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Performance and Structural Analysis of Different Lithium-Ion Battery Chemistries for Electric Vehicle Applications

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Abstract

Lithium-ion batteries (LIBs) stand at the forefront of electric vehicle (EV) technology and have become a driving force behind the development of advanced energy storage systems. In this study, performance and structural analysis of different lithium-ion battery (LIB) chemistries—namely Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), Lithium Cobalt Oxide (LCO) and Lithium Nickel Cobalt Aluminum Oxide (NCA)—is presented. The study explores important performance parameters like energy density, power density, cycle life and thermal efficiency at different operating scenarios. Each chemistry's structural integrity is examined through mechanical and thermal stress tests, including vibration, impact and thermal runaway tests. Home Simulation and Experimental Methods for the Comparison of All Solid-State Battery Electrolytes with Potential Applications in Electric Vehicles are Trade-offs between Safety, Energy & Power Densities, and Life Time. High-energy-density chemistries as NMC and NCA are found to be well-suited for long-range EVs but LFP shows a better optimization of thermal stability and safety to heavy-duty applications. It highlighted integrative optimization strategies for the design of EV batteries, with requirements that differ across different chemistries, which emphasize tailoring to chemistry response and foundation-level understanding. This work offers valuable guidance for the design of durable, high-performance and cost-effective battery technologies targeting next-generation EVs.

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INTRODUCTION

Lithium-ion batteries (LIBs) are indispensable components of electric vehicles (EVs), and their performance is critical to the success of the vehicle. LIBs (Lithium Ion Batteries) are energy-dense, have relatively long-lasting performance and deep + fast charging capabilities which is why they are suited for modern EV driving range without adding much extra space or weight to the battery. Their lightweight nature not only improves energy-

efficiency but also overall vehicle performance. Furthermore, LIBs also provide excellent energy conversion efficiency, which minimizes the loss of energy flow during charging and discharging processes. Their wide-temperature spectrum power consistent also reinforces reliability. Furthermore, LIBs are easy to recharge and provide a long cycle life and enable fast charging capabilities (convenient and cost-effective for long-term use). They are also compatible with regenerative braking systems which further mitigate energy loss and improve efficiency in EVs. Using LIBs as a cleaner alternative of fossil fuels plays an important role in frees greenhouse gas emission responsible for achieving globally sustainable transport and environmental conservation. Different types of lithium-ion battery (LIB) chemistries have desirable performance properties for specific applications enabled by their unique compositions [1–4]. Some, for example can be: lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), Lithium Cobalt Oxide (LCO) and lithium nickel cobalt aluminum oxide (NCA). In electric vehicles (EVs), nickel manganese cobalt (NMC) batteries are very popular due to their high energy density, but balance safety, life and cost. The high thermal stability- and long cycle life- of LFP batteries makes them inherently safe, which is why they are favored for durability applications (heavy-duty EVs and energy storage systems). While LCO batteries are higher in energy density and primarily used in portable electronic devices, their short lifespans under stress, as well as safety concerns preclude using them for EVs. With a unique ability to provide high energy density and long cycle life, NCA batteries enjoy popularity for automobile applications among other use cases though the need for enhanced management systems is necessary due to higher costs and thermal sensitivity. Every chemistry has its advantages and disadvantages in the trade-off between energy density, safety, cost, and lifecycle performance — choices need to be made based on their specific EV needs and application. Performance and structural analysis of the lithium-ion battery (LIB) is an important field of research for improving electric vehicle (EV) technology as well as providing dependable, secure, and rational energy storage systems. Performance calculations reveal data on important metrics like energy density, power density, cycle life and thermal management which relate to the EV driving range, charge time and overall efficiency of an EV. On the contrary, structural analysis assesses batteries for mechanical and thermal stability during operating conditions such as vibration, impact, and temperature changes [5]. This two-pronged approach ensures that batteries not only provide peak performance, but also do so in a manner where their integrity can be maintained over time and the risk of events like thermal runaway and mechanical failure is reduced. As manufacturers balance performance with structural elements, there is still room to improve battery designs for a broad spectrum of automotive verticals from high-performance EVs to mass-market models. In addition, these analyses

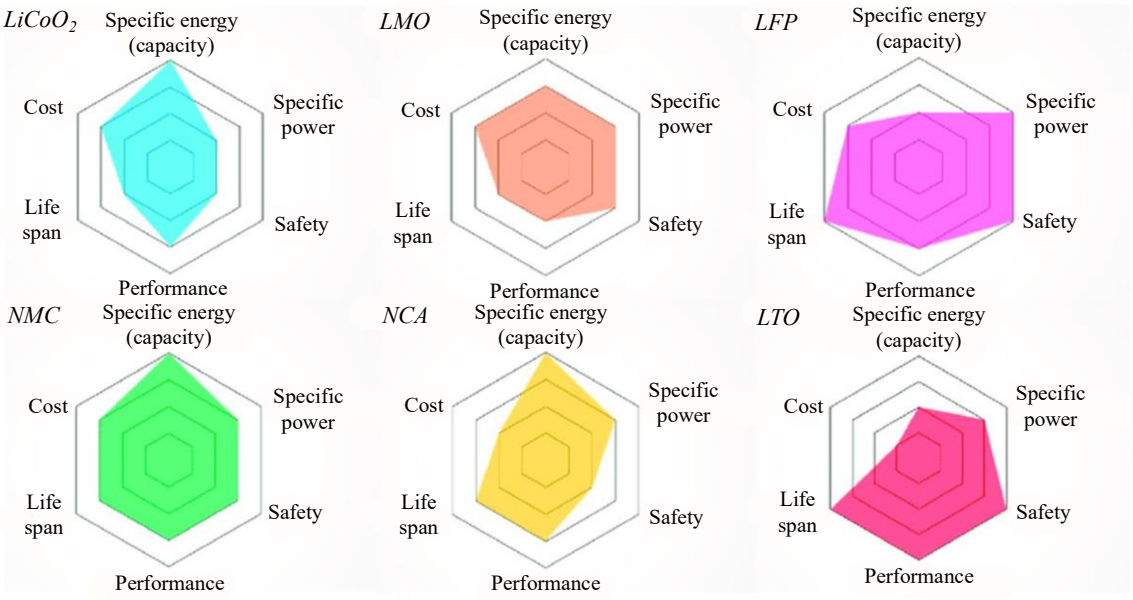

Figure 1. Comparisons of different types of Li-ion batteries used in EVs [26].

lay the groundwork for the innovation of more advanced battery technologies that are safer and environmentally friendly while being cost-effective also to accelerate EVs adoption towards their global sustainability targets (Figure 1).

Problem Definition

Increasing adoption of electric vehicles (EVs) has set an unprecedented demand for lithium-ion batteries (LIBs) to provide optimized performance, safety and reliability. Nevertheless, due to the vast range of chemistries offered by LIBs including Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), Lithium Cobalt Oxide (LCO) and Lithium Nickel Cobalt Aluminum Oxide (NCA), their performance is trade-off dependent in terms of energy density versus thermal stability, lifecycle, and structural durability [6–10]. While crucial for EV efficiency and safety, the comparative performance and structural characteristics of these chemistries are largely under-explored utilizing relevant operating conditions that include thermal stress, mechanical vibrations as well as cycling degradation. This absence of whole-system assessments makes it difficult to identify the right LIB chemistry suited for different kinds of EV applications by providing a good trade-off between diverse parameters such as range, safety, cost and durability. If the industry lacks strong data understanding on performance metrics and structural criteria for different LIB chemistries, it will be challenging to design batteries fulfilling specifications, from high-performing vehicles down the range of mass-market EVs. Accordingly, the challenge is in recognizing and quantifying critical performance and structural characteristics of long list of possible LIB chemistries that guide impactful selections for future EV battery technology development [11–14].

Objectives

1. Comparison of energy density, power density, efficiency, cycle life and thermal stability of different lithium-ion battery chemistries (NMC vs LFP vs LCO vs NCA) under different conditions
2. Evaluation of Mechanical and Thermal Stability which encompasses exposure to vibration, impact, thermal runaway, and other stressors typical of EV applications.
3. Analyze the trade-offs between performance, safety, cost and lifetime of each lithium-ion battery chemistry in order to understand their suitability for different EV applications including passenger vehicles, heavy-duty and high-performance vehicles.
4. Battery Selection Guidance by Actionable insights and recommendations on choosing the best lithium-ion battery chemistry for unique EV design and operational needs.
5. Future Directions in EV Battery Technology considering Specific challenges and opportunities to be addressed in LIBs that can help guide future research directions for all EV battery systems [15].

Scope

This paper documents an extensive battery performance and structural evaluation of lithium ion chemistries; NMC, LFP, and NCA for EV applications. Worst of all, their massiveness makes it questionable to study them going forward making their energy density, thermal stability, charge-discharge rates and cycle life essential parameters toward assessing whether they'd be suitable for use in EVs. Structural assessment will determine the mechanical stability of battery cells and modules in response to electro-mechanical stresses such as vibrations and thermal shocks during operation. As the demand increases for ideal energy storage systems in EVs, this study seeks to resolve safety-performance-durability trade-offs by answering fundamental questions on battery chemistries and how they can be discovered and optimized [16].

Methodology

This work takes a systematic approach to assess the performance and of LIB chemistries, NMC, LFP, LCO and NCA relevant for electric vehicle (EV) applications in terms of both their structural characteristics. The methodology consists of the following steps:

1. *Choosing battery chemistries*
    a. Source commercial samples of NMC, LFP, LCO, and NCA batteries.

   b. The cell should be uniform in terms of shape, size and capacity for a fair comparison.
2. *Performance testing*
   a. *Energy and power density:* Quantify energy density and power output in a laboratory setting using standard battery characterization equipment.
   b. *Charge/discharge curves:* Perform charge-discharge cycling at different C-rates (and with time), to assess efficiency and cycling retention.
   c. *Thermal performance:* Evaluate thermal characteristics by measuring heat generation and dissipation in various loads and ambient temperature conditions.
   d. *Cycle life testing:* Conduct accelerated aging tests to evaluate degradation over long-term charge-discharge cycles [17].
3. *Structural analysis*
   a. *Mechanical test:* Study component resistance to mechanical stresses (vibration, impact and compression) through simulation and in-lab testing.
   b. *Thermal stress analysis:* Use a high-temperature condition to analyze the structure, assess risks of thermal runaway.
   c. *Post-mortem failure mode analysis:* After testing, determine what the common modes of failures are during cycling (e.g., electrode degradation, separator destruction).
4. *Simulation and modeling*
   a. Create computational models to analyze mechanical and thermal behavior for different conditions like road vibrations and high/low temperatures.
   b. Verification of simulation results against experimental data for accuracy and reliability
5. *Comparative evaluation*
   a. For each battery chemistry, compare / contrast performance metrics with respect to structural resilience.
   b. Examine feasibility for long-range vs. low-cost batteries for EV adaptability (or high performance EVs, heavy-duty vehicles)
6. *Data analysis and visualization*
   a. Statistical methods to analyze experimental data, look for trends and comparisons
   b. Use graphs, charts and tables to present findings for clarity and impact [18–25].
7. *Recommendation and conclusion*
   a. Offer practical details about how to select LIB chemistries for particular EV applications.
   b. Identification of gap areas for improvement for battery lifespan and performance

This approach allows for an inclusive assessment of LIB chemistries while coupling experimental and computational approaches to inform advanced systems development for EV battery applications.

LITERATURE REVIEW

The developments in lithium-ion battery (LIB) technologies over the last few decades for electric vehicles (EVs) have played key roles in enhancing the performance, safety, and sustainability of electric transportation. In particular, there are high-energy-density chemistries like those of Nickel Manganese Cobalt (NMC) and Nickel Cobalt Aluminum Oxide (NCA) batteries that can store more energy in a vehicle, so the driving range is much greater on single charge. Such advancements in energy density are critical to help alleviate range anxiety, one of the primary obstacles when it comes to EV adoption. Besides, the solid-state battery is also on a rising trend by replacing the electrolyte with a solid electrolyte which enables higher energy densities, improved safety and thermal stability. Solid-state batteries are a safer and more reliable alternative for EVs as they are less likely to leak or go into thermal runaway compared with conventional LIBs. The significantly exciting increment is again in fast charging technologies with a focus on the reduction of its charge time. Designs of new batteries now, combined with charging protocols using artificial intelligence to compress this charging cycle without hurting battery health or lifespan[26]. Also, battery management systems (BMS will) also be getting more and more advanced with the use of complex algorithms and machine learning to monitor and optimize performance, efficiency, safety, and life. Research on recycling and second-life will play an

increasingly important role for LIBs, especially with the increase in EVs that will need to be accounted for. Advancements in battery recycling technology enable the extraction of valuable raw materials such as lithium, cobalt, and nickel from end-of-life batteries, significantly mitigating the environmental consequences and expense of new battery production. Systems to manage heat transfer such as better hardware and cooling techniques have been developed for batteries, helping improve their performance and longevity. Lastly, advancement in battery packs that are lightweight, durable and affordable has helped enhance the efficiency and reduce the cost of EVs. Combined, these innovations are advancing lithium-ion battery technologies to make EVs more efficient, practical and sustainable while improving the whole user experience. When it comes to choosing the optimal lithium-ion battery (LIB) chemistry for electric vehicle (EV) applications, there are some critical challenges and trade-offs that must be considered. The biggest challenge is that in fact when balancing energy density and power the costs [27–30]. To create the long driving ranges necessary for consumer acceptance of EVs, one turns necessarily to high-energy-density chemistries (like Nickel Manganese Cobalt [NMC] and Nickel Cobalt Aluminum Oxide) which provide this. But these are costlier because of expensive raw materials such as cobalt and nickel. Alternatively, LFP batteries are much cheaper and can achieve better thermal stability and safety properties, at the expense of a lower energy density. However, their lower energy density means that they have a shorter driving range, so they wouldn't work well for long-range EVs. A very important trade-off is thermal stability vs. performance. LFP batteries are generally safer and only need basic thermal management, compared to high-energy chemistries like NMC and NCA that face overheating and thermodynamic runaway risks. These require sophisticated active thermal management systems to maintain safety during operation. Additionally, cycle life and performance degradation and aging is another obstacle. NMC and NCA boast better energy density and power output, but their degradation is faster than LFP which shortens their lifetime and performance. This requires constant battery changes or costly management solutions for the batteries. In addition, the environmental and resource impacts are not minor factors influencing LIB chemistry selection. For instance, chemistries such as NMC and NCA use cobalt and nickel that have a tremendous supply chain volatility, are mined from regions with significant ethical and environmental issues. On the one hand it uses iron which is more abundant and environmentally friendly while LFP batteries have lower energy density but are limited to not being used in high-performance applications. Last but clearly not least, cost and infrastructure considerations such as the needed charging infrastructure as well as sophisticated battery management systems (BMS) must also play an important role in deciding on purchasing a particular vehicle. These compensations underscore the importance of carefully considering the performance profile, cost efficiency, environmental effect and sustainability of a custom battery chemistry against others to select for various EV uses. Past investigations focused on performance characteristics and cycle life of lithium-ion batteries (LIBs) for electric vehicle (EV) applications have revealed fundamental information on the performance of different battery chemistries under practical conditions. To examine the performance of different LIB chemistries (e.g., NMC, LFP, LCO and NCA) at different loads, extensive research focused on various metrics including energy density, power output, and efficiency as well as charge/discharge cycles. NMC and NCA batteries provide high energy density, ideal for long-range EVs but fall short of cycle life and thermal stability as compared to LFP battery technologies, which offer lower cost and longer performance. However, many studies have also investigated the charge/discharge rate and efficiency of these chemistries, especially at fast charging conditions where the high-power demand can significantly raise temperature resulting in a loss of cycle life. Researchers have recognized that LFP batteries do not degrade as quickly in high-temperature conditions, but ultimately produce less energy overall, resulting in vehicle range compromises [31]. In addition, research on thermal management has investigated the methods of heat production and removal under high-performance cycling, as well as their effects on battery performance and durability. For structural reliability, many researches have addressed the mechanical behavior of LIBs under various mechanical loadings, such as vibrations, shocks or impacts that are expected to influence vehicle usage. The heat generated is a big concern depicted from the literature, especially in high energy chemistries such as NMC and NCA, which are more sensitive towards internal heating and mechanical damage leading to thermal runaway. Some studies have looked into the ability of battery packs to survive long-

term driving-induced vibrations and shocks, and all have concluded that the structural design of a battery module has a major impact on its mechanical integrity under such stress, while maintaining safety and performance. Mechanical and thermal failure modes were consequently studied, including cell swelling, separator damage, and electrolyte leakage, to assess their effect on battery safety. In addition, post mortem studies of aged battery cells have provided insights into degradation modes including capacity fade, impedance rise and anode/cathode degradation which are necessary for understanding long-term durability in different LIB chemistries. Accelerated aging tests and simulation models have been used to estimate the lifetime of LIBs to design a more reliable battery management system (BMS) capable of reducing these problems. In general, previous work has developed an increased understanding of the relationship between performance metrics and structural durability that continues to inform development of more advanced chemistries and designs as the EV market evolves.

STRUCTURAL AND PERFORMANCE ANALYSIS

Theoretical Aspects

The lithium-ion battery (LIB) chemistries under investigation include Nickel Manganese Cobalt (NMC)**,** Nickel Cobalt Aluminum Oxide (NCA)**,** Lithium Iron Phosphate (LFP)**,** and Lithium Cobalt Oxide (LCO)**,** each offering distinct characteristics suited for different electric vehicle (EV) applications. NMC batteries are known for their high energy density, making them ideal for long-range EVs, while NCA batteries, with similar advantages, are commonly used in high performance vehicles. LFP batteries, although having lower energy density, provide excellent thermal stability, longer cycle life, and are more cost-effective, making them suitable for mass-market EVs and fleet applications [32,33]. LCO batteries, typically used in smaller devices, are being evaluated for their high specific energy but face challenges in terms of thermal stability and lifecycle performance compared to other chemistries. Each chemistry has unique trade-offs in terms of cost, safety, energy density, cycle life, and thermal stability, making them candidates for different EV market segments (Figure 2).

The performance testing equipment for LIBs are typically housed in a small chamber with specialized instruments to maintain environmental conditions and measure critical parameters (capacity, cycle life, energy density). In the case of capacity testing, batteries (or battery packs) are charged and discharged under a specific rate (usually C/5) with current and voltage simultaneously monitored to determine the amount of energy that is stored and delivered. Cycle life testing involves subjecting the battery to many charge-discharge cycles at different rates and temperatures, measuring capacity retention and degradation over time [34, 35]. Energy density: Energy is the output of the battery pack, which is measured by taking a measurement of its voltage and capacity– i.e. assuming both go up linearly, which is not bad approximation in case of lithium-ion batteries – and then calculating Wh total energy out

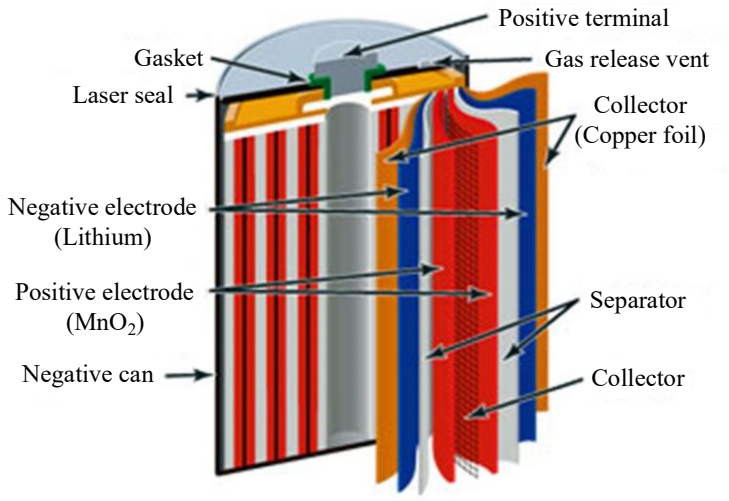

Figure 2. Structure of lithium ion battery.

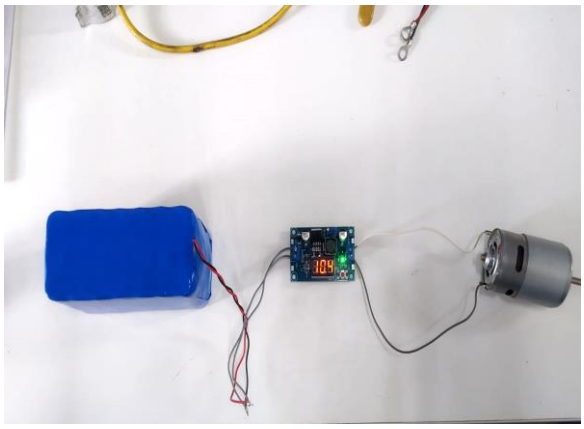

Figure 3. Battery charging.

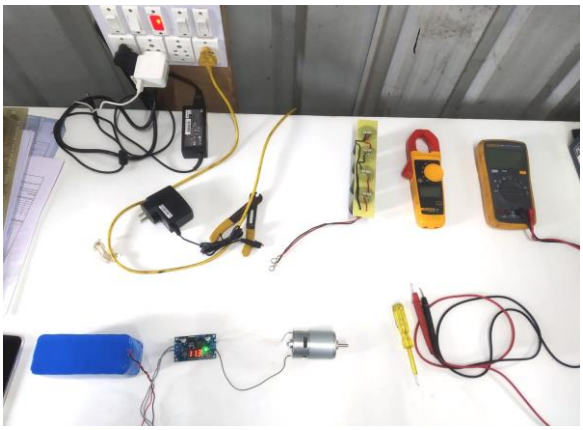

Figure 4. Battery discharging.

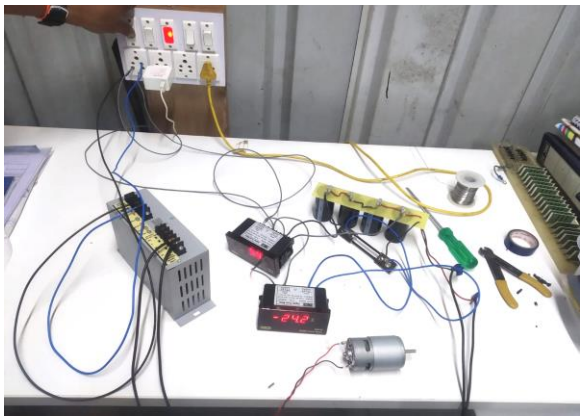

Figure 5. Supercapacitor charging.

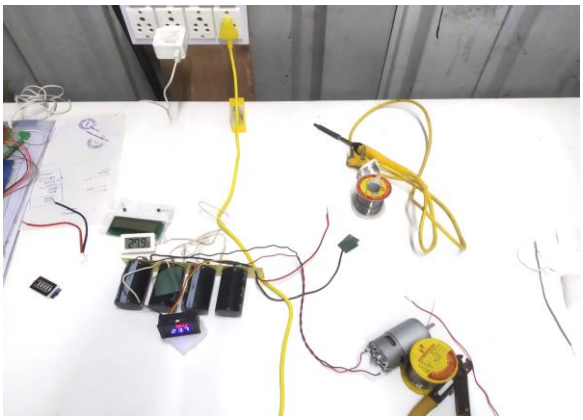

Figure 6. Supercapacitor dis-charging.

Table 1. List of Parameters required for Simulation using Matlab / Simulink.

Battery parameters	Nominal voltage	48 V
	Rated capacity	100 ah
	Initial stage of charge	100%
Vehicle parameters	Mass	100 kg
	No of wheels per axle	2
	Horizontal distance from CG to front axle	0.7 m
	Horizontal distance from CG to rear axle	0.7 m
	CG height above ground	0.5 m
	Gravitational acceleration	9.81 m/s^2
	Drag coefficient	2
	Air density	1.18 kg/m^3
Gear, differential and motor parameters	Carrier to drive shaft teeth ratio	4
	Follower to base teeth ratio	2
	Inductance	$12e^{-6}$ H
	No load speed	2000 rpm
	Rated speed	1800 rpm
	Rated load	5 kW
	Rated DC supply	50 V

based on these two variables, producing the results expressed usually as Wh/kg (Figures 3–6). This is tested using a battery testing station having controllable power supplies to gather real-time data under

different operating conditions e.g. electrochemical performance determining galvanometer with changes in charge/discharge rates and Temperature. Those tests results are used to evaluate the relative efficiency, lifetime and usability of a given LIB chemistry for EV automotive applications. Various advanced techniques are used in the structural analysis of lithium-ion batteries (LIBs) employed on electric vehicles, to determine their mechanical and thermal integrities. FEA is used to model a battery and simulate how it will respond structurally under various conditions of mechanical stress like compression, impact, or vibration, helping to identify possible failure modes and internal stress distributions. This uses thermal imaging to watch how the temperature varies around the battery when it is charged/discharged, which can help provide an indication of potential hotspots, and give some indication of how well the thermal management elements are working Vibration testing using Electrodynamic shakers uses a simulated real-world driving environment to check the battery's performance against vibrations, shocks, and impacts. All of these techniques are complementary and are combined to expose architectural deficiencies, guarantee safe function/performance, and useable for design optimization purposes toward lifetime-enhancing LIBs in electric vehicles (Table 1).

Simulation: (Time of Simulation Study for 1000 Seconds)

Simulation tools and models are crucial for performance analysis and modelling the structure or mechanics of lithium-ion batteries (LIBs) to be used in electric vehicle applications. For FEA, software such as ANSYS and COMSOL Multiphysics allow for detailed modeling and simulation of mechanical, thermal, and electromagnetic behavior in the battery cells / packs. In thermal simulations, Fluent or STAR-CCM+ are used to simulate heat generation, dissipation (convection and conduction), and fluid dynamics with respect to the optimization of thermal management systems. Battery dynamic models, like charge-discharge cycling, power output and energy efficiency are often developed using MATLAB/Simulink as well (Figure 7). Simulation tools play a vital role in predicting the performance and durability of batteries under different operating conditions, while also providing design suggestions for using better materials for improving safety and efficiency of EV applications (Table 2).

Performance Analysis

The lithium-ion battery (LIB) chemistries differ in energy density and power density, as well as in capacity retention which are important performance metrics. Energy density is the amount of energy a battery can store for a given mass or volume and NMC and NCA chemistries generally have the highest energy densities but this makes them well suited to long-range electric vehicles. Power density, which determines how quickly energy can be delivered, is high for NCA batteries allowing them to offer strong power output ideal for performance-focused EVs. Conversely, LFP batteries have a lower energy density but much better capacity retention—the percentage of original cell capacity over many charge/discharge cycles—making them suited to applications like long cycle life. LCO batteries provide higher energy density but are also more prone to faster degradation in both capacity and power over time. Depending on the performance requirements of a given EV model, these trade-offs dictate which battery chemistry will be selected. Lithium-ion batteries (LIBs) yield a substantially different efficiency depending on temperature ranges, temperature intervals, and turning-up/turning-down rates. This type of battery, especially those with NMC and NCA types of chemistry, are vulnerable to degradation at an elevated temperature, resulting on loss of efficiency along with a risk of thermal runaway. On the other hand, low temperatures can raise internal resistance and thus lower available power while also reducing overall efficiency. Efficiency is also affected by charging and discharging rates as fast charging creates excess heat which at times may reduce the performance and lifespan. Interestingly, while LFP batteries are more thermally stable and generally operate at a larger variety temperatures and charge conditions with less loss of performance, they too experience some degradation at the temperature extremes. Conversely, energy dense batteries normally the NCA and NMC are probably to be more efficient in terms of power generated/energy expended but demonstrate lower efficiency through rapid charge/discharge cycles as they may have a low tolerance to temperature and high power. Since these efficiency factors are critical to the proper functioning of any battery system, a good understanding is therefore essential for electric vehicle applications (Figure 8).

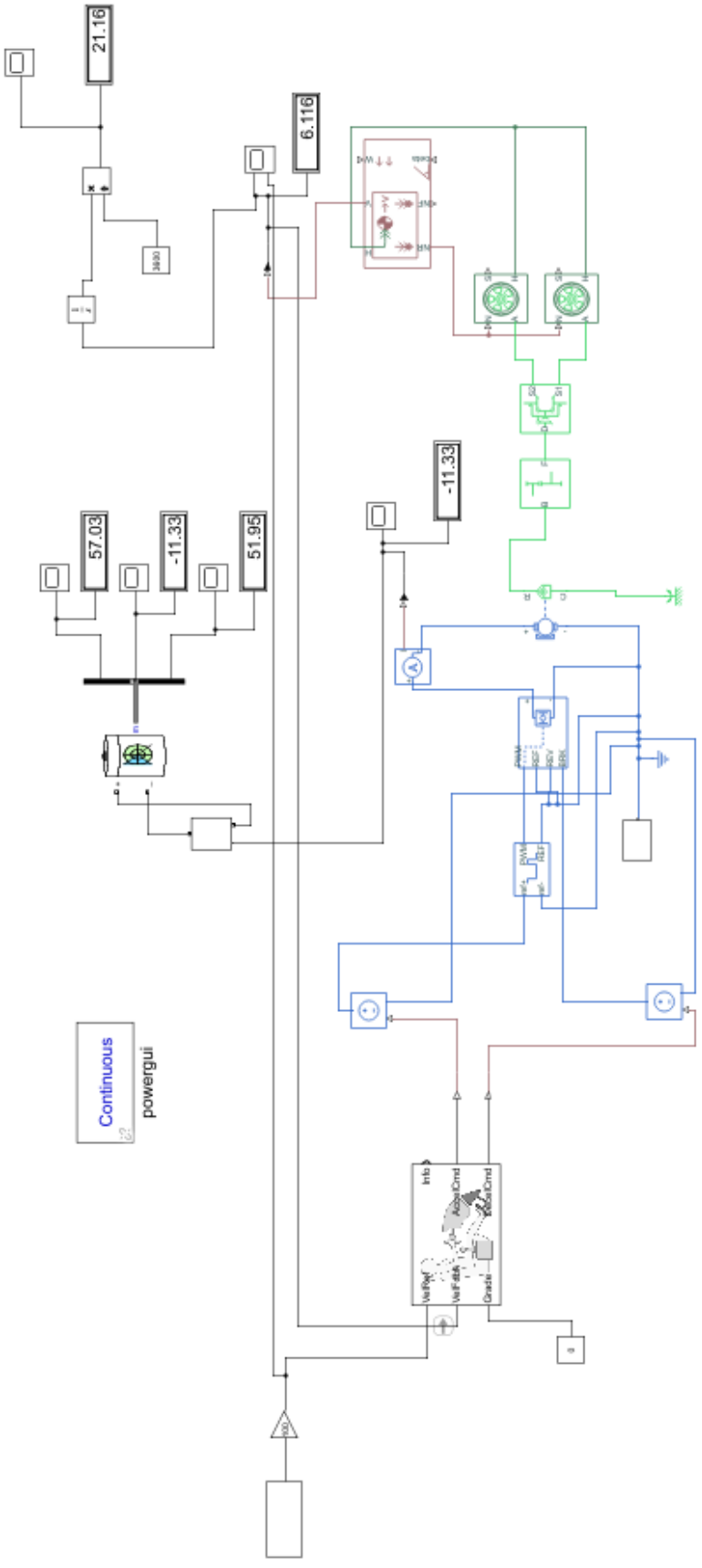

Figure 7. Simulink model of E-Bicycle using Matlab / Simulink.

Table 2. Comparative analysis of lithium ion battery chemistries.

Specifications	Lead-acid	LFP	NMC	NCA
Nominal voltage (V)	2	3.2	3.6 – 3.7	3.6 – 3.7
Typical operating range (V/cell)	1.6 – 2.4	2.5 – 3.6	2.5 – 4.2	2.5 – 4.2
Specific energy (Wh/kg)	30 – 50	90 – 150	150 – 220	200 – 260
Typical charge rate	0.2C	0.5C	0.5C	0.5C
Typical discharge rate	0.1-0.5C	1-2C	1-2C	1C
Charge temperature (°C)	-20 – 50	0 – 55	0 – 50	0 – 50
Discharge temperature (°C)	-20 – 50	-20 – 55	-20 – 50	-20 – 50
Cycle life (100%DOD)	200 – 300	1000 – 4000	500 – 2000	500 – 2000
Thermal runaway temperature (°C) and comment	100 – 150	270	210	150
	Plastic container gets soften and melt	Very safe even if fully charged	High charge promotes thermal runaway	High charge promotes thermal runaway

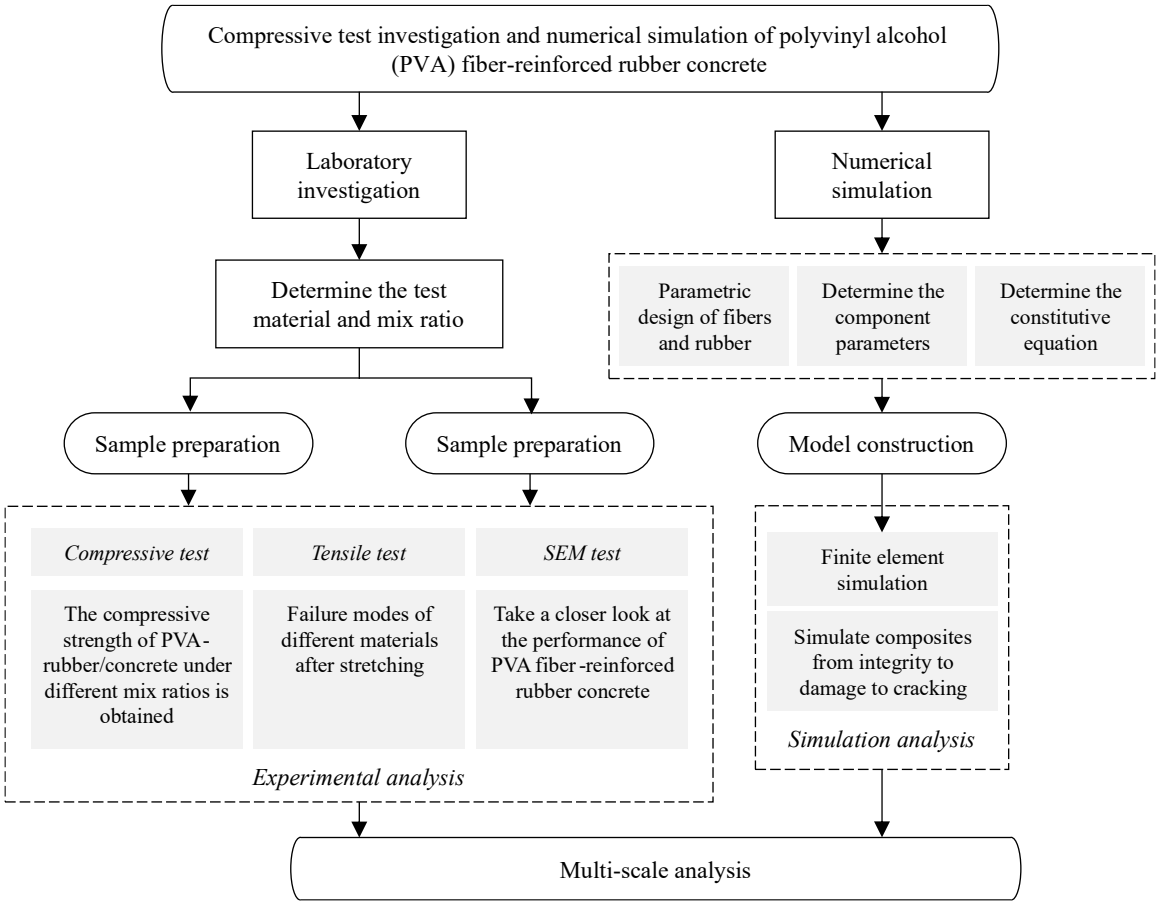

Figure 8. These trade-offs influence the choice of battery chemistry based on the specific performance requirements of different EV models.

The capacity fade and longevity of lithium-ion batteries (LIBs) depend on the cycling, an intrinsic repetition of charge-discharge. Constant cycling over the years slowly degrades the active materials inside of the battery, like its cathode and anode, resulting in capacity fade—less energy that can be stored and delivered by a battery. In turn, higher energy density chemistries such as NMC (nickel manganese cobalt) and NCA (nickel cobalt aluminium), which have a more aggressive cycling behavior and are sensitive to temperature and high discharge rates, tend to fade quicker. LFP batteries, on the other hand, have a more gradual capacity degradation and longer service life, which allows for better

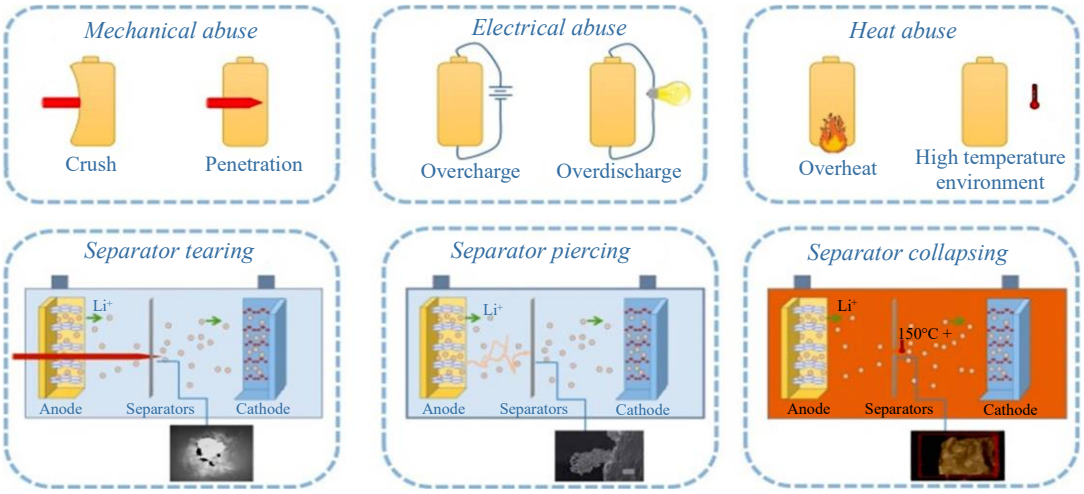

Figure 9. Significant impact on the capacity fade and lifespan of lithium-ion batteries chemistries for different areas

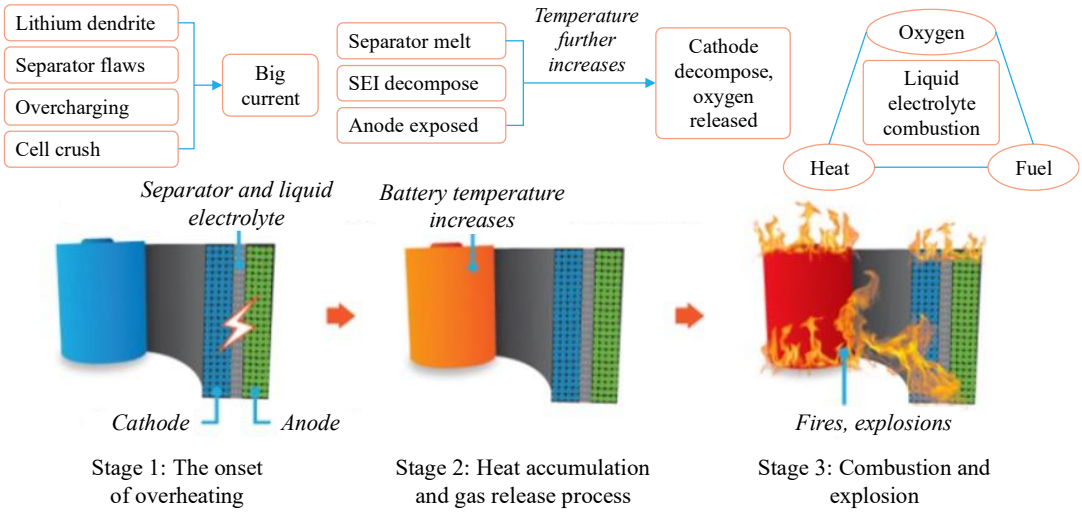

Figure 10. Failure analysis of lithium batteries.

long-term stability and durability in applications where these traits are desirable. Capacity fade is influenced by the charging/discharging rate, temperature, depth of discharge, etc. While appropriate battery management systems (BMS) can mitigate some of this degradation by regulating operating conditions, cycling is nevertheless one of the most significant drivers of LIBs lifespan (Figure 9).

Introduction Thermal management is very important in the application of lithium-ion batteries (LIBs), especially for electric vehicle, that efficient heat dissipation will greatly affect the LIB efficiency and security. Lithium-ion battery (LIBs) produce heat that results from internal resistance and chemical reactions during charge and discharge cycles. Poor management of this excess heat reduces battery performance, life and increases the risk of thermal runaway. Chemistries such as NMC and NCA generate more heat when subjected to higher discharge rates, necessitating advanced thermal management systems TMS for heat dissipation and maintenance of nominal operating temperatures. On the other hand, with higher thermal stability, LFP batteries are less prone to heat-related degradation but need active cooling in high-performance applications. Various strategies for heat dissipation are employed, be it liquid or air cooling, so as to maintain a temperature which is within the operational limits of the battery. Well-managed thermal not only preserves the longevity of a battery, but also allows the controlled power to reach vehicle performance consistently without risk of overheating (Figure 10).

Structural Analysis

Mechanical integrity of cell, module and pack with lithium-ion battery is an important criterion for safety, performance and lifetime in electric vehicle. At the level of cell, the casing and constituents of battery must be able to withstand mechanical stresses exerted by vibrations, shocks and impacts without compromising electrical connection or avoiding leakage (Figure 11). The cells that form the modules need to be assembled into packs at the module level, and needing strong structures from both mechanical strength and thermal management, these can take considerable structural capacity, but still deform such that performance is affected or lead to internal short circuits during abuse situations. In addition to this, pack designs need to include thermal management features to prevent overheating and reinforcement for spatial interruptions (i.e., deformation) when the cells are heated up or cooled down. With battery management systems (BMS), the entire module is monitored and controlled so that each cell does not get overcharged or deep discharged, something that can cause permanent structural failure of a battery. Better design and engineering makes the entire system stable, avoids such catastrophic failures such as thermal runaway, thus improving safety and longevity of EV batteries. In regard to electric vehicle applications, the capability for lithium-ion battery (LIB) to withstand vibration, impact and thermal runaway is an important part of safety and reliability. The vibration-resistance property allows the battery to operate (without damage) under mechanical stresses that are part of vehicle operation—road bumps and driving conditions—that can cause internal components or electrical connections to break. Similar to energy density, impact resistance is also critical in that LIBs should not be damaged in the event of an unanticipated bump or externally applied force, which would otherwise lead to localized structural failure or shorting. Thermal runaway is the inability to control high-temperature within the battery, which can be due to internal short circuits and external heat sources leading to fires or explosions. To counter this, chemistries including LFP are preferred for lower thermal reactivity, while active thermal control systems and strong cell/module architecture prevent over temperature. A smart battery management system (BMS) is essential to mitigating risks and the mechanical designs must be strong enough to keep LIBs function properly at extreme conditions. Physical and thermal stress degradations play a pivotal role in LIBs performance, lifespan and safety. The battery cannot withstand physical stress like vibrations, shocks and mechanical impacts as the internal components of a battery like anode-cathode-separator can get physically damaged. The damage can cause cracking of the electrode, short circuit, separator puncturing, capacity losing, internal resistance increasing or even safety hazards and so forth. Thermal stress further connects to degradation due to the thermal expansion and contraction of the battery materials, which can lead to structural deformity/loss of electrical contact/electrolyte degradation. In particular, high temperatures lead to electrochemical instability, resulting in electrode delamination, lithium plating and cathode metal-ion dissolution associated with capacity fade and growth of impedance. The cumulative effect of different types of imposed loads

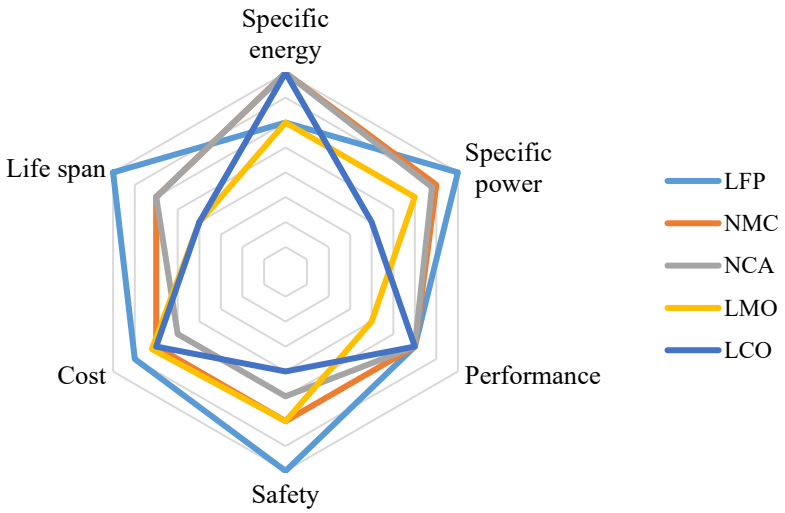

Figure 11. Comparison of different LIB technologies.

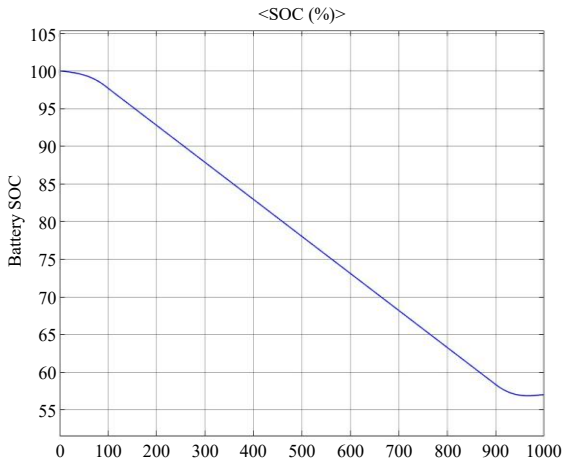

Figure 12. Variation of battery state of charge.

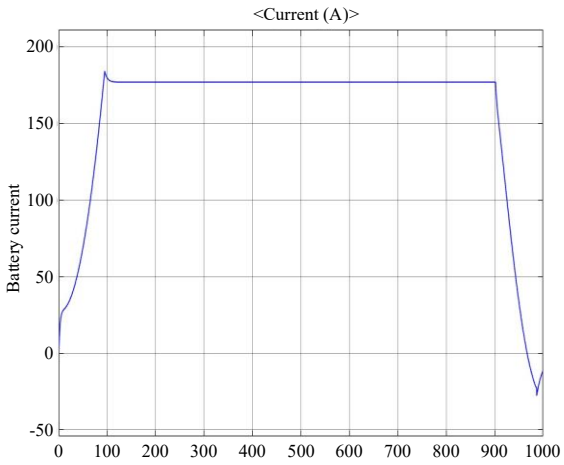

Figure 13. Variation of battery current.

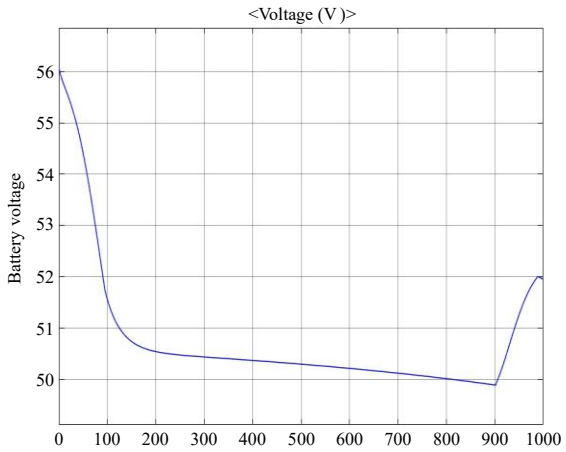

Figure 14. Variation of battery voltage.

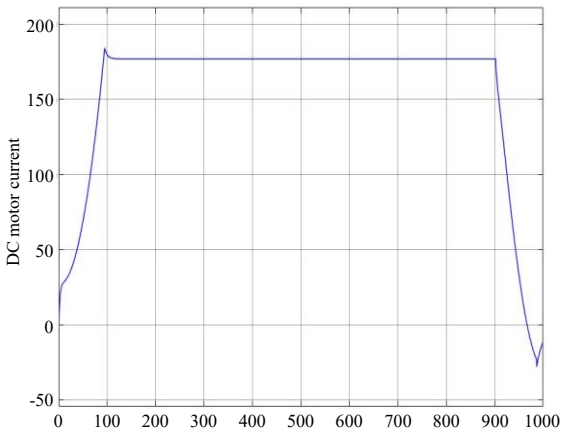

Figure 15. Variation of battery voltage.

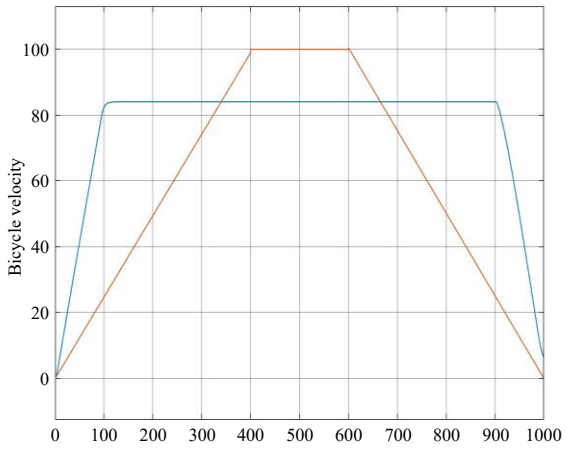

Figure 16. Variation of battery voltage.

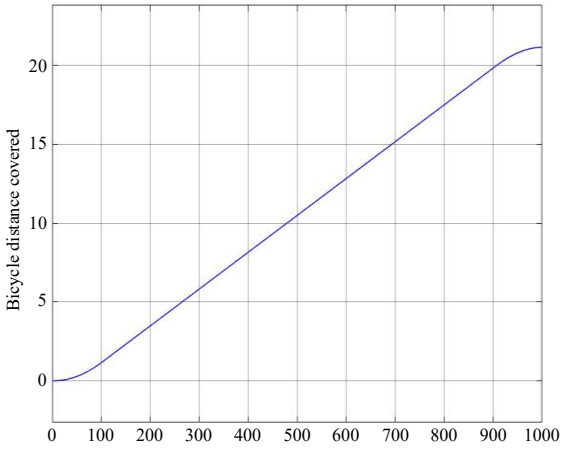

Figure 17. Variation of bicycle distance covered w.r.to time

affects the entire cell performance, efficiency, and safety, which necessitates a well-suited thermal management system as well as structural integrity designs to prevent premature battery failure in rigorous applications. The mechanical properties of materials are critical for assessing the structural stability of lithium-ion batteries (LIBs). Anode, cathode, separator and electrolyte (basic components

of LIBs) are the key materials for LIB applications; those materials should be provided with necessary mechanical/thermal/electrochemical properties so that actual samples with good durability can be obtained. Specifically, anodes such as graphite and silicon have to remain structurally sound throughout cycling (i.e., without cracking or volume expansion) in order to avoid loss of capacity. NMC and LFP as cathode materials need to be thermally and mechanically robust under high voltage, with other deteriorations not being significant (Figures 12–17). The separator material (commonly polymer membrane) should be mechanically robust, thermally stable and chemically insoluble to ensure the short-circuit-proof separator can preserve ionic conduction. Things seem to be simpler: Material properties such as elasticity, thermal conductivity and fracture toughness directly affect the mechanical/physical behavior during stress (e.g. vibration or impact) as well as heat dissipation of battery cell preventing failures like thermal runaway. An in depth understanding of these characteristics enables a better design of battery packs that are more resilient, stable and safe over the lifetime of electric vehicles (Table 3).

Table 3. Comparative analysis based on strengths, limitations and applications of different lithium ion battery chemistries

LIB chemistry	Strengths	Weaknesses	Suitability for EV applications	Trade-offs (performance, cost, safety, environmental impact)
NMC (Nickel Manganese Cobalt)	• High energy density • Good thermal stability • Longer lifespan	• Expensive due to cobalt and nickel • Environmental concerns regarding mining • Less thermal stability at higher currents	• Suitable for long-range passenger cars • Ideal for high-performance vehicles like sports cars and luxury EVs	• *Performance:* High energy density, good power output • *Cost:* Expensive due to raw materials • *Safety:* Good, but requires thermal management • *Environmental impact:* Mining of nickel/cobalt is environmentally harmful
NCA (Nickel Cobalt Aluminum)	• High energy density • Excellent power output • Longer lifespan • High efficiency at high power loads	• High cost • Cobalt usage • Requires sophisticated thermal management	• Primarily used in high-performance EVs like Tesla • Suitable for long-range, high-power vehicles	• *Performance:* Excellent power and energy density • *Cost:* High due to cobalt and nickel • *Safety:* Requires effective thermal management • *Environmental impact:* Mining issues for cobalt/nickel
LFP (Lithium Iron Phosphate)	• Superior thermal stability • Long cycle life • Lower cost • Safer with lower risk of thermal runaway • Environmentally friendly	• Lower energy density • Heavier and bulkier • Slower charging speeds compared to NMC and NCA	• Ideal for mass-market passenger cars • Buses and fleet vehicles due to cost-effectiveness and long life span	• *Performance:* Lower energy density, but good stability • *Cost:* Cost-effective • *Safety:* High safety with excellent thermal stability • *Environmental impact:* More sustainable and eco-friendly
LCO (Lithium Cobalt Oxide)	• High energy density • Excellent specific energy • Widely used in consumer electronics (smaller applications)	• Poor thermal stability • Expensive due to cobalt • Limited cycle life and capacity fade at high rates of charge/discharge	• Consumer electronics and smaller EV applications (e.g., scooters, e-bikes) • Not typically used in larger EVs due to cost and performance limitations	• *Performance:* High energy density but lower cycle life • *Cost:* Expensive due to cobalt • *Safety:* Less safe compared to other chemistries, prone to thermal runaway

				• *Environmental impact:* Cobalt mining concerns

RESULT AND DISCUSSION

Simulation Results With lithium Ion Battery

Similar simulation is performed using different types of batteries and results are summarized below (Table 4):

- Insights from performance and structural analyses of lithium-ion batteries (LIBs) are vital to improve their use in electric vehicles (EVs). Based on this, performance analyses of various LIB chemistries show the exchange-off between energy density, cycle life and thermal behavior for different LIB classes to aid the proper choice of battery in a given EV application. Structural analyses stress the significance of mechanics and temperature to avoid functioning failures such as deformation, capacity drift, or even thermal runaway. Such analyses point to improved battery designs, materials choices and cooling systems that will allow for lasting longevity, safety and reliability. In the end, they offer data that allows you to optimize things like EV performance but under actual operating conditions for safety and longevity (Figure 18).
- The performance and structural analysis of lithium-ion batteries (LIB) also has important application in selection of the battery for EV design. The battery chemistry (NMC, LFP, NCA, etc.) is a trade-off between energy density, cycle life, price and thermal stability. NMC or NCA batteries are used in long-range and high-performance vehicles because of their higher energy density, whereas LFP is preferred for lower-cost, longer lifetime applications like buses or fleet cars. The critical knowledge of thermal management, mechanical integrity and safety will be important for identifying batteries that can meet real-world operating conditions so as to secure the safety and reliability of EVs. Such parameters will help us develop EVs which represent the sweet spot between price, performance and durability while adequately addressing safety.
- Financial side of study on performance and structural analysis for various lithium-ion battery chemistries toward electric vehicle (EV) applications A major challenge is the broad range of real operating conditions, like temperatures during deployable use (in contrast to lab), charging/discharging rates and mechanical stresses that are different in real life vs. lab environments etc. Moreover, as new materials are available it is difficult to replicate their behavior over long periods leading to potential voids in long-term performance forecasting. This is because the correlation of different variables like thermal management systems, battery management systems (BMS) and vehicle driving conditions can make analysis difficult and involve complexity as they are all interconnected in a battery design. Further budgetary constraints and source materials for some battery chemistries hold back general applicability of findings to specific EV segments. Such challenges also emphasize the requirement of further research to gain a deeper insight into how batteries behave over long terms and with variable events that may happen in real situations.
- In terms of potential future work related to battery chemistry for EV applications, there is much excitement about both performance and structural tailoring of different lithium-ion battery chemistries. A lot of potential exists in developing new materials that increase energy density, thermal stability, and safety ranging from solid state batteries to silicon based anodes. BMS enhance Various BMS optimization strategies can also be the target of research to optimize performance, lifespan, and safety. More advanced modeling and simulation approaches may offer better characterization of long term degradation mechanisms and in-service environments. Other possibilities involve sustainable and green battery chemistries less reliant on rare materials such as cobalt and nickel. Read this also: AI Is Going to Revolutionize Electric Car Battery Testing.

Table 4. Simulation results of different batteries for performance parameters

Types of battery	SOC in %	Current in A	Voltage in V	Velocity in Km/hr	Distance in Km
Li-ion	59.97	-5.679	51.91	3.063	20.11
Lead acid	61.57	-5.687	50.57	3.068	20.11

Nickel cadmium	64.78	-5.679	51.39	3.063	20.11
Nickel metal hydride	62.83	5.679	52.08	3.063	20.11

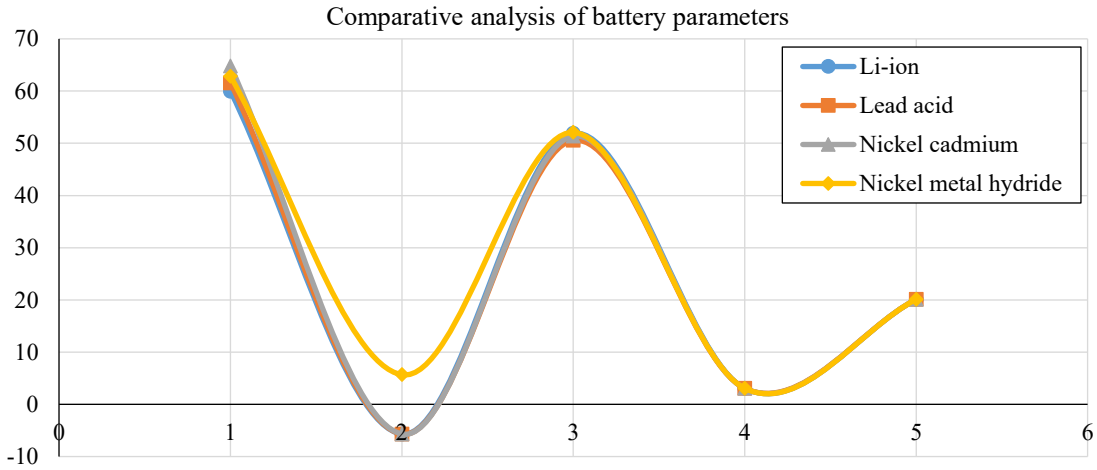

Figure 18. comparative analysis of different battery parameters

CONCLUSION

- Key findings from the performance and structural in situ analyses of different lithium-ion battery chemistries for electric vehicle (EV) applications Both NMC and NCA chemistries provide high energy density and power output which is suitable for long-range and high-performance EVs, although at a higher cost and with more environmental impact as both nickel and cobalt are used.
- On the other hand, LFP batteries are low-cost (in terms of raw materials), highly thermally stable with long cycle life making them ideal for fleet and mass-market applications despite their lower energy density. Although LCO battery chemistry has the benefit of a relatively high specific energy, it is not as popular in the EV space owing to poor cycle life and thermal stability. Structural analyses highlight mechanical stability and heat management as essential features of a durable battery—especially in conditions like vibrations or elevated temperatures.
- Cycling also affected capacity fade and lifespan, which we'll discuss together later; better battery management systems are needed to reduce degradation during cycling. In summary, these results highlight the necessity of a trade-off between performance and safety with cost, environmental impact (blue box), and optimal chemistries dependent on applications for specific EVs.
- A literature review of the performance and structural analysis of lithium-ion battery (LIB) chemistries for electric vehicle (EV) applications reveals several LIB chemistries for optimal use cases.
- NMC (Nickel Manganese Cobalt) or NCA (Nickel Cobalt Aluminum) Batteries for Long Range and High-Performance EVs. These lithium-ion batteries offer very high energy density, high power output, and are suitable for use in high-performance and long-range cars. These chemistries are better suited for high-end passenger cars and sports EVs with a greater power density between energy efficiency and driving range.
- LFP (Lithium Iron Phosphate) batteries are a great option for cost-competitive applications, including city buses, electric fleet vehicles and economical passenger vehicles. They offer a lower cost, exceptional thermal stability and safety coupled with long cycle life at the expense of slightly lower energy density. With their larger structural integrity and safer environmental footprint, they lend themselves to applications where range isn't as critical but longevity is important.
- NCA batteries are a good choice for high-performance EVs needing burst power output to accelerate or run at sustained high speeds. For High-Energy Demand Applications They are more efficient because they cope slightly better at high discharge rates, thus are very good for vehicles with electrical systems that need to be able offer up high peak power.

- As they are less likely to exhibit capacity fade over life and have enhanced longevity during repeated charging/discharging cycles, LFP chemistries are also recommended for lower-cost EV applications, particularly those that will be cycled frequently (e.g., urban and commercial EVs), where rapid cycling is required.
- Drive the research towards more sustainable chemistries with less dependency on cobalt and nickel, e.g. solid-state batteries or nickel-free alternatives more research can mitigate environmental concerns about battery recycling and second-life applications.
- The best LIB chemistries are relative to the performance, safety and cost requirements, as well as targeted vehicle applications. Designing within those conditions is important to improving the efficiency, safety and sustainability of electric vehicle batteries — you must be tailor made according to their working conditions.
- New Trends of LIBs−Lithium Ion Battery Future Direction for EV Application Starting from High Performance to High Safety and Green Sustainability system Development
- Perhaps the most exciting of them all is solid-state batteries. These batteries replace the liquid electrolyte with a solid state (known) and provide higher energy density, greater safety (less risk of thermal runaway), and longer cycle life. Solid-state tech may help get around some of the existing limitations of traditional LIBs, including lower energy density and sensitivity to higher temperatures.
- High-Energy Density Chemistries with Investigations on silicon anodes and nickel-rich cathodes are being pursued to substantially improve energy density while decreasing dependence on expensive and environmentally problematic materials, such as cobalt. This would also mean a longer driving range by weight and more space-efficient battery packs that made EVs lighter and cheaper.
- Faster Charging Tech Advances in electrolytes chemistry and anode/cathode materials should lower internal resistance, allowing batteries to charge much faster than today — without actually aging them. If ultra-fast charging is achieved for EVs, it would enable them to offer the same kind of dependency that you could have with traditional vehicles when it comes to long-distance driving.
- A growing demand for sustainability will go hand-in-hand with the growing adoption of EVs. Battery recycling will also continue to evolve in furthering processes to extract high-value materials (for example, lithium, cobalt, nickel), as well as reducing the impact on the environment of battery disposal. Closed-loop recycling systems may help batteries to become more environmentally friendly without as big of a dependence on mining.
- There are several initiatives focusing on lowering the cost of LIBs with newer manufacturing methodologies, newer materials and volume scalability in place. Since battery packs account for a sizable percentage of the cost of an electric vehicle (EV) today, introducing cheaper alternatives will result in cheaper EVs which can then be accessible by more consumers.
- In the near future, Battery Management Systems (BMS) will likely become smarter by integrating advanced capabilities like artificial intelligence (AI) and machine learning to optimize charging cycles, predict battery lifespan, and improve energy efficiency. Smart devices which will provide more accurate and efficient working performance, health updates and safety.
- In addition to traditional LIBs, hybrid battery systems that leverage both supercapacitors and lithium-ion technology for high power output with energy storage will become a hot area of interest. Other alternative batteries such as flow batteries and sodium-ion have been researched more thoroughly, providing competitive performance, but with the prospect of lower cost and environmental impact.
- As a summary, higher energy density, faster battery charging time; high safety standard and sustainability for EVs with lower manufacturing costs must be the trend of future LIB development. Such developments will make electric cars more affordable, convenient and Sustainable with the full transition to green public transport options.

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