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Comparison of Non-Pneumatic Tires with Traditional Tires for Enhanced Automotive Safety and Sustainability

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Abstract: ***Traditional pneumatic tires are limited by puncture risks and other maintenance, leading to higher environmental waste and safety hazards. This paper explores the design and analysis of Non-Pneumatic Tires (NPTs) as a cost effectively and future alternative. This study evaluates the mechanical performance, load-carrying mechanisms, and vibration characteristics of NPTs. Numerical modeling techniques using Finite Element Analysis (FEA). The findings suggest that NPTs can significantly reduce vehicle downtime and improve safety, positioning them as a critical technology for the future of autonomous and electric mobility.***

Keywords: Non pneumatic tires, Finite element analysis, Load bearing design, Vibration behavior, Sustainable mobility

1. Introduction

Tires have long been considered a primary consumable component in automotive engineering. However, traditional pneumatic tires remain inherently vulnerable to air-pressure maintenance issues and catastrophic puncture failures, which significantly impact both vehicle safety and operational economics. It is estimated that approximately 20% of tire waste- equivalent to 200 million tires scrapped annually- is the result of punctures or irregular wear caused by improper inflation. To address these challenges, Non-Pneumatic Tires (NPTs), often referred to as "puncherless tires," have emerged as a solution that replaces compressed air with an engineered elastic structural lattice.

This research aims to analyze the structural design, material selection, and computational modeling of NPTs to optimize them for mainstream passenger vehicle applications, ensuring they meet the high-speed and load-bearing requirements of modern transportation.

2. Literature Review

The historical development of NPT technology dates back to 1938, when J.V. Martin invented a safety tire featuring rubber-encased hoops and criss- cross spokes. In recent years, this technology has seen a massive resurgence led by Michelin with the introduction of the "Tweel" and more recently the "UPTIS" (Unique Puncture-proof Tire System).

- **Structural Mechanics:** NPTs are generally classified into "top-loading" and "bottom-loading" configurations. Research indicates that top-loading designs, where the load is suspended from the upper spokes, provide more efficient stress distribution and increased load capacity.
- **Lattice Architectures:** Extensive studies have compared traditional hexagonal honeycombs with auxetic lattices. Auxetic structures, characterized by a negative Poisson's ratio, contract transversely under compression, which leads to superior energy absorption, indentation resistance, and fracture toughness compared to standard Geometries.
- **Commercial Evolution:** While the Michelin Tweel has successfully served low-speed off-road markets since 2012, the UPTIS represents a breakthrough for passenger vehicles. By utilizing fiberglass-reinforced rubber spokes, UPTIS achieves the shear and flex properties necessary for highway speeds exceeding 130km/h.

3. Methodology

The design and validation of NPTs require a multidimensional approach involving material science and advanced simulation.

3.1 Material Characterization

Thermoplastic Polyurethane (TPU) is the industry standard for the elastic spokes due to its high elongation at break (>800%) and excellent damping properties. To enhance structural rigidity for automotive use, Carbon Fiber (CF) reinforcements are integrated. Empirical data shows that a 20% short carbon fiber content can improve tensile strength by 63.65% and compressive strength by 105.51%.

3.2 Finite Element Analysis (FEA) Modeling

To accurately predict the behavior of hyperelastic materials like TPU and rubber, and various constitutive models are employed in an FEA environment.

- **Boundary Conditions:** For a standard passenger vehicle platform, a static vertical force of 7848 N is often applied. However, for high-load capacity (HC) designs, design loads can reach 110.25 kN to simulate heavy transport.
- **Optimization Constraints:** Common targets for optimization include a vertical deflection range between 18 and 20 mm and a contact pressure between 0.6 and 0.8 MPa.

4. Results and Discussion

4.1 Comparative Load-Bearing Performance

Recent experimental results for High-Load Capacity (HC) NPTs using a "pi"-shaped support substructure demonstrate significantly higher unit load efficiency compared to traditional designs. The unreinforced HC tire unit load is 2.972 times that of a solid tire and 1.615 times that of a pneumatic tire.

Tire Type	Mass (kg)	Design/Max Load (kN)	Unit Load (kN/kg)
HC NPT (Unreinforced)	257.8	110.25	0.428
HC NPT (Reinforced)	269.4	110.25	0.409
Standard Solid Tire	272.2	39.2	0.144
Pneumatic Tire	143.8	39.2	0.265

4.2 Impact of Structural Enhancements

Incorporating a **spiral steel ring** within the tread has a dual effect on tire mechanics. It successfully increases overall vertical and longitudinal stiffness, which improves load stability. However, it also results in a reduction of torsional stiffness, which must be accounted for in vehicle handling simulations.

4.3 Simulation Validation and Error Analysis

FEA model accuracy was verified against physical testing data for vertical displacement. The simulation results for HC NPTs showed two distinct inflection points at loads of 7.35kN and 36.75kN.

Metric	Simulation Result
Maximum Error (Vertical Displacement)	8.72%
Error at High Load (> 29.4 kN)	< 2.5%
Accuracy for Commercial NPT (Tweel)	> 95%

Large errors at lower loads were attributed to manufacturing and assembly gaps in the metal connection interfaces of the physical prototypes, which minimize as the load increases toward compaction.

4.4 NVH and Thermal Characteristics

NPTs are susceptible to the "polygon effect," where discrete spoke contact causes periodic force fluctuations. Mitigation strategies include gradient spoke thicknesses to disrupt resonance. Thermal dissipation is facilitated by the open-spoke design; however, under thermo-mechanical coupling, TPU material modulus decreases, leading to a corresponding drop in vertical stiffness.

5. Conclusion

Non-pneumatic tire technology represents a transformative shift toward automotive safety and environmental sustainability. The implementation of "\pi"-shaped support substructures and fiber reinforcements allows NPTs to achieve nearly triple the unit load capacity of traditional solid tires while remaining puncture-proof. Future research should prioritize the integration of smart sensors into the lattice to enable real-time health monitoring of the structure.

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