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Crash Safety of High-Voltage Battery Systems in BEVs: Standards, Structures, and Thermal Runaway Mitigation

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Abstract. Battery electric vehicles (BEVs) introduce crash-safety challenges distinct from internal-combustion platforms because their high-voltage lithium-ion packs can suffer mechanical insult, electrical shorting, and heat-driven escalation to thermal runaway. This paper synthesizes current knowledge on battery crash safety across four domains: (i) regulatory frameworks and test standards that govern post-crash electrical isolation and fire safety; (ii) structural design of pack enclosures and their integration into the vehicle load path to improve crashworthiness; (iii) prevention and containment of thermal runaway through materials, architecture, and millisecond-scale isolation strategies; and (iv) post-crash battery management system (BMS) responses and safe-handling protocols. Drawing on experimental abuse tests, finite-element simulations, and emerging pack architectures, we outline design trade-offs between weight, stiffness, energy absorption, and serviceability. We identify gaps in multi-physics modeling fidelity, module-to-pack scaling laws, and standardized post-crash procedures for first responders. The review concludes with a research agenda prioritizing structural batteries with programmable deformation, rapid reconfiguration/isolation circuitry, and validated digital twins that couple electro-thermo-mechanical failure modes under realistic crash pulses.

Keywords: EV battery crash safety, Battery pack structural integrity, Thermal runaway prevention, Finite-element simulation

1. Introduction

The past decades have witnessed a disconcerting build-up of evidence regarding the existence of MPs not only in environmental samples but also within human biological systems. The presence of MPs has been revealed in vital human tissues such as blood circulation, respiratory tissues, placental tissue, and GI tract waste, raising extremely worrying concerns about their possible toxicological effects on human biology [1,2]. These findings have led to an immediate pursuit of scientific inquiry about mechanisms by which these MPs gain access to human biological systems and how they could affect physiological processes.

This paper assesses systematically the routes, mechanisms, and health effects linked to microplastic exposure in human populations. The alarming increase in available evidence within both in vivo and in vitro studies indicates disturbing hints of cytotoxicity, inflammation, and tissue

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damage effects [3]. Thus, integrating these outcomes into a holistic risk assessment is crucial. The main purpose of this paper is to review the recent developments within microplastics toxicology studies, particularly focusing on human exposure routes, tissue distribution trends, available toxicological studies, and knowledge gaps within this field that exist to date.

Owing to global strategies concerning carbon emissions and proposals to deal with depleted fossil fuels, Battery Electric Vehicles (BEVs) have emerged as crucial to the sustainable transformation of the automotive sector, with market shares and manufacturing proliferating rapidly. As functionally integral parts within BEVs' propulsion systems, high voltage Lithium-Ion batteries directly affect range and dynamics but simultaneously entail specific crash safety issues—contrary to conventional fuel-powered vehicles, which tend to pose limited danger to occupants on impact due to deformed, holed, or shorted batteries, which can immediately result in thermal runaway due to low resistance to short circuits. Therefore, this paper shall discuss specific crash safety issues presented by High Voltage Lithium-Ion batteries and describe specific protective mechanisms to effect safe travel. This paper shall examine present literature to identify present gaps in understanding crash safety aspects within BNEVs.

This paper will discuss on BNEV Battery Protection Design for Crash Safety. Facing the modern society, there is a growing market demand on electric vehicles. More and more buyers are showing interest on these electric vehicles. However, it is also important to take into account the safety and standardization of these electric vehicles.There have been growing reports on collision cases between electric vehicles which result into fire and explosion occurrences. Most of such cases result from thermal runaway because of the collision. Therefore, it is very important to avoid such occurrences.From this perspective, although some cases can occur, manufacturers of electric vehicles can avoid generating more cases via post-collision safety and handling processes.

The paper will break down into four parts they are: overview of EV Battery crash safety and standards,battery pack structural integrity and design for crashworthiness,thermal runaway prevention during crash situations and post crash safety and handling.The first part shall analyze on [1] and [3], primarily on how BEVs function during collision tests and battery safety which is very crucial to personal safety within.Be it noted that within the second part,points to be raised shall cover some design and tests which can increase safety within battery pack [4-8].The discussion on next part shall cover experience research and crucial factors toward battery thermal runaway accidents [9-11].The final segment shall focus on post collision safety and solutions [12].

2. Background: sources, persistence, and environmental distribution of microplastics

2.1. Overview of EV battery crash safety and standards

Electric vehicles (EVs) pose unique safety challenges due to their high-voltage battery systems during crashes. Research, such as the EVERSAFE project, has investigated crash loading, battery response, and rescue challenges, identifying pouch-type lithium-ion (Li-ion) cells as particularly vulnerable [1]. This project employed accident analysis, simulation, testing, and literature reviews, using conventional vehicles as surrogates to determine deformation and acceleration loads, and analyzing potential flammable or toxic gas emissions from battery components [1].

NHTSA's Battery Safety Initiative coordinates research and activities to mitigate EV battery risks. This includes data collection from field incidents, research into battery diagnostics, BMS cybersecurity, and failure modes for high-voltage charging [11]. NHTSA also enforces safety regulations, overseeing recalls, and contributes to developing global standards like GTR No. 20, which addresses in-use operational safety, post-crash electrical safety, and battery fire safety [12].

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2.2. Battery pack structural integrity and design for crashworthiness

Maintaining the structural integrity of the battery pack is crucial for mitigating crash risks. Researchers are developing innovative designs and materials to enhance crashworthiness. This includes bio-inspired honeycomb structures [7] and topology optimization for improved stiffness and crash performance [5]. The battery pack enclosure is designed to be part of the crash load path, with optimized crash wall structures significantly enhancing safety and reliability [12]. Crush and crash analyses of enclosures highlight the importance of both upper and lower components for overall structural integrity [8]. Simulation-based validation evaluates battery pack integrity against drop, vibration, and mechanical shock [10].

Advanced techniques for structural enhancement include vehicle-level crash structures like continuous side-sill/rear-member/lower-bar cages to redirect impact loads, and three-dimensional form-fit interfaces for longitudinal load paths [2]. Modular three-stage crash cross members absorb side-impact energy sequentially, while dual-function impact reducers/air ducts and interlocking crash bodies manage deformation [2]. Energy-absorbing housings, trays, and underbody shields feature innovations such as load-bearing vapor-chamber tray lids, gap-tuned side-sill shields, and inclined front walls to direct loads away from critical components [2]. Crushable cooling conduits, on-demand inflatable cushions, and multi-layer air-column shells provide energy absorption and thermal insulation. Material tailoring, including tailored stamp-hardened strips, hybrid composite-metal bottom plates, and variable-width rocker rails, further optimizes stiffness and programmable deformation [2].

2.3. Thermal runaway prevention in crash events

Thermal runaway is a critical risk from battery damage in crashes. EV battery crash safety techniques prioritize minimizing structural damage to prevent this [2]. A battery's ability to withstand impact without thermal runaway is paramount [9]. NREL, in collaboration with Hyundai, researches how mechanical damage causes battery failure and internal short-circuiting, stressing that heat management can reduce thermal runaway likelihood [9]. This involves cell-level damage analysis, high-speed abuse testing, and detailed analysis of thermal, electrochemical, gas, and temperature distributions to inform design improvements [9].

Crucial for preventing thermal runaway are millisecond-scale electrical isolation and controlled de-energization techniques. These include distributed smart connection sheets that segment the pack into sub-60V units upon crash detection [2]. Passively self-retracting dovetail contacts mechanically open circuits, and cell-level disconnectable battery architectures use solid-state switches for rapid disconnection [2]. Predictive pre-crash power isolation algorithms can trigger isolation before metal deformation [2]. Series-to-parallel reconfiguration with fast discharge mechanisms and refrigeration loops can dissipate stored energy and prevent reignition of damaged cells [2].

2.4. Post-crash safety and handling

Post-crash safety measures are crucial, including automatic EV battery disconnection to prevent hazards [6]. Guidelines for safe handling are being developed for emergency responders [1]. The EVERSAFE project investigated rescue procedures in Germany and Sweden, offering recommendations for improved post-crash actions for both rescue services and vehicle manufacturers [1].

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NHTSA's Battery Safety Initiative emphasizes post-crash safety through standards like GTR No. 20, which includes requirements for electrical and fire safety [11]. This initiative also addresses thermal runaway, water immersion, and vibration resistance [11]. Coolant is vital to prevent overheating, as leakage can cause fires [6]. Understanding BMS behavior post-crash is essential for comprehensive safety strategies [11].

3. Safety design of battery pack and fracture analysis

The integration of the battery pack with the vehicle structure is a key issue related to the crash safety of the vehicle. This includes the cellular structure of the battery pack, which provides a beneficial effect related to the crash worthiness of the vehicle. Structural battery pack designs that involve the use of the battery pack within the vehicle's crash structure are also used to improve the interior space of the vehicle. The issue related to the development of such battery pack structures is the ability to achieve a good balance related to energy absorption capacity and low mass [11]. The importance of the crushable frame length and the center of gravity of the vehicle has been widely noted within the various studies related to EVs and crash worthiness. The use of finite element simulation is essential in the analysis of the crash characteristics of the conceptual EV with the damage-tolerant battery pack structure of the vehicle [11].

The industry is also seeing the adoption of battery pack structures that are collapsible and multifunctional to improve the driving range and the mass of the vehicle [12]. The use of battery absorption structures has, over the past period, replaced the traditional vehicle chassis structures and has led to improvements in efficiency and the range of the vehicle [12]. Battery pack structures were not previously considered structures and were avoided during the design of the vehicle's frontal area. The current thought includes the involvement of the battery pack structure during frontal and angled impacts to absorb energy [12].

Material choice and manufacturing methods also play a significant role in the crush performance of battery enclosures. Materials that are lighter and stronger are important not only for the crush resistance of the battery enclosures but also for reducing mass moment of inertia of the enclosures and thus the pack's mass moment of inertia and overall mass as well. The studies undertaken for crush and crash simulation emphasize the importance of specific materials and manufacturing techniques for both the upper and lower enclosures of the pack. The use of advanced material and manufacturing techniques is of utmost importance for the development of optimized crash wall structures to improve the safety and reliability of the pack.

The performance of multicell Square Tube structures, for instance, revealed a considerable improvement within the crashworthiness capability during the side pole collision, achieving a bottom shell intrusion decline of over 45% within the critical region [12]. The material of choice and various material thicknesses, such as the use of high-strength steel, play a significant role within the development of robust and light-weight battery pack containment structures, with a view to achieving a reduction in the overall mass along with a rise within the level of crashworthiness of the structure [8].

Algorithmic design and simulation are essential for the optimization of the battery's crash safety performance, allowing engineers to simulate and analyze the behavior of the battery pack within a variety of crash tests and allowing further improvements to be developed over time [10]. Mathematical models and simulation of EV battery performance during a crash simplify the processing of EV battery crash tests, supported by the data of abuse tests performed [9]. Topology optimization increases both the static stiffness and the crash worthiness of BEVs [5].

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NREL and Hyundai's joint work focuses on the complexity of battery models for EVs, which involve the coupling of mechanical, thermal, chemical, and high-voltage phenomena over a wide range of scales [9]. NREL uses in-house tensile and compressive tests and imaging techniques to analyze dynamic and high-speed impacts, taking thousands of pictures per second during the cell failure event. This further enables the simulation of thermal, electrochemical, and gas/temperature distributions, which then lead to model improvements of the simulation tool kits, thus enhancing EV simulation times [9]. The idea is to further develop such studies from the battery module level to the level of the entire EV pack's simulation models. "The Other than providing a physical safeguard, the Battery Management System (BMS) remains essential for post-crash safety issues such as automatic disconnection of the battery to avoid any kind of risk related to short circuits and dangers of electrical shock [6]. Studies that involve the safety programs of the battery ensure the collaboration of work related to the dangers posed to EV batteries related to the event of a vehicle crash [11]. Improved electrical disconnect strategies, such as distributed smart connection sheets and passive self-retractable dovetail contacts, quickly isolate the battery pack or disconnect the power in the event of a crash detection signal [2]. Battery disconnectable architectures and pre-crash power isolation algorithms improve the BMS's reaction to unusual data and the pre-detection of a collision to isolate the power before deformation occurs [2]. This is achieved through the use of disconnection strategies enabled by rapid discharging and cooling systems that remove the stored energy and thus prevent thermal runaways [2]. The intention is to disconnect the electrical system safely after the collision to avoid secondary damage such as fire and explosion dangers [6].

4. Conclusion

This review paper has explored the critical aspects of BNEV battery protection design with a specific focus on crash safety. The author has discussed the importance of structural integration, advanced materials, algorithmic design, and post-crash BMS response in ensuring the safety of electric vehicle batteries during collisions. For the past years of development, significant progress has been made in the automobile battery field, driven by the need to mitigate risks such as thermal runaway, fires, and explosions, which are unique to high-voltage lithium-ion battery systems in EVs [1,6].

Throughout this review of existing literatures, key findings indicate that comprehensive safety strategies involve multi-faceted approaches. Structural integrity is enhanced through innovative designs like bio-inspired honeycomb structures [7], topology optimization [5], and the integration of battery enclosures as load-bearing components. Advanced materials and manufacturing processes, including multicell square tube structures [12] and high-strength steel [8], are crucial for creating lightweight yet robust battery enclosures capable of withstanding crash forces. Algorithmic design and advanced simulation techniques, such as finite element modeling and high-speed abuse testing, are indispensable for predicting battery behavior under various crash scenarios and optimizing designs for crashworthiness [5,12]. Finally, sophisticated post-crash safety protocols, including automatic battery disconnection [6], advanced electrical isolation mechanisms [2], and the continuous monitoring capabilities of the BMS [12], are essential for preventing secondary hazards and ensuring the safety of occupants and emergency responders.While significant progress has been made, further research is needed to address the evolving challenges of battery technology and vehicle design. This research is expected by the author to be furthered on developing more robust and lightweight battery enclosures, improving the accuracy of crash simulations, and enhancing post-crash safety protocols to minimize risks to occupants and emergency responders.

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