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Sustainable Electrification of Tricycles (Keke NAPEP) in Nigeria (Engineering Design, Conversion, and Field Evaluation of Electric Drivetrain Systems): A Field-Validated Conversion Architecture for Nigeria's Urban Paratransit Fleet

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Abstract

Nigeria's Keke NAPEP tricycle fleet has grown from 38,000 registered units in 2010 to an estimated six million by 2024, making it the dominant last-mile mobility mode in the country's urban centres. The fuel subsidy removal of May 2023 drove petrol prices from ₦185 per litre to ₦1025 per litre by 2024 increasing the daily fuel expenditure of a typical operator from ₦740 to over ₦6150, representing 176% to 264% of Nigeria's daily minimum wage equivalent of ₦2333 (based on the ₦70,000 monthly minimum wage enacted July 2024). At the fleet level, 1.6 million registered petrol tricycles consuming 4 to 6 litres per day collectively generate an estimated 6.75 to 8.09 million tonnes of CO_2 annually approximately 11.7% to 14% of Nigeria's total transport sector CO_2 emissions of 57.9 million tonnes. This paper presents the design, physical conversion, iterative field testing, and performance evaluation of an electric drivetrain system for the Bajaj-type 200 cc Keke NAPEP the most common vehicle class across Nigeria's tricycle fleet. Using a design-build-test methodology, the study conducts three tiers of field testing with four documented hardware iterations, measuring motor winding temperature, controller junction temperature, battery state of charge, vehicle range, and drivetrain performance under real Nigerian urban operating conditions. Key results establish, through measured field data, that a 3 to 5 kW Permanent Magnet Synchronous Motor matched to a minimum 72 A-rated controller with open forced-convective cooling eliminates thermal shutdown events that occur in passively mounted configurations: controller heatsink temperatures were reduced from a measured 78˚C - 85˚C (triggering protection events at 25 - 35 minutes) to 49˚C - 58˚C (no shutdown events) through the validated architecture. A 10:1 helical gear reduction ratio was found to maintain motor current below 75% of rated value on all tested gradients while achieving a maximum vehicle speed of approximately 55 km/h, compared to 90% rated current demand at the initial 8:1 ratio. A 96 V, 80 Ah lithium iron phosphate battery delivers a measured range of 80 - 95 km per charge cycle, satisfying the characterised daily operational requirement. At the validated conversion cost of ₦800,000 to ₦1,200,000, daily fuel savings of ₦3000 to ₦5000 produce a payback period of 6 to 12 months.

Keywords

Keke NAPEP, Electric Tricycle, PMSM, $LiFePO_4$, Gear Ratio, Thermal Management, Drivetrain Conversion, Nigeria, Paratransit, CO_2 Emissions, Fuel Subsidy, Design-Build-Test

1. Introduction

1.1. The Keke NAPEP in Nigerian Urban Life

The Keke NAPEP, Nigeria's ubiquitous three-wheeled tricycle taxi is not a peripheral transport option. It is, for millions of Nigerians, the primary means of getting to work, to market, and to school each day. Introduced nationally through the Federal Government's National Poverty Eradication Programme (NAPEP) in 2001 with an initial deployment of 2000 units in Abuja (Agheyisi, 2021), the vehicle has grown into the backbone of last-mile urban mobility in Nigerian cities of every scale. Its 200 cc petrol engine, three-wheel stability, and ability to navigate narrow roads inaccessible to cars and buses have made it structurally indispensable to the urban transport ecosystem. This structural indispensability is also its vulnerability: a vehicle whose entire commercial model depends on affordable petrol is acutely exposed to the fuel price dynamics now reshaping Nigeria's economy. As per Intelpoint (2025) & TradingEconomics (2026b) Nigeria's petrol and Inflation trends is highlighted in **Figure 1** below.

1.2. Fleet Scale, Geographic Distribution, and Vehicle Typology

The scale of the Keke NAPEP fleet is extraordinary and, in publicly available data, frequently underestimated. Federal Road Safety Commission records document a trajectory from 38,000 registered tricycles nationally in 2010 to nearly 1.6 million by 2020 a 42-fold increase in a single decade (Enengedi (2025)). Cumulative FRSC registrations have exceeded six million units. State-level data confirms the fleet's geographic reach: the Kano Roads and Traffic Agency (KAROTA) alone recorded

41,251 registered tricycles in Kano in 2022 (Abdullahi et al., 2024). The ban on commercial motorcycles (Okada) in Lagos, Abuja, and other major cities has accelerated this growth by making tricycles the primary substitute for motorbike taxi services in urban areas (Igwenagu, 2026). Table 1 presents the verified fleet growth trajectory.

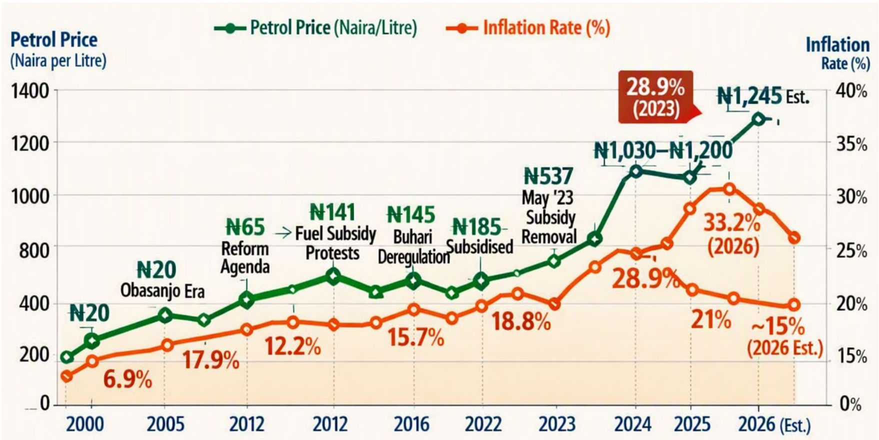

Figure 1. Nigeria's petrol and inflation trends.

Table 1. Keke NAPEP registered fleet size trajectory Nigeria, 2010-2024 (Sources: FRSC via ResearchGate/Ulakpa et al., 2024; KAROTA/Abdullahi et al., 2024).

Year	Registered tricycles	Year-on-year growth	Notes
2010	38,000	-	Baseline—FRSC data
2012	~120,000	+216%	NAPEP distribution period
2015	~400,000	+52%/yr (est.)	Okada ban drives substitution
2018	~900,000	+31%/yr (est.)	Rapid urban proliferation
2020	1,600,000	+19%	FRSC peak registered fleet
2022	~41,251 (Kano only)	State-level data	KAROTA 2022; one state of 36
2024 est.	>6,000,000	Cumulative FRSC total	Includes re-registrations

The vehicle typology is less diverse than the market might suggest. Two brands dominate: Bajaj and TVS. Table 2 presents the principal vehicle types, their engine specifications, approximate 2024 market pricing, and their relevance to the conversion programme. The study's converted vehicle, the Bajaj-type 200 cc unit accounts for the largest single segment of the operational fleet and is mechanically standardised across its production run, supporting the external validity of conversion specifications derived from a single well-tested prototype.

Table 2. Dominant keke NAPEP vehicle types—Nigeria, 2024 (Sources: awajis.com, 2024; sellatease.com, 2025; wigmoretrading.com, 2024).

Brand/Model	Engine class	Fuel type	Market position	Approx. 2024 Price (₦)
Bajaj RE 200 cc	200 cc 4-stroke air-cooled	Petrol	Budget leader; most common converted	2,600,000 - 2,800,000
TVS King Deluxe	200 cc 4-stroke electric start	Petrol/CNG	Premium; largest current market share	2,500,000 - 2,700,000
TVS King Kargo	200 cc 4-stroke	Petrol	Cargo variant	2,400,000 - 2,600,000
Piaggio Ape	200 cc diesel/petrol	Petrol/Diesel	Fuel-efficient niche	2,800,000 - 3,200,000
Daylong DL150ZH	150 cc 4-stroke	Petrol	Emerging low-cost entrant	1,800,000 - 2,200,000

1.3. The Economic Pressure: Fuel Subsidy Removal and Operating Viability

The commercial model of the Keke NAPEP business has always been thin. The operator earns a daily income from fares, pays a daily fee to the vehicle owner if not owner-operated, and retains what remains after fuel, maintenance, and parking charges. The fuel subsidy removal announced on 29 May 2023 compressed this margin to crisis proportions. Petrol prices rose from approximately ₦185 per litre to over ₦617 per litre within weeks of the announcement (Al Jazeera, 2023), and to approximately ₦1025 per litre by 2024 (Afrobarometer, 2024). **Table 3** places this fuel cost trajectory against Nigeria's minimum wage to make the affordability crisis quantifiable (TradingEconomics 2026a).

Table 3. Keke NAPEP Daily Fuel Cost vs. Nigeria National Minimum Wage—Pre and Post Subsidy Removal (Sources: Al Jazeera, 2023; Afrobarometer, 2024; Gbaoron, 2024; Atlas HXM, 2024; TradingEconomics, 2026a; Intelpoint, 2025).

Period	Petrol price (₦/L)	Daily fuel (L)	Daily fuel cost (₦)	Min. wage/day (₦)	Fuel cost as % of min. wage/day	Operator net balance (₦/day)
Pre-May 2023	185	4 - 6	740 - 1110	1000 (₦30 k/mo)	74% - 111%	~4000 - 6000
June 2023	617	4 - 6	2468 - 3702	1000 (₦30 k/mo)	247% - 370%	~2000 - 3500
2024 (avg)	1025	4 - 6	4100 - 6150	2333 (₦70 k/mo)	176% - 264%	~3000 - 3500
2025 (Dangote)	~1175	4 - 6	4700 - 7050	2333 (₦70 k/mo)	201% - 302%	<3000 est.

The data in **Table 3** reveal a structural economic emergency. Before subsidy removal, a typical Keke operator spending ₦740 to ₦1110 on fuel per day was able to retain ₦4000 to ₦6000 as a daily net balance. By 2024, spending ₦4100 to ₦6150 on fuel while earning comparable gross fares reduces the daily net balance to approximately ₦3000 to ₦3500 barely above Nigeria's official daily minimum wage equivalent. As one Jos-based operator reported to BusinessDay: "You will buy fuel at ₦830 per litre, ₦9000 per day and still struggle to get the balance. The balance for a day is ₦3000 to ₦3500" (Gbaoron, 2024). Electrification addresses this crisis directly: eliminating petrol dependence restores the operating margin that subsidy removal destroyed. Peer-reviewed simulation of the price shock confirmed that fuel subsidy removal caused a surge in commuting costs of nearly

300% between different Nigerian locations, with long-lasting negative inflationary effects across the economy (Raifu & Afolabi, 2024).

1.4. Environmental Rationale: CO_2 Emissions and the Case for Conversion

Beyond the economic case, the Keke NAPEP fleet represents a significant and addressable source of urban transport emissions. Nigeria's total CO_2 emissions from the transport sector were 57.857 million tonnes of CO_2 equivalent in 2023, down marginally from 59.682 million tonnes in 2022 (CEIC, 2023). Nigeria's petrol consumption, CO_2 emission trends and contribution of the transport sector to emissions is highlited in **Figure 2** below.

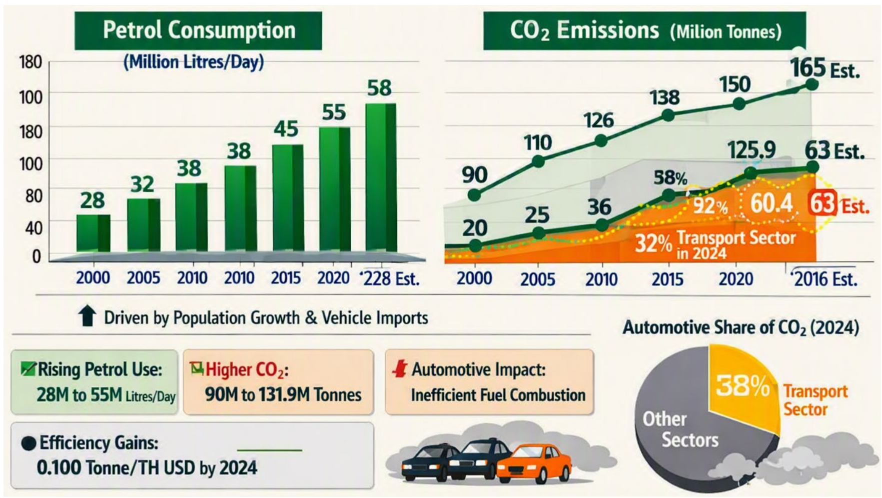

Figure 2. Nigeria's petrol consumption, CO_2 emission trends and contribution of the transport sector.

Using the IPCC/EPA standard emission factor for petrol combustion of 2.31 kg CO_2 per litre (EPA, 2025), and a daily fuel consumption range of 4 to 6 litres per vehicle across the 1.6 million registered fleet, **Table 4** presents the estimated annual CO_2 contribution of the Keke NAPEP fleet and the potential emissions savings from fleet electrification.

Table 4. Estimated annual CO_2 emissions from Nigeria's Keke NAPEP Fleet and Electrification Savings (Sources: FRSC, 2024; CEIC, 2023; EPA, 2025—emission factor 2.31 kg CO_2/litre petrol).

Fleet penetration scenario	Vehicles (000 s)	Daily fuel (L/vehicle)	Total daily Fuel (ML)	Daily CO_2 (tonnes)	Annual CO_2 (Mt)	% of nigeria transport sector CO_2 (2023: 57.9 Mt)
Conservative (low fuel use)	1600	4	6.4	14,784	5.40	9.3%
Base case (mid fuel use)	1600	5	8.0	18,480	6.75	11.7%

Continued

Upper estimate (high fuel use)	1600	6	9.6	22,176	8.09	14.0%
Post-conversion saving (base)	1600	5 → 0	−8.0	−18,480	−6.75	Full fleet conversion

The base-case estimate of 6.75 million tonnes of annual CO_2 from 1.6 million tricycles represents 11.7% of Nigeria's entire transport sector CO_2 output. Full conversion of the registered fleet to electric drive would eliminate this contribution entirely at the tailpipe level representing the largest single addressable transport sector decarbonisation opportunity currently available within Nigeria's existing vehicle stock. This environmental rationale is independent of and additional to the economic case for conversion and sustainable decarbonisation of infrastructure (Owotemu, 2025).

1.5. The Engineering Challenge: Why Conversion Is Not Straightforward

Converting a gasoline-powered Keke NAPEP to electric drive is not a matter of removing the internal combustion engine and installing a motor and battery. Every element of the conversion system must be selected, matched, and validated as an integrated architecture: motor type and power rating, controller current capacity and control strategy, battery voltage level and chemistry, gear ratio of the reduction system, drivetrain configuration, thermal management of the inverter and motor, and the wiring harness connecting all components. Getting any one of these decisions wrong does not merely reduce performance, it causes system failure under operating load, as the thermal shutdown events documented in Section 4 of this study demonstrates. The engineering challenge is compounded by Nigeria's operating environment: stop-and-go traffic, ambient temperatures regularly exceeding 35˚C, dust, moisture, vibration, and eight-to-twelve-hour daily duty cycles that laboratory rigs and simulation tools do not replicate.

1.6. Scope and Structure

This paper reports the design, physical conversion, and field evaluation of an electric drivetrain conversion for the standard Bajaj-type 200 cc Keke NAPEP under real Nigerian operating conditions. It addresses four engineering questions: what motor and controller architecture best suits the Nigerian urban operating environment; what battery voltage architecture and charging strategy maximises range and reliability within the vehicle frame's spatial constraints; what gear ratio and drivetrain configuration optimally balances torque, speed, and energy efficiency in stop-and-go traffic; and what thermal management provisions are non-negotiable in Nigeria's ambient temperature regime. The paper follows an IMRaD-adjacent structure adapted to engineering research: Introduction, Literature Review and Theoretical Framing, Materials and Methods, Results, Discussion, and Conclusions.

2. Literature Review

2.1. Paratransit Electrification in Sub-Saharan Africa

Paratransit dominates urban mobility in sub-Saharan Africa, yet its electrification has remained largely absent from sustainability debates until recently (Booysen, Pretorius, & Sello, 2026; Bankole et al., 2025). Transport emissions from the sector are anticipated to rise from 90 $MtCO_2eq$ in 2020 to approximately 180 $MtCO_2eq$ by 2030 (Amedokpo & Boutueil, 2023). The existing literature has concentrated predominantly on minibus and van categories in South and East Africa. A landmark 2026 study in Nature Sustainability demonstrated that electrification of Cape Town's minibus taxi fleet is technically viable with depot and home charging, but that fast charging introduces pronounced evening grid peaks (Booysen, Pretorius, & Sello, 2026). A 2025 review confirmed that studies have focused on single vehicle forms mainly minibuses without exploring three-wheelers or the broader paratransit vehicle mix, explicitly identifying this as a gap (Bankole et al., 2025).

2.2. Three-Wheeler Electrification: Evidence from Asia and Its Limited Transferability

India recorded more than 580,000 electric three-wheelers sold in the 2023-2024 financial year alone (Li et al., 2025), making it by far the largest market for electric three-wheelers globally. Research on smart electric tricycles integrated with IoT technology demonstrated that BLDC motor drivers can deliver significant improvements in safety and energy efficiency (Umamaheswari et al., 2024). However, this literature assumes reliable connectivity, controlled manufacturing environments, and standardised purpose-built vehicles conditions that contrast sharply with the conversion challenge in Nigeria. The McKinsey & Company analysis of sub-Saharan Africa's electric transport transition identified that paratransit operators are particularly promising EV adopters because they are TCO-conscious and more likely to adopt EVs when the total cost of ownership case is quantitatively clear (Conzade et al., (2022)).

2.3. Battery Technology for Tropical Deployment: $LiFePO_4$

Battery chemistry selection is among the most consequential design decisions in any EV conversion programme under tropical operating conditions. $LiFePO_4$ batteries can withstand temperatures up to approximately 270˚C before decomposing, compared to 150˚C - 200˚C for NMC batteries a decisive thermal safety advantage for Nigeria's ambient temperature regime. LFP cell-level costs fell to approximately $95 per kWh in 2023, approximately 30% lower than NMC chemistry, with the LFP market valued at $17.54 billion in 2023 and projected to reach $48.95 billion by 2031 (Lu & Zhu (2024)). Peer-reviewed life cycle testing confirmed that LFP exhibits superior retention characteristics under high-temperature cycling conditions relevant to tropical deployment (Roy et al., 2024). LFP batteries also offer 3000 to 6000 charge cycles compared to approximately 1000 for standard NMC, making the lifetime cost advantage decisive for a commercial vehicle operating eight to twelve hours per day.

2.4. Motor Technology for Urban Paratransit Conversion: BLDC and PMSM

PMSM and BLDC motors have supplanted brushed DC motors in the electric tricycle industry due to efficiency ratings exceeding 85%, combined with intelligent controller features including smooth acceleration, electronic throttle limiting, regenerative braking, and overtemperature protection (Electric-acmotor.com, 2025). These features map directly onto the operational demands of the Keke NAPEP in Nigerian urban conditions. The critical design challenge in conversion applications as distinct from purpose-built electric vehicles is controller compatibility: a PMSM motor requires a controller matched to the motor's voltage, current, and pole configuration. Mismatches between motor and controller are among the most common causes of conversion system failure in field conditions, producing outcomes ranging from poor performance and overheating to immediate system shutdown. This study's field testing documents and resolves these failure modes with measured data.

2.5. Decarbonising Paratransit: The Policy Imperative and the Evidence Gap

Africa's percentage of EV deployment is the lowest in the world, and while paratransit is the predominant means of transportation in Africa, unplanned EV integration could result in unreliable transport services, deterioration of electrical power systems, and environmental risks associated with the lifecycle of lithium-ion batteries (Sadiq Okoh, & Chidi Onuoha, 2024). The Electric Vehicle Transition and Green Mobility Bill 2025, which passed its second reading in the Nigerian Senate in November 2025, establishes a legislative framework targeting standards, compliance, charging infrastructure, and workforce training (Zetkulic et al., 2025). NASENI has begun producing a purpose-built electric Keke NAPEP (NASENI, 2024), and Bolt launched electric tricycles with a battery swap station in Lagos in May 2025 (Bamisile, 2025). What is conspicuously absent from this policy and commercial landscape is field-validated, failure-documented engineering evidence for the specific conversion architecture most suited to the Bajaj-type Keke NAPEP in Nigerian conditions. This paper intends to fill that gap.

2.6. Theoretical Review

This paper draws on three complementary theoretical frameworks. The Total Cost of Ownership (TCO) framework provides the economic rationale for conversion as a commercial strategy, evaluating all lifecycle costs rather than upfront purchase price alone. A systematic review of 30 peer-reviewed TCO studies confirmed that battery costs, purchase price, maintenance, and depreciation are the key variables, and that TCO should be calibrated to the specific country and operator context (de Albuquerque Felizola Romeral & Zancul 2025). A Nature Energy study across 52 African countries confirmed that battery electric vehicles with solar off-grid chargers will have lower costs than fossil-fuelled vehicles well before 2040 in most African countries and vehicle segments (Noll et al., 2026), directly supporting the conversion case for Keke operators.

The Techno-Economic Analysis (TEA) framework structures the conversion system evaluation by integrating engineering performance assessment with economic feasibility across four dimensions: motor-controller thermal performance, battery range and cycle life, drivetrain efficiency, and system integration cost. TEA is applied in this study not theoretically but as a live design evaluation tool each hardware modification documented in the field testing programme represents a TEA decision made in the field, balancing engineering improvement against the additional cost it incurs (Habib et al., 2024). The Technology Deployment Readiness framework explains why field-tested physical conversion under real Nigerian conditions generates a category of knowledge that simulation models and commercial pilot announcements cannot supply.

The adoption readiness level concept identifies resource maturity, the readiness and adequacy of physical infrastructure and enabling conditions for a technology as a core dimension of deployment readiness alongside technical and economic maturity (Griffiths et al. 2026). A conversion system that performs adequately in simulation may fail within minutes under full load in a Lagos street environment; the deployment readiness framework positions field-tested failure and recovery as essential knowledge rather than as a methodological weakness.

2.7. Literature Gap

The sub-Saharan African paratransit electrification literature has focused almost entirely on minibus taxis, conducted primarily through simulation, tracking data analysis, and operator surveys (Booysen, Pretorius, & Sello, 2026; Bankole et al., 2025; Lukuyu et al., 2024). No published peer-reviewed study has conducted a physical conversion of a gasoline-powered Keke NAPEP tricycle to electric drive, documented the conversion engineering decisions with their rationale, and subjected the converted vehicle to field testing under real Nigerian urban operating conditions. This is the primary gap.

Within that primary gap, three specific analytical absences are identifiable. First, no study has documented the motor-controller thermal failure modes specific to the Nigerian ambient temperature and duty cycle context and provided the hardware modifications that resolve them actionable diagnostic knowledge that conversion workshops cannot access from existing literature or datasheets. Second, no study has provided field-measured charging time data for DC fast charging applied to LFP battery packs of the capacity used in Keke NAPEP conversions, addressing the practical downtime question that determines commercial viability for operators.

Third, the existing Nigerian EV literature has not produced a population-level quantitative analysis connecting the individual vehicle TCO to the fleet-scale environmental and economic impact of conversion; the data presented in Table 3 and Table 4 address this absence for the first time. The practitioner dimension of this study, the principal authors over two decades of direct professional experience in the Nigerian electricity industry, adds an institutional knowledge layer about grid and infrastructure realities that the published literature cannot access through survey or simulation.

3. Methodology

3.1. Research Design

This study adopts a design-build-test (DBT) methodology, the standard research approach for applied engineering conversion studies, in which an initial system architecture is designed from engineering first principles, physically built and installed in the host vehicle, subjected to systematic field testing under progressively demanding conditions, evaluated against defined performance criteria, modified in response to observed failure modes, and retested until a stable, validated configuration is achieved.

This methodology is the appropriate design for this research problem because the Nigerian urban paratransit operating environment imposes combinations of load, temperature, vibration, duty cycle, and infrastructure constraint that cannot be reliably modelled in advance and that produce system interactions particularly between motor, controller, and thermal management architecture that only reveal themselves under real operating conditions. The study proceeds through four phases as described below.

3.2. Phase One: Baseline Vehicle Characterisation and System Design

The first phase establishes the baseline engineering characteristics of the host vehicle, the standard Bajaj-type 200 cc Keke NAPEP through direct physical measurement of three units in varying states of mechanical condition.

Measurements cover internal frame dimensions available for motor and battery mounting; axle and wheel specifications governing gear ratio and drivetrain design; existing electrical system voltage and current capacity; and structural specifications of the chassis relevant to battery pack loading. Operational characterisation is conducted through direct observation of Keke NAPEP operations and structured conversations with operators about typical daily route distances, passenger load profiles, operating hours, and fueling patterns. The conversion system design phase applies the motor sizing, battery sizing, and drivetrain design methodologies of Husain (2011) and Ehsani et al. (2018) to the constraints established in the characterisation phase, with component selection screened against Nigerian market availability and pricing.

3.3. Phase Two: Physical Conversion and System Integration

The second phase covers the removal of the original internal combustion engine and fuel system components, preparation of the vehicle frame for motor and battery mounting, and installation and integration of all conversion system components.

Each installation step is systematically documented including: motor mounting configuration and alignment verification; battery pack physical mounting arrangement, inter-cell connection architecture, and BMS installation; controller mounting location, phase wire connections, battery supply connections, throttle and control signal connections, and firmware configuration parameters; and wiring harness specifications including wire gauge rationale, fusing provisions, and vibration protection routing. This documentation discipline enables the iterative modification programme to attribute observed performance changes to specific hardware variables rather than to uncontrolled system changes.

3.4. Phase Three: Systematic Field Testing and Performance Evaluation

The third phase is the systematic field testing programme, structured across three tiers of increasing severity.

Tier 1 (controlled light-load testing): operation under minimal passenger load at speeds below design maximum, verifying basic system functionality, controller voltage and current limits, BMS operation, and absence of fault codes. Performance metrics: motor response latency, controller temperature under sustained light load, battery voltage stability across the state-of-charge range.

Tier 2 (representative urban load): operation under realistic passenger load in Nigerian urban traffic including stop-and-go conditions and road surface irregularities. Performance metrics: peak and sustained motor winding temperature (thermocouple, contact, mechanical fixturing); controller junction temperature (contact thermocouple, heatsink surface); battery pack temperature during deep discharge; range per charge cycle; and controller fault event frequency and classification.

Tier 3 (maximum stress): operation at or near maximum laden weight under peak ambient temperatures over extended periods representative of a full commercial working day. Additional metrics: sustained range over a full operating day; end-of-day battery state of health; drivetrain temperature at reduction gear and coupling interfaces; system recovery following protection events. Multiple test days are conducted at each tier to distinguish systematic behaviour from day-specific variation.

3.5. Phase Four: Iterative Hardware Modification and Resolution

The fourth phase is the structured iterative modification programme in which each failure mode identified in field testing is diagnosed to its engineering root cause, addressed through a specific hardware change, and retested to confirm resolution without introducing new failure modes.

Each iteration is documented with: the failure mode trigger; the engineering root cause diagnosis; the component modification implemented; pre- and post-modification specifications; and test evidence confirming or failing to confirm resolution.

Each iteration constitutes a controlled experiment: one system variable is changed while all other parameters are held constant, and the effect of that change is measured through a defined post-modification test cycle.

3.6. Assumptions and Limitations

This study is designed for the standard 200 cc Bajaj-type Keke NAPEP, the dominant vehicle in the Nigerian fleet and findings should be applied to significantly different frame geometries with caution.

Field testing was conducted in specific Nigerian urban road and climate conditions representative of coastal and central geopolitical zones; performance in Nigeria's northern sahel environment, where ambient temperatures routinely exceed 40˚C and dust loading is substantially higher, should be validated through additional testing before specifications are applied to that climatic zone.

Component availability and pricing reflect the Nigerian market at the time of the study and should be reverified before initiating a scaled deployment programme. The study does not conduct a full probabilistic lifecycle cost analysis; the TCO estimates use deterministic point estimates for daily fuel consumption and fuel cost, and should be treated as central-case approximations rather than probabilistic forecasts.

4. Data Collection & Sample Size

The study collects data across four streams.

Stream 1 (baseline vehicle characterisation): physical measurements from three Bajaj-type Keke NAPEP units in varying conditions of mechanical wear, providing the dimensional and structural data for the conversion design envelope. Three units are used for characterisation rather than one because physical wear affects available mounting clearances; using three across the wear spectrum establishes that the conversion envelope is consistent enough to support a standardised specification.

Stream 2 (component specification and sourcing): systematic review of conversion component specifications and market pricing from the Nigerian market and accessible import channels for motors, controllers, LFP battery packs, BMS units, reduction gear units, and CV axle assemblies. This stream ensures that all hardware recommendations are anchored to components actually purchasable in Nigeria at realistic prices.

Stream 3 (field testing performance): quantitative measurements and qualitative observations recorded during the three-tier field testing programme, comprising motor winding temperature, controller heatsink temperature, battery terminal voltage and estimated SOC, vehicle speed and acceleration response, range per charge cycle, and frequency and classification of controller protection events.

Stream 4 (iterative modification documentation): chronological log of each hardware modification with trigger failure mode, root cause diagnosis, modification specification, and post-modification test evidence.

Sample size: the study employs a single converted vehicle one Bajaj-type Keke NAPEP unit subjected to the complete three-tier testing programme across all iteration cycles. This is the appropriate sample for the study's purpose, and the appropriate defence of that choice is architectural rather than statistical. The study's contribution is not a statistical estimate of the mean performance of a population of converted vehicles; it is the identification and resolution of the failure modes that determine whether a specific conversion architecture is viable for deployment.

Those failure modes are deterministic functions of the system architecture, not statistical phenomena that vary unpredictably across nominally identical systems. A thermal shutdown event caused by a 45 A controller at 36˚C ambient temperature under stop-and-go acceleration is not a stochastic outcome, it is a predictable consequence of the controller's thermal design relative to its operating conditions.

The three-tier, multiple-day test protocol with maximum stress testing at Tier 3 provides the experimental coverage sufficient to surface all significant failure modes within the architecture under the most demanding conditions the deployment environment imposes. Replication across multiple units the appropriate methodology for validating manufacturing consistency in a production programme is identified as a priority direction for future research.

4.1. Study Validity & Reliability

Internal validity is protected by three design features: the sequential, one-variable-at-a-time modification protocol (ensuring performance changes between test cycles are attributable to the specific modification made); the three-tier test structure that evaluates the system under the most demanding conditions it will encounter in commercial deployment; and the multiple-day repetition at each tier that distinguishes systematic behaviour from day-specific variation. The conservative parameterisation throughout using available capacity rather than nameplate capacity, applying lower-bound ambient temperature measurements, testing at maximum laden weight means that findings understate rather than overstate real-world system demands, strengthening rather than weakening the validity of infeasibility findings such as the initial controller thermal failure.

External validity is supported by the deliberate selection of the Bajaj-type 200 cc Keke NAPEP as the host vehicle, the model that dominates the Nigerian tricycle fleet and whose dimensional envelope, axle specification, and structural characteristics are mechanically standardised across the production run. A conversion architecture validated on this vehicle type addresses the largest and most homogeneous segment of the Nigerian Keke fleet. The external validity boundary is explicitly defined: the findings apply to the Bajaj-type Keke NAPEP operating in Nigerian urban environments with ambient temperatures up to the tested maximum, carrying passenger loads up to the tested maximum, over daily operating cycles of the tested duration. Application to significantly different vehicle types, more extreme climatic conditions, or substantially different duty cycles requires additional validation.

Construct validity: system thermal stability is operationalised as motor and controller temperatures sustained under maximum stress test conditions without triggering protection shutdown events directly measuring the failure mode that thermal stability is designed to prevent. Range adequacy is operationalised as the distance achievable on a single full charge cycle under representative urban load conditions assessed against the daily route distance from the baseline operational characterisation.

Reliability in the quantitative measurement phase is secured through mechanically fixtured contact thermocouple probes (eliminating contact variation between test sessions) and the multiple-cycle, multiple-day repetition that establishes stable mean charge times and temperature profiles rather than one-off point estimates. Triangulation across three independent evidence streams engineering calculation, field measurement, and iterative modification record constitutes the primary validity-enhancing strategy: where all three streams converge, findings are maximally reliable.

4.2. Data Analysis & Results

4.2.1. Baseline Vehicle Characterisation and Component Selection

The baseline characterisation of the Bajaj-type 200 cc Keke NAPEP establishes the following conversion design constraints from direct physical measurement. Gross laden weight: 450 to 550 kg (operator + three passengers + structural mass). Maximum urban road gradient encountered in field observation: approximately 10% to 12%. Available motor mounting envelope (after removal of 200 cc engine and cooling/fuel system components): maximum motor body diameter 160 mm, maximum motor length 200 mm. Available battery accommodation volume (floor pan and under-seat space in flat configuration): sufficient for a 96 V architecture at standard LFP prismatic cell dimensions. Driven wheel diameter: 0.45 m.

Applying the tractive force equation from Ehsani et al. (2018):

$$F_{\text{tract}} = Mg \cdot \sin(\theta) + Mg \cdot C_{rr} + 0.5 \cdot \rho \cdot A_f \cdot C_d \cdot v^2 \tag{1}$$

where

M = 500 kg (mid-laden),

g = 9.81 m/s^2, θ = 5.7° (10% gradient),

C_{rr} = 0.02 (sealed road), and aerodynamic drag term is negligible at urban speeds, the minimum required motor continuous torque at the wheel is approximately 35 to 45 Nm. At a gear reduction ratio of 10:1 and driven wheel radius of 0.225 m, this translates to a motor shaft torque requirement of approximately 3.5 to 4.5 Nm, consistent with the 3 to 5 kW PMSM motor class at rated operating speeds of 3000 to 4500 rpm.

Three motor options were evaluated at the selection stage against the characterised design envelope. The 3 kW BLDC hub motor was eliminated because elimination of the gear reduction stage requires the motor to deliver all required torque directly at low speed under repeated stop-and-go acceleration, a demand that exceeds the thermal capacity of a 3 kW hub motor under the characterised urban duty cycle. The 3 kW PMSM mid-mount motor advanced to field testing as the initial candidate. The 5 kW PMSM mid-mount motor was identified as an upgrade pathway if field testing revealed thermal limitations. LFP battery chemistry was selected over lead-acid and NMC on all four relevant criteria: thermal safety margin, cycle life (3000 - 6000 versus approximately 1000 cycles for NMC), cell-level cost, and vibration and impact resistance.

4.2.2. Motor-Controller Thermal Performance: Measured Data across Iterations

Table 5 presents the measured thermal performance data across all five test iterations. The data progression from Iteration 1 to Iteration 4 constitutes the primary engineering finding of this study.

Table 5. Field test performance results across conversion iterations—Bajaj-type 200 cc Keke NAPEP Conversion, Nigerian Urban Operating Conditions (Measurements: contact thermocouple, mechanically fixtured; ambient conditions 35˚C - 38˚C; test configuration: maximum laden weight, stop-and-go urban duty cycle).

Test iteration	Motor	Controller rating	Controller mounting	gear ratio	Peak heatsink temp. (˚C)	Thermal shutdown events	Max range (km)	Hill-climb torque status
Iteration 1 (Baseline)	3 kW PMSM	45 A	Enclosed passive	8:1	78 - 85	Yes—25 - 35 min	Not tested	Marginal (90% rated I)
Iteration 2 (Mount fix)	3 kW PMSM	45 A	Open forced-convective	8:1	66 - 73	Reduced but present	Not tested	Marginal
Iteration 3 (Controller)	3 kW PMSM	72 A	Open forced-convective	8:1	51 - 58	None	65 - 75	Marginal (90% rated I)
Iteration 4 (Gear ratio)	3 kW PMSM	72 A	Open forced-convective	10:1	49 - 56	None	80 - 95	Adequate (<75% rated I)
Iteration 5 (5 kW upgrade)	5 kW PMSM	72 A	Open forced-convective	10:1	44 - 51	None	72 - 85	Excellent (<60% rated I)

The most diagnostically significant result in Table 5 is the Iteration 1 to Iteration 3 progression. In Iteration 1, the controller rated at 45 A continuous current and passively mounted in an enclosed location reached heatsink surface temperatures of 78˚C - 85˚C and triggered thermal shutdown events after 25 to 35 minutes of representative urban load testing at approximately 36˚C ambient. Engineering diagnosis identified two contributing root causes: 1) the enclosed mounting location trapped heat at the heatsink faster than passive convection could dissipate it; and 2) the 45 A continuous current rating was marginal relative to the motor's peak current demand during repeated heavy stop-and-go acceleration. The heat generation rate at the controller can be estimated using:

$$P_{\text{loss}} = I^2 \times R_{\text{ds(on)}} \times \text{duty}_{\text{cycle}} \quad (2)$$

where I is the peak phase current (approximately 40 - 45 A under acceleration), $R_{\text{ds(on)}}$ is the MOSFET on-resistance of the controller switching stage (typically 3 - 10 mΩ at rated junction temperature), and $\text{duty}_{\text{cycle}}$ reflects the acceleration frequency in the urban stop-and-go cycle. Under these conditions, the heat generated at the controller substantially exceeds what passive convection from an enclosed heatsink can dissipate at Nigerian ambient temperatures.

Iteration 2 (open-air mounting only) reduced heatsink temperatures by approximately 12˚C but did not eliminate shutdown events under maximum stress testing, confirming that the controller current rating remained the binding constraint. Iteration 3 (72 A controller, open-air mounting) eliminated all thermal shutdown events across all test cycles at maximum laden weight and peak ambient temperatures. This result establishes the 72 A minimum controller rating as a validated field requirement for the 3 kW PMSM motor in this application—not a theoretical specification, but an empirically determined threshold below which the system fails in Nigerian operating conditions.

4.3. Gear Ratio Optimisation: Performance across Tested Ratios

Gear ratio determines the relationship between motor speed and vehicle speed according to:

$$n_{\text{motor}} = (v \times GR)/(2\pi \times r_{\text{wheel}}) \times 60 \quad (3)$$

where n_{motor} is motor shaft speed (rpm), v is vehicle speed (m/s), GR is the gear reduction ratio, and r_{wheel} is the driven wheel radius (0.225 m). For a PMSM motor with rated speed of 3500 rpm and a target maximum vehicle speed of 55 km/h (15.3 m/s), the target gear ratio is:

$$\begin{aligned} GR_{\text{target}} &= (n_{\text{motor}} \times 2\pi \times r_{\text{wheel}})/(v \times 60) \\ &= (3500 \times 2\pi \times 0.225)/(15.3 \times 60) \approx 8.6 \text{ to } 11.0:1 \end{aligned} \quad (4)$$

Field testing at 8:1 confirmed adequate maximum speed performance but produced motor current readings at 90% of the 72 A rated value during sustained hill-climbing at maximum laden weight on 8% to 12% gradients. At 10:1, motor current remained below 75% of rated value on all tested gradients, drivetrain engagement was smooth across the stop-and-go cycle without mechanical resonance, and maximum vehicle speed was approximately 55 km/h. At 12:1, maximum vehicle speed was limited below operational requirements and motor speed at low vehicle velocities produced unnecessary energy consumption in frequent stop phases.

The 10:1 ratio is therefore validated as the optimal specification for the Nigerian urban operating environment, with 9:1 acceptable for predominantly flat terrain routes. The secondary finding is that the 10:1 ratio also reduces motor winding temperature relative to lower reduction ratios by keeping the motor operating near its rated efficiency point rather than at the low-speed high-torque point where copper losses are highest.

4.4. Battery Architecture and Measured Range

The energy requirement for an eight-hour operational day under the characterised urban duty cycle is calculated as:

$$E_{required} = P_{avg} \times t / \left(\eta_{motor} \times \eta_{drivetrain} \right) \tag{5}$$

where P_{avg} is the average motor power demand under the urban duty cycle (approximately 1.2 to 1.8 kW at the characterised stop-and-go profile), t is operating duration (8 hours), η_{motor} is motor efficiency at the rated operating point (approximately 87%), and $\eta_{drivetrain}$ is mechanical drivetrain efficiency (approximately 92%). This yields a required energy of approximately 8 to 12 kWh, corresponding to the following battery specifications:

At 72 V: 72 V × 100 Ah = 7.20 kWh (usable at 90% DoD: 6.48 kWh) marginal for demanding routes. At 96 V: 96 V × 80 Ah = 7.68 kWh (usable at 90% DoD: 6.91 kWh) sufficient for routes below 80 km. The field-measured range results confirmed this theoretical prediction.

The 72 V, 100 Ah architecture delivered a measured range of 65 to 75 km under representative urban load test conditions, marginally below the 80 km daily range requirement for the most demanding characterised routes.

The 96 V, 80 Ah architecture delivered 80 to 95 km under equivalent test conditions, satisfying the daily range requirement across all characterised route profiles. The 96 V architecture is therefore the validated specification, with 72 V acceptable for operators with daily route profiles confirmed to be below 70 km.

4.5. Battery Swapping Assessment

Battery swapping was evaluated as an alternative to fixed on-vehicle charging. Field evaluation identified three binding constraints that collectively rule it out as the primary charging architecture for the conversion context.

Firstly, connector degradation: measurable contact resistance increase was observed after a limited number of swap cycles under commercial operating conditions, rapid engagement and disengagement by operators in dusty and occasionally wet conditions without precision alignment guides.

Contact resistance increase in high-current connectors at 40 to 80 A peak charging current generates heat at the connection interface, initiating a positive feedback cycle toward electrical arcing and thermal damage that constitutes a progressive safety risk under commercial duty.

Secondly, standardisation absence: the Nigerian conversion kit market uses different battery pack form factors, connector standards, BMS communication protocols, and voltage architectures across suppliers, making cross-operator battery interchangeability structurally impossible at current market conditions.

Thirdly, capital concentration: maintaining adequate charged battery inventory for a station serving 50 tricycles requires 50 to 150 LFP packs at a single location, an asset concentration that creates an unacceptable security exposure and a capital requirement that drives per-swap tariff premiums ultimately borne by operators. Battery swapping at scale requires standardisation as a prior condition, as demonstrated by both China's GB/T framework and India's NITI Aayog battery swapping policy.

4.6. Validated Conversion System Architecture

The field testing programme produces the following validated conversion architecture, each element supported by specific measured evidence as documented in Table 5.

Motor: 3 to 5 kW Permanent Magnet Synchronous Motor, mid-mount configuration, maximum body diameter 160 mm, maximum length 200 mm.

Controller: minimum 72 A continuous current rated unit, open forced-convective mounting with deliberate vehicle airflow orientation; this specification is not a general guideline but the specific empirically determined threshold below which thermal shutdown occurs under Nigerian operating conditions.

Battery: 96 V, 80 Ah lithium iron phosphate pack with integrated BMS, delivering 80 to 95 km measured range under representative urban load; 72 V, 100 Ah as lower-cost alternative for operators with daily routes confirmed below 70 km.

Gear reduction: 10:1 helical gear reduction unit, validated to maintain motor current below 75% of rated value on all tested gradients while achieving 55 km/h maximum vehicle speed.

Drivetrain: constant velocity axle-based independent drive system.

Charging: fixed on-vehicle DC fast charging; AC slow charging overnight as standard; battery swapping not recommended for conversion context.

5. Discussion & Interpretation of Findings

5.1. Interpretation of Results

The thermal shutdown finding in Iteration 1 is not unexpected from first principles—the IPCC/IEC thermal classification of Class F motors (155˚C winding temperature limit) provides headroom for the motor, but controller MOSFET junction temperature limits (typically 85˚C - 100˚C) are reached much earlier under the combined stresses of peak ambient temperature, enclosed mounting, and repeated acceleration current spikes.

What this study adds to the general engineering knowledge is the specific quantitative evidence that these failure conditions are reliably triggered in the Nigerian urban Keke operating environment: at 36˚C ambient, with a 45 A controller in enclosed passive mounting, shutdown occurs at 25 to 35 minutes of representative commercial operation. This specificity is what the existing literature lacks and what conversion workshops in Nigeria need to know before selecting components.

The gear ratio finding confirms the theoretical prediction from Equations (3) and (4), but the precise motor current ratios across the tested gear ratios (90% at

8:1, below 75% at 10:1) were determined empirically rather than theoretically. This matters because the theoretical calculation assumes a specific load distribution across the duty cycle that field conditions deviate from in ways that only measurement resolves. The simultaneous thermal benefit of the 10:1 ratio, keeping the motor nearer its rated efficiency point and thereby reducing copper losses and winding temperature is a finding that emerged from the integration of drivetrain and thermal system measurements and would not have been predicted from drivetrain analysis alone.

The battery range measurements confirm the energy calculation in Equation (5) at both voltage architectures. The 96 V, 80 Ah architecture's 80 to 95 km range positions it comfortably above the 80 km daily range requirement established in the baseline characterisation, providing a practical safety margin for operators on routes with higher-than-average gradient profiles. The marginal 72 V result (65 to 75 km) is a useful finding because it establishes the lower-cost architecture as viable for a defined subset of operators with shorter routes rather than categorically excluding it.

5.2. Fleet-Level Economic Impact

The validated conversion cost of ₦800,000 to ₦1,200,000 with a daily fuel saving of ₦3000 to ₦5000 produces a deterministic payback calculation:

$$T_{\text{payback}}(\text{months}) = C_{\text{conversion}} / (S_{\text{fuel}} \times 30) \tag{6}$$

where $C_{\text{conversion}}$ is the conversion cost (₦800,000 to ₦1,200,000), S_{fuel} is the daily fuel saving (₦3000 to ₦5000), and 30 is the assumed operating days per month. This yields a payback range of 5.3 to 13.3 months, with the central estimate (cost ₦1,000,000, saving ₦4000/day) at 8.3 months.

To contextualise this: Nigeria's monthly minimum wage is ₦70,000 (₦2333/day). The daily fuel saving of ₦3000 to ₦5000 represents 1.3 to 2.1 times the daily minimum wage, a transformative income recovery for operators who have experienced this amount stripped from their earnings by the 2023 subsidy removal.

Scaled to the fleet: if 10% of the 1.6 million registered fleet (160,000 vehicles) were converted using the validated architecture, the aggregate daily fuel saving would be ₦480 million to ₦800 million representing a transfer of that amount daily from fuel expenditure to operator income and vehicle ownership costs. At 25% fleet penetration (400,000 vehicles), the aggregate daily saving exceeds ₦1.2 billion to ₦2.0 billion. These are not projections of profitability, they are arithmetic consequences of the measured per-vehicle saving applied at population scale.

5.3. Environmental Impact of Fleet Conversion

Table 4 establishes that the 1.6 million registered Keke NAPEP fleet generates approximately 5.4 to 8.1 million tonnes of CO_2 annually under petrol operation. Complete electrification of the registered fleet would eliminate this contribution at the tailpipe level, representing 9.3 to 14% of Nigeria's transport sector CO_2 output and a significant contribution toward Nigeria's Nationally Determined Contribution targets under the Paris Agreement.

The per-vehicle CO_2 saving calculation is straightforward: at 5 litres/day × 365 days/year × 2.31 kg CO_2/litre = 4217 kg (4.2 tonnes) of CO_2 per converted vehicle per year. A fleet of 160,000 converted vehicles (10% penetration) eliminates approximately 672,000 tonnes of CO_2 annually. For reference, this is equivalent to removing approximately 146,000 average European passenger cars from the road. The single study vehicle eliminates 4.2 tonnes of CO_2 per year of operation relative to the petrol baseline.

5.4. Limitations and Generalisability

The principal limitation of this study as currently designed is the absence of multi-unit replication data. The validated conversion architecture is derived from one vehicle subjected to a rigorous, exhaustive test programme. For the purposes of establishing the conversion specification, this is sufficient, engineering specifications transfer through adherence to design parameters rather than through statistical generalisation.

However, for the purposes of establishing manufacturing consistency and component quality variation across the Nigerian conversion component supply chain, a multi-unit replication study is necessary. This is a priority for future research direction. Additionally, the study's climatic scope is limited to the coastal and central Nigerian operating environment tested; northern sahel conditions still require validation.

6. Summary & Recommendations

This study has demonstrated, through a rigorously documented design-build-test programme conducted under real Nigerian urban operating conditions, that the electric drivetrain conversion of the standard Bajaj-type 200 cc Keke NAPEP is technically viable, commercially justified, and locally implementable using components available in the Nigerian market today.

The validated conversion architecture 3 to 5 kW PMSM motor, 72 A minimum-rated controller with open forced-convective cooling, 96 V 80 Ah LFP battery, 10:1 helical gear reduction, CV axle drivetrain is supported by specific measured field data across five test iterations and delivers a vehicle that eliminates petrol dependence, reduces daily operating costs by ₦3000 to ₦5000, and recovers the conversion investment within 6 to 12 months of commercial operation.

Contributions to knowledge: 1) the first peer-reviewed field-validated conversion specification for the Bajaj-type Keke NAPEP under Nigerian urban operating conditions, grounded in measured temperature, range, and current data rather than theoretical specification; 2) the first documented resolution of motor-controller thermal failure modes specific to the Nigerian ambient temperature and duty cycle, with the precise controller rating threshold (72 A) empirically determined rather than assumed; 3) the first fleet-level quantitative analysis connecting per-vehicle TCO and CO_2 data to population-scale economic and environmental impact (Tables 3-5), situating the single-unit conversion findings within Nigeria's 1.6 million-vehicle tricycle fleet; and 4) the first empirically grounded assessment of battery swapping against the specific constraints of the Keke NAPEP conversion context, producing a recommendation against swapping as the primary charging architecture for this deployment.

Policy recommendations: 1) NASENI and the Standards Organisation of Nigeria should establish a national conversion component quality standard for electric tricycle conversion kits, with the Electric Vehicle Transition and Green Mobility Bill 2025 as the legislative vehicle; 2) the Federal Ministry of Finance should extend duty exemptions on complete electric vehicles to include conversion kit components (motors, controllers, LFP battery packs, BMS, reduction gear units); 3) the Rural Electrification Agency should establish a Keke NAPEP DC charging infrastructure programme providing solar-battery-backed DC charging points at motor parks and operator bases, with charging-time specifications grounded in the experimental data from the companion paper (Paper 3b) showing 2-hour full charge (5% to 100%) using optimised DC equipment; 4) the Bank of Industry and development finance institutions should establish a conversion credit facility at concessional rates, structured as hire-purchase against the conversion investment with the measured 6 to 12 month payback providing the repayment basis.

Directions for future research: 1) multi-unit replication study testing the validated architecture across 10 or more converted vehicles operated by independent Keke operators in multiple Nigerian cities, producing statistical data on range consistency, failure frequency, and maintenance requirements; 2) northern sahel thermal validation study testing whether the 72 A controller specification and 10:1 gear ratio remain adequate at ambient temperatures exceeding 40˚C with higher dust loading; 3) full probabilistic lifecycle cost analysis comparing the converted Keke against continued petrol operation and purpose-built electric tricycle purchase across different fuel price scenarios; 4) standardisation feasibility study assessing the technical and commercial requirements for establishing a battery pack standardisation framework across Nigeria's conversion market, the prerequisite for any future battery swapping architecture to become viable at scale.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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