

ELECTRIC VEHICLES – A CHALLENGE WE ARE (NOT) READY FOR IN TERMS OF FIRE SAFETY

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Abstract: Electric vehicles bring significant advantages in reducing harmful gas emissions and advancing modern transportation, but they also present challenges in terms of fire safety. The specific characteristics of electric vehicle conflagrations, caused by the thermal runaway of lithium-ion batteries, include high temperatures, the release of toxic gases, and the potential for re-ignition, which make them more difficult to extinguish compared to conflagrations in internal combustion engine vehicles. This paper analyzes the key challenges in extinguishing these fires, such as risks to firefighters, issues in enclosed spaces, and the limitations of current firefighting methods. Additionally, it offers recommendations for improving infrastructure, developing specialized firefighting techniques, and training firefighters. It also provides a comprehensive overview of the issues and potential solutions for effectively addressing electric vehicle fires.

Key words: electric vehicles, fires, thermal runaway, lithium-ion batteries, firefighting services, infrastructure, training.

1. INTRODUCTION

Electric vehicles have become a symbol of technological progress and sustainable development, experiencing remarkable growth in sales worldwide. In the European Union, the share of electric vehicles among newly registered cars increased from 3% in 2020 to over 10% in 2023, while Norway reached an impressive 80% share of electric vehicles among new registrations. [1],[2]. In Serbia, the number of registered electric vehicles have risen from 800 in 2020 to more than 2,500 by 2023, indicating a gradual adaptation of the market [2].

However, with the increasing number of electric vehicles, new challenges are emerging, mainly in terms of safety and fire protection. The key issue is the thermal runaway of lithium-ion batteries, a process in which an uncontrollable rise in temperature of the battery occurs, accompanied by the release of toxic and flammable gases [3],[4]. This phenomenon, coupled with the difficulties in extinguishing battery fires, makes electric vehicle fires more complex and hazardous compared to fires in internal combustion engine vehicles [5],[6]. Additionally, safety in enclosed spaces such as garages and tunnels represents a unique challenge, as these environments can amplify the effects of a fire and make difficult both evacuation and firefighting efforts [7],[8].

The purpose of this paper is to explore the specific characteristics of conflagrations in electric vehicles and analyze the technical challenges faced by firefighting and rescue units. It is based on analyses of existing researches and practical experiences to provide a comprehensive foundation for the further development and proposals of solutions in this field.

2. SPECIFIC CHARACTERISTICS OF FIRES IN ELECTRIC VEHICLES

Electric vehicles, as part of modern technological advancements, bring significant changes to the automotive industry. On the other hand, the increasing number of electric vehicles also necessitates solving specific challenges related to their safety, particularly in the case of fires. Although firefighting and rescue units currently encounter fires in electric vehicles less frequently compared to internal combustion engine vehicles due to their lower prevalence, the unique characteristics and

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consequences of these fires make them far more complex to control and extinguish. These challenges primarily come from the characteristics of the lithium-ion batteries that power electric vehicles.

2.1. Thermal Runaway: A Critical Factor in Lithium-Ion Battery Fires

Thermal runaway is the primary and most critical phenomenon that triggers fires in electric vehicles. Lithium-ion batteries, which dominate on the market, use high-energy cells designed to maximize performance, but carry the risk of uncontrolled reactions. This phenomenon occurs when the internal temperature of cell exceeds a critical point, leading to a chain reaction. The key factors contributing to thermal runaway include:

- **overheating:** caused by excessive load during charging or discharging of the battery;
- **mechanical damage:** for instance, due to a collision or physical impact;
- **short circuit:** occurring within the cell itself or in the connected modules[3],[4].

Once thermal runaway is triggered, there is a rapid release of energy, resulting in a sharp increase in temperature, release of flammable and toxic gases, and potentially release of flames. During this process, flammable and toxic gases such as carbon monoxide (CO), hydrogen fluoride (HF), and hydrogen cyanide (HCN) are emitted. These gases not only pose significant health and life risks but also increase the complexity of extinguishing the fire. Hydrogen fluoride, for instance, reacts with moisture in the air to form corrosive acids, further endangering the safety of firefighters and the surrounding environment[7],[8].

2.2. Fire Behavior in Electric Vehicles Compared to Internal Combustion Engine Vehicles

Fires in internal combustion engine (ICE) vehicles most commonly occur due to fuel leaks, which create pool fires. These fires are intense but relatively predictable and can be controlled by using traditional firefighting supplies such as water, foam, or powder. For firefighters, such interventions are routine and do not pose significant challenges.

Nevertheless, battery fires in electric vehicles present a more complex challenge due to the specific characteristics of lithium-ion batteries:

- **prolonged duration:** due to their high energy density, fires in electric vehicles last significantly longer, making extinguishment more challenging and increasing the consumption of firefighting resources;
- **re-ignition risk:** thermal runaway can lead to the reappearance of flames even after the fire appears to be extinguished, prolonging firefighting interventions;
- **explosive gas emissions:** sealed battery cells can generate high pressure, resulting in jet flames that are unpredictable and pose significant risks to firefighters and the surrounding environment.[5],[8].

The additional complexity of electric vehicle fires lies in the release of toxic and flammable gases such as carbon monoxide (CO), hydrogen fluoride (HF), and hydrogen cyanide (HCN), which endanger the health of firefighters as well as the general population. The combination of prolonged duration, explosive emissions, and toxic gases makes these fires a unique challenge, requiring specialized equipment, training, and adapted firefighting tactics.

2.3. Safety Challenges in Enclosed Spaces During Electric Vehicle Fires

Conflagrations involving electric vehicles in enclosed spaces, such as garages or tunnels, pose a significant challenge due to specific conditions that amplify the danger. These spaces limit natural ventilation, allowing the accumulation of toxic gases such as carbon monoxide (CO), hydrogen fluoride (HF), and hydrogen cyanide (HCN). The concentrations of these gases can endanger health and life, while high temperatures may cause severe structural damage to the facility. Such effects were observed, for instance, in the 2020 conflagration at Stavanger Airport's parking garage, where the consequences of the fire were significantly intensified due to the enclosed environment (approximately 300 cars were burned or damaged) [7],[8].

In tunnels, where evacuation is hindered by limited exits and the length of the space, fires involving electric vehicles pose an additional danger. The release of flammable gases combined with

high temperatures can lead to a domino effect, where the fire spreads to other vehicles or infrastructure. According to data from the European LASH FIRE project, the use of automatic fire detection systems and sprinkler activation can significantly reduce the risk of fire spread and facilitate the intervention of firefighting and rescue units [1],[7].

It is also recommended to implement fire isolation systems, such as immersion containers or mobile barriers, which can help contain fires in garages. Those systems are already being tested in some countries with the aim of increasing firefighting efficiency and reducing damage [8],[9].

3. CHALLENGES IN EXTINGUISHING ELECTRIC VEHICLE FIRES

Electric vehicles represent not only a technological innovation, but also a significant challenge for firefighting services, particularly in extinguishing fires involving lithium-ion batteries. Compared to traditional internal combustion engine vehicles, fires in electric vehicles require a specialized approach due to the unique characteristics of their battery systems.

One of the key risks associated with electric vehicles is high voltage, which in some models can range between 400 and 800 volts, and in certain cases exceed 1,000 volts. Contact with damaged cables or battery packs can cause severe injuries or even fatalities. These cables are typically marked with orange insulation, but their location varies depending on the vehicle model, complicating the safety of interventions. High electricity pose a serious risk of injury or fatality if firefighters accidentally come into contact with a damaged cable or battery. Water, often used as an extinguishing agent, can act as a conductor of electricity, further complicating firefighting efforts [2],[8],[9].

Interventions involving fires in electric vehicles often last significantly longer than those in internal combustion engine vehicles. In addition to prolonged durations caused by high temperatures and thermal runaway, large amounts of water are frequently required, as well as post-extinguishment monitoring to track developments. Electric vehicle fires can smolder for hours or even days, necessitating prolonged attention and depleting the resources of firefighting units. The risk of re-ignition, known as reactivation (typically within the first 24–48 hours), further complicates the situation and requires specific procedures to isolate the vehicle after the intervention [2],[7],[10].

An additional challenge is that electric vehicles are often not properly marked, making it difficult to quickly identify risks. Unlike internal combustion engine vehicles, electric vehicles do not produce engine noise when powered on, which can create a false sense of security that the vehicle is off. Some vehicles feature logos and labels such as "Electric," "EV," or "Zero Emission," while in certain countries, such as Norway, special green license plates clearly indicate electric power. However, such markings are not universal. Recognizable structural features, such as the absence of an exhaust pipe, the presence of a charging port, and a distinctive front grille design without a traditional radiator, can also help with identification. To quickly determine the vehicle type, firefighting and rescue teams can use the ERG guide or app (Emergency Response Guide). This app enables rapid search for vehicle model information, including the locations of high-voltage cables and battery modules. In situations where digital tools are unavailable, printed emergency guides provide the same essential information. The lack of standardized markings remains a challenge, making firefighter training and the development of universal labeling systems crucial for improving safety and efficiency during interventions [2]. Electric vehicles that have been submerged, for instance, during floods, require additional precautions as water can cause short circuits in the batteries. Once such a vehicle is removed from the water, the risk of thermal runaway increases significantly. Rescue teams must implement specific protocols to assess the battery system's condition and prevent further reactions [5],[8].

The unique nature of electric vehicle fires also lies in their prolonged reactivity. After extinguishment, battery modules can continue to emit heat, which may lead to re-ignition. This requires special attention when storing damaged vehicles after a fire, as well as specialized isolation containers to minimize the risk of further reactions [5],[8].

For safe cutting of vehicle bodies and isolation of high-voltage cables, specialized tools and equipment are necessary. Standard tools used for internal combustion engine vehicles are often

inadequate for working on electric vehicles. Additionally, thermal cameras have become an essential tool for identifying overheated battery components during interventions, allowing more precise extinguishment and reducing the risk of re-ignition [4],[7].

The complexity of interventions involving electric vehicles, their prolonged duration, and the unpredictability of situations place additional psychological pressure on firefighters and rescuers. This can impact their performance and safety, underscoring the necessity for continuous psychological support and education for firefighters before interventions occur [8]. Given that battery designs and high-voltage layouts vary between manufacturers, firefighter training must be tailored to the most common models in the local market.

4. CONCLUSION

Electric vehicles are becoming increasingly prevalent in modern society, but they also bring specific challenges, particularly regarding conflagrations. Although fires in electric vehicles occur less frequently compared to internal combustion engine vehicles, their nature is far more complex. Mechanisms such as thermal runaway, accompanied by the release of toxic gases, significantly complicate interventions and increase risks for firefighters, infrastructure, and the environment.

Thermal runaway is particularly dangerous as it triggers chemical reactions within the batteries, producing extremely high temperatures and toxic gases, which endanger the health of firefighters and complicate the extinguishing process. Traditional approaches, such as the use of water or foam, are often insufficient for fully controlling such fires. Additionally, the potential for re-ignition extends the duration of interventions and requires the deployment of significant resources.

The situation becomes even more complex in enclosed spaces, such as garages and tunnels, where limited space and poor ventilation further enlarge risks. The accumulation of gases, difficulties in evacuation, and potential damage to infrastructure make fire involving electric vehicles in such environments particularly hazardous.

Improving the approach to extinguishing electric vehicle fires requires a combination of technological innovations, firefighter training, and infrastructural solutions. The development of early fire detection systems and automatic sprinklers in garages and tunnels are key steps toward risk reduction. The installation of specialized immersion areas for battery containment could further aid in the rapid control and isolation of thermal runaway incidents.

The training of firefighters and rescuers must be tailored to the most common models on the market. Understanding the structure of battery packs, recognizing the symptoms of thermal runaway, and utilizing specialized equipment are key elements for safe and efficient intervention. Additionally, the standardization of procedures would ensure consistent responses and reduce errors during interventions.

The further development of firefighting technologies for lithium-ion batteries, as well as collaboration between the automotive industry, regulatory bodies, and emergency services, is essential for adapting existing standards to the needs of the modern era. Only an integrated approach can ensure safety in a world with an increasing number of electric vehicles.

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