***International Journal of Engineering Research and Development***
*e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com*
*Volume 21, Issue 9 (September 2025), PP 237-245*

# Advancing Fire Safety in Electric Mobility

Sreeraj Rajasekharan Pillai
*Fire and Life Safety Engineer*
*National Group of Companies, BAHRAIN*

***Abstract***
*This research paper discusses the essential fire safety issues related to Electric Vehicles or EVs, which arise due to the large use of lithium-ion battery technology. Although statistically uncommon compared to Internal Combustion Engine (ICE) vehicle fires, EV battery fires contain their own complexities such as thermal runaway, release of highly toxic and flammable gases, long burn times, and the high risk of reignition because of stranded energy. The article takes a closer look at the basic principles of thermal runaway, juxtaposing the unique fire behavior of EVs and ICE car models. It then proceeds to discuss fire safety issues in the entire lifecycle of the EV such as the quality of the battery chemistry, battery manufacturing, charging infrastructure and post-incident management. An in-depth analysis of the existing mitigation measures such as sophisticated Battery Management System (BMS), multi-level battery pack design to provide thermal containment, and latest in-vehicle fire suppression designs are discussed. Also, the paper examines the changing regulatory environment around the world, and the active nature of some areas such as China in establishing high levels of safety standards. Finally, it explores future trends and innovations, such as inherently safer battery chemistries (solid-state, sodium-ion, self-extinguishing electrolytes) and advanced predictive safety systems, emphasizing the imperative for continued research, development, and cross-sector collaboration to ensure public confidence and the safe proliferation of electric mobility.*

**Keywords:** *Battery Chemistry, Battery Management Systems (BMS), Electric Vehicles (EVs), Fire Safety, Thermal Runaway, Vehicle Fires*

---

Date of Submission: 07-09-2025 Date of acceptance: 18-09-2025

---

## I. INTRODUCTION

The automotive market is going through a radical change, and Electric Vehicles (EVs) are at the center of this shift. The rapid adoption of EVs is a cornerstone of environmental sustainability initiatives, aiming to significantly reduce greenhouse gas emissions and achieve ambitious carbon neutrality targets worldwide. It is estimated that by 2030, the number of EVs will grow significantly, reaching up to 85 million, which proves the crucial role of EVs in the transportation landscape. This expanding market is also an indication of a significant economic growth as the automotive battery market alone is bound to earn more than 70 billion dollars by 2028, which is a sign of the massive investment and technological progress in the field of electrification.

Although the benefits of EV usage and speed of market growth are obvious, the fire safety of EVs has emerged as a critical area of concern. EV battery fires, primarily involving lithium-ion batteries, exhibit distinctive characteristics that set them apart from traditional Internal Combustion Engine (ICE) vehicle fires, introducing novel complexities for safety professionals and emergency responders. Despite consistent statistical evidence showing that EV fires are rarer than ICE vehicle fires, e.g. 0.004% of electric car to 0.08% of ICE vehicles in Sweden and 60 times less than gasoline-powered vehicles in the U.S., EVs are frequently the focus of disproportionate media and public attention (Manansala, 2025). This heightened focus is largely due to their dramatic visual intensity, prolonged burn times, and the inherent difficulties in their suppression. The identified gap between the statistical uncommonness of EV fires and the social perception of the danger posed by them puts the EV industry and the regulatory agencies in a serious dilemma. The distinctive and aesthetically striking nature of EV fires, including very high temperatures, emission of poisonous gas, and a possible re-ignition process, provides a strong narrative that may drown out the objective facts about their rarity. This circumstance indicates that in order to encourage greater EV usage, it is necessary to go beyond improving real safety to also engage in systematic public education efforts, which could be led by fire safety agencies, to close this perception disparity and deal with public anticipations.

Moreover, the fast expansion of the EV market as a driver of technological innovations has resulted in a situation in which safety regulations often cannot keep up with the pace of development (Brown et al., 2010). The active and strong regulatory changes in China, especially the GB 38031-2025 standard that states “no fire, no explosion" for two hours following thermal runaway is a very good exception as it practically moves the safety reference point of the world (Edmondson, 2025). The given situation shows that the contemporary regulatory environment is defined by a constant search of ways to change the standards in accordance with the current risks and technological changes. These differences in the rigor of regulation in different jurisdictions can also cause disparities between the safety levels of global EV markets, and manufacturers with international interests must cope with this issue. This necessitates a more agile and collaborative approach to global standard harmonization, potentially leveraging the stringent requirements of leading markets to accelerate safety improvements worldwide. Moreover, the greater costs of testing, quality assurance, and compliance, as pointed out in the challenges manufacturers face, are not only being pushed by performance innovation but also by the high costs of complying with these constantly changing and ever stricter safety requirements.

In the research paper, the author attempts to offer in-depth and professional analysis of the fire safety issues of Electric Vehicles. It aims to: (1) explain the basic principles of EV battery technologies and thermal runaway mechanisms; (2) compare unique fire characteristics of EVs and those of ICE vehicles; (3) identify and analyze the fire safety challenges throughout the entire EV life cycle, both during manufacturing and during incident response; (4) elaborate on the mitigation measures, management systems, and emergency response efforts; (5) discuss the changing global regulatory environment and its effects on safety innovation; and (6) review the future trends and emerging technologies about EV fires. The end product is to provide an organized and evidence-based knowledge to technical professionals, academics, and policymakers working in the development, safety and regulation of EV.

## II. FUNDAMENTALS OF EV BATTERY TECHNOLOGIES AND FIRE HAZARDS

The Electric Vehicle market is now dominated by lithium-ion (Li-ion) batteries, which are mostly characterized by the high energy density, good power-to-weight ratio, and long cycle life, all of which are essential factors in allowing competitive driving ranges and car performance overall (Ding et al., 2018). These are commonly graphite-anode and cathode made of a variety of metal oxides or phosphates, including lithium cobalt oxide, lithium manganese oxide, lithium iron phosphate (LFP), or lithium nickel manganese cobalt oxide (NMC), suspended in a non-aqueous organic electrolyte.

The two most popular Li-ion alloys, Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) have different properties and pronounced safety considerations. NMC batteries are high-energy-density batteries, which directly convert to greater driving range per charge, which has since the 2010s become a global standard in Battery Electric Vehicle (BEV) manufacturing (Tiwari, 2024). Nonetheless, the standard NMC batteries are also temperature sensitive and are less effective in low temperatures and may also degrade with age. A notable fire safety risk arises from the volatility of their organic electrolytes, the presence of highly oxidized metal oxides, and the thermal instability of the anode's Solid Electrolyte Interphase (SEI) layer, rendering them vulnerable to fire if punctured or improperly charged. Environmental and cost considerations are also brought in by the dependence on such critical minerals as cobalt.

On the other hand, LFP batteries are also becoming more popular because of their reduced cost, better safety profile, and increased sustainability, since they do not require critical minerals, like manganese and cobalt (Feng et al., 2022). Their main safety benefit is that they have a higher thermal stability, and this allows the elimination of the chances of overheating and thermal runaway by a large margin. The LFP batteries also have a higher cycle life as compared to NMC variations. Although these are advantageous, they have a reduced energy density, which causes a reduced driving range in most cases. Recent studies have provided a more refined view of LFP safety, where LFP batteries are less likely to start a thermal runaway process, but when it happens, the gases emitted are more toxic and carry a higher flammability risk than NMC do, and with a higher hydrogen content (Ufine, 2025). This finding demonstrates that many facets of battery chemistry make safety a multi-dimensional concept that is not confined to one parameter such as thermal stability. Although LFP can have less tendency in the development of thermal runaway, the effects of this phenomenon, including the flammability and toxicity of the emitted gases, might pose various and even more difficult management situations. This implies that battery design, safety requirements and emergency response plans should be carefully optimized to not only avert thermal runaway, but also properly address the various hazards of the off-gases of different battery chemistries in the event of thermal runaway.

In addition to these dominant chemistries, a number of new technologies of battery have potential to provide a high level of safety. Lithium Titanate (LTO) batteries have been known to have a high safety profile and a low probability of thermal runaway and can be used over a wide temperature range (Nemeth et al., 2020). They also have an impressive cycle life, which is usually more than 10,000 charge-discharge cycles and fast charging abilities. Nevertheless, they have a disadvantage in the form of their extremely low energy density that prevents their broad use in fully electric vehicles at the moment. Sodium-ion batteries do not use critical materials, instead making use of the high supply of sodium (available in saltwater) to make cheap projections (Li et al., 2019). They also have greater safety characteristics than a lithium-ion battery, such as being able to be stored at 0 V, which contributes greatly to lessening fire risk during transportation and assembly. Although the energy density is marginally lower, analysts expect them to be used with high potential in EVs with smaller dimensions, bikes, and three-wheelers.

A more important development is the Solid-State Battery (SSB) which uses solid electrolytes, rather than flammable liquid ones (Machín et al., 2024). The design promises intrinsically better safety, with lower leakage and fire potential, lower dendrite formation tendency and very low short circuit potential as well as greater energy density. It is also possible that SSBs can provide the benefit of increased life expectancy and tolerance to temperature. Although these are strong benefits, SSBs are presently having issues with the complexity of manufacturing, material constraints, and increased production expenses. However research indicates that although less prone to triggering thermal runaway, their high energy density would give rise to very high temperatures reaching over 1500°C in case of an internal short circuit.

This shows a fundamental and enduring conflict between improvement of EV performance, including increased range and reassuringly rapid charging, and the inherent safety properties of battery chemistries. The motivation to increase the energy density is essential towards adoption in the market, but it also increases the magnitude of a scenario of a runaway event. This has led to a constant and growing investment in enhanced safety control and containment mechanisms to offset the high risk. The long-term implication is that further battery development will be likely to aim at improving this performance-safety trade-off, perhaps by prioritizing intrinsic safety as well as energy density, or by coming up with completely new chemistries that are inherently decoupled between high performance and high risk of flammability.

### Understanding Thermal Runaway: Definition, Underlying Chemical Reactions, And Triggers

Thermal runaway is a critical phenomenon in battery safety, defined as a violent, self-sustaining chain reaction of exothermic chemical reactions within a battery cell (Held et al., 2022). The result of this reaction is an uncontrolled and sudden rise in temperature of the system. It is also marked by a very high rate of progression, where the temperature of the cell can shoot up to more than 600°C or even 900°C. This uncontrolled energy release may lead to battery fire or even explosion in a few minutes, which is basically the uncontrolled release of the chemical energy stored in the battery.

Any type of abuse or natural defects can trigger thermal runaway. Battery cells may be mechanically damaged, including physical impacts, punctures, or crushing, which may affect the structural integrity of the cell and cause internal short circuiting and localized heating. Electrical abuse such as overcharging or over-discharging beyond safe limits may result in excessive heat and pressure build up inside the battery. These electrical problems can also be further aggravated by faulty wiring or improper maintenance. Another frequent triggering event is internal short circuits, which may occur due to manufacturing flaws, contamination during manufacture, or the development of lithium dendrites, needle-like structures that may pierce the separator between the anode and cathode, especially when fast charging at low temperatures. Finally, external heat, including exposure to high ambient temperature or other external heat sources can increase the temperature of the battery to a critical point, thus initiating the exothermic reactions that characterize thermal runaway. In thermal runaway, the chemical reactions inside the battery produce oxygen, which enables the fire to continue even without the oxygen in the atmosphere. One of the most dangerous and critical things about thermal runaway is the emission of dozens of gases, most of which are extremely toxic and flammable. The composition and concentration of the released gases may vary greatly based on the battery chemistry, its state of charge (SOC) and the stage of the thermal runaway event.

### Distinct Features of EV Battery Fires

Although the statistical evidence shows that EV fires are less frequent than ICE ones, they pose specific and challenging issues to fire suppression and safety measures because of the peculiarities of the lithium-ion power systems. The variations are deep and require special methods of detection, containment, and extinguishing.

**Table 1: Comparative Characteristics of EV Battery Fires vs. ICE Vehicle Fires**

| Characteristic | EV Battery Fires | ICE Vehicle Fires |
|---|---|---|
| Cause | Thermal runaway, battery damage, electrical failures | Fuel system leaks, exhaust heat, aging parts, electrical faults |
| Primary Fuel | Lithium-ion battery components, electrolytes | Gasoline, diesel |
| Fire Temperature (typical range) | Up to 1,200°F , potentially higher , though NFPA notes similar flame temps to ICEVs (815-1000°C) | Around 600°F |
| Burn Duration | Hours to days | Relatively quickly once fuel consumed |
| Reignition Risk | High | Low |

| | | |
|---|---|---|
| Toxic Emissions (key compounds) | Hydrogen fluoride, carbon monoxide, hydrogen cyanide, heavy metals | Smoke and fumes, typically carbon monoxide, fuel vapors |
| Water Volume Needed for Suppression | Up to 150,000 liters , average ~10,000L , 3,000-8,000 gallons | 1,000-2,000 liters |
| Suppression Difficulty | Very difficult, water cannot penetrate sealed packs, self-sustaining reaction | Standard methods effective |
| Explosion Risk | High, pressure buildup, vapor cloud explosion risk | Less common, may occur with fuel tank ruptures |
| Debris Projectiles | Likely | Chance of debris release |

As shown in Table 1, the unique characteristics of EV battery fires pose significant challenges. The fires of lithium-ion batteries have the potential to produce very high temperatures. Although NFPA testing in August 2023 showed no notable difference in the temperature of the flames (815-1000°C) between EVs and ICEVs, which dispels a popular myth, the seriousness and intensity of the fire is closely associated with the energy density of the battery (EV Fire Safe, 2023).

The biggest challenge is the high possibility of re-ignition, whereby a battery pack may re-ignite hours, days or even weeks after the initial fire has been extinguished. This has been explained by the fact that there is stranded energy- the remaining electrical energy that is held up in the damaged but not used battery cells- a feature that is basically unknown in normal gasoline car fires. This knowledge changes the paradigm of the post-incident management of EVs. It means that the conventional 'all clear' signal of firefighting is not enough. Constant inspection, such as thermal imaging, special storage provisions as well as extensive training of all stakeholders in the chain of custody (firefighters, tow operators, salvage yards), are not just best practices, but essential requirements. The continuity of this risk also makes it difficult to claim insurance and to evaluate liability because the risk is long-term even after the first occurrence.

Moreover, EV battery fires emit a complex mixture of highly toxic and flammable gases, such as hydrogen fluoride, carbon monoxide, hydrogen cyanide etc. This is extremely dangerous to the health of emergency responders and requires the application of full Personal Protective Equipment (PPE) and Self-Contained Breathing Apparatus (SCBA). EV battery fires frequently need large sustained amounts of water to cool the battery and break the thermal runaway loop since it is usually impossible to spray water directly onto the internal cells of sealed battery packs. This may be tens of thousands of liters, much higher than the 1,000-2,000 liters that are usually required to extinguish ICE vehicle fires.

## III. FIRE SAFETY CHALLENGES ACROSS THE EV LIFECYCLE

The fire safety issues in Electric Vehicles do not just lie in one of the stages but are spread across the entire lifecycle, including the basic chemistry and manufacturing processes, operational use, charging, and incident management. The risks associated with each phase are different and need particular mitigation measures.

### Inherent Risks of Battery Chemistry and Design

The root of the EV fire safety issues is the volatility of the lithium-ion battery components. The organic electrolytes typically employed are highly flammable and the thermal instability of some cathode materials, including those used in NMC batteries, and the anode layers themselves can also add to the risk of thermal runaway. One of the most basic design issues is the trade-off between energy density and safety. Although increased energy density is important to achieve greater driving range and smaller battery packs, it is also associated with greater fire severity and higher temperatures during thermal runaway. This requires a fine balance in battery design to achieve the maximum performance and reduce the inherent risks. Different cell formats, including cylindrical, prismatic, and pouch cells, also present varying thermal resistance and propagation characteristics. Pouch cells, for instance, with their thin Mylar walls, exhibit quicker heat gain and loss.

### Manufacturing and Production Line Safety Challenges

The manufacturing process for EVs involves the handling of high-voltage battery systems, which necessitates specialized procedures to prevent electrical hazards and manage the inherent risks of thermal runaway. With the growth of automation in EV manufacturing, the most important thing is to provide the necessary machine safety measures and training of workers. The challenges of noise level and repetitive motion tasks, though not directly related to fire hazards, are part of the general safety issues of the workplace, and may affect the efficiency and health of the workers. A zero-tolerance towards fire/explosion and micron-level accuracy in the production of batteries are crucial tasks, because even the smallest flaws can trigger disastrous outcomes. This demands high-volume, high-speed production processes that simultaneously maintain extremely low defect rates.

### Fire Hazards Associated with EV Charging Infrastructure

EV charging stations are also a source of high concentration of electrical power, which increases the risk of thermal runaway as EV batteries contain high energy density (Wahedi & Bicer, 2024). This adds to the fire risk of both the user and emergency responders. The powerful voltages and substantial electrical service required for charging, particularly for rapid charging stations, present inherent electrical hazards and a risk of overheating and malfunctions. Thermal runaway can also be caused by overcharging due to cumulative errors or Battery Management System (BMS) failures. The position of the charging stations, particularly those that are located in limited areas such as parking garages or near high value property can greatly increase the risk of fire spread. Best practices strongly recommend locating charging stations externally, or if indoors, ensuring robust fire protection provisions, such as a minimum 120-minute fire rating for structural elements. Furthermore, charging should ideally not occur within 15 meters (50 feet) of any combustible materials or hazardous installations.

**Operational and Collision-Related Fire Risks**

Although EVs are statistically less likely to catch fire during normal operation than ICE vehicles, the presence of excessive heat due to friction between components (though this is less likely in EVs because of fewer moving parts) and the natural deterioration of battery cells over time may add to the risk of fire. The most important cause of EV battery fires is physical damage caused by vehicle collisions. Effects may weaken the integrity of the battery structure to cause internal short circuits that cause thermal runaway. This is a risk that is especially increased when internal battery damage is not evident immediately following an accident. Incorrect charging procedures, including charging at too low or too high temperatures may also compromise the chemical stability of the battery and enhance the chances of ignition.

One of the most crucial and distinctive issues of EVs is the possibility of fires breaking out or re-escalating days, weeks, or even months after the first one (Electric Vehicle Safety Information, 2023). This is a phenomenon that is commonly associated with stranded energy in the damaged cells and is a continuous and unpredictable threat. This knowledge completely changes the conventional paradigm of post-incident management of vehicles. It means that a seemingly safe damaged EV can become a fire hazard days or weeks after an event, particularly following collisions or flooding. This unique challenge requires mandatory and continuous observation, including thermal imaging, and special and long-term storage procedures. This brings about major ripple effects in the salvage, repair and insurance sectors, requiring new standards to determine the safety of damaged batteries prior to resale or disposal. This latent hazard adds a level of complexity and possible liability that has never been experienced in the automotive industry and all the stakeholders need to be proactive and informed.

## IV. CURRENT MITIGATION STRATEGIES

The complex fire safety issues in Electric Vehicles require a holistic solution that incorporates prevention, detection, and suppression measures at different levels of vehicle design and operation.

**Battery Design and Engineering for Fire Safety**

Safety mechanisms are integrated at the cell, module, and pack levels, applying to everything from the design and construction of individual cells to the overall battery cases. At the cell level, the sophisticated design methods involve high quality separators, optimized formulations of the electrolyte and robust mechanical enclosures to reduce risks. As an example, a separator that has better heat resistance and thermal stability, which uses nanocellulose coating or three-dimensional skeleton frameworks, can stop the thermal runaway. Stability can also be improved by coating the conductive materials on positive electrodes and using heat treatment. At the module level, the spacers are normally used between cells to reduce heat exchange, and thermal barriers around modules to safeguard other modules. These enclosures are usually lined with materials having high melting points and low thermal conductivity such as metal oxides, nitrides and fiberglass finishes and are used to separate battery packs into isolated cell groups. Between cell vents and battery cover, heat shields are fitted, which are usually multi-layered materials with high temperature resistance (up to 1400°C) and mechanical strength, to guard against hot streams of gas. It is also encapsulated in a fireproof box, immersed in dielectric cooling fluid and heat-spreading materials are placed in close contact with single cells. Thermal protection aerogels, foams, ceramics, and mica are also becoming increasingly popular in thermal protection because of their low thermal conductivity and the ability to survive thermal runaways. Structural design of battery packs is strengthened at the pack level to resist mechanical impact in case of collision. This involves the incorporation of side sills, rear lower members and transverse lower bars to create a protective cage to the battery to guarantee effective dissipation of crash energy. Pack-level vents eliminate the accumulation of hot and high-pressure gases, and thermal protection mats offer insulation between modules and the outer casing. Integrated cooling and power generation is done by use of phase change materials and heat pipes in some designs.

**High-end Battery Management Systems (BMS)**

The Battery Management System (BMS) is an important factor in the safe and efficient functioning of EV battery packs. BMS units constantly measure the voltage, current, and temperature of each of the battery cells, and identify anomalies that might cause thermal runaway. They take protective measures like averting overcharging, over-discharging and short circuiting, which are typical causes of thermal events (Kumar et al., 2023). In terms of thermal control, BMS uses elaborate measures to ensure that battery cells are kept at the best temperatures. Active thermal management systems are used as cooling systems that remove heat out of cells by using air or cooling plates with standard automotive coolants or refrigerants especially when charging fast or high discharge rates.

Such systems should be designed in such a way that the coolant fluids are of low electrical conductivity to avoid violent reactions with high voltage electronics. Passive thermal management systems, like heat shields or insulation, aim at preventing the spread of thermal runaway by preventing an overabundance of heat transfer between an impacted cell and the remainder of the battery pack. This involves the employment of phase change materials, heat pipes, integrated fins and airflow channels in module housing to cool the system. More sophisticated BMS systems also have enhanced fire detection designs to detect battery overheating or fire hazards as soon as possible. Early warning systems use a wide range of signals, such as gas production analysis, which may give thermal runaway warnings 16 to 26 minutes before temperature, voltage, and pressure signals (Cui et al., 2023). Sensors of electrolyte vapors can also measure the early escape of electrolyte vapors and trigger safety measures such as disconnection of the charging source to stop the development of thermal runaways. Optical fiber sensors inserted into cells can monitor internal temperature and pressure, detecting abrupt changes that indicate imminent thermal runaway even before safety venting.

**In-Vehicle Fire Suppression Systems**

In-vehicle fire suppression systems in EVs are a developing field, and the main concern is to combat the specifics of lithium-ion battery fires. Most manufacturers are working on built-in systems that spray fire suppressants to put out a cell fire within minutes of ignition to prevent thermal runaway spreading to other cells instead of slowing it down. These systems have sensors that measure battery temperature and voltage in real time and software that controls the exact time and place of suppressant release.

New types of suppression agents are being designed to be used in lithium-ion battery fires. Aqueous Vermiculite Dispersion (AVD) is an innovative product that is used to extinguish fires, cool battery cells, and provide a heat-resistant oxygen barrier to eliminate the possibility of re-ignition (Wang et al., 2024). It is non-flammable, eco-friendly and efficient in limiting thermal conduction. Other promising agents are perfluorohexanone (C6F12O) which has low toxicity, is non-corrosive and has rapid suppression capabilities, and liquid nitrogen, which suppresses, slows, and cools thermal runaway without producing damaging byproducts. Such agents may be incorporated in localized suppression devices in battery arrays or structural spacers, or they may be deposited using targeted spray units and valve-controlled channels. For public transport, sealed, liquid-cooled fire protection enclosures with nitrogen tanks and electromagnetically controlled circuit breakers offer specialized solutions. While these in-vehicle systems are advancing, traditional firefighting methods for EV fires present limitations. Water is the major extinguishing medium used to cool the battery casing, but frequently finds it difficult to get into the compartmentalized battery packs and access individual cells. Special equipment, such as underbody spray systems, are designed to spray large amounts of water onto the battery case, and can safely and effectively work under a burning vehicle. Fire blankets have the potential to hold the flames and stop them spreading to the exposures, but they can also accidentally trap the flammable gases, which can become explosive on reintroduction of air. Tools that cut holes in battery packs to spray water directly onto cells are promising as a way to quickly control thermal runaway, but are not commonly recommended by manufacturers because of the risk of electrocution and the presence of jet-like flames.

## V. REGULATORY LANDSCAPE AND STANDARDIZATION

The fast development of the Electric Vehicle technology and the peculiarities of fire risk related to the battery systems have stimulated the creation and modification of the international regulations and industry standards. These frameworks are designed to provide safety during the EV lifecycle, but the pace and rigor of these frameworks differ depending on the region.

**Global Regulations and Standards (UN, ISO, SAE, NHTSA)**

The international organizations and national agencies are working on the creation and revision of EV battery safety standards. One of the major international standards is the United Nations Global Technical Regulation No. 20 (UN GTR No. 20) on Electric Vehicle Safety. Phase 1 of GTR No. 20 includes requirements for in-use operational safety, post-crash electrical safety, and battery fire safety, specifically mandating that vehicle occupants not be exposed to hazardous environments caused by thermal propagation triggered by an internal short circuit leading to single cell thermal runaway. Phase 2 development is currently underway, aiming for a battery technology-agnostic approach that mitigates risks in all operational modes and considers factors like gas management, flooding impact, and low conductivity coolants. The regulation is steadily moving towards formalization and is expected to require detection of thermal runaway followed by an "escape time" for occupants.

Another way in which EV battery safety is ensured is through ISO (International Organization for Standardization) standards. As an example, IEC 62660 is an international standard that addresses the safety and performance of secondary lithium-ion cells used to propel electric road vehicles, and is adopted in Europe, which covers mechanical, electrical and thermal abuse. However, this standard does not mandate the same outcome-focused criteria as some more recent national regulations, such as China's.

To simulate a wide range of real-world automotive conditions and test the response to abuse, standards such as SAE J2464 have been created by the Society of Automotive Engineers (SAE), which specifies a set of tests of Rechargeable Energy Storage Systems (RESS). They include mechanical (e.g., shock, drop, penetration, crush), thermal (e.g., high temperature, thermal stability, single cell failure propagation resistance), and electrical (e.g., short circuit, overcharge, forced discharge) abuse. SAE is also involved in the establishment of standards in vehicle electrification, such as charging connector systems, and is leading in the development of new standards.

The National Highway Traffic Safety Administration (NHTSA) in the U.S. coordinates research and activities to address EV battery safety risks. NHTSA conducts investigations into field incidents related to battery safety and participates in the development of Phase 2 of UN GTR No. 20. While GTR20 requires a 5-minute warning between a single cell entering thermal runaway and danger to occupants, NHTSA proposes a warning system triggered by temperatures inside the battery system significantly exceeding the maximum operating temperature, arguing that single-cell detection might be "unduly design restrictive". NHTSA also issues interim guidance for emergency responders, emphasizing assumptions about high-voltage battery energy, toxic gas risks, and safe storage distances for damaged vehicles.

**China's Proactive Approach to EV Battery Safety**

China has taken a leading and proactive stance in mandating stringent EV battery safety regulations, setting a global benchmark for the industry. China's GB 38031-2020, implemented at the start of 2021, was the first mandated standard globally to require a 5-minute warning for occupants to escape the vehicle after an initial thermal event, during which no hazardous situation (fire, smoke, or explosion) could occur. Based on this, the new GB 38031-2025 standard, which will come into effect on July 1, 2026, was announced by the Ministry of Industry and Information Technology (MIIT) of China. This revolutionary rule is the first standard in the world, which states that batteries should not be able to catch fire or blow up even after internal thermal runaway occurs, for a duration of two hours after the initial event. Also, produced smoke should not be detrimental to the occupants in the vehicle. The standard also stipulates new tougher tests, such as bottom impact testing to test the ability of the battery to withstand underside collisions, and fast-charging cycle safety testing, where the battery must be able to pass 300 rapid charging cycles without fire or explosion in short-circuit tests. It also includes internal heating as a testing trigger mechanism.

The implications of China's stringent "no fire, no explosion" mandate are significant. It compels manufacturers to significantly improve the safety of cells and packs, to exert greater control over the purity of materials and manufacturing tolerances, since any small flaws can cause disastrous failures. The automakers are now thinking about fire safety much earlier in the design process, and are grappling with the "huge curveball" of the new 2-hour requirement. While the increasing dominance of LFP chemistry in China's EV market makes adherence to this challenge somewhat easier due to LFP's higher thermal stability , no energy storage system is 100% inherently safe. This proactive regulatory push by China is moving much quicker than other regions, which are still in various stages of drafts, revisions, and updates without mandated standards of comparable stringency. This disparity in regulatory stringency across different regions can lead to varied safety levels in global EV markets, creating a need for more agile and collaborative approaches to global standard harmonization.

## VI. FUTURE TRENDS AND INNOVATIONS

The future of EV fire safety will be determined by the development of battery chemistry, thermal management, predictive systems, and regulatory frameworks. Solid-state batteries (SSBs) are regarded as one of the most promising solutions to safer energy storage as solid electrolytes minimize leakage and flammability, but high-temperature failures, material limitations, and cost are still of concern. Sodium-ion batteries are also on the rise, with better stability, capability to be stored at 0V, and ignition resistance in penetration tests, and are becoming appealing to safer mass deployment. Meanwhile, research into self-extinguishing electrolytes—such as lithium-metal batteries incorporating flame-suppressing additives—represents a significant step toward intrinsic safety, aiming to chemically arrest combustion at its source. Collectively, these developments mark a transition from reactive fire protection to preventative design at the material level.

Alongside chemistry, innovations in containment and predictive technologies are central to the next generation of EVs. Advanced cooling systems, inter-cell separators, and fire-resistant materials such as ceramic blankets, aerogels, and intumescent polymers are being integrated to slow or block thermal propagation, especially in high-density cell-to-pack configurations. At the same time, AI-driven diagnostics, digital twins, and dense sensor networks are improving early detection of anomalies, from subtle temperature variations to electrolyte vapor release, enabling preemptive interventions before thermal runaway escalates. Beyond vehicle design, safe adoption depends on parallel advances in infrastructure and policy—such as robust charging station standards, adequate power supply safeguards, and standardized post-incident handling of damaged EVs to prevent secondary ignition. Together, these innovations form a comprehensive framework that combines technology, materials science, and regulation to strengthen EV fire resilience and public trust.

## VII.CONCLUSION

The proliferation of Electric Vehicles is an undeniable force in the global transition towards sustainable transportation, offering substantial environmental benefits and driving significant economic growth. Nevertheless, such a radical change also brings a new set of fire safety issues, the main cause of which is the peculiarities of the lithium-ion battery technology. Although statistical data always show that EV fires are less common than those in Internal Combustion Engine vehicles, their specificities, such as the immediate development of thermal runaway, the release of highly toxic and combustible gases, long burning time, and the continued risk of re-initiating due to stranded energy, require disproportionate attention and demand specific mitigation measures.

The analysis reveals a fundamental tension between the pursuit of higher energy density for extended EV range and the inherent safety characteristics of battery chemistries. This requires sustained battery development and incorporation of advanced safety measures to offset the higher possible severity of thermal incidents. The subtle interpretation of the battery chemistry safety, especially the varying flammability and toxicity levels of the off-gases of LFP and NMC batteries, highlights that safety is a multi-dimensional phenomenon that needs a multi-dimensional response. Additionally, the problem of stranded energy essentially changes the post-incident management and requires constant monitoring and special handling procedures during the chain of custody of the EV. To solve these issues, it is necessary to focus on them in a holistic and systemic way, which is not limited to the vehicle itself but covers the whole EV ecosystem. This also involves strict quality control during production, strong fire protection in charging systems, and extensive and specialized training of emergency personnel. The current regulatory landscape, characterized by a "catch-up" dynamic, highlights the need for more agile and harmonized global standards, potentially leveraging the proactive and stringent benchmarks set by regions like China.

The future of EV fire safety lies in continued research and development across several fronts: the exploration of inherently safer battery chemistries such as solid-state and sodium-ion technologies, and the development of self-extinguishing electrolytes; advancements in active and passive thermal management and containment materials; and the integration of predictive safety systems, including digital twins and AI-driven diagnostics, for early detection and proactive intervention. Furthermore, the evolution of smart charging infrastructure and the standardization of post-incident protocols are critical for ensuring comprehensive safety across the EV lifecycle. Ultimately, the safe proliferation of electric mobility hinges on a collaborative commitment from manufacturers, regulators, emergency services, and researchers to continuously innovate, adapt, and educate. By fostering a deeper understanding of EV fire dynamics and implementing robust, integrated safety solutions, public confidence can be solidified, paving the way for a more secure and sustainable transportation future.

## REFERENCES


[1]. *04.4 Risks with EV Battery Fire - EV fire overall | EV Fire Safe*. (2023). EV Fire Safe. https://www.evfiresafe.com/risks-ev-fires

[2]. Brown, S., Pyke, D., & Steenhof, P. (2010). Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy*, *38*(7), 3797–3806. https://doi.org/10.1016/j.enpol.2010.02.059

[3]. Cui, Y., Shi, D., Wang, Z., Mou, L., Ou, M., Fan, T., Bi, S., Zhang, X., Yu, Z., & Fang, Y. (2023). Thermal runaway early warning and risk estimation based on gas production characteristics of different types of Lithium-Ion batteries. *Batteries*, *9*(9), 438. https://doi.org/10.3390/batteries9090438

[4]. Ding, Y., Cano, Z. P., Yu, A., Lu, J., & Chen, Z. (2018). Automotive Li-Ion Batteries: Current status and future Perspectives. *Electrochemical Energy Reviews*, *2*(1), 1–28. https://doi.org/10.1007/s41918-018-0022-z

[5]. Edmondson, J. (2025, May 28). New Standards put China in the Lead for the Safest & Largest EV Market. *IDTechEx*. https://www.idtechex.com/en/research-article/new-standards-put-china-in-the-lead-for-the-safest-and-largest-ev-market/33109

[6]. *Electric vehicle safety information*. (n.d.). https://www.nfpa.org/education-and-research/electrical/electric-vehicles

[7]. Feng, T., Guo, W., Li, Q., Meng, Z., & Liang, W. (2022). Life cycle assessment of lithium nickel cobalt manganese oxide batteries and lithium iron phosphate batteries for electric vehicles in China. *Journal of Energy Storage*, *52*, 104767. https://doi.org/10.1016/j.est.2022.104767

[8]. Held, M., Tuchschmid, M., Zennegg, M., Figi, R., Schreiner, C., Mellert, L. D., Welte, U., Kompatscher, M., Hermann, M., & Nachef, L. (2022). Thermal runaway and fire of electric vehicle lithium-ion battery and contamination of infrastructure facility. *Renewable and Sustainable Energy Reviews*, *165*, 112474. https://doi.org/10.1016/j.rser.2022.112474

[9]. Kumar, R. R., Bharatiraja, C., Udhayakumar, K., Devakirubakaran, S., Sekar, K. S., & Mihet-Popa, L. (2023). Advances in batteries, battery modeling, battery Management System, Battery Thermal Management, SOC, SOH, and Charge/Discharge characteristics in EV applications. *IEEE Access*, *11*, 105761–105809. https://doi.org/10.1109/access.2023.3318121

[10]. *LFP vs. NMC Battery: Pros, Cons, and Key Comparisons*. (2025, July 28). Ufine Battery [Official]. https://www.ufinebattery.com/blog/lfp-vs-nmc-battery-what-is-the-difference/

[11]. Li, F., Wei, Z., Manthiram, A., Feng, Y., Ma, J., & Mai, L. (2019). Sodium-based batteries: from critical materials to battery systems. *Journal of Materials Chemistry A*, *7*(16), 9406–9431. https://doi.org/10.1039/c8ta11999f

[12]. Machín, A., Morant, C., & Márquez, F. (2024). Advancements and Challenges in Solid-State Battery Technology: An In-Depth Review of solid electrolytes and anode innovations. *Batteries*, *10*(1), 29. https://doi.org/10.3390/batteries10010029

[13]. Manansala, J. (2025, September 2). EV Fires vs. ICE Fires: Safety Comparison and Analysis. *Lectron EV*. https://ev-lectron.com/blogs/blog/ev-fires-vs-ice-fires-safety-comparison-and-analysis

[14]. Nemeth, T., Schröer, P., Kuipers, M., & Sauer, D. U. (2020). Lithium titanate oxide battery cells for high-power automotive applications – Electro-thermal properties, aging behavior and cost considerations. *Journal of Energy Storage*, *31*, 101656. https://doi.org/10.1016/j.est.2020.101656

[15]. Tiwari, U. (2024, March 22). *What are electric car batteries made of?* Malvern Panalytical. https://www.malvernpanalytical.com/en/learn/knowledge-center/insights/what-are-electric-car-batteries-made-of

[16]. Wahedi, A. A., & Bicer, Y. (2024). Comprehensive risk assessment of a renewables-based stand-alone electric vehicle charging station with multiple energy storage technologies. *Energy Storage*, *6*(2). https://doi.org/10.1002/est2.587

[17]. Wang, Y., Chen, T., Li, Y., Qin, G., Zhang, P., & Liu, X. (2024). Preparation of a novel aqueous vermiculite dispersion fire extinguishing agent to inhibit lithium-ion battery fires. *Case Studies in Thermal Engineering*, 105356. https://doi.org/10.1016/j.csite.2024.105356