

ELECTRIC VEHICLE SAFETY: AN INNOVATIVE AND CRITICAL ANALYSIS OF FIRE RISKS AND MITIGATION STRATEGIES

SEGURANÇA DE VEÍCULOS ELÉTRICOS: UMA ANÁLISE INOVADORA E CRÍTICA DOS RISCOS DE INCÊNDIO E DAS ESTRATÉGIAS DE MITIGAÇÃO

SEGURIDAD DE VEHÍCULOS ELÉCTRICOS: UN ANÁLISIS INNOVADOR Y CRÍTICO DE LOS RIESGOS DE INCENDIO Y LAS ESTRATEGIAS DE MITIGACIÓN



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ABSTRACT

The growing adoption of electric vehicles (EVS) represents a significant transformation in sustainable urban mobility. However, fire safety, particularly with regard to lithium-ion batteries, has emerged as a relevant challenge. This study adopts a qualitative and exploratory approach, with analytical and documentary emphasis, grounded in the innovative and pioneering nature of the research within the Brazilian context. The main objective of this article is to propose a critical analysis of global trends in electric vehicle safety, with particular emphasis on fire suppression and related innovations aimed at enhancing safety for users, owners, and residential condominiums. Furthermore, the study highlights the need for international harmonization and for the development of specialized training for fire response professionals. The research is innovative and pioneering in consolidating dispersed data and proposing an integrated and strategic approach to the prevention and suppression of fires in EVS. The results underscore the need for specific regulations, specialized training, and technological innovations to ensure safe and effective electric mobility. The study encompasses international data, emerging regulations, and technological innovations, offering a current and forward-looking overview of EV safety.

Keywords: Electric Vehicles. Lithium-Ion Batteries. Fire. Thermal Runaway. Vehicle Safety.

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RESUMO

A crescente adoção de veículos elétricos (VEs) representa uma transformação significativa na mobilidade urbana sustentável. No entanto, a segurança contra incêndios, especialmente no que se refere às baterias de íons de lítio, tem emergido como um desafio relevante. Este estudo adota uma abordagem qualitativa e exploratória, com ênfase analítica e documental, fundamentada no caráter inovador e pioneiro da pesquisa no contexto brasileiro. O principal objetivo deste artigo é propor uma análise crítica das tendências globais em segurança de veículos elétricos, com ênfase particular na supressão de incêndios e nas inovações correlatas voltadas ao aumento da segurança de usuários, proprietários e condomínios residenciais. Além disso, o estudo destaca a necessidade de harmonização internacional e do desenvolvimento de treinamentos especializados para profissionais de resposta a incêndios. A pesquisa é inovadora e pioneira ao consolidar dados dispersos e propor uma abordagem integrada e estratégica para a prevenção e o combate a incêndios em VEs. Os resultados ressaltam a necessidade de regulamentações específicas, capacitação especializada e inovações tecnológicas para garantir uma mobilidade elétrica segura e eficaz. O estudo abrange dados internacionais, regulamentações emergentes e inovações tecnológicas, oferecendo uma visão atual e prospectiva sobre a segurança de VEs.

Palavras-chave: Veículos Elétricos. Baterias de Íons de Lítio. Incêndio. Fuga Térmica. Segurança Veicular.

RESUMEN

La creciente adopción de vehículos eléctricos (VE) representa una transformación significativa en la movilidad urbana sostenible. Sin embargo, la seguridad contra incendios, especialmente en lo que respecta a las baterías de iones de litio, ha surgido como un desafío relevante. Este estudio adopta un enfoque cualitativo y exploratorio, con énfasis analítico y documental, fundamentado en el carácter innovador y pionero de la investigación en el contexto brasileño. El objetivo principal de este artículo es proponer un análisis crítico de las tendencias globales en la seguridad de los vehículos eléctricos, con especial énfasis en la supresión de incendios y en las innovaciones relacionadas orientadas a mejorar la seguridad de usuarios, propietarios y condominios residenciales. Además, el estudio destaca la necesidad de armonización internacional y del desarrollo de capacitación especializada para profesionales de respuesta ante incendios. La investigación es innovadora y pionera al consolidar datos dispersos y proponer un enfoque integrado y estratégico para la prevención y supresión de incendios en VE. Los resultados subrayan la necesidad de regulaciones específicas, formación especializada e innovaciones tecnológicas para garantizar una movilidad eléctrica segura y eficaz. El estudio abarca datos internacionales, regulaciones emergentes e innovaciones tecnológicas, ofreciendo una visión actual y prospectiva sobre la seguridad de los VE.

Palabras clave: Vehículos Eléctricos. Baterías de Iones de Litio. Incendio. Fuga Térmica. Seguridad Vehicular.

1 INTRODUCTION

The global transition to electric vehicles (EVs) represents a major milestone in the pursuit of sustainability, decarbonization, and improved urban air quality. Although battery production increases environmental impacts due to higher CO₂ emissions into the atmosphere, EVs demonstrate greater benefits during continuous use, particularly when charged with electricity generated from cleaner energy sources (Gomes et al., 2025). Nevertheless, this paradigm shift is not without challenges, with the safety of lithium-ion batteries emerging as a focal point of growing concern (Dong; Gou; Gui, 2024). One primary area of attention regarding EVs relates to collisions and traffic accidents. The study by Alter et al. (2023) presented data on accidents and found no increase in fatality rates when compared to collisions involving internal combustion vehicles, shedding light on everyday use and potential accidents associated with this type of vehicle. Another relevant concern in the context of fleet electrification involves vehicle charging.

Concerns regarding fires, particularly in confined environments such as underground parking garages, remain significant. High energy-density batteries, which constitute the core of EVs, present intrinsic risks associated with thermal runaway, an uncontrolled reaction that may culminate in fires of exceptional intensity, prolonged duration, and the release of toxic gases. This complex scenario poses substantial challenges for emergency response teams (Fire Safety Research Institute, 2023).

This study adopts a qualitative and exploratory approach, with analytical and documentary emphasis, grounded in the innovative and pioneering nature of the research within the Brazilian context.

The main objective of this article is to propose a critical analysis of global trends in electric vehicle safety, with emphasis on fire suppression and related innovations aimed at enhancing safety for users, owners, and residential condominiums, as well as on the need for international harmonization and the development of specialized training for fire response professionals (Vockan Automotivo, 2024).

The specific objectives are as follows: to analyze actions and regulations currently in force worldwide, with the purpose of identifying effective strategies for risk mitigation and fire suppression in electric vehicles, thereby contributing to the safe and expanded adoption of this technology; and to emphasize the importance of research on electric vehicles within the scientific and technological context, highlighting related issues that are open to future investigation and the innovative contributions already achieved in the field.

The article is organized into five sections to ensure clarity, coherence, and logical flow of the argument. The Introduction contextualizes the topic and outlines the research

objectives. Subsequently, the Methodology section presents the procedures adopted to conduct the study. The Literature Review discusses and analyzes the main theoretical and scientific references relevant to the subject. The Results and Discussion section then presents and discusses the research findings based on the theoretical framework. Finally, the Conclusion summarizes the main findings and their implications and contributions to the field of study.

2 METHODOLOGY

This study adopts a qualitative and exploratory approach, with analytical and documentary emphasis, grounded in the innovative and pioneering nature of the research within the Brazilian context (Amado, 2017). The research was conducted between January and April 2025 and focused on a critical analysis of fire risks in electric vehicles and the mitigation strategies adopted worldwide.

Sources were collected and analyzed in Portuguese, English, and Spanish. The databases consulted included Scopus, ScienceDirect, IEEE Xplore, Google Scholar, and SciELO, in addition to technical repositories from institutions such as UNECE, ABNT, EV FireSafe, the Fire Safety Research Institute, Frontiers in Energy Research, and legislation available on the websites of public authorities and regulatory bodies.

The search parameters comprised the following descriptors and their combinations: “electric vehicle fire,” “lithium-ion battery,” “thermal runaway,” “fire safety electric vehicle,” “thermal runaway battery,” “EV fire mitigation,” “electric car fire,” and “vehicle safety.” Searches were limited to publications from 2018 to 2025.

The bibliographic review method involved critical reading, thematic categorization, and cross-validation of information through source triangulation (Cavalcante; Oliveira, 2020). Documents were classified according to criteria of timeliness, relevance, institutional origin, and technical rigor (Arantes, 2025). The analysis adopted a comparative perspective, integrating empirical data, existing regulations, and technological trends, with the aim of providing a systematized and forward-looking overview of the topic.

3 LITERATURE REVIEW

3.1 INCIDENCE AND ETIOLOGY OF FIRES IN ELECTRIC VEHICLES: UNRAVELING THE COMPLEXITY

Although available data indicate a lower frequency of fires in electric vehicles (EVs) when compared to their counterparts, internal combustion vehicles (ICVs), the nature of fire events involving EVs requires in-depth analysis. Fires associated with lithium-ion batteries

are distinguished by their ability to burn for extended periods, releasing extreme heat and harmful gases, which amplifies the risk of structural damage and fire propagation in confined spaces.

Contrary to common misconceptions, the International Council on Clean Transportation (2022) reports that the probability of fire in EVs is up to 60 times lower than in ICVs. Tesla, a pioneer in the sector, reports an occurrence rate 11 times lower per kilometer traveled compared to the average of vehicles in the United States. Nevertheless, it is essential to recognize that, when they do occur, EV fires present specific characteristics that require specialized attention.

The primary causes of such events include battery overheating, often associated with manufacturing defects, collision-related damage, and issues during charging, particularly under overcharging conditions (EV FireSafe, 2024). The distinctive characteristics of these fires are detailed below.

Thermal Runaway: The Destructive Chain Reaction

Thermal runaway constitutes the core challenge. Once initiated in a single battery cell, it triggers a cascade of intense heat generation and the release of flammable gases, rendering the fire intrinsically difficult to control.

Reignition: A Persistent Threat

The risk of reignition after initial suppression is significantly higher in EV battery fires, requiring prolonged and vigilant monitoring.

Toxic Gases: A Hidden Hazard

Battery combustion releases toxic and corrosive gases, such as hydrogen fluoride, which pose serious threats to human health and may contaminate buildings and equipment.

Flame Consumption Time

Rapid Onset, Prolonged Suppression: thermal runaway may lead to rapid flame development, becoming visible within minutes.

Extended Duration: unlike ICVs, in which fuel is depleted relatively quickly, an EV battery may burn for hours, or even days in some cases, due to stored energy and the autocatalytic nature of thermal runaway. Reignition remains a risk until adequate cooling is achieved.

Temperatures: Intense and Concentrated Heat

High Temperatures: lithium-ion battery fires may exceed 1,000°C in the vicinity of the burning cells, significantly higher than temperatures observed in ICV fires.

Concentrated Heat: the heat generated tends to be concentrated around the battery area, intensifying risks to adjacent structures.

Destructive Potential to Built Structures: A Tangible Threat

Significant Risk: intense heat and prolonged burning pose considerable danger to the integrity of nearby buildings.

Structural Damage: prolonged exposure to high temperatures may compromise structural elements such as steel, through deformation, and concrete, through cracking and loss of strength.

Fire Propagation: radiant heat may ignite combustible materials within or near buildings, facilitating fire spread to the structure.

Destructive Reach of Released Heat: An Expansive Hazard Zone

Wide Variation: the destructive reach of heat depends on fire intensity, battery size, and the properties of surrounding materials.

Direct Damage: within a radius of 1 to 3 meters, spontaneous ignition of combustible materials may occur due to radiant heat, while nearby vehicle components may suffer severe damage or melting.

Indirect Damage: heat-sensitive materials such as paint, plastics, and wiring may be damaged at greater distances, potentially up to 5 to 10 meters or more, depending on fire duration and intensity.

Propagation Risk: flammable objects near the vehicle, even several meters away, may reach ignition temperatures over time, particularly in prolonged fires.

Additional Considerations: Overlooked Complexities

Projectile Release (Thermal Runaway Venting): during thermal runaway, battery cells may expel pressurized gases and incandescent fragments over several meters, posing a risk of secondary fires.

Dense and Toxic Smoke: the smoke produced is dense, irritating, and laden with toxic substances, constituting a significant health hazard in surrounding areas.

Global concerns regarding fires in electric vehicles are reflected in reports of bans and restrictions in countries such as China (Zhejiang Province), South Korea, and Malaysia. In Australia, recommendations to suspend the installation of chargers in buildings until clear governmental guidelines are established underscore the urgency of the issue (Felisbert, 2024; EVB.COM, 2024). In countries such as China and South Korea, proactive measures have been implemented to restrict EV charging in underground parking facilities, reflecting a precautionary stance in response to potential risks (News Motor, 2024; Brito, 2024).

3.2 DISTINCTIVE FEATURES OF LITHIUM-ION BATTERY FIRES: A DETAILED ANALYSIS

Fires involving lithium-ion batteries exhibit distinctive characteristics that set them apart from conventional fires. Temperatures may reach levels of up to 1,000°C, accompanied by the release of toxic and corrosive gases, such as the highly hazardous hydrogen fluoride (Fire Safety Research Institute, 2023). The occurrence of thermal runaway, in which combustion in a single cell triggers an uncontrollable chain reaction, constitutes a critical factor that significantly hinders fire suppression.

Another particularly relevant feature is the phenomenon of reignition. Even after the apparent suppression of flames, the battery may re-ignite, requiring continuous and prolonged monitoring by emergency response teams (Frontiers in Energy Research, 2022).

It is essential to emphasize the following points regarding incidence and causes:

- **Positive Data, Persistent Challenges:** although studies indicate a significantly lower probability of fires in EVs compared to internal combustion vehicles (ICVs), as evidenced by Tesla data reporting an incidence 11 times lower per kilometer traveled and by a Swedish study from 2022 showing that only 0.004% of the EV fleet experienced fires compared to 0.08% of gasoline and diesel vehicles, the fires that do occur present complex challenges due to the intrinsic characteristics of lithium-ion batteries.
- **Primary Causes and Thermal Runaway:** primary causes include battery overheating, physical damage to cells resulting from collisions, manufacturing defects, and failures in electrical installation. Thermal runaway, as an uncontrolled chain reaction, releases intense heat and toxic gases, making suppression efforts particularly difficult.
- **Risk of Reignition: Continuous Surveillance:** the need for prolonged monitoring, even after initial fire containment, is imperative due to the high risk of reignition.

Firefighting and Prevention Strategies: An Imperative for Innovation

- Fire suppression in EVs generally requires the use of large volumes of water to cool the battery and interrupt the progression of thermal runaway. In addition, Class D extinguishers and specific agents, such as Aqueous Vermiculite Dispersion (AVD), have emerged as promising alternatives for fires involving lithium batteries.

Nevertheless, the challenges inherent in extinguishing fires in electric vehicle batteries are substantial. The effectiveness of large quantities of water in cooling the battery and interrupting thermal runaway is not absolute, and Class D extinguishers, including foam and dry chemical agents, are only effective when complete flame smothering is achieved. The absence of universally accepted firefighting protocols for electric vehicles, including standardized cooling and isolation techniques, reflects a field in continuous development, with fire brigades worldwide still in the process of establishing these critical guidelines.

Current research explores innovative approaches to fire suppression, including:

- **Immersion Techniques:** studies investigate immersing batteries in water tanks or specific solutions to effectively cool and isolate cells undergoing combustion.
- **Ventilation and Gas Control:** the management of toxic gases released during combustion is an area of intensive research, focusing on the development of safe ventilation and containment techniques.
- **Development of Safer Battery Materials:** although not directly related to fire suppression, research on solid-state electrolytes and other battery technologies aims to inherently reduce the likelihood and severity of fires.

At present, there is no single, universally effective solution capable of instantly extinguishing fires in electric vehicles, given the complex nature of lithium-ion batteries and the thermal runaway phenomenon.

4 RESULTS AND DISCUSSION

Preventive fire safety measures play a crucial role in mitigating fire risks, including regular battery maintenance, safe charging practices, and regulations aimed at limiting charging levels in underground parking facilities. South Korea's proposal to restrict EV battery charging to 90% in residential building garages (Straits Times, 2024) illustrates this proactive approach.

Additional prevention and risk mitigation strategies include:

- **Periodic Inspections:** regular inspections of batteries and electrical systems are essential to identify and correct potential issues. Safe
- **Charging Practices:** using only manufacturer-recommended chargers and ensuring adequate electrical installations are fundamental preventive measures.
- **Prevention of Physical Damage:** avoiding collisions and impacts that may damage the battery is critical to minimizing fire risk. Application of

- **Thermal Fire Blankets:** high-temperature-resistant fire blankets may be used to cover a burning vehicle. Although they do not extinguish internal battery fires, they help contain flames, reduce fire spread, and decrease the release of smoke and toxic gases, facilitating targeted cooling.
- **Specialized Cooling Equipment:** companies are developing directed cooling systems that can be connected to the battery to accelerate cooling and improve fire control (InsideEVs, 2024).
- **Thermal Imaging Cameras:** essential for monitoring battery temperature during and after a fire, assisting firefighters in identifying hot spots and assessing the risk of reignition.

Although fires in electric vehicles receive heightened attention due to the complexity of battery combustion, their probability of occurrence remains significantly lower than that of internal combustion vehicles. Continuous research is vital to further improve battery safety and firefighting methods.

Restrictions and considerations implemented in different countries and regions include:

- **China (Zhejiang Province):** prohibition of EV access to underground garages in hotels and other buildings in cities such as Hangzhou, Ningbo, and Xiaoshan, due to concerns over spontaneous combustion and recent incidents (Radio Free Asia, 2024; CarExpert, 2024). EVs are directed to designated outdoor parking areas.
- **South Korea (Seoul):** advisories urging EV drivers to avoid underground parking when batteries are charged above 90%, aiming to prevent overcharging-related fires (The Straits Times, 2024). Plans include recommending a maximum charging limit of 90% or less in underground parking facilities and restricting the maximum charging rate at public chargers to 80%.
- **South Korea (National):** prohibition, since December 2023, of installing EV chargers below the second underground level in buildings to ensure emergency access for firefighters (The Japan Times, 2024).
- **Malaysia:** discussions and proposed guidelines by the Ministry of Housing and Local Government (KPKT) to prohibit EV chargers in parking areas of stratified properties and underground levels due to fire safety concerns (Firefighter.com.my, 2024/2025, estimated date).

- Australia: a recommendation by the real estate services company MICM advising Owners' Corporations to suspend EV charger installation projects until receiving guidance from the Federal Government, citing elevated insurance and fire risks (CarExpert, 2023).

These restrictions and alternatives demonstrate a cautious and adaptive approach across different regions, seeking to balance EV adoption with public safety. Based on these experiences, the following alternatives have been identified:

- Designated Outdoor Parking: directing EVs to park in specific areas away from main buildings.
- Limitation of Charging Levels: advising or recommending limits on battery charge levels to safer percentages.
- Charging at Ground Level or Upper Basement Levels: prioritizing charger installation in locations more accessible to emergency services.
- Awaiting Governmental Guidelines: suspending installations until clearer safety standards and technological solutions become available.

It is essential to recognize that:

- Prolonged Suppression and Higher Water Consumption: EV fires may require significantly more time and water to extinguish than fires involving internal combustion vehicles, making continuous battery cooling critical to prevent reignition.
- Firefighter Safety as a Priority: appropriate personal protective equipment (PPE), including self-contained breathing apparatus (SCBA), is indispensable due to the release of toxic gases.
- Ongoing Research and Development: continuous research and development efforts are underway to identify more effective and faster solutions for extinguishing EV fires, with the potential emergence of new technologies and extinguishing agents.
- Absence of Comprehensive Global Prohibitions and Extensive Published Research: a generalized and formally decreed global prohibition on EV charging in all residential and commercial underground facilities is not currently the norm. While concerns are evident and certain regions or specific building administrations have adopted precautionary measures, readily available research does not indicate the existence of in-depth scientific articles documenting such prohibitions and alternatives at a global scale with detailed authorship and publication data. Most available information derives from news reports and sector-specific publications.

4.1 REGULATIONS AND TECHNOLOGICAL INNOVATIONS: SHAPING A SAFER FUTURE

Global regulations reflect a concerted effort to ensure the intrinsic safety of electric vehicles (EVs). The United Nations Economic Commission for Europe (UNECE), through Global Technical Regulation No. 20 (GTR No. 20), has established stringent standards for batteries, covering aspects ranging from impact resistance to thermal safety (UNECE, 2020). In the Brazilian context, standards such as NBR 17019 define technical criteria for the installation of EV chargers, aiming to prevent short circuits and fires (Fase Energia, 2024).

In parallel with the regulatory framework, technological innovations have emerged as fundamental pillars of safety. The development of self-extinguishing batteries and advanced thermal management systems designed to mitigate the occurrence of thermal runaway represents significant progress in this field (Self-extinguishing batteries, 2023).

Regulation of Electric Vehicle Charging in Residential Condominiums

In Brazil, Bill No. 158/2025 signals a movement toward regulating the installation of charging infrastructure in residential condominiums, seeking to clarify issues related to safety and the responsibilities of individual unit owners (Chamber of Deputies, 2025). Standards such as NBR 17019 specify technical requirements for charger installation, including mandatory protection against overloads and the requirement for adequate ventilation (Fase Energia, 2024).

In several regions, the development of specific standards for EV charger safety is underway. In Brazil, the São Paulo Fire Department has proposed regulations addressing the installation of ventilation systems, heat sensors, automatic sprinklers, and battery shutoff points in garages and parking facilities. Additionally, a minimum safety distance of five meters between charging spaces and other risk areas has been recommended (Revista Incêndio, 2024; Poder 360, 2024).

Strategies for Extinguishing Fires in Electric Vehicles

The unique nature of lithium-ion batteries requires specific firefighting approaches. Governments at different levels and in various parts of the world are implementing or considering a range of preventive and mitigation measures, including:

- **Intensive Cooling:** the application of large volumes of water or specialized cooling agents to control battery temperature and prevent reignition.
- **Site Isolation:** the implementation of physical barriers to prevent fire spread and exposure to toxic gases.
- **Protective Equipment:** the use of appropriate personal protective equipment by firefighters, including respiratory protection against toxic gases.

- **More Rigorous Safety Testing:** adoption of specific tests to assess battery resistance to impact, penetration, and other conditions that may trigger fires.
- **Manufacturing and Quality Standards:** establishment of norms for battery production and assembly to ensure safety and durability.
- **Vehicle Design Requirements:** requirements for EV designs that facilitate battery cooling in cases of overheating and provide protection during collisions.

Strategic governmental investments in research and development have accelerated the advancement of inherently safer technologies, such as self-extinguishing batteries and sophisticated thermal management systems (Amphenol, 2024; Agência Gov, n.d.).

Governmental and Industrial Actions: A Collaborative Effort for Safety

Governments and the automotive industry have demonstrated a growing commitment to improving EV safety through the implementation of significant measures. Charging restrictions in underground parking facilities in countries such as China, Malaysia, and South Korea (Autoesporte, n.d.), as well as recommendations in Australia to postpone installations until clear standards are established (CarExpert, 2023), exemplify this proactive stance.

In addition, global initiatives prioritize specialized firefighter training and investment in advanced safety technologies (Firefighter.com.my, 2024). Firefighting strategies for electric vehicles must integrate efficient cooling techniques, the safe management of toxic gases, and the development of charging infrastructure with safety as a priority, including the installation of fire detection systems and automatic sprinklers.

The establishment of a national safety protocol in Brazil remains under discussion, highlighting the urgency of clear standards for the prevention and suppression of EV fires (A Tarde, n.d.; Move News, n.d.; Sindiconet, n.d.; Fonsi, n.d.; CNN Brasil, n.d.). At the international level, there is a clear movement toward the harmonization of safety standards, with the aim of aligning EV safety with that of internal combustion vehicles. Key governmental and industrial actions are outlined below.

Training for Emergency Response Teams

- **Development of Training Curricula:** creation of specialized programs for firefighters and rescue teams addressing the specific risks and safe procedures associated with EV fires.
- **Appropriate Equipment:** investment in equipment that enhances battery cooling and protects responders from exposure to toxic gases.

Safe Charging Infrastructure

- **Standards for Charger Installation:** definition of rigorous standards for the installation of public and private charging points to prevent overloads and short circuits.

- Inspections and Certifications: implementation of inspection and certification processes to ensure the safety of charging installations.

Public Awareness

- Informational Campaigns: development of campaigns to educate the public about potential risks and necessary precautions related to electric vehicles.
- Information for Owners: provision of clear and accessible information on the safe handling, charging, and maintenance of EVs.

Research and Development

- Research Funding: financial support for studies aimed at improving battery safety and developing innovative technologies for fire prevention and suppression.

International Cooperation

- Information Sharing and Best Practices: collaboration among governments and international agencies to exchange knowledge and develop common approaches to electric vehicle safety.

It is essential to recognize that specific governmental actions may vary significantly depending on regional contexts and the level of EV adoption. Nonetheless, the global trend points to increased attention and regulation regarding electric vehicle safety, encompassing both fire prevention and firefighting strategies.

4.1.1 An Innovation in the Suppression of Lithium-Ion Battery Fires

In our research, several authors state that there are currently no products, processes, or inventions capable of extinguishing fires in which lithium-ion batteries act as the oxidizing agent. Nevertheless, we identified FirePro as a promising fire suppression technology that proposes the use of a condensed aerosol system specifically designed for the suppression of lithium-ion battery fires (Figure 1). This system is based on a solid compound claimed to be patented, known as FPC (Figure 2), which is used as the active fire suppression agent.

This is a modern technology that shows potential effectiveness and has been applied in various settings, including electrical panels, electrical rooms, data centers, and maritime installations (Argus Engenharia, 2024b).

Components of FirePro systems: innovative fire suppression devices and the FPC product.

Figure 1*FirePro system*

Source: ARGUS (2024b).

Figure 2*FPC product*

Source: ARGUS (2024b).

However, after conducting patent searches in the Brazilian National Institute of Industrial Property (INPI), no patent records were found for FPC products in Brazil. The system entitled *FPC Assembly Module, Electronic Device, and Assembly Method* corresponds to patent application BR 11 2024 004027 5 A2, classified under IPC H05K7/14 and H05K5/06. The application was filed on August 15, 2022, and published in Brazil on June 25, 2024, with Unionist priority claimed in China under application No. 202111026212.3, dated September 2, 2021. The invention relates to an FPC assembly module, an electronic device, and a corresponding assembly method.

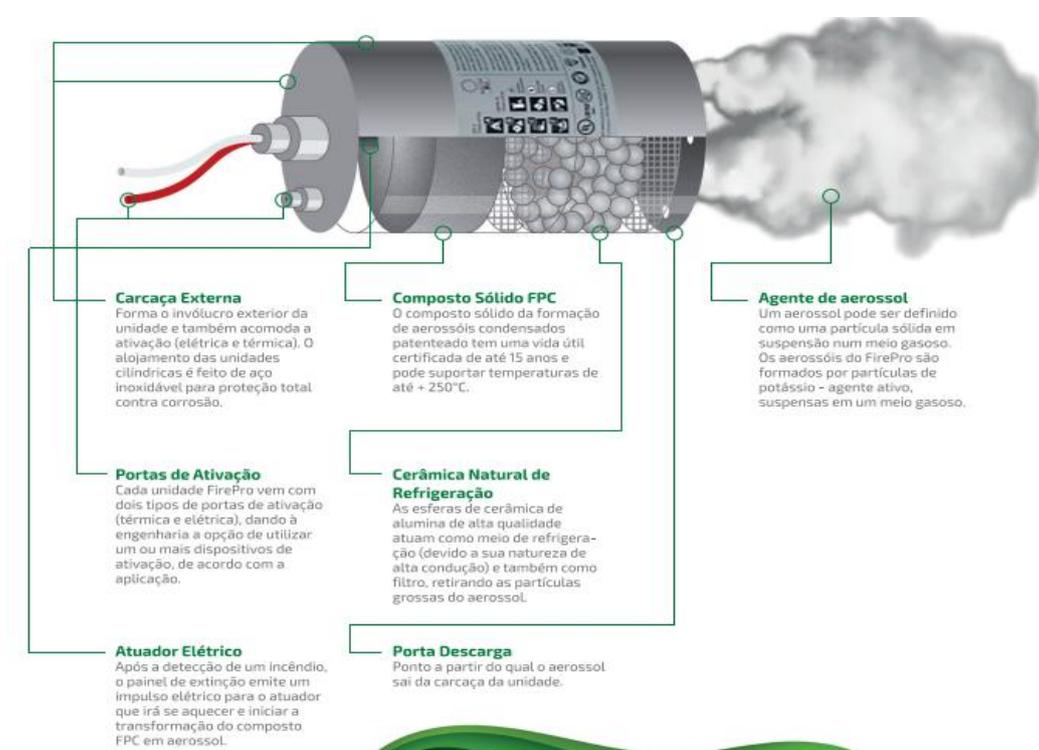
The patents related to FirePro products are registered with the World Intellectual Property Organization (WIPO) and are certified under the International Trademark Registration system in accordance with the Madrid Agreement and Protocol. In addition, FirePro holds Canadian Patent No. 2,250,325, European Patent No. 0925808, and Patent Application WO-2015057107-A1 (*Thermal Mechanism for Activation of a Fire Extinguishing Generator*), with a priority date of October 16, 2013. These rights are assigned to FirePro Systems Ltd., and the listed inventors are Khaustov Aleksandr Grigorievich, Solovev Vladimir Aleksandrovich, and Sokolnikov Aleksandr Sergeevich.

This innovation is grounded in the basic theory of fire, proposing the interruption of the combustion process by removing one of its essential elements. The system operates by removing or limiting the primary oxidizing agent, oxygen, through smothering by condensed aerosol, thereby inhibiting the chain reaction of combustion. This mechanism enables effective application in enclosed environments (Argus Engenharia, 2024b), as illustrated in Figure 3 below.

4.1.2 Description of the storage component of the innovative fire suppression system:

Figure 3

Fragmented image of the storage capsule of the suppression system



Source: Argus (2024b).

Regarding the Bridgehill thermal blanket, no patent records were identified that describe a thermal blanket system for temperature control and fire protection. However, the CarPro X and Standard blankets have been approved in accordance with NFPA 701 standards and hold licensing and registration with the Brazilian National Institute of Industrial Property (INPI). To date, no specific licensing records have been identified in the INPI Brazil database for the aforementioned products.

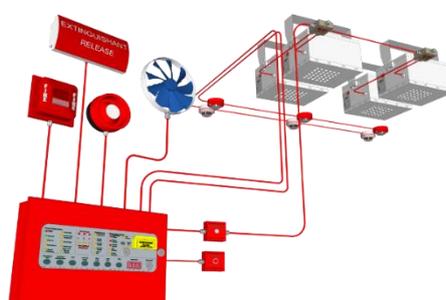
The FirePro Hero system reports having been tested and certified under ISO 9001 and ISO 14001 standards, approved by the United States Environmental Protection Agency (EPA/USA) and by the European Green Label program. The system is designed to protect

environments ranging from 0.08 m³ to 57 m³ by means of smothering through condensed aerosol, which inhibits the chain reaction of the combustion process. Its application is suitable for enclosed spaces or, alternatively, for use in combination with the Bridgehill fire barrier blanket, as well as through the coordinated deployment of multiple units activated simultaneously or sequentially (Argus Engenharia, 2024a), as illustrated in Figures 4 and 5 below.

4.1.3 Proposed combination for open areas and parking facilities using the innovative fire barrier system:

Figure 4

FirePro circuit



Source: ARGUS (2024a; 2024b).

Figure 5

Bridgehill fire barrier blanket



Source: ARGUS (2024a; 2024b).

Therefore, there is a clear need for experimental and physical testing in Brazilian test facilities, as well as for national certification, given the absence of patent protection in Brazil. The lack of domestic patent records reinforces the importance of conducting locally validated trials to assess technical performance, safety, and regulatory compliance under Brazilian conditions.

In this context, the U.S.-based startup 24M claims to have developed a novel battery technology with the potential to significantly transform the market. Supported by Volkswagen, this innovation, known as the Impervio battery separator, is designed to prevent overloaded battery cells from igniting and may represent an important milestone for the broader adoption of electric vehicles. Overcharging is one of the primary mechanisms associated with the initiation of battery fires, and the technology was tested in batteries exhibiting dendrite formation as well as internal short circuits. The tests were conducted on lithium-ion cells composed of nickel, manganese, cobalt, and graphite, with a capacity of 10 ampere-hours. In both cases, the cells were fully charged and subsequently subjected to 100 percent overcapacity, a condition that can lead to fire or explosion (InsideEVs, 2024).

5 FINAL CONSIDERATIONS

Electric vehicles are an established reality and are closely associated with efforts to mitigate environmental damage and improve air quality in major cities worldwide. Although electric vehicles present an intrinsically lower risk of fire when compared to internal combustion engine vehicles, the singular characteristics of lithium-ion battery fires require the development and implementation of specific and effective prevention and suppression strategies.

A fire involving an electric vehicle may evolve into a long-duration event, characterized by high temperatures and significant destructive potential to adjacent structures. This behavior is driven by intense and prolonged heat release, as well as by the emission of toxic gases. The destructive reach of the heat, although variable, represents a considerable risk within a radius of several meters around the affected vehicle. It is therefore imperative that emergency response teams adopt intensive cooling strategies and implement strict precautionary measures in light of the specific risks inherent to such incidents.

Fire safety in electric vehicles has emerged as a growing concern, demanding the implementation of robust regulatory standards and sustained investment in specialized training for emergency professionals, as well as the establishment of governmental regulations applicable to public authorities, private entities, and society as a whole.

The continued enforcement of rigorous regulations, combined with sustained advances in technological innovation, constitutes a fundamental pillar for promoting the safe and sustainable adoption of electric vehicles, as well as for updating existing legislation to reflect emerging risks and solutions.

Electric vehicle safety represents a multifaceted challenge that requires a holistic approach, integrating strict regulatory frameworks, continuous technological innovation, and

strong international collaboration. Persistent efforts in research and development will be essential to ensure public safety and to foster the sustainable adoption of electric vehicles on a global scale.

Current actions and regulations at the international level demonstrate a concerted effort to mitigate the risks associated with the charging and operation of electric vehicles in confined environments. Continued investment in the development of inherently safer battery technologies, together with the formulation of effective fire suppression protocols, will be decisive in ensuring public safety and in paving the way for widespread and reliable adoption of electric vehicles.

In the pursuit of safe and sustainable electric mobility, long envisioned by pioneers such as Tesla on the global stage and Gurgel in Brazil, several dilemmas persist in the minds of electric vehicle users and the general population. These include the relationship between vehicle costs and their actual environmental impact; the extent to which industry is developing effective products to combat fires in electric vehicles; the longevity of lithium-ion batteries versus alternative technologies that may emerge in the medium and long term, given that lithium is a finite natural resource; the cost-benefit balance for ride-hailing and taxi drivers when acquiring electric vehicles and whether incentives for internal combustion vehicles through federal, state, and municipal tax policies offset this transition; and the challenges faced by the Armed Forces in incorporating electric vehicles into armored fleets due to fire risks.

These issues represent important avenues for future research and must be addressed by scholars to further clarify and demystify the topic, as this study has sought to do with respect to fires in electric vehicles, a subject once highly controversial and now increasingly better understood.

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