


Figure 2 – Construction of vehicle pneumatic tyre

numerical simulations has advanced the constitutive modelling of tyre materials and reduced the risk of blast effect.

The accuracy of finite element analysis (FEA) in modelling composite tyres depends on the accuracy of the material models used. Two common approaches in modelling structural reinforcements are the use of the composite materials theory [29] and separate modelling of the rubber matrix and cords using “rebar” elements [30]. However, none of these approaches takes into account the frequency response of the vehicle tyre material, which is crucial in understanding the behaviour of the tyre and predicting blowouts under different loads. The viscoelastic properties of the tyre rubber composite result in a complex friction behaviour that is influenced by factors such as the contact area, sliding velocity, inflation pressure, ambient temperature and environmental loads. Without considering the vibration and frequency response of the material, it is difficult to accurately describe the behaviour of the tyre and make reliable predictions.

The current research presents a combination of experimental measurement and numerical simulation to efficiently determine the dynamic behaviour of vehicle tyre composites. This approach eliminates the need for complex composite material connections and allows for investigation under various load conditions. The proposed methodology for future tyre numerical simulation will focus on simulating the interaction between the tyre and road surface under different loads to evaluate tyre safety during vehicle drive.

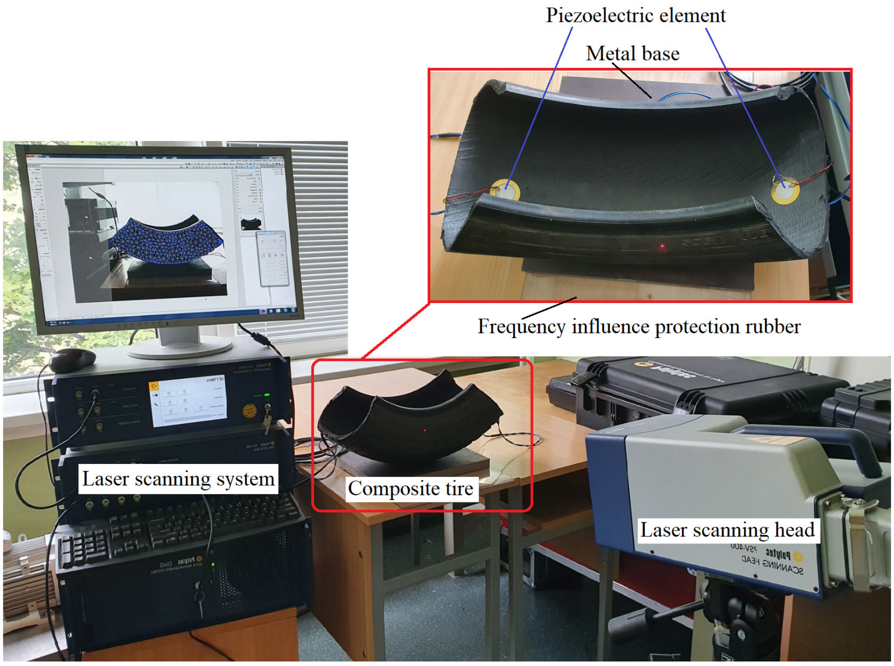
2. PRE-EXPERIMENTAL PART

The pre-experiment aimed to determine the tyre vibration response properties through vibration analysis. The data obtained were used to simplify composite material issues during numerical modelling and to better understand the tyre’s behaviour under load. Only a quarter of the tyre was studied as it has full symmetry in the circumferential direction. The tyre was analysed using piezoelectric vibration testing, which determined the tyre’s vibration characteristics (mode shapes) and showed its surface movement under dynamic loads.

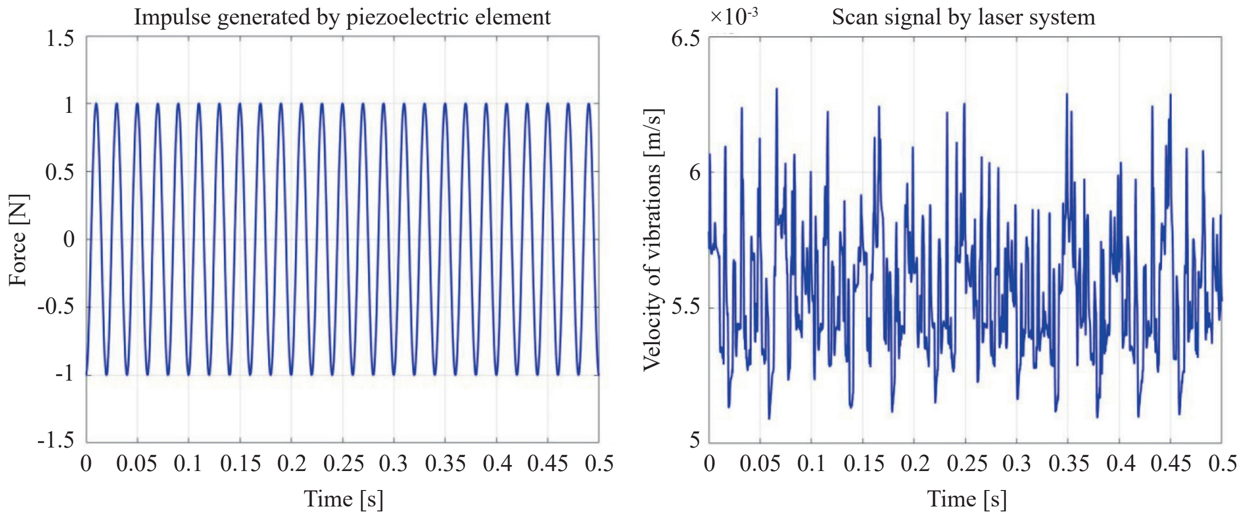
The experimental tests were conducted using a two-sample measurement design and based on a one-sample statistical method to estimate uncertainty in repeated measurement data processing [31]. The test setup consists of a metal base with low-frequency influence protection rubber, the test object securely attached to the metal base, and a laser scanning system to measure tyre surface vibrations under piezoelectric vibration element impact signals (as shown in *Figure 3a*). The vibration tests were performed by measuring tyre surface deformation velocity from the piezoelectric element’s vibration impulse. The tests were based on a double-sample measurement and single-sample statistical method to estimate uncertainty in repeated measurement data processing [32]. To minimise measurement errors, the average results were utilised. The piezoelectric element generated a sinusoidal impulse at 50 Hz frequency and the vibration velocity was measured using the laser scanning head. An example of test data can be seen in *Figure 3b*.

The tests yielded the tyre surface deformation velocity as the main result. The laser scans each grid point during a piezoelectric vibration impulse with good and optimal scan conditions, making the grid of points and laser focus suitable for reflecting materials. The frequency domain has a bandwidth of 0.5 kHz with a step resolution of 0.1 Hz. The frequency response is presented in the velocity domain as this allows for clearer visibility of resonance points in the spectrum analysis. The deformation velocity amplitude on the tyre scanning surface in the frequency response domain is depicted in *Figure 4*.

The frequency analysis reveals that the main resonance frequency of the tyre composite structure is in the low-frequency range and near the end of the middle-frequency range. The main resonant modes are observed



a) Measuring bench for the pre-experimental part of research



b) The example of measuring data from the tests

Figure 3 – The pre-experimental part details

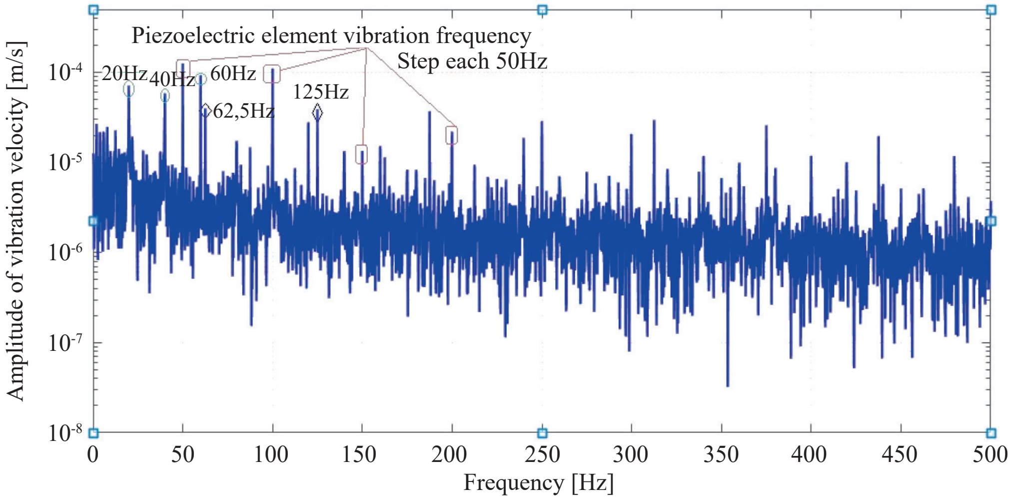


Figure 4 – The velocity amplitude on the tyre scanning surface in the frequency response domain (in logarithm)

in this range, with the main and first resonance frequency equal to 20 Hz with harmonics and 62.5 Hz with harmonics. The presence of these second resonant frequencies can be attributed to the complex composite structure of the object. It should be noted that the 50 Hz frequency and its harmonics generated by the piezoelectric element micro-vibration impulse should be ignored during comparison.

3. NUMERICAL MODELLING AND OPTIMISATION

The numerical modelling was done using the finite element analysis (FEA) with the commercial software ANSYS®. A standard road vehicle tyre was used, with its properties taken from research studies [17, 19]. Non-linear material models of the tyre were selected for comparison, including an ideally elastic material with a stress-strain relationship derived from a strain energy density function. A 3D model of the tyre was created and a quarter of it was used for the simulation, as the object is symmetrical and using a part of it would greatly reduce the simulation time without affecting the results.

The tyre model was analysed in a 3D volume and was divided into a mesh of hexahedral and tetrahedral hybrid elements. To accurately capture the impulse generated in the near boundary layers, up to seven inflation layers were created with an expansion factor of up to 1.5 (*Figure 5*). The boundary conditions for the tyre modelling, which were connected to pre-experimental tests, are presented in *Figure 5*.

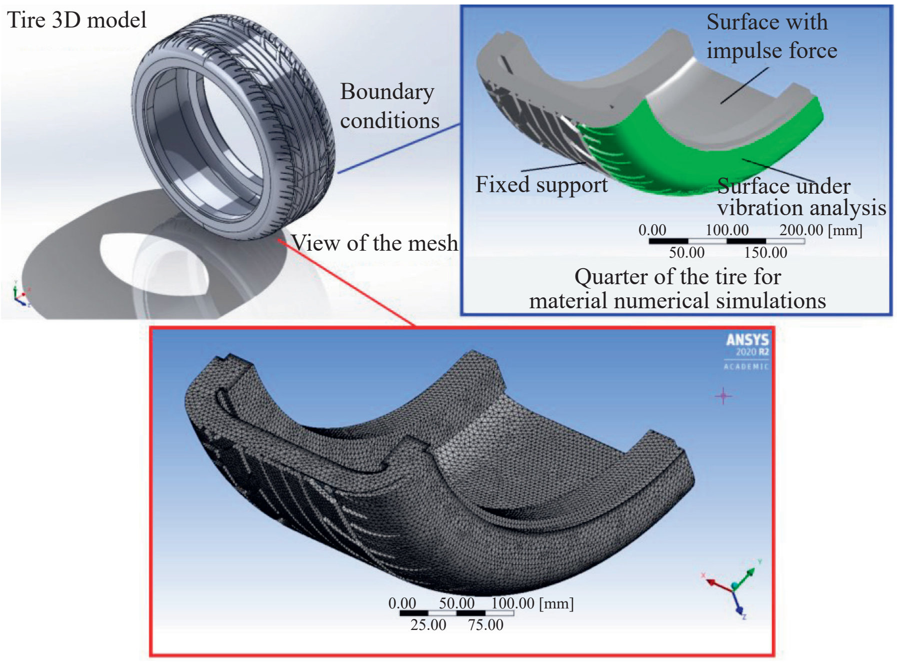


Figure 5 – View of tyre material numerical model parameters

The numerical code was based on the finite element method (FEM) using the Newmark method, and was used for dynamic simulation. The equilibrium equation, as described in [33–35], can be expressed as:

$$[M]\{\ddot{x}\}_t+[C]\{x\}_t+\{F\}_t^{int}=\{F\}_t^{ext} \tag{1}$$

where $\{F\}_t^{int}=[K]\{x\}_t$ are the vector of internal forces; $\{F\}_t^{\ddot{u}}$ are the vector of external forces (in the current situation – impulse from experimental part of research); $\{\ddot{x}\}_t$, $\{\dot{x}\}_t$, $\{x\}_t$ are the acceleration, velocity and displacement vector at solution time (*t*); [*M*], [*C*] and [*K*] are matrices of masses, damping and stiffness, respectively.

Since the variable vectors are assumed to be linear within the time step, the equations for acceleration, velocity and displacement will have a form:

$$\ddot{x}_t=b_{\ddot{u}}\left(x_t-x_{t-\Delta t}\right)+b\,\dot{x}_{t-\Delta t}+b\,\dot{x}_{t-\Delta t} \tag{2}$$

$$\dot{x}_t=b_4\left(x_t-x_{t-\Delta t}\right)+b_5\dot{x}_{t-\Delta t}+b_6\ddot{x}_{t-\Delta t} \tag{3}$$

$$x_t=x_{t-\Delta t}+\Delta t\dot{x}_{t-\Delta t}+\left(\frac{1}{2}-\beta\right)\Delta t^2\ddot{x}_{t-\Delta t}+\beta\Delta t^2\ddot{x}_t \tag{4}$$

The γ and β are the dimensionless specific integration parameters which varied. Where $b_1 \ldots b_6$ are the calculated integration constants in a simplified view, an extended view of those constants shown in *Table 1*.

Table 1 – Specific integration parameters of constants γ and β

Constant	b_1	b_2	b_3	b_4	b_5	b_6
Specific parameters	$1/\beta \cdot \Delta t^2$	$1/\beta \cdot \Delta t$	$\beta - 1/2$	$\gamma \cdot \Delta t \cdot b_1$	$1+\gamma \cdot \Delta t \cdot b_2$	$\Delta t \cdot (1+\gamma \cdot b_3 - \gamma)$

The Newmark method that was used has the advantage of avoiding time-consuming operations involving the inversion of the stiffness matrix, as only the mass diagonal matrix is inverted. However, the method is conditionally stable and this imposes a limitation on the time step based on the stability condition, which is its main disadvantage:

$$\gamma \ge 1/2;\ \beta \le 1/2;\ \text{and}\ \ \Delta t \le \frac{1}{\omega\sqrt{(\gamma/2)-\beta}_{max}} \tag{5}$$

where ω_{max} is the highest element frequency in the structural system mesh.

The specific process of the current model is the design optimisation task (*Figure 6*) for the tyre material numerical model with pre-experimental data and comparison. For successful optimisation, the following important steps must be included in the analysis flowchart, regarding [35]:

- Parameterisation: this involves selecting the variables for design optimisation and simplifying the model structure.
- Pre-experiment: this provides a valid and effective method for validating the model, collecting information and data to prevent problems during the simulation of the composite material structure.
- FE analysis numerical test: the model database is established based on the pre-experiment data and simulation in each optimisation step. The simulation settings remain the same as previously indicated.
- Approximate model: this is a model that approximates the input variables (experimental surface vibration and frequency response) and output variables (surface vibration and simulation model frequency response) during optimisation. In this research, the Kriging model was selected for building the approximate model.
- Optimisation calculation: a reasonable algorithm is used to solve the objective function through minimisation.

Various types of results can be obtained from the current numerical modelling after optimisation. In *Figure 7*, the comparison of results from the tyre surface deformation velocity in frequency response from the experimental part and from numerical simulation after optimisation are shown.

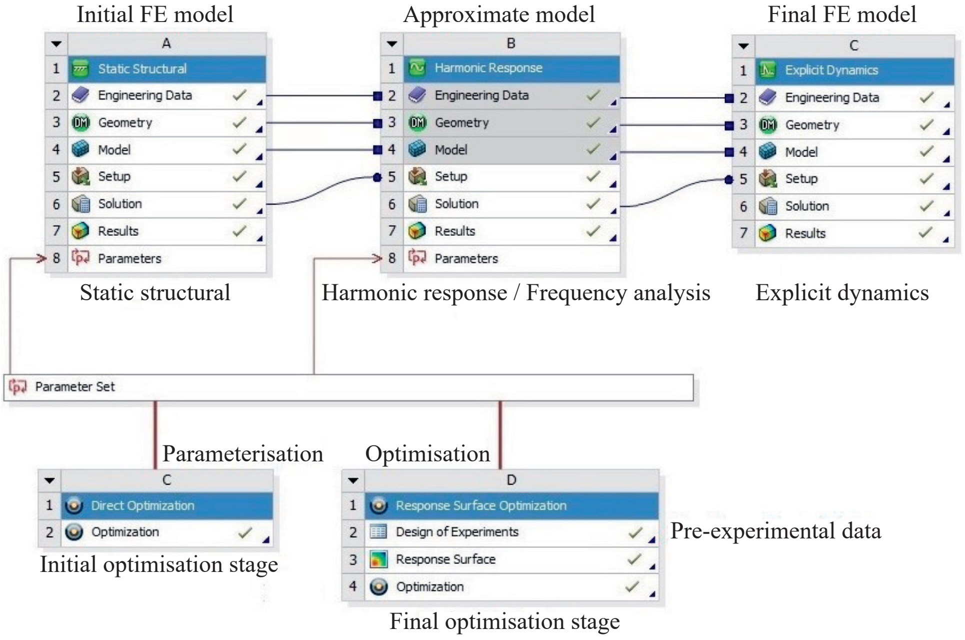


Figure 6 – ANSYS flowchart of the research task

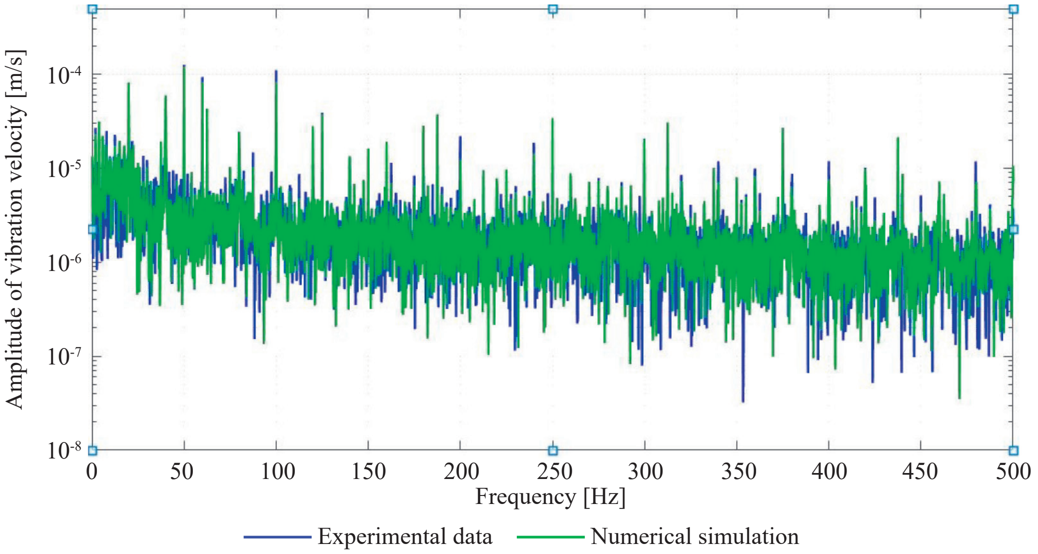
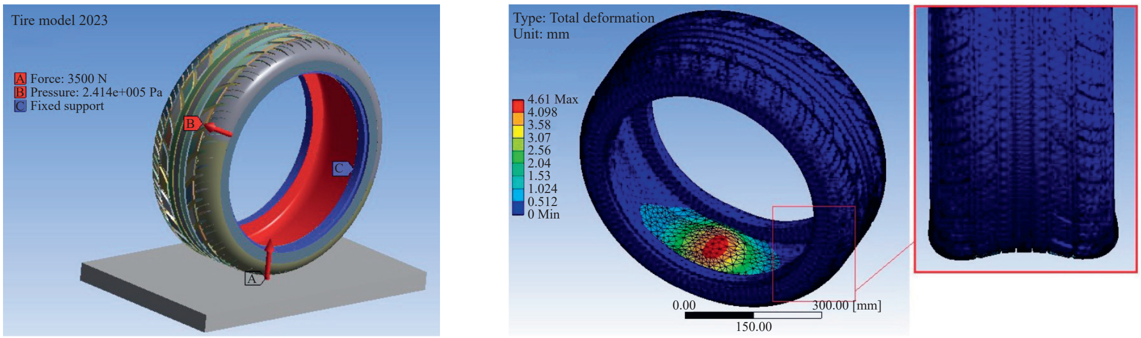


Figure 7 – The graphs of the comparison of tyre frequency response between the experimental and numerical research

The difference between the frequency responses of experimental and numerical modelling is less than ~4% at more frequency points. The difference in the resonance points is no greater than ~2%. The logarithmic spectrum of velocity amplitude shows that, even after optimisation, there is still a significant difference in amplitude at a few frequencies, but they are low compared to all the frequencies investigated. The results indicate that the proposed numerical simulation methodology, combined with the experimental measurements and optimisation, accurately models tyre material behaviour and avoids problems in composite structure modelling. The current model is used in simulating the dynamic processes of vehicle tyres under loads.

4. INVESTIGATING THE IMPACT OF VARIOUS LOADS ON TYRE PARAMETERS

The pneumatic tyre pressure was modelled by inflating the inner surface volumes of the tyre to 2.41 bar (35 psi) in the first case, which is the recommended inflation pressure for the tyre under research. In other cases, the pressure was reduced to 2.16 bar; 1.91 bar and 1.66 bar (by -0.25, -0.5, -0.75 bar). The tyre's support surfaces in the model were chosen as the surfaces in contact with the wheel rim, and the tyre was modelled in contact with the road surface. The boundary conditions for this tyre modelling are shown in *Figure 8a*.



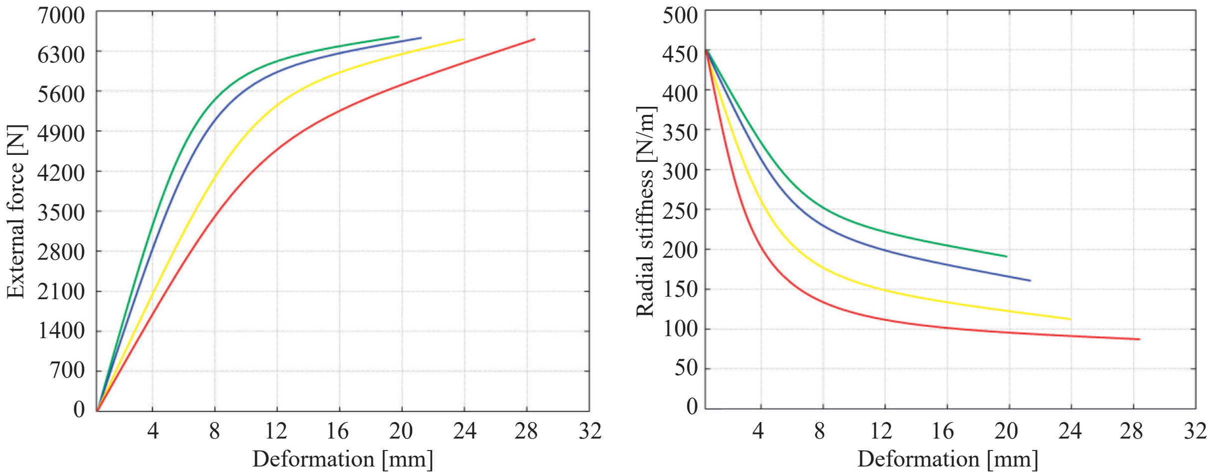
a) View of the boundary conditions for numerical modelling

b) Visualization of numerical simulation results

Figure 8 – View of numerical model parameters

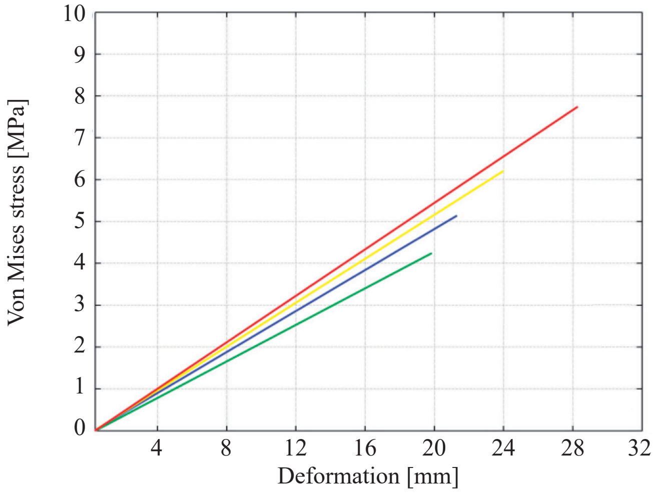
The example of numerical simulation results for tyre behaviour is shown for a 3.25 kN external load (in the middle range of loads during simulation), as seen in *Figure 8b*. A wide range of simulation results was obtained from the numerical modelling of both pneumatic and airless tyres. The main results are displayed for comparative analysis and include: external force / radial stiffness / equivalent stress in rubber vs. tyre deformation (displacement) (*Figure 9*).

The simulation results and graphs of tyre deformation under external force indicate that the pneumatic tyre with the recommended air pressure inflation shows the least amount of deformation. In comparison, pneumatic tyres with reduced air pressure inflation of 0.25, 0.5 and 0.75 bar exhibit higher levels of deformation by



a) External force

b) Radial stiffness



c) Equivalent stress in the rubber component

Tire inflation pressure: — 2.41 bar — 2.16 bar — 1.91 bar — 1.66 bar

Figure 9 – Graphs of tyre numerical modelling results (parameters depend on tyre deformation)

approximately 10.2%, 23.1% and 48.7%, respectively. It is also worth noting that, when subjected to external forces that exceed the tyre's maximum weight capacity, as determined by the manufacturer, the tyre exhibits significant stiffening and internal stress. The significant differences in deformation among each case can be attributed to the nonlinear behaviour of the tyre material. This makes it difficult to accurately match the applied external forces. The radial stiffness vs. tyre deformation diagrams illustrate that as the tyre deforms from the outer surface to the centre of the rim, its radial stiffness decreases (stress increases). These results can be explained by the fact that the maximum weight capacity of the tyre is around 615 kg (tyre index 91T). Reducing the inflation air pressure in a tyre leads to a significant increase in tyre deformation, which increases the risk of permanent damage to the tyre and potential road traffic accidents. When subjected to external loads that exceed the maximum allowed weight, the tyres exhibit extremely poor performance in terms of deformation and are at a higher risk of micro-cracking failure. This is because the material characteristics of the tyre have reached the yield point in the plastic region, increasing the risk of a blowout. For these reasons, it is not recommended to overload tyres (especially with lower inflation pressure than recommended) when they have low inflation air pressure, especially for electric vehicles.

5. DISCUSSION

The objective of this research was to improve the understanding of accidents through incident investigations by analysing the reliability and maintenance of composite pneumatic tyres used in transportation engineering. The study presented both theoretical and experimental approaches to investigate the behaviour of these tyres.

The simulation results indicated that the pneumatic tyre inflated with the recommended air pressure showed the least amount of deformation. In contrast, pneumatic tyres inflated with reduced air pressure (0.25; 0.5 and 0.75 bar) exhibited progressively higher levels of deformation. The deformation differences among each case were attributed to the nonlinear behaviour of the tyre material, which made it challenging to accurately match the applied external forces.

Furthermore, the study found that when the tyres were subjected to external forces exceeding the manufacturer's maximum weight capacity, they exhibited significant stiffening and internal stress. This observation suggests that overloading the tyres, especially with lower inflation pressure than recommended, increases the risk of permanent damage to the tyre and potential road traffic accidents. The research highlights the importance of maintaining proper inflation pressure in pneumatic tyres. It demonstrates that reducing the inflation pressure significantly increases tyre deformation, leading to an elevated risk of micro-cracking failure and blowouts. It is particularly crucial to avoid overloading tyres with lower inflation pressure, especially for electric vehicles.

The presented numerical simulation approach allows engineers to efficiently determine the dynamic properties and behaviour of vehicle tyres under various load conditions. It provides a realistic model for understanding the impact of inflation pressures and loads on road traffic safety. However, the research acknowledges the need for experimental research to validate the presented numerical modelling approach, specifically incorporating tyre frequency analysis to assess tyre deformation under different loads. Future studies should expand the proposed methodology for numerical simulation to include tyre-road interactions under various load conditions. This broader investigation will allow researchers to explore the safety aspects of different tyre types, such as summer/winter tyres and pneumatic/airless tyres.

6. CONCLUSIONS

In the conducted research, theoretical and experimental research on the composite pneumatic tyre used in transport engineering is presented. The finite element method, used for numerical simulation combined with pre-experimental measurements based on optimisation by material vibration response, was used for tyre material behaviour modelling to avoid problems of complicated composite modelling. Piezoelectric vibration test was used for the pre-experimental test of the tyre quarters. The simulation results indicate that the pneumatic tyre with the recommended air pressure inflation shows the least amount of deformation. In comparison, pneumatic tyres with reduced air pressure inflation of 0.25, 0.5 and 0.75 bar exhibit higher levels of deformation by approximately 10.2%, 23.1% and 48.7%, respectively. It is also worth noting that, when subjected to external forces that exceed the tyre's maximum weight capacity, as determined by the manufacturer, the tyre exhibits significant stiffening and internal stress. The reduction of inflation air pressure in the tyre provides a significant increase in tyre deformation. The more deformed the pneumatic tyre is, the more risk of permanent damage to the tyre exists, which leads to road traffic accidents. When closer to the maximum allowed external load, the tyres show extremely worse characteristics by deformation and probably will have a micro-cracking failure, since as a result, its materials characteristics reached the yield point in the plastic region, increasing the risk of a blowout.

The numerical simulation approach described in the research allows engineers to efficiently determine the dynamic properties and behaviour of vehicle tyres under various load conditions. The research suggests that the proposed methodology can be used to obtain a realistic model of vehicle tyre dynamic processes and assess the impact on road traffic safety with different inflation pressures and loads. In the next step, it will be worthwhile to conduct experimental research that incorporates tyre frequency analysis to validate the presented numerical modelling approach for tyre deformation under different loads. The proposed methodology for numerical simulation of vehicle tyres in the future will involve simulating tyre-road interactions under various load conditions to investigate the safety aspects of different tyre types, such as summer/winter and pneumatic/airless. The findings emphasize the importance of maintaining proper inflation pressure and avoiding overloading to ensure road traffic safety. The presented numerical simulation approach provides a valuable tool for engineers to assess tyre dynamics and behaviour, and it is recommended for further experimental validation and broader application in simulating tyre-road interactions.

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Skirtingų Apkrovų Veikiamos Transporto Priemonės Padangos Skaitinis Modeliavimas ir jos Poveikis Eismo Saugumui

Santrauka

Pagrindinis transporto saugumo ir patikimumo analizės tikslas yra didinti supratimą apie eismo įvykius ir jų priežastis atliekant eismo įvykių tyrimus. Šiame darbe dėmesys yra skiriamas kompozitinėms pneumatinėms padangoms naudojamoms transporto sektoriuje. Darbe yra pristatomi tiek teoriniai, tiek eksperimentiniai tyrimai. Pneumatinės padangos matematinis modeliavimas buvo atliekamas skaitinėms simuliacijoms naudojant baigtinių elementų metodą ir pirminių matavimų duomenis, pagrįstus medžiagos vibracijų atsako optimizavimu. Pirminių matavimų duomenims gauti buvo atliekamas padangos ketvirčio pjezoelektrinis vibracijų matavimas. Simuliacijų rezultatai parodė, kad pneumatinė padanga su rekomenduojamu oro slėgiu deformuojasi mažiausiai. Siekiant atlikti palyginimą, darbe buvo tiriamos pneumatinės padangos su rekomenduojamu ir atitinkamai sumažintu oro slėgiu: 0.25; 0.5 ir 0.75. Papildomai, darbe buvo nustatyta, kad padangai esant veikiamai išorinės jėgos, kuri viršija maksimalią gamintojo leidžiamą apkrovą, padanga tampa pastebimai standesnė ir ją pradeda veikti didesni vidiniai įtempiai. Darbe pristatyta metodologija gali būti naudojama siekiant atkurti realius transporto priemonių padangose vykstančius dinaminius procesus ir siekiant nustatyti skirtingų padangos slėgių poveikį eismo saugumui.

Raktiniai žodžiai
baigtinių elementų metodas; kompozitinė; Padanga; eismo saugumas; skaitinės simuliacijos.