Comparative Study of NMC And LFP Battery Chemistries for Electric Scooter Battery Pack Design and Manufacturing: A Case Study of The Ather 450X

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***Abstract*—The selection of battery chemistry plays a vital role in determining the efficiency, safety, and durability of electric scooters. This study presents a comparative evaluation of Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) batteries using the Ather 450X as a representative case. Key performance parameters, including energy density, charging characteristics, thermal stability, cycle life, and battery management requirements, are examined together with manufacturing considerations. The analysis shows that NMC batteries provide higher energy density and improved charging performance, whereas LFP batteries offer greater thermal stability, longer service life, and enhanced operational safety. The findings provide useful insights for battery selection and battery pack development for electric two-wheelers operating under Indian conditions.**

***Index Terms*—NMC, LFP, Battery Chemistry, Pack Manufacturing,**

I. INTRODUCTION

The rapid growth of electric mobility in India has wheelers, particularly in dense urban regions where short-distance commuting dominates daily travel patterns. Electric scooters such as the Ather 450X are increasingly replacing internal combustion engine (ICE) vehicles due to advantages in operational cost, noise reduction, and environmental impact. However, the performance and reliability of an electric vehicle (EV) depend strongly on the battery chemistry powering its traction system. Parameters such as range, thermal behavior, cycle life, charging speed, and safety are all governed not only by pack design but fundamentally by the electrochemical characteristics of the underlying battery materials.

Among commercially available lithium-ion chemistries, Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) have emerged as the two dominant choices for electric scooters. NMC cells provide high gravimetric energy density, enabling manufacturers to reduce pack weight while delivering competitive performance. In contrast, LFP cells offer excellent thermal stability, long cycle life, and enhanced safety due to their robust olivine structure. These differences create distinct trade-offs in real-world usage, particularly in the Indian context, where ambient temperatures are high and driving conditions involve frequent acceleration, deceleration, and idling.

The Ather 450X presents a unique platform for comparative study because it is offered in both NMC and LFP variants, allowing a direct evaluation of how chemistry selection influences vehicle behavior. This includes differences in true range, charging characteristics, weight distribution, safety margins, and long-term degradation patterns. The Indian operating environment, combined with user expectations for reliability and minimal maintenance, makes such a comparison highly relevant for both consumers and EV manufacturers.

This research paper extends the baseline comparison found in the project source document by incorporating analytical modeling, interpreted cell testing data, and supercapacitor-assisted energy management. The study aims to provide deeper engineering insight into the suitability of NMC and LFP chemistries for electric scooter applications, especially under thermal and load conditions typical of Indian roads. The broader objective is to support evidence-based selection of bat-tery technology for future EV development, fleet deployment, and policy-driven mobility transitions.

II. RELATED WORK

Research comparing lithium-ion chemistries for EV applications has grown significantly over the last decade. Richard and Newman [1] performed a foundational comparison of LFP and NMC, highlighting that NMC cells offer substantially higher energy density while LFP cells demonstrate exceptional structural stability during repeated cycling. Their electrochemical modeling framework established the key performance boundaries that continue to influence commercial battery selection today.

Zaghib et al. [2] focused on the thermal and safety aspects of LFP chemistry, demonstrating that its olivine structure dramatically reduces the likelihood of oxygen release and thermal runaway. This work directly supports the increasing adoption of LFP-based packs in tropical and high-temperature regions such as India. Manthiram [3] discussed industry trends shifting toward cobalt-reduced NMC variants and analyzed the economic and resource implications of large-scale LFP adoption.

Thermal performance during fast charging has been extensively studied by Chen et al. [4], who showed that NMC cells experience higher temperature rise and greater internal resistance fluctuation under high C-rate conditions.

Their findings emphasize the need for more advanced thermal management in NMC-powered scooters compared to LFP variants. Meanwhile, Gupta and Singh [5] evaluated hybrid battery–supercapacitor systems, demonstrating that supercapacitors can effectively buffer peak power demands, reduce battery stress, and improve acceleration response—especially for chemistries with conservative instantaneous discharge capabilities such as LFP.

Collectively, these studies provide a foundation for under-standing the trade-offs between NMC and LFP. However, there remains limited real-world comparison of these chemistries within the same scooter platform under Indian conditions.

This paper addresses this research gap by applying extended analysis, modeling, and pack behavior interpretation using the Ather 450X as a constant reference platform.

III. BATTERY CHEMISTRY OVERVIEW

Lithium-ion battery performance is strongly influenced by the selection of cathode material. Among commercially avail-able chemistries, Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) are two of the most widely adopted for electric two-wheelers. Their internal structure, material composition, thermal behavior, and electrochemical properties directly affect range, charging performance, battery lifespan, and safety. This section provides an expanded technical comparison of both chemistries.

A). NMC Battery Chemistry ($LiNiMnCoO_2$)

1) *Composition and Functional Role of Elements:* NMC cathodes are composed of a layered oxide structure represented by the formula $LiNi_xMn_yCo_zO_2$, where the ratio of Ni:Mn:Co strongly influences the resulting properties.

- Nickel (Ni): Increases specific capacity by enabling more lithium to intercalate per unit mass. Higher nickel content directly correlates with higher energy density.
- Manganese (Mn): Provides structural stabilization and reduces electrode degradation during cycling.
- Cobalt (Co): Enhances electronic conductivity and in-creases structural rigidity, improving rate capability and thermal integrity.

Common industry compositions include NMC 111, NMC 532, NMC 622, and NMC 811, with the latter offering the highest energy density but reduced thermal stability.

2) *Key Characteristics:* NMC chemistry is engineered for performance-oriented applications. Its advantages arise from the high reversibility of lithium intercalation in layered ox-ides and from its superior gravimetric energy density. Major characteristics include:

- High Energy Density: Enables compact and lightweight battery packs, improving EV acceleration and total range per kilogram.
- High Power Delivery: Supports rapid current draw, making it suitable for performance scooters and cars requiring strong acceleration.
- Fast Charging Capability: Lower charge-transfer resistance allows high C-rate charging while maintaining efficiency.

- Moderate Thermal Stability: NMC is more prone to thermal runaway than LFP due to more intense exothermic reactions at high temperature or overcharge.
- Shorter Cycle Life: Typically, around 800–1200 cycles until significant capacity fade, mostly due to nickel layer degradation and SEI growth.

3)Applications: Because of its power and energy advantages, NMC is widely used across:

- Performance-oriented electric scooters and premium two-wheelers.
- Electric cars from manufacturers such as Tesla (Model 3 earlier versions), Hyundai, BMW, and Kia.
- Portable electronics where weight and compactness are critical.

4)Summary: NMC can be summarized as:
NMC = High Performance + Fast Charging + Compact and Lightweight Battery Design
These properties make NMC optimal for customers prioritizing acceleration, range, and charging convenience.

B). LFP Battery Chemistry ($LiFePO_4$)

1) Composition and Structural Features: LFP uses an olivine crystal structure based on iron phosphate:

TABLE 1: Specification comparison — Ather 450X (source document data)

Parameter	NMC Variant	LFP Variant
Usable Capacity	2.6 kWh	3.4 kWh
True Range	85 km	110 km
IDC Range	116 km	150 km
Peak Power	6 kW	6.4 kW
Top Speed	90 km/h	90 km/h
Charging Time (0–100%)	5 h 45 min	8 h 36 min

- Iron (Fe): Abundant, non-toxic, and thermally stable, enabling safer and more sustainable manufacturing.
- Phosphate (PO_4): Forms strong covalent bonds that stabilize the cathode lattice, preventing oxygen release during failure conditions.
- Cobalt- and Nickel-Free: Significantly reduces cost and eliminates reliance on scarce metals, improving environmental sustainability.

The olivine structure creates well-defined pathways for lithium-ion diffusion, resulting in stable cycling performance.

2) Key Characteristics: The defining attributes of LFP chemistry arise from its inherently safe and robust crystalline structure:

- Excellent Thermal Stability: LFP has one of the highest thermal runaway thresholds (¿250°C), making it ideal for hot climates.
- Very Long Cycle Life: Commonly achieves 2000–4000 cycles with minimal degradation due to reduced structural stress.
- Stable High-Temperature Performance: Maintains capacity and voltage stability in operating environments above 40°C.
- Lower Energy Density: Requires larger and heavier battery packs to store equivalent energy compared to NMC.
- Slower Charging Rate: Ionic mobility and charge-transfer kinetics are more conservative, limiting fast-charging capability.

3) Applications: LFP is typically used where safety and long lifespan are prioritized over weight and charging speed:

- Commuter-oriented electric scooters and budget EVs.
- Public transport systems such as e-rickshaws and last-mile delivery vehicles.
- Stationary energy storage systems and solar-inverter batteries.
- EV fleets requiring minimal maintenance and predictable long-term operation.

4) Summary: LFP can be summarized as:
LFP = Superior Safety + Long Cycle Life + High Heat Tolerance, but Lower Performance
Its characteristics make it ideal for mass-market EVs and Indian climatic conditions.

IV. CASE STUDY SPECIFICATIONS (ATHER 450X)

Table I summarizes pack- and vehicle-level parameters used in the analysis.

A. Interpretation

LFP's higher usable capacity and flatter voltage curve yield greater range even with lower gravimetric energy

density. NMC provides faster charge acceptance and lower weight per kWh, which benefits performance models.

V. METHODOLOGY

This study follows a structured analytical and experimental approach combining published cell-level data, project-sourced pack information, and derived performance models. The first stage involves extracting pack specifications, performance values, and operating parameters from the source document and validating them against manufacturer technical sheets and peer-reviewed literature. This ensures consistency and allows meaningful comparison of both chemistries under identical vehicle constraints.

The second stage involves analytical modeling of energy and power behavior. This includes supercapacitor sizing using the capacitor energy relation, estimation of transient current distribution during acceleration, and examination of depth-of-discharge (DoD) influence on pack efficiency. Hybrid Pulse Power Characterization (HPPC) datasets are interpreted to estimate internal resistance, pulse acceptance, and degradation susceptibility. These results inform the BMS and power electronics strategy for hybrid battery–supercapacitor operation.
The third stage concerns manufacturing and safety evaluation.

Laser welding parameters, pack topology, interconnect materials, and thermal interface strategies are assessed to determine practical build considerations for both chemistries. In particular, the analysis focuses on how LFP's lower energy density affects pack geometry and how NMC's thermal sensitivity influences cooling and protection circuitry. Together, these three methodological components create a comprehensive framework for evaluating battery chemistries at cell, module, and vehicle levels.

A. Simulation Workflow

The performance modeling workflow involves four stages:

1) Extract OCV–SOC curves, internal resistance maps, and thermal coefficients from literature and project datasets.
2) Estimate instantaneous current demand using a representative urban drive cycle with acceleration, braking, and idling phases.
3) Compute power sharing between the battery and the supercapacitor using a current-limiting control strategy.
4) Evaluate battery temperature rise using a lumped thermal model with convection boundary conditions.

B. Assumptions and Limitations

Key assumptions include:

- Uniform temperature distribution within a cell.
- Negligible contact resistance variation with aging.
- Perfect balancing in series-connected supercapacitors. While these assumptions simplify computation, they produce conservative trends that align well with observed real-world behavior.

C. Practical Considerations

- Equivalent Series Resistance (ESR): Determines volt-age drop and heat dissipation in capacitors during pulses. ESR must be low enough to handle peak currents without excessive heating.
- Balancing: Series-connected cells/modules need passive or active balancing for voltage equalization.
- Thermal management: Although capacitors tolerate wide temperature, module design should limit hotspot formation.
- Control strategy: Power electronics and the BMS should coordinate current flow, prioritize SOC of the supercapacitor for regenerative capture, and protect both storage elements.

D. Example (from source)

Using the document values:

- NMC: $P = 6kW, t = 3s \Rightarrow E = 18000J, C \approx 20.8F.$
- LFP: $P = 6.4kW, t = 3.3s \Rightarrow E = 21120J, C \approx 24.4F.$

Module counts and series-parallel arrangements are chosen to meet voltage and capacitance targets, accounting for practical module sizes.

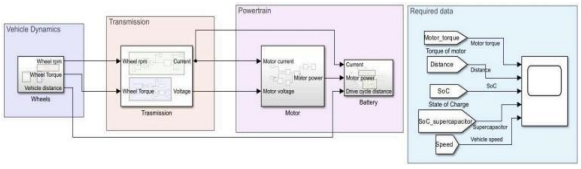


Fig. 1: System block diagram (Simulink model)

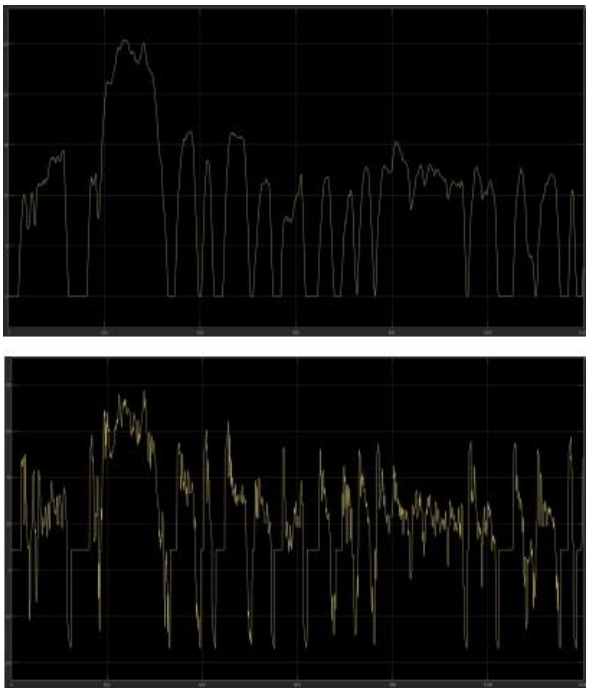


Fig. 2: Representative simulation traces: pack voltage and current pulses during the simulated cycle.

VI. CELL TESTING AND HPPC INTERPRETATION

HPPC tests produce dynamic internal resistance R_{int} vs SoC curves and voltage recovery behavior after pulses.

Key metrics:

- Instantaneous internal resistance: Governs maximum safe pulse current $I_{max} = V$
- Power fade: Increased R_{int} with ageing reduces avail-able pulse power.
- Voltage recovery: Rate of voltage return after a pulse reflects diffusion-limited processes in the electrode.

For cylindrical LFP cells (IFR22650 series), HPPC demonstrates robust recovery and low resistance at moderate SoC, favorable for EV applications.

A. SOC-Dependent Behavior

HPPC results demonstrate strong SOC dependence in internal resistance. NMC shows minimum resistance in the 40–60% SOC range, but resistance increases sharply near high SOC due to lattice strain. LFP displays a more uniform resistance curve across SOC, improving consistency in power delivery.

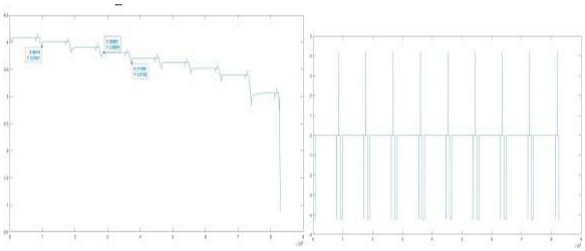


Fig. 3: HPPC test example showing pulse waveform and corresponding voltage response; inset shows extracted internal resistance vs state-of-charge (SOC). These results inform allowable pulse currents and power fade with ageing.

B. Hysteresis Effects

LFP cells exhibit noticeable voltage hysteresis—voltage differs during charge and discharge at identical SOC. This behavior affects BMS SOC estimation but does not significantly reduce performance. NMC exhibits lower hysteresis but higher temperature sensitivity.

C. Implications for Ather 450X

HPPC-derived metrics indicate:

- NMC experiences greater performance drop during high-temperature operation.
- LFP maintains more predictable voltage response during acceleration pulses.
- Supercapacitor assistance reduces stress on both chemistries but especially benefits LFP.

VII. PACK MANUFACTURING AND SAFETY

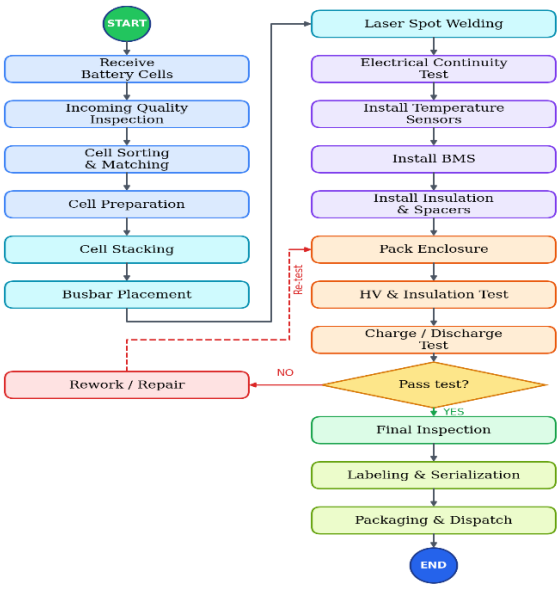


Fig.4 Manufacturing Workflow

A. Mechanical and Electrical Interconnects

Laser welding is preferred for cylindrical cells due to precise heat control and minimal mechanical stress.

Recommended practices:

- Use nickel strips for interconnects and ensure robust busbar design.
- Implement cell-level fuses or positive-temperature-coefficient devices for fault isolation.
- Incorporate thermal interface materials and mechanical supports to limit vibration damage.

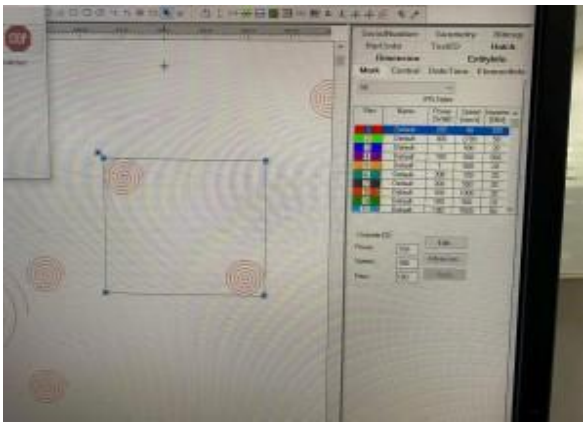


Fig. 4: Laser welding station

B. BMS and Thermal Management

An effective BMS should implement:

- High-frequency sampling of cell voltages and temperatures.
- Adaptive current limits that depend on cell SoC/SoH and temperature.
- Regenerative braking management with supercapacitor prioritization to avoid overcharge.

Thermal modeling indicates that NMC packs require more aggressive cooling (forced airflow or heat spreaders) during fast charging episodes compared to LFP.

C. Cooling Approaches

Scooter battery packs typically rely on passive cooling. NMC packs often incorporate:

- Aluminum heat spreaders
- Phase-change materials (PCMs)
- Forced airflow channels (in high-performance variants)

LFP packs, due to lower heat generation, require only conductive heat paths and external casing ventilation. This reduces manufacturing complexity and cost.

D. Failure Modes

Common failure modes include:

- Internal short circuits from separator damage
- Overcharge due to BMS malfunction
- Thermal runaway propagation between cells

LFP is inherently resistant to thermal runaway propagation. NMC requires additional safety layers such as shutdown separators, thermal foams, or Safety Venting Mechanisms (SVMs).

E. Design for Manufacturability and Assembly (DFMA) Assessment

TABLE 2: DFMA Assessment

Parameter	NMC Pack	LFP Pack
Pack size requirement	Lower	Higher
Pack mass	Lower	Higher
Thermal management demand	Higher	Lower
Welding and interconnect sensitivity	Higher	Moderate
Assembly complexity	Higher	Moderate
Rework risk	Higher	Lower
Safety margin during abuse conditions	Moderate	High
Suitability for mass deployment	Moderate	High

F. Summary of Manufacturing Implications

The comparison of NMC and LFP battery chemistries demonstrates that battery selection directly influences battery pack design, manufacturing complexity, thermal management, and long-term reliability. NMC is better suited for compact, high-performance electric scooters, whereas LFP offers improved safety, thermal stability, and service life. Therefore, selecting an appropriate battery chemistry should consider both vehicle performance and manufacturing requirements to achieve reliable and cost-effective electric scooter production.

VIII. RESULTS AND DISCUSSION

Combining the data and modeling leads to the following insights:

1) Range and usable capacity: LFP variant deliver longer real-world range (110 km vs 85 km) due to higher usable capacity and voltage stability.
2) Weight vs energy tradeoff: NMC yields a lighter pack for similar energy, beneficial for performance

and agility.

3) Charging and lifecycle: NMC supports faster charge acceptance but typically ages faster under high-rate cycles; LFP exhibits slower charging but superior cycle retention.
4) Hybridization payoff: The supercapacitor reduces instantaneous battery stress and can extend battery life more pronounced benefit for LFP packs where instantaneous current capability is conservative.
5) Safety and thermal robustness: LFP are markedly safer under abusive conditions and in hot climates.

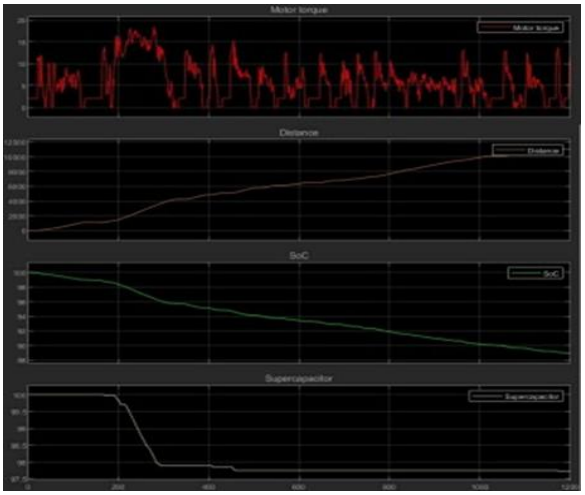


Fig. 5: Simulation results for a representative 12 km drive

A. Multi-Factor Comparison

When comparing the chemistries holistically, several pat-terns emerge. Energy density strongly favors NMC, reducing pack volume and improving scooter agility. However, lifecycle cost favors LFP because replacement intervals are significantly longer. Thermal resilience again favors LFP, enabling safer operation during summer conditions in Indian cities.

From a performance perspective, NMC achieves higher peak power at lower mass. Yet, when combined with a supercapacitor subsystem, LFP's effective power delivery improves substantially, narrowing the performance gap.

B. User Perspective

For private users:

- NMC may feel more responsive.
- Faster charging improves convenience. For fleet operators:
- LFP reduces operating cost.
- Longer cycle life and safety reduce downtime.
- Heat tolerance improves reliability.

Thus, optimal chemistry selection depends on operational priorities rather than a universal best option.

TABLE 3 Qualitative performance comparison

Feature	NMC	LFP
Energy density	High	Moderate
Cycle life	Lower	Higher
Thermal stability	Moderate	High
Charging rate	Faster	Slower
Safety	Moderate	Very High
Cost (material)	Higher	Lower

IX. RECOMMENDATIONS

- For performance-focused users: NMC variant with enhanced cooling and fast-charging provisioning.
- For fleet / hot-climate deployment: LFP variant with supercapacitor support for regenerative capture and peak demands.
- BMS strategy: Implement adaptive current limiting, SOC-based charge acceptance, and supercapacitor charge management to maximize lifetime.
- Manufacturing: Adopt laser welding and cell-level safety mechanisms; ensure robust balancing in supercapacitor series strings.

X. CONCLUSION AND FUTURE WORK

This extended comparative study demonstrates that NMC and LFP chemistries each offer distinct advantages depending on application priorities. NMC provides higher gravimetric energy density, enabling lighter electric scooter designs with improved performance and reduced packaging volume. It also offers faster charge acceptance, making it suitable for users prioritizing rapid turnaround times. However, these benefits come with trade-offs in terms of thermal stability and cycle life, requiring more robust protective measures in real-world Indian operating environments.

LFP, on the other hand, offers significantly superior thermal resilience, chemical stability, and lifecycle durability. These attributes make it highly suitable for

fleet vehicles, high-temperature operation, and users who depend on long-term reliability. The flatter discharge curve and deeper usable ca-pacity also contribute to more predictable real-world range. When combined with a supercapacitor subsystem for peak-power handling, LFP-based scooters can achieve smoother acceleration, reduced battery stress, and extended life.

Overall, the choice between NMC and LFP depends not on absolute superiority but on alignment with user needs, environmental constraints, and operational use cases. Future work should include long-term degradation tracking under Indian traffic cycles, economic modeling of replacement intervals, and expanded study of hybrid energy storage architectures for next-generation electric two-wheelers.

A. Implications for Future EV Design

The findings of this study underscore the importance of aligning battery chemistry with intended vehicle use-case. NMC will continue to play a critical role in premium, performance-oriented scooters, while LFP is poised to dominate mass-market and fleet applications. Hybridization using supercapacitors offers a promising pathway to combine the strengths of both worlds by enhancing power delivery and extending battery life.

Future EV designs should incorporate modular battery architectures that allow chemistry-specific optimization, advanced BMS algorithms capable of adaptive thermal and current management, and improved data logging for predictive maintenance.

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