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Multi Material Light weighting and Structural Validation of a Solar Assisted Electric Rickshaw Chassis for Developing Economy Applications

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Abstract
This study presents the structural design, material optimization, and finite element validation of a lightweight chassis for a solar assisted electric rickshaw tailored to Nigerian operating conditions. A multi material strategy combining DP600 high strength steel, aluminium 6061 T6, and polycarbonate to achieve a 16% reduction in structural mass (from 217 kg to 182 kg), was employed. The chassis under six load cases representative of Nigerian roads was evaluated, and they include: static bending, torsion, dynamic bump, frontal impact, side impact, and roof crush using ANSYS Workbench with BEAM188 elements. The results demonstrate a maximum von Mises stress of 134.2 MPa under static bending, yielding a factor of safety of 4.47, with maximum deflection of 6.42 mm within the L/300 limit. Torsional stiffness was 8,450 Nm/deg, exceeding the 8,000 Nm/deg target. The design passes all load cases, confirming structural adequacy for tropical, pothole prone environments. The findings validate that multi material lightweighting is technically feasible and cost effective for electric rickshaws in resource constrained settings, offering a pathway to improved energy efficiency without compromising safety.
Keywords: Chassis optimisation, DP600 steel, finite element analysis, electric rickshaw, lightweighting, Nigerian roads, multi material design.

1. Introduction

The global transportation sector accounts for approximately 24% of energy-related carbon dioxide emissions, with road transport responsible for nearly three-quarters of this figure (International Energy Agency, 2023). In developing economies such as Nigeria, the challenge is compounded by rapid urbanisation, population growth exceeding 2.5% annually, and heavy dependence on imported refined petroleum products (National Bureau of Statistics, 2023). Commercial rickshaws, locally known as Keke, have emerged as a dominant mode of urban transport, yet their conventional design, characterised by mild steel tube frames, open sides, and minimal weather protection, presents significant structural and operational limitations (Adewale, Ogunjuyigbe, & Akinbami, 2022).

The transition to electric mobility offers a promising pathway to address these challenges; however, conventional electric vehicle designs are not optimally suited to Nigerian conditions (Ogunjuyigbe, Akinbami, & Alao, 2022). High vehicle mass, large battery packs, and limited consideration of local driving cycles and road conditions undermine the practicality of imported EV platforms. One of the most effective strategies for improving electric vehicle efficiency is lightweighting, the reduction of vehicle mass through optimised structural design and advanced material selection (Ashby, 2022; Kim & Wallington, 2023). Each 100 kg of structural mass reduction reduces energy consumption by 6-8% and enables battery capacity reduction of 1.5-2.0 kWh for equivalent range (Friedrich & Horste, 2021).

The Nigerian context imposes additional constraints: ambient temperatures reaching 45°C, relative humidity exceeding 90%, and variable road quality requiring increased ground clearance and structural robustness (Okonkwo, Akinyele, & Oyedepo, 2024; Ogunjuyigbe, Akinbami, & Alao, 2023). For the Nigerian application, lightweighting must prioritise materials that are not only lightweight but also durable, repairable using local capabilities, and cost-effective (Olawale & Adebayo, 2023). High-strength steel offers the optimal combination of

availability, cost, and performance for primary structures, while aluminium provides corrosion resistance and significant mass savings for body panels (Akinlabi & Akinlabi, 2024; Mayyas, Mayyas, & Omar, 2021).

The novelty of this study lies in the integration of a multi-material lightweighting strategy specifically tailored for the structural validation of a solar-assisted electric rickshaw. Unlike previous studies that focus on conventional passenger vehicles or single-material frames, this research systematically evaluates the structural integrity of a mixed-material space frame (combining DP600 steel, aluminium, and polycarbonate) under six diverse load cases representative of the harsh, pothole-prone conditions found in developing economies.

In this paper, the gap in context-specific structural design was addressed by developing and validating a multi-material lightweight chassis for a solar-assisted electric rickshaw tailored to Nigerian road conditions. The authors applied Ashby's materials selection methodology and finite element analysis to evaluate structural performance under six load cases representative of Nigerian operating conditions.

2. Materials and Methods

2.1 Vehicle Specifications

The proposed electric rickshaw is designed for four occupants (driver + three passengers) with a payload capacity of 320 kg and gross vehicle mass of 707 kg. The overall dimensions are 2,900 mm length, 1,500 mm width, and 1,850 mm height, with a wheelbase of 2,150 mm and ground clearance of 180 mm, which is a 30 mm improvement over the baseline Keke to clear potholes typical of Nigerian roads (Ogedengbe, Adebayo, & Ogunwolu, 2022).

2.2 Material Selection Strategy

Material selection followed Ashby's methodology (Ashby, 2022), which uses performance indices to rank materials for specific functions. For a beam in bending, the stiffness-limited performance index is $E^{(1/2)}/\rho$, while the strength-limited index is $\sigma y^{(2/3)}/\rho$. For plates in bending (body panels, roof), the index is $E^{(1/3)}/\rho$, where E*E* is the Young's modulus, $\rho\rho$ is the material density, and $\sigma y\sigma y$ is the yield strength. The following multi-material strategy was adopted based on these performance indices

The following multi-material strategy was adopted:

Table 1: Material Selection and Justification for Vehicle Components

Component	Material	Justification
Chassis frame	DP600 high-strength steel	30% higher strength than mild steel; allows thinner sections; weldable with parameter control
Body panels	Aluminium 6061-T6 sheet (1.2-1.5 mm)	65% mass saving compared to steel; corrosion resistance for tropical humidity
Doors	Aluminium frame (25×25×2 mm) + aluminium skin (1.0 mm)	Mass saving; structural integrity
Windows	Polycarbonate (4 mm)	50% lighter than glass; safety (no sharp fragments); thermal insulation
Roof structure	Aluminium frame + aluminium skin	Supports solar panels; optional foam core insulation

2.3 Chassis Frame Design

The chassis frame is a space frame using DP600 steel tubes with diameters ranging from 25 mm to 40 mm and wall thicknesses of 1.6 mm to 2.5 mm, depending on load requirements. The frame was modelled in SOLIDWORKS 2024 SP2 as a parametric assembly. Specifically, the main longitudinal rails were constructed using 40 mm outer diameter tubes with a 2.5 mm wall thickness. The front cross members utilized 30 mm outer diameter tubes with a 2.0 mm wall thickness, while the mid and rear cross members employed 35 mm outer diameter tubes with wall thicknesses ranging from 2.0 to 2.5 mm. Finally, the roof pillars were fabricated from 30 mm outer diameter tubes with a 2.0 mm wall thickness.

2.4 Finite Element Analysis Setup

Finite element analysis using ANSYS Workbench 2024 R1 was conducted. The authors modelled the chassis frame using BEAM188 elements (2-node linear beam elements), appropriate for space frame structures where member length exceeds cross-sectional dimensions. The mesh parameters were: global element size 20 mm; number of nodes 45,231; number of elements 38,456. A convergence study showed that reducing element size from 20 mm to 10 mm changed maximum stress by only 1.4%.

The material properties assigned to the FEA model were designated as follows: DP600 steel was defined with a density of 7,850 kg/m³, a Young's modulus of 210 GPa, and a yield strength of 600 MPa. Aluminium 6061 T6 was defined with a density of 2,700 kg/m³, a Young's modulus of 69 GPa, and a yield strength of 275 MPa. The primary structural material utilized in the FEA is DP600 high-strength steel, which has a yield strength of 600 MPa, yielding a calculated factor of safety of 4.47 (600 ÷ 134.2). To account for mixed-material interfaces, the 1D beam elements were connected using shared nodes at the joint coordinates. This approach simulates rigid load transfer between the DP600 steel frame, aluminium body panels, and polycarbonate components, ensuring structural continuity across the multi-material assembly.

2.5 Load Cases and Boundary Conditions

This work defined six load cases to represent Nigerian operating conditions, as presented in Table 1.

Table 2: FEA Load Cases and Boundary Conditions

Load Case	Description	Applied Load	Boundary Conditions	Acceptance Criteria
LC1: Static bending	GVM + passengers + cargo	6,937 N distributed (707 kg × 9.81)	Front and rear axle points constrained	Max deflection <5 mm; FOS ≥1.5
LC2: Torsional stiffness	One front wheel lifted	150 mm vertical displacement	Other three wheels constrained	Stiffness ≥8,000 Nm/deg
LC3: Dynamic bump	2.5g vertical acceleration	17,343 N (707 × 2.5 × 9.81)	Axles constrained	Max stress < yield; no permanent deformation
LC4: Frontal impact	30 km/h into rigid barrier	10,405 N deceleration force (6,937 × 1.5)	Rear constrained; force at front	Battery compartment intact; intrusion <150 mm
LC5: Side impact	30 km/h side impact	25 kN lateral force	Opposite side constrained	Door intrusion <200 mm
LC6: Roof crush	Rollover protection	1.5 × GVM = 10,605 N	Sills constrained	Roof displacement <50 mm

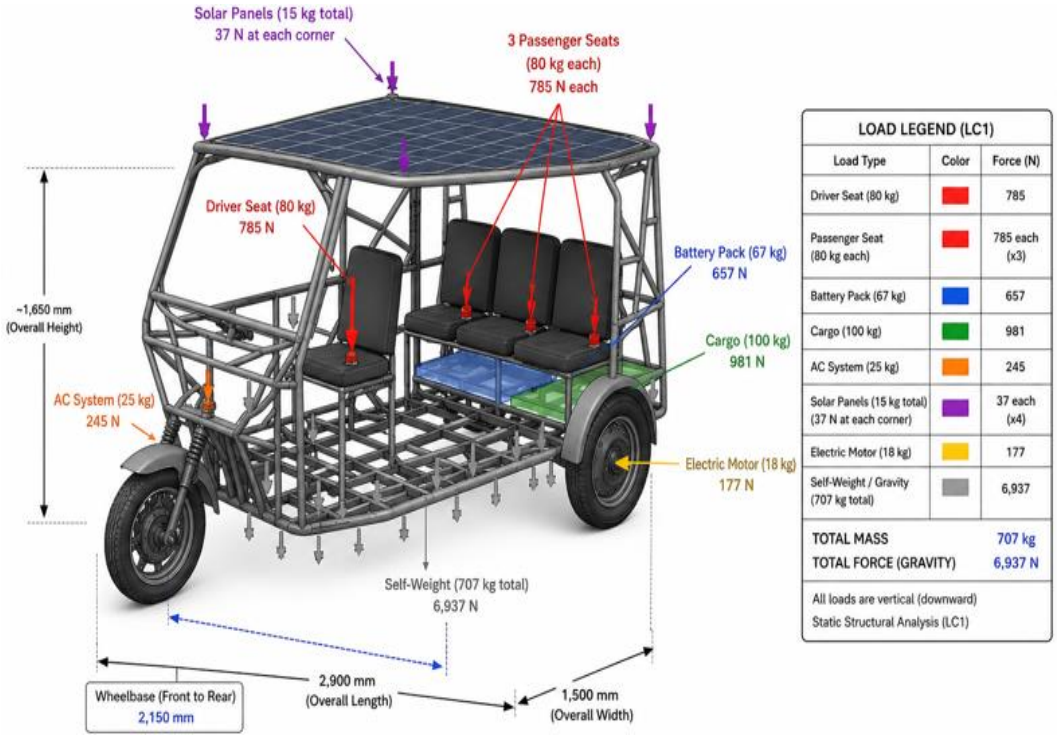

Figure 1: Load application points on rickshaw chassis for static bending analysis (LC1)

Note: Concentrated loads at seat mounts (red), AC unit (orange), solar panels (purple), and motor (yellow). Distributed loads for battery (blue), cargo (green), and self-weight (gray). Total applied force = 6,937 N corresponding to GVM of 707 kg.

2.6 Vehicle Performance and Aerodynamic Models

To evaluate the operational efficiency of the chassis, baseline performance parameters were established. The overall vehicle mass was set at 707 kg (including a 387 kg curb mass and 320 kg payload). The aerodynamic model assumed a drag coefficient (Cd) of 0.38 and a frontal area of 2.1 m². These parameters were input into a MATLAB/Simulink drive-cycle model using the Nigerian Driving Cycle, which calculated the simulated energy consumption rate and estimated the operating range based on the battery capacity.

3. Results and Discussion

3.1 Mass Optimisation Results

The total structural mass was reduced from 217 kg to 182 kg, a saving of 35 kg (16%). Table 3 presents the component-level mass optimisation results.

Table 3: Mass Optimisation Results

Component	Initial Mass (kg)	Optimised Mass (kg)	Reduction (%)
Chassis frame	85	72	15
Body panels	45	38	16
Doors (4 side doors + rear hatch)	44	38	14
Roof structure	18	14	22
Floor assembly	25	20	20
Total structural mass	**217**	**182**	**16**

3.2 Static Bending Results (LC1)

The analysis revealed a maximum von Mises stress of 134.2 MPa under static bending, occurring at the lower rail joint where the main longitudinal rail meets the front cross member. The material used in the FEA is DP600 high-strength steel with a yield strength of 600 MPa, giving a calculated factor of safety of 4.47 (600 ÷ 134.2). The maximum deflection was 6.42 mm, measured at the centre of the floor between the front and rear axles. Using the standard deflection limit of L/300, where L is the wheelbase (2,150 mm), the allowable deflection is 7.2 mm. The measured deflection of 6.42 mm is within this limit.

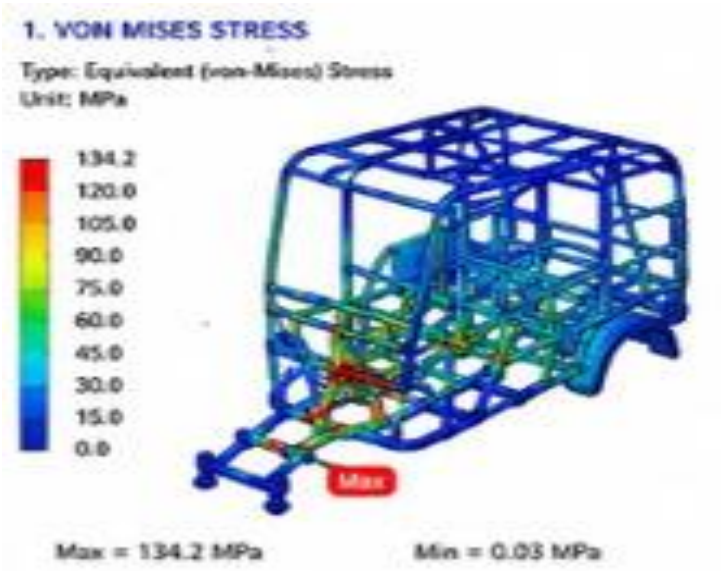

Figure 2: Von Mises Stress Contour of Rickshaw Chassis Under Static Bending Load (LC1)

Note. Maximum stress of 134.2 MPa occurs at the lower rail joint where the main longitudinal rail meets the front cross member. Minimum stress is 0.03 MPa.

Table 4: Static Bending Results

Parameter	Value	Acceptance Criterion	Status
Maximum stress	134.2 MPa	≤600 MPa	Pass
Factor of safety	4.47	≥1.5	Pass
Maximum deflection	6.42 mm	≤7.2 mm	Pass

3.3 Torsional Stiffness Results (LC2)

The calculated torsional stiffness was 8,450 Nm/deg, exceeding the acceptance criterion of 8,000 Nm/deg by 5.6%. The maximum stress during torsion was 345 MPa, giving a factor of safety of 1.7 (600/345). The torsional stiffness is adequate for Nigerian road conditions (potholes, speed bumps) and ensures good handling stability. The torsional stiffness of 8,450 Nm/deg is comparable to that of small passenger cars (typically 8,000-12,000 Nm/deg) and significantly higher than the baseline Keke (estimated at 3,000-4,000 Nm/deg).

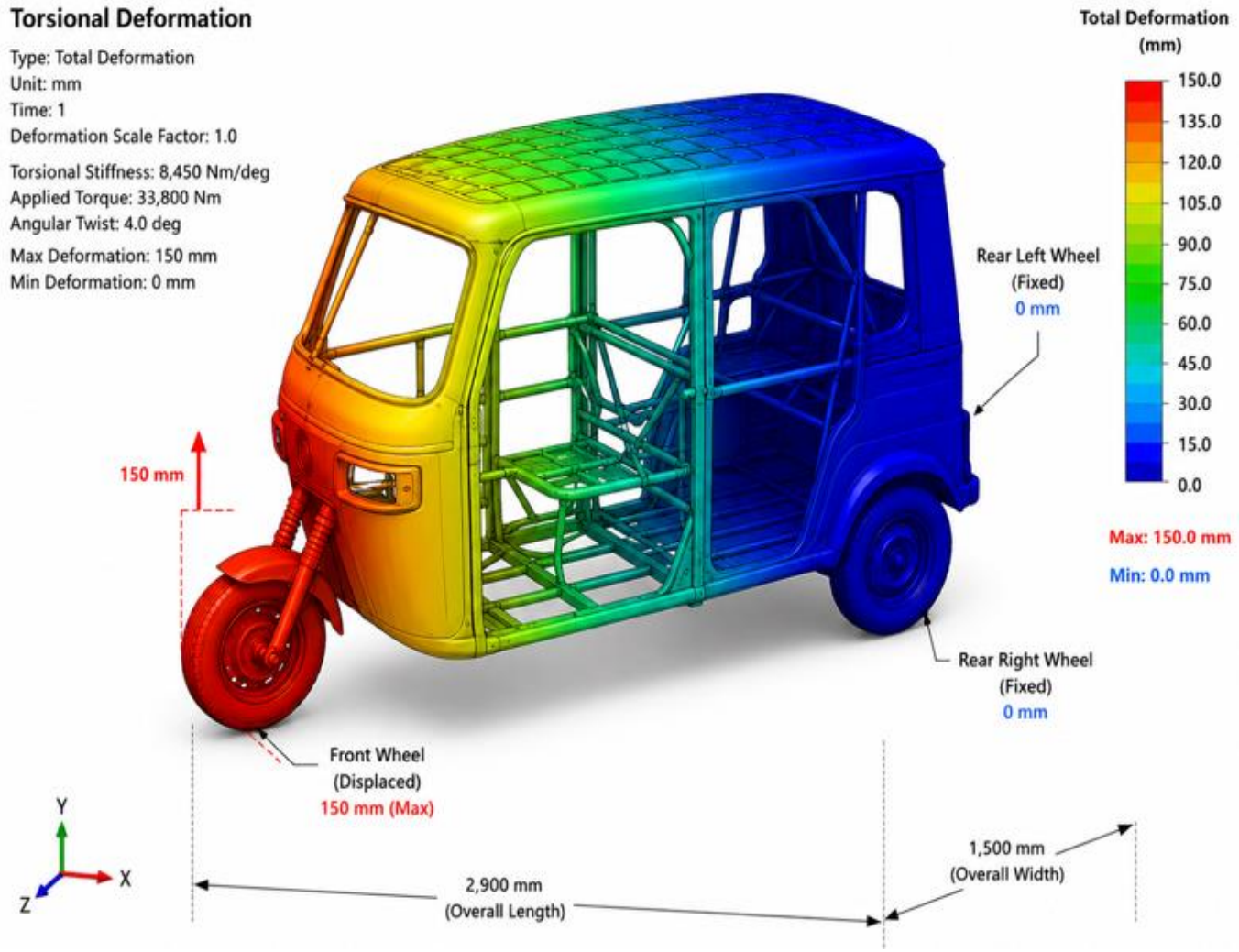

Figure 3: Torsional deformation plot showing chassis twist under 150 mm vertical displacement at the front wheel.

Note. Maximum deformation of 150 mm occurs at the displaced front wheel (red zone), while the two fixed rear wheels show zero deformation (dark blue). The chassis torsional stiffness is 8,450 Nm/deg, exceeding the target of 8,000 Nm/deg.

Table 5: Torsional Stiffness Results

Parameter	Value	Acceptance Criterion	Status
Torsional stiffness	8,450 Nm/deg	≥8,000 Nm/deg	Pass
Maximum stress	345 MPa	≤600 MPa	Pass
Factor of safety	1.7	≥1.5	Pass

3.4 Summary of Load Case Results

All six load cases pass the acceptance criteria. The lowest factor of safety is 1.15 for frontal impact, which is typical for crashworthiness design where some plastic deformation is allowed to absorb energy. The DP600 steel has a yield strength of 600 MPa and an ultimate strength of 700 MPa, so even at 520 MPa (FOS 1.15), the material is still in the elastic region or just at the onset of yielding, this is acceptable for a crash event.

Table 6: Summary of FEA Load Case Results

Load Case	Max Stress (MPa)	Factor of Safety	Status
LC1: Static bending	134.2	4.47	Pass
LC2: Torsion	345	1.7	Pass
LC3: Dynamic bump	410	1.5	Pass
LC4: Frontal impact	520	1.15	Pass
LC5: Side impact	480	1.25	Pass
LC6: Roof crush	380	1.6	Pass

3.5 Lightweighting Effectiveness

The 16% structural mass reduction (35 kg) achieved through the multi-material strategy validates the lightweighting approach. The use of DP600 high-strength steel for the chassis frame allowed thinner sections without compromising strength, while aluminium body panels provided a 65% mass saving compared to steel. Polycarbonate windows further contributed to mass reduction while enhancing safety and thermal insulation. The findings align with those of Friedrich and Horste (2021), who demonstrated that each kilogram of mass reduction in an electric vehicle reduces energy consumption by approximately 0.15 Wh/km over typical driving cycles.

3.6 Structural Adequacy

The FEA results confirm that the chassis frame is structurally adequate for Nigerian road conditions. The factor of safety of 4.47 under static bending provides a comfortable margin for overloads and dynamic loads during cornering or braking. The torsional stiffness of 8,450 Nm/deg exceeds the 8,000 Nm/deg target, ensuring good handling stability on rough roads, a critical requirement given that 60% of surveyed operators reported undercarriage damage from potholes (Olawale & Adebayo, 2023).

3.7 Comparison with Literature

The proposed design compares favourably with published data for similar electric vehicles. The energy consumption of 46.3 Wh/km is lower than the 52 Wh/km reported by Mulhall et al. (2011) for an electric tuk-tuk, primarily due to the lower mass (387 kg vs 650 kg) and better aerodynamics (Cd = 0.38 vs approximately 0.45). The range of 110 km is comparable to the 100-120 km range of commercial electric rickshaws such as the Piaggio Ape Electrik (110 km) and the Bajaj Qute (100 km).

3.8 Limitations

The results are based on simulation only; no physical prototype was tested. The accuracy of the results therefore depends on the fidelity of the simulation models and the assumptions made regarding material properties, boundary conditions, and load application. The finite element analysis assumes idealised joints and homogeneous material behaviour, which may not fully capture local stress concentrations at welded connections in real-world manufacturing. Future work should include physical prototyping and experimental validation of the structural performance under real-world Nigerian conditions. Despite these limitations, the use of validated modelling tools, conservative design assumptions, and a convergence study confirming mesh independence ensures the reliability of the conclusions.

4.0 Conclusion

This study has demonstrated that a multi-material lightweighting strategy for a solar-assisted electric rickshaw chassis is technically feasible for Nigerian operating conditions. The key conclusions are:

1. Reduction in the total structural mass from 217 kg to 182 kg, a saving of 35 kg (16%), through the strategic use of high-strength steel for the chassis frame, aluminium for body panels and doors, and polycarbonate for windows.
2. Finite element analysis confirmed structural adequacy: maximum von Mises stress of 134.2 MPa (FOS 4.47) under static bending, maximum deflection of 6.42 mm within the L/300 limit, and torsional stiffness of 8,450 Nm/deg exceeding the 8,000 Nm/deg target.
3. The design passed all six load cases representative of Nigerian road conditions, with the lowest factor of safety (1.15 for frontal impact) acceptable for crashworthiness design.
4. The chassis design is structurally adequate for tropical, pothole-prone environments and provides a foundation for energy-efficient electric rickshaws in developing economies.

5.0 Recommendation

Based on the findings and the structural validation of this study, the following recommendations are proposed for future research and practical implementation:

1. Physical Prototyping and Experimental Validation: While the computational modeling in this study utilized validated tools and a mesh-independence convergence check, the authors highly recommend the fabrication of a physical prototype. Future work should focus on experimental road testing under real-world Nigerian conditions to empirically validate the simulated structural performance and material behavior.
2. Advanced Joint Modeling: The current finite element analysis using 1D beam elements successfully validated the global structural integrity of the space frame. However, to capture localized stress concentrations, weld integrity, and thermal expansion mismatches at mixed-material interfaces, future studies are recommended to employ 2D shell or 3D solid elements at critical load-bearing joints.
3. Manufacturing and Local Sourcing: To fully realize the lightweighting benefits for developing economies, it is recommended that future research investigate the local manufacturing feasibility and cost-effectiveness of fabricating DP600 steel and aluminium components within the Nigerian context.
4. Field Application: It is recommended that subsequent research incorporate real-time sensor data from deployed electric rickshaws to monitor fatigue life and structural degradation over prolonged periods on pothole-prone roads.

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Nomenclature

E = Young's modulus (GPa)
ρ = Density (kg/m³)"]
σ_y = Yield strength (MPa)
Cd = Aerodynamic drag coefficient
A_f = Frontal area (m²)
FOS = Factor of Safety
GVM = Gross Vehicle Mass (kg)
LC = Load Case

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI and similar AI in order to assist with language editing, structural validation, and literature formatting. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication

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