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# Assessing Risks of Electric Vehicles in Underground Parking Facilities: Strategies for Enhancing Urban Sustainability

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A B S T R A C T

As cities confront the dual challenges of global warming and urban environmental degradation, adopting sustainable mobility strategies has become essential for future resilience and sustainability. The use of electric vehicles, which have minimal emissions and are constructed in an energy-efficient manner, represents a viable solution to this issue. Conversely, the secure and effective implementation of electric vehicles in car parks presents a multitude of technical and infrastructural challenges. Despite the anticipated substantial rise in the use of electric vehicles in the near future, there are proposals for them to be subject to a range of restrictions due to fire safety concerns. It has been established that charging processes represent the primary cause of fires in electric vehicles. The utilisation of charging stations in enclosed and particularly subterranean garages situated within edifices that serve a multiplicity of purposes, including commercial, residential and retail, is on the rise. As a result, it poses a greater risk in a potential fire scenario than a charging station located in the open air. The pressure on charging times, especially for electric vehicles, requires the use of chargers with a higher power rating, which may increase the risk. It is noted that although electric vehicle fires and combustion engine vehicle fires have similar characteristics, there are differences in the fire behaviour of electric vehicles. This paper aims to provide a strategic guide to achieving urban sustainability goals by looking at innovative approaches to the deployment of electric vehicles in car parks and solutions to potential risks. The use of car parks is crucial to strengthening the role of electric vehicles in future urban mobility systems. It aims to facilitate the harmonisation of electric vehicles and charging stations, contributing to a more sustainable future by reducing the environmental impact of cities.

# Yeraltı Otoparklarında Elektrikli Araç Risklerinin Değerlendirilmesi ve Kentsel Sürdürülebilirlik Stratejileri

M A K A L E   B İ L G İ S İ

***Anahtar Kelimeler**:*
elektrikli araç yangını, kapalı otopark, şarj istasyonu entegrasyonu, acil müdahale

Ö Z E T

Şehirler, küresel ısınma ve çevresel bozulma gibi iki önemli zorlukla karşı karşıya kalırken, sürdürülebilir ulaşım stratejilerinin benimsenmesi, sürdürülebilir bir gelecek için zorunluluk haline gelmiştir. Elektrikli araçların, minimum emisyon ve yüksek enerji verimliliği sağlamak üzere tasarlanması, bu sorunlara yönelik etkili bir çözüm sunmaktadır. Ancak, elektrikli araçların otoparklarda güvenli ve etkili bir şekilde kullanılabilmesi, beraberinde çeşitli teknik ve altyapısal zorlukları da gündeme getirmektedir. Yakın gelecekte elektrikli araç kullanımında beklenen önemli artışa rağmen, yangın güvenliği endişeleri nedeniyle bu araçların çeşitli kısıtlamalara tabi tutulmasını öneren yaklaşımlar giderek daha fazla tartışılmaktadır. Araştırmalar, elektrikli araçlarda meydana gelen yangınların birincil nedeninin şarj işlemleri olduğunu ortaya koymuştur. Ticari, konut ve perakende gibi çeşitli amaçlara hizmet eden yapılardaki kapalı, özellikle yer altı garajlarında şarj istasyonlarının kullanımı giderek artmaktadır. Sonuç olarak, olası bir yangın senaryosunda, kapalı alanlardaki şarj istasyonları, açık havada bulunan şarj istasyonlarına kıyasla daha büyük bir risk teşkil etmektedir. Özellikle elektrikli araçlar için şarj sürelerini azaltma baskısı, riski artırabilecek daha yüksek güç kapasitesine sahip şarj cihazlarının kullanımını zorunlu kılmaktadır. Elektrikli araç yangınlarının, içten yanmalı motorlu araç yangınlarıyla benzer özellikler taşımasına rağmen, yangın davranışlarında belirgin farklılıklar gösterdiği vurgulanmaktadır. Bu çalışmada, otoparklarda konuşlandırılan elektrikli araç yönelik olası riskler ele alınmıştır. Söz konusu duruma yönelik çözümler incelenerek, kentsel sürdürülebilirlik hedeflerine ulaşmak için stratejik bir rehber sunulması amaçlanmaktadır. Otoparkların kullanımı, elektrikli araçların gelecekteki kentsel hareketlilik sistemlerindeki rolünü güçlendirmek açısından büyük bir öneme sahiptir. Elektrikli araçlar ve şarj istasyonlarının uyumlaştırılmasını kolaylaştırarak, şehirlerin çevresel etkisini azaltmayı ve daha sürdürülebilir bir geleceğe katkıda bulunmayı amaçlamaktadır.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| m | combustion rate (kg/s) | m″ | combustion flux (kg/m$^2$/s) |
| ΔHe | heat of combustion (MJ/kg) | ŋ | combustion flux |
| Af | base or surface area of the fuel or fire | ΔHc | state of charge |

## INTRODUCTION

The growing prevalence of electric vehicles and the imperative for environmental sustainability necessitate a corresponding evolution in the infrastructure of car parks, with the requisite adaptations to accommodate these technologies. In this context, it is of paramount importance to ensure the safe and efficient use of electric vehicles, particularly in indoor car parks, in order to facilitate modern urbanism and transport planning. The integration of electric vehicle charging infrastructure, fire safety, energy management and user accessibility represent key issues that must be addressed in the redesign of car parks. The installation of electric vehicle charging points in car parks offers dual benefits; it provides convenience for car owners and plays an important role in meeting cities' energy management and sustainability goals. The strategic placement of charging stations is of critical importance for the efficient distribution of energy and the sustainable satisfaction of users' charging needs. Nevertheless, adherence to the established fire safety protocols and regulations is indispensable for the safe and effective operation of charging stations. It is imperative to consider the potential fire risk associated with electric vehicle batteries, particularly in enclosed parking facilities.

The rise in the number of fires caused by electric vehicles in recent years has prompted concerns about the safety of this new technology. The high energy density of electric vehicle propulsion batteries and the potential for battery cells to ignite due to the risk of thermal runaway necessitate the implementation of safe storage and charging practices, particularly in enclosed settings. In this context, it is of paramount importance to develop effective fire-suppression systems and emergency protocols for the mitigation of electric vehicle fires, particularly in indoor car parks. Furthermore, it is of paramount importance for both electric vehicle users and car park operators to engage in regular maintenance and safety inspections, with the objective of reducing the risk of fire. The objective of this study is to provide an overview of recent studies addressing different aspects of the deployment of electric vehicles in car parks. A comprehensive examination of the technical and safety aspects of the deployment of electric vehicles in car parks will be conducted. It is of paramount importance to integrate electric vehicles in a safe, efficient and sustainable manner if modern urbanism and transport planning are to progress. The objective of this approach is to present novel approaches and solutions to relevant audiences for the deployment of electric vehicles in indoor car parks, based on an analysis of existing literature and technology.

### Electric Vehicle Safety and Risks in Underground Parking: A Literature Review

The proliferation of electric vehicles has precipitated substantial shifts in the realms of sustainable transportation and environmentally conscious urbanism. In this context, a number of academic studies and technical reports have been published in recent years examining the deployment of electric vehicles in car parks and the integration of charging infrastructure.

The influence of energy management strategies pertaining to the utilisation of electric vehicles in indoor car parks and the impact of charging stations on energy demand has been subjected to investigation. The research addressed the integration of renewable energy sources, energy storage solutions and the sustainability of the charging infrastructure of electric vehicles (Wang et al., 2023).

Smith and Brown undertook a review of the extant regulations and standards pertaining to the deployment of electric vehicles in car parks, identifying deficiencies in this domain. The study recommended that safety and performance standards should be updated and that a regulatory framework should be developed to adapt to new technologies (Wang et al., 2023).

The potential fire risk associated with electric vehicle batteries and the optimal strategies for mitigating this risk in parking facilities have been subjected to rigorous examination. The study presents a series of innovative fire safety protocols designed to prevent thermal runaway events in drive coils. Additionally, it offers a range of approaches aimed at enhancing the efficacy of fire suppression systems in car parks (Bai et al., 2022).

Liu et al. examined the accessibility of electric vehicle users to charging stations in parking garages, as well as the challenges they face in this regard. The study highlighted the necessity for the ergonomic design of the charging infrastructure and the creation of user-friendly applications with the objective of enhancing the user experience (Liu et al., 2022).

The calculations were conducted using the Fire Dynamics Simulator (FDS) program to analyse the potential outcomes of an electric vehicle fire in an underground car park. The scenario involved 10 vehicles and was designed to represent a realistic setting for such an incident. The present study employs numerical analysis to elucidate the dispersion and temperature distribution of hydrogen fluoride in the aftermath of the fire. It has been established that a fire involving a small-capacity lithium-ion battery releases hydrogen fluoride in quantities that are dangerous even for individuals exposed to the fire (Krol & Krol, 2022).

In the study conducted by Hao et al. on the requisite charging infrastructure for electric vehicles and its integration in indoor car parks, efficiency analyses pertaining to the optimal positioning of charging stations were conducted. The objective is to enhance energy efficiency by employing sophisticated algorithms to identify the optimal location for charging stations (Hao et al., 2021).

In a study examining the environmental impact of electric vehicle fire extinguishing systems, it was found that the water used for extinguishing and cooling purposes in the event of an electric vehicle fire was significantly contaminated. It was therefore stated that the residual liquid in question, due to the concentrations of heavy metals such as lithium, cobalt, nickel and manganese, exceeds the current limit values for discharge into the sewerage system. It was further recommended that appropriate pre-treatment should be applied in practice (Mellert et al.,2020).

The question of whether the charging of electric vehicles in car parks poses a fire risk, and what measures are necessary to ensure that the risk remains at an acceptable level, has been addressed by Mellert et al. The study comprised a comprehensive assessment of the fire risk associated with electric vehicles during the charging process. This encompassed an evaluation of the fire risk posed by the electrical installation in the car park during charging, the vehicle layout in the car park and the active fire extinguishing systems. It has been argued that the findings derived from the statistical analysis and literature review are not sufficiently robust to indicate that the charging of electric vehicles in closed car parks will increase the probability of fire (Mellert et al.,2020).

It has been asserted that the extant regulatory framework pertaining to the installation of charging points for electric vehicles is adequate to ensure that the fire risk associated with the charging of electric vehicles in enclosed car parks is maintained at an acceptable level. It is stated that the commissioning of these charging stations should be carried out in accordance with the relevant legislation and in compliance with the recommendations of the vehicle and charging station manufacturers regarding the application. It is inadvisable to utilise electrical sockets and extension cables that have not been specifically designed for the purpose of charging vehicles. In indoor car parks where electric vehicles can be charged, the necessity for fixed water-based fire extinguishing systems is no greater than in other car parks (Brandt & Clansberg, 2020).

The present study investigates emergency response methods for fire incidents occurring in electric (battery) construction equipment operating in underground conditions, such as those found in mines in Finland. It is stated that thermal runaway in the drive batteries is the most common fire scenario. It is therefore generally recommended that water or water-based extinguishing materials be used for the purpose of extinguishing fires caused by electric vehicle drive batteries. In the event of a drive battery fire occurring underground, it is imperative that underground operations are immediately ceased. Attempting to allow the battery pack to burn and self-extinguish is not a viable option, given the potential deterioration of rock integrity due to the high heat generated and the inevitable production losses that will occur. Instead, high-voltage resistant personal protective equipment specific to electric vehicles should be utilised, rather than conventional personal protective equipment typically employed for risks associated with the extinguishing of the battery pack with water (Välisalo, 2019).

The objective of this study is to examine the conditions under which underground car parks in Spain are used by electric vehicles. In addition, the study will review relevant literature, assess compliance with standards and requirements, and identify potential hazards. Furthermore, the study will investigate the necessity for near-future solutions to establish testable performance guidelines for qualified emergency response personnel. In particular, it was recommended that information and discussions aimed at influencing consumer perceptions in a way that is not grounded in evidence be avoided. This is to prevent the creation of an agenda that is not based on facts (Blanco-Muruzábal et al.,2022).

In Türkiye, the Istanbul Metropolitan Municipality and Fire Department conducted a training exercise to extinguish a 75.2 kWh propulsion battery used in electric buses. The objective of the exercise is to ascertain the potential hazards associated with electric vehicle drive battery fires and to evaluate the measures that can be taken to mitigate these risks. Additionally, the exercise aims to assess the effectiveness of various fire extinguishing techniques in such scenarios. It was indicated that 11 distinct extinguishing agents were employed in the aforementioned exercise, and the effects produced were quantified and assessed with the aid of a thermal camera (İstanbul Metropolitan Municipality Fire Department, 2024).

A review of the occurrence of battery fires in electric vehicles, related safety issues and fire protection strategies, as presented by Brzezinska and Bryant. It has been posited that as the market share of electric vehicles continues to expand, the incidence of fires resulting from accidents involving such vehicles has concomitantly increased. It was asserted that pragmatic engineering methodologies for mitigating the risk of fire in electric vehicles are constrained. In this context, it was posited that the generally accepted heat release rate (HRR) for fire engineering design in car parks is approximately 7 MW. It has been demonstrated that the rate of growth of fires in propulsion batteries in electric vehicles is significantly faster than in vehicles powered by conventional fuels. The findings of the study, which employed fire dynamic simulation (CFD) to anticipate the dispersion of smoke and temperature during an electric vehicle fire, are presented herein. This demonstrates that as the fire intensifies, the temperature within the garage rises and visibility declines. This indicates that the circumstances under which people may be safely removed from the garage are becoming increasingly unfavourable. It is indicated that the estimated evacuation time for individuals may vary according to the intended purpose of the garage. The objective of the fire dynamic simulations (CFD) conducted in this context is to ascertain whether an electric vehicle fire in a garage presents a risk to individuals who may be trapped inside and whether there is sufficient time to evacuate before the critical boundary conditions of the fire occur (Brzezinska ve Bryant, 2022).

Dorsz and Lewandowski conducted a comparative analysis of the characteristics of fires in electric and internal combustion engine cars. The utilisation of fire dynamic simulations (CFD) facilitated the attainment of results pertaining to the impact of fire on life and property safety in enclosed structures. It is therefore imperative that fire prevention and extinguishing systems are correctly designed in existing building and tunnel structures to cater for the potential occurrence of battery electric vehicle fires in underground garages or tunnels. In the event of a fire, ventilation or sprinkler system are provided to indicate the horizontal escape routes of individuals in danger and to facilitate favourable conditions for evacuation. It is observed that the available data for these systems, which form the basis of rescue and firefighting operations, is inadequate (Dorsz & Lewandowski,2022).

The primary distinction between the origin, progression, and extinguishing of fires in electric vehicles and those in conventional vehicles lies in the utilisation of lithium-ion (Li-ion), nickel metal hydride (Ni-MH), and other similar components in the drive battery for energy storage (Iclodean et al., 2017). In contrast to conventional liquid or gas fuel tanks (petrol, diesel, LPG, CNG), the principal distinctions between these alternative energy sources lie in the electric traction motor, on-board charger, charging port, DC/DC converter and other power electronics components, as well as the thermal systems employed to regulate them (Larminie & Lowry,2003). The batteries used in electric vehicles are considered to be the main source of hazard, as they are susceptible to a number of influences, including mechanical, thermal and electrical, which can lead to the initiation and/or growth of fire. Similarly, in the case of traction batteries, the higher the temperature of the chemistry, the more exothermic the reaction chain, especially when it comes to the dangerous heating curve. The thermal effects of the reaction cause a significant increase in heat released. As a result, there may be a fire or explosion hazard (Hou et al., 2020). In this context, it is asserted that a multitude of factors exert an influence on the drive battery. Such incidents may include instances of overcharging, short circuits, mechanical impact (such as the penetration of the cell by a nail or other object), and thermal impact (exposure to extreme temperatures) (Bisschop et al., 2020). The analysis also encompasses other factors, including the state of charge (SoC), the state of health (SoH), the capacity and energy density of the battery, and the ambient temperature (Essl et al.,2020).

The occurrence of fires in electric vehicles in enclosed spaces, such as road tunnels and car parks, has given rise to concerns among the general public. This situation gives rise to measures such as the prohibition of the parking of electric vehicles, particularly in enclosed car parks. It is an inevitable consequence of the success of electromobility that electric vehicles will become widespread, thereby reducing the use of fossil fuels and increasing the use of renewable energy. It was highlighted that technical solutions should be implemented to address the fire risks and potential consequences associated with electric vehicles. The study concluded that a comprehensive risk assessment and systematic hazard identification are necessary for electric vehicle fires. A workshop was convened with representatives from three distinct fire and rescue organisations in Sweden. The efficacy of emergency rescue forms/response manuals was evaluated, and the results are presented below. It is therefore recommended that improvements be made to the statistics on electric vehicle fires, as the data currently available lacks information on the main causes of such fires. Such a course of action could result in the introduction of new regulatory measures that lack a robust and evidence-based foundation. The data analysed by Hynynen et al. indicates that fires in electric vehicles are no more common than in vehicles with internal combustion engines. It has been argued that the most effective risk mitigation measure to limit the spread of EV fires is the implementation of appropriate infrastructural arrangements. The implementation of fire detection and extinguishing systems, in addition to the creation of a safe distance between parked vehicles, are regarded as fundamental strategies (Hynynen et al.,2023). In a study on safety approaches to electric vehicle fires that may occur in underground car parks, it is stated that, in comparison to conventional internal combustion vehicles with high sales values and high prevalence, electric vehicles give rise to concerns regarding fire safety.

Boehmer et al. and Bisschop et al. conducted a study on the safety approaches to electric vehicle fires that may occur in underground car parks. It has been asserted that electric vehicles give rise to concerns regarding fire safety when compared to conventional internal combustion vehicles, which are currently in high demand and widely prevalent. Furthermore, it was posited that these concerns have been exacerbated by the occurrence of electric vehicle fires in previous years. It has been established that the majority of fires in electric vehicles are caused by thermal leakage from the drive batteries. Furthermore, it has been demonstrated that the phenomenon in question is caused by external fires that occur as a result of thermal runaway, which manifests spontaneously in parking lots or while driving, and sometimes following traffic accidents (Wang et al., 2012).

It has been posited that the most significant aspect of drive battery fire dynamics in electric vehicles is the battery material and chemistry (Ouyang et al.,2019). The safety of lithium-based battery packs is a topic of concern, particularly in relation to their scale of use and energy density (Ouyang et al.,2019). The deformation of electric vehicle drive batteries can result in the generation of sparks, flammable gases and the release of toxic chemicals as a consequence of combustion (Tobishime et al.,1999). The aforementioned issues have the potential to result in the ignition of a fire, which may subsequently evolve into a combustion process and/or a gas explosion. While a typical electric vehicle drive battery system is unlikely to ignite in normal conditions, external influences, including thermal, mechanical, and electrical factors, may lead to such an outcome when the battery is subjected to unfavourable operating conditions or collision accidents (Liu et al., 2021).

The presence of low ceilings, particularly in enclosed parking facilities, serves to facilitate the propagation of fire and may impede the implementation of rescue operations. The rise in the overall number of electric vehicles is also driving the installation of electric vehicle charging stations in public car parks, which represents a novel risk factor for car park fires. In light of these considerations, Sun et al. propose the prohibition of electric vehicle charging in parking facilities or the imposition of restrictions on the number and density of parked vehicles (Sun et al.,2020).

In the context of fire assessments involving electric vehicles, the drive battery is frequently identified as the primary causal factor. However, that electric vehicle battery fires can be caused by a number of factors, including charging system failures, overloading of high-voltage power cables or external interventions (such as arson) UK Road Vehicle Fires Dataset,2019) (Huang & Nakamura, 2020). A study conducted by the Swedish Research Institute has revealed that the failure of an electric vehicle drive battery can result in a range of potential consequences, including ventilation, fire and an internal explosion of the battery cells. Furthermore, it is indicated that in the event of the accumulation of gas from the batteries within a confined space of the vehicle body, an external explosion may occur beyond the boundaries of the battery pack. However, such external explosions are not included in the assessment of the drive batteries during the validation tests (Bisschop et al.,2019).

The occurrence of fires in electric vehicles can be attributed to one or more of the following potential causal factors (Sun et al., 2020).

The ignition of a fire in an electric vehicle may be caused by a number of factors, including exposure to extreme weather conditions (such as low or high temperatures and high humidity) or damage caused by saltwater. Internal cell failure may also be a contributing factor.

A fire may be ignited during the charging of an electric vehicle. This may be caused by overcharging, the presence of faulty or unsafe charging stations, or installation-related faults.

In the event of an electric vehicle being involved in a collision or other form of damage, or if the road surface is uneven, the fire will continue to burn.

In instances where fires have been observed in electric vehicle batteries, it has been noted that the fire may rekindle due to thermal leakage, which may occur even after the initial fire has been extinguished.

It has been posited that thermal leakage, resulting from a markedly elevated battery temperature, represents the primary causal factor in the aforementioned incidents of electric vehicle fires (Babrauskas,2003). The occurrence of thermal runaways in batteries is frequently accompanied by the emission of smoke, sparks and flames. Furthermore, the release of gas in a confined space may result in an explosive reaction if the accumulated gas is in contact with the surrounding oxygen. Conversely, when the ambient temperature is low, the temperature gradient experienced by the cells within the drive battery packs results in a reduction in performance. In this regard, there is a notable elevation in the internal resistance value. In such circumstances, an additional thermal effect may be generated, thereby increasing the probability of fire. It is therefore recommended that electric vehicles be stored in a closed garage, particularly when not in use, in order to protect them from exposure to extreme temperatures, both hot and cold, which may be experienced outdoors. Conversely, electric vehicles are anticipated to be recharged with minimal delay and to offer high driving dynamics. In particular, the intensive charging and discharging of the drive battery cells, in conjunction with other drive components that generate external heat, can result in a Joule effect within the drive battery structure. Furthermore, this situation has the potential to elicit unintentional chemical reactions, which could result in an internal short circuit. The utilisation of rapid charging techniques, particularly those conducted in parking facilities, is regarded as one of the most hazardous concerns within this domain. It can be reasonably deduced that the following factors contribute to an elevated risk of fire: the lack of competence of the service provided for electric vehicles; the absence of technical standards for the charging station and its sub-components; and the BMS functions that do not possess sufficient safety parameters (Larsson & Mellander, 2017)

In the event of thermal runaway, which can be triggered by mechanical, thermal and electrical damage occurring in batteries, a reduction in voltage level is observed as a consequence of damage to the electrodes in the battery cells. The pressure within the battery pack rises as a consequence of the chemical reaction between the active materials, the evaporation of the organic electrolyte, and the formation of a flammable gas. This results in the accumulation of gas within the battery pack (Kong et al., 2018). In this context, it is stated that the primary parameters to be measured during the testing of propulsion batteries are voltage, current, and temperature (IEC Standart Part 2 Reliability and Abuse Testing). Furthermore, it is postulated that the ramifications of electric vehicle fires that may transpire in indoor parking lots will be considerably more grave than those in outdoor settings.

The Heat Release Rate (HRR) value serves as the foundation for evaluating potential fire hazards. This parameter, which corresponds to the total heat release value caused by the fire, provides a standardised measurement approach for the size of the fire that occurs. It serves as a point of reference for the design of security systems intended to mitigate the risk of fire in parking lots, particularly in the context of electric vehicles. The heat release rate (HRR) is calculated in accordance with the Equation (1.1) and Equation (1.2) below.

$$HRR \ = m \, \Delta \mathrm{He} \tag{1.1}$$

$$HRR = \ Af \ m'' \eta \ \Delta \mathrm{H \ c} \tag{1.2}$$

In this context,

- m is the combustion rate, determined by the mass loss rate obtained from the test and expressed in kilograms per second (kg/s).
- ΔHe is the heat of combustion, expressed in megajoules per kilogram (MJ/kg).
- Af is the base or surface area of the fuel or fire, which serves as the basis for the electric vehicle.
- m″ is the combustion flux, expressed in kilograms per square metre per second (kg/$m^2$/s).
- ŋ, is the combustion efficiency, dependent upon the source of oxygen. The heat of combustion value for electric vehicle propulsion batteries,
- ΔHc, is contingent upon the specific type of propulsion battery employed and the battery charge rate (state of charge, SoC).

There are a number of different approaches that can be taken with regard to the fire size caused by the electric vehicle drive battery. It is notable that the 2250 kg Tesla Model S is equipped with a propulsion battery comprising a total of 18,650 individual cells, with each cell weighing 45 g. It is therefore evident that the heat release rate (HRR) value can vary considerably, from a few kW for a battery cell to several hundred kW for a single EV battery module and up to MW for a full capacity electric vehicle propulsion battery pack (Sun et al., 2020) (Liu et al., 2016). The fundamental premise is contingent upon the point of origin of the fire reaction, which may manifest as a cell, module, or package.

Furthermore, the energy released in the event of an electric vehicle fire can be quantified through the calculation of the average heat flux (q″) of the battery pack and its surface area. In order to facilitate the calculations, it would be appropriate to assume that the battery charge rate (state of charge, SOC) is 100%, which represents the most adverse fire scenario. To illustrate the functionality of an electric vehicle powered by a propulsion battery with Lithium Titanate (LTO) chemistry, it can be observed that the average heat flux (q″) is approximately 2.3 MW/$m^2$ when the battery capacity is 100%. Assuming a traction battery area of approximately 3 $m^2$ (Af), the average heat release rate (HRR) of an electric vehicle fire can be calculated using Equation (1.3).

$$HRR = \ Af \ q'' = \ 3 \, m2 \ \times \ 2.3 \, MW/m2 \ \approx \ 7 \ MW \tag{1.3}$$

The calculated heat release rate (HRR) value is also employed in the determination of the quantity of water or alternative fire-extinguishing agents that are necessary in the event of an electric vehicle fire (US Department of Transportation 2014).

## Strategies for Reducing Fire Severity and Enhancing Fire Suppression

The extinguishing of battery fires in electric vehicles is a challenging endeavour, necessitating the use of significant quantities of extinguishing agents. It has been observed that, on occasion, the potential for re-ignition to occur following the extinguishing process may manifest randomly. Extinguishing electric vehicle battery fires in full-scale tests has demonstrated that the quantity of water necessary to extinguish such fires can range from 2,500 to 6,000 litres, which exceeds the water capacity of a standard fire truck. Furthermore, it has been documented that the recommended liquid flow rate for quenching and cooling purposes is relatively high, with a rate of approximately 200 litres per minute (VDA, 2017) (Zhang et al., 2022).

It is generally accepted that in the event of an electric vehicle fire caused by a drive battery, the most appropriate course of action is to cool the source. It is often challenging to gain access to the fire area due to the fact that the battery pack is frequently situated in locations that are difficult to reach. Conversely, the efficacy of cooling and suppressing agents other than water is frequently called into question. The utilisation of chemical substances represents one of the principal methods of fire control. Whilst such substances are effective in extinguishing flames, the potential for explosion is heightened with the accumulation of flammable gases. It has been demonstrated that in instances where only carbon dioxide or other chemical agents are employed to extinguish a battery fire, the fire can be successfully contained; however, the battery pack remains uncooled and unreignited. Consequently, in the context of cooling and controlling electric vehicle drive battery fires, despite the potential negative effects, such as short circuits or toxic discharge, water is currently regarded as the most effective intervention method for cooling electric vehicle fires, despite the inherent risks (Schiemann et al., 2016) ( Bisschop et al., 2019).

Large-scale fire tests utilising water mist systems have been conducted by Colella. The findings indicated that water mist can be an effective method for regulating fire temperatures (Colella, 2016).

In light of the rising number of electric vehicle (EV) charging stations, the National Fire Protection Association (NFPA) of America has developed a set of standards aimed at enhancing safety. These standards recommend that EVs with damaged or depleted drive batteries be stored or parked at a minimum distance of 15 metres from charging stations, flammable materials, and other vehicles. Furthermore, the recommendation is that the charging process be conducted for interventions and/or approaches (detections), with monitoring of the operations conducted via a thermal camera (NFPA, 2024)

Conversely, in contrast to the NFPA, the SAE J2293 and J1772 standards stipulate that electric vehicles should be stored in areas with fireproof walls on three sides and a minimum of 15 metres of open space on the fourth side until the requisite inspections have been completed in accordance with the procedures set out in SAE J2990. It is recommended that ventilation be provided to facilitate the circulation of potentially hazardous gases and that the vehicle be protected from precipitation in the event of an opening (or potential damage or fragmentation) in the drive battery shell (SAE International, 2024).

In addition, the EDUCAM information and training platform on the use of electric vehicles stipulates that, in the event of a fire in an electric vehicle, the relevant emergency response guide must be followed (Educam, 2024):

- It is therefore imperative that the auxiliary battery employed for low-voltage systems be disconnected,

- In order to safeguard the item from all surrounding elements, a safety distance of 10 metres must be maintained for a minimum of 48 hours, with a further 2 metres of safety distance to be observed after this period,

- Furthermore, the manufacturer's instructions indicate that the product should not be deployed inside buildings and that, in the event of leakage, the area should be isolated using an appropriate collection device.

## Fire Safety Standards and Simulation Techniques in Parking Facilities

In the event of a fire in a confined space, it is imperative that the relevant safety measures are put in place to ensure the protection of individuals. In this context, it is stated that simulations (CFD) should be conducted to ensure the safety of individuals in the event of an electric vehicle fire in a closed garage. In light of the CFD simulation results, which demonstrate the feasibility of meeting the specified evacuation time requirements in the event of a fire, it can be stated that as the fire progresses, the temperature within the garage will increase and visibility will diminish. Although this situation has a negative impact on the ability to evacuate from the garage, it is important to note that the fire brigade teams that will respond should commence extinguishing operations at the scene of the incident. Additionally, the fire flames should not exceed a height of 1.8 metres above the ground, and the ambient temperature should not exceed 60 °C (British Standards Institution, PD 7974-6:2004, 2019).

In accordance with the parking regulations currently in force in Türkiye, all newly constructed parking lots with a capacity of more than 20 vehicles are required to allocate at least 10% of their total number of spaces to electric vehicles. Furthermore, the installation of charging stations in these parking lots is also mandatory. It is recommended that at least one charging station be installed for every ten electric vehicle parking spaces. Furthermore, the charging stations should be situated in the closest possible proximity to the electric vehicle parking spaces, and their technical specifications must comply with the conditions specified in the relevant regulations. Furthermore, the regulation stipulates a transition period for existing parking lots. Consequently, it is obligatory to reserve 10% of electric vehicle parking spaces and install charging stations in these parking lots by 2026 ([Otopark Yönetmeliği]). Conversely, the Electric Vehicle Charging Stations Regulation in Türkiye encompasses the requisite permits and licenses for the establishment of charging stations, the technical specifications of charging stations, and the operation and inspection of charging stations (EPDK, 2017) (TC Ministry of Environment and Urbanization,2018).

In addition, the selection of the agent employed in fire-fighting operations merits consideration in the context of electric vehicles. In this context, the most commonly recommended extinguishing agents by manufacturers of Li-ion batteries are water, chemical/dry powder, CO2 and dry-foam. It is important to consider the potential drawbacks of water, as it can release lithium and facilitate its reaction with hydrogen, which could result in further adverse outcomes (Ghiji et al., 2020) (Park, 2013). Despite the cooling effect of water, which has a detrimental impact on short circuits and the flow/exit of toxic liquids and gases, it is currently regarded as the most effective and accurate extinguishing method. In this context, it is asserted that the practice of throwing a burning vehicle into a water-filled container has commenced in numerous countries across the globe (Rosenbauer America 2022).

The risk of fire in a parking lot caused by an electric vehicle is a significant concern, particularly in relation to the potential impact on emergency response teams. In this instance, it is imperative that the fire be contained. In the context of underground parking facilities, it is of paramount importance to ensure that physical access to the fire scene is conducted in a safe and secure manner, with the objective of reaching the burning vehicle. It is essential to ensure adequate ventilation of the environment and the prompt evacuation of smoke. In some instances, camera systems deployed at the scene of a fire may be able to identify the point of origin. Nevertheless, in the absence of any other identifying features, it becomes exceedingly challenging for emergency response teams to ascertain the vehicle that initiated the fire. In this context, it is necessary to ascertain whether the vehicle in question is an electric vehicle, once it has been physically reached. It may prove challenging to discern the brand, model, writing, emblem, and other identifying elements among the dense smoke. Nevertheless, in the event that the device is connected to a power source, it is crucial to ascertain the specific charging cable that is linked to the charger, as this can serve as a crucial identifier. It is established that inhaling the smoke produced during fire-fighting operations is a significant health hazard. It has been asserted that this phenomenon, which is not solely attributable to the battery, is significantly prevalent due to the combustion of the carbon fibre structural components employed for the purpose of reducing the weight of electric vehicles (Coldcut Systems, 2024).

The diverse chemical compositions of electric vehicle propulsion batteries may exhibit disparate behaviours in the event of potential thermal runaway. To illustrate, the maximum resistance temperature in cells utilising lithium iron phosphate (LFP) chemistry is approximately 600 °C, whereas this value rises to over 1000 °C in cells employing nickel manganese cobalt oxide (NMC) chemistry. Conversely, it has been demonstrated that in the event of thermal runaway in cells utilising LFP chemistry, the particle ejection is less pronounced than in cells employing NMC chemistry. This can result in disparate consequences for the surrounding environment, particularly in terms of dispersion. Conversely, cells utilising LFP and low-nickel content NMC chemistries exhibit reduced energy density. Consequently, even in the event of a cell catching fire, the probability of the fire spreading to neighbouring cells is deemed to be low. Furthermore, the diverse cells within the drive batteries utilized in electric vehicles are distinguished by their morphology and dimensions. To illustrate, cylindrical and prismatic cells are equipped with natural ventilation capabilities as a consequence of their intrinsic design. Furthermore, given that cells with diminished energy capacity are capable of storing less energy, the potential for thermal runaway is also less pronounced in comparison to larger cells.

Battery management systems that are capable of meeting the requisite safety standards are designed to ensure that each cell of the drive battery operates within safe limits, while simultaneously managing the energy and thermal effects within the battery at the pack level. This is of critical importance to the safe and efficient operation of the battery. In this context, the thermal management provided by the battery management system ensures effective and sustainable conditions are maintained to avoid high thermal stresses caused by excessive heat, following periods of power-intensive driving or fast charging. In this context, following the conclusion of a period of intensive driving or fast charging, the battery management system enables the thermal management system to operate in an effective manner. This guarantees the implementation of effective and sustainable measures to prevent the occurrence of elevated thermal stresses resulting from the presence of excessive heat. Furthermore, the utilisation of thermal insulation between modules and cells in battery packs serves to mitigate the risk of thermal runaway scenarios. The insulation of intercellular spaces can be achieved through the use of foams, sheets, or resins, which effectively prevent the transfer of heat between cells by providing a thermal barrier. Nevertheless, the cooling of a thermally isolated cell is also challenging due to the limited cooling capacity resulting from the system isolation. This limitation is particularly evident. This approach has the indirect effect of reducing the amount of heat that can be removed from the cells, while simultaneously limiting the speed at which the cells can be charged and the high performance requirements. In addition to the density of the cells and/or modules in the battery packs and the insulation between them, the material from which the outer shell of the battery is made is also a significant factor. In the unlikely event of a fire, the use of electro-coated steel with a melting point above 1500 °C will prove to be a more effective form of protection than aluminium and some polymer composites. Additionally, the selection of appropriate interface materials is crucial. Adhesives with high thermal conductivity are essential to facilitate efficient heat transfer to heat sink surfaces or cooling plates at the cell level. Conversely, the utilisation of thermal insulation and flame retardant materials positioned between the cells serves to effectively impede the transfer of unwanted heat. It is imperative that such materials are of a structure that does not produce toxic fumes. It is considered that this constitutes an important design input, providing additional time for passenger evacuation in the event of an electric vehicle fire.
Consequently, an array of studies is currently underway, with the objective of integrating machine learning and artificial intelligence models – two of the most prevalent approaches in the field today – into battery management systems. The application of artificial intelligence (AI) to the design and testing processes for propulsion batteries is a promising avenue of research, particularly with regard to the enhancement of safety and the mitigation of thermal runaway. Notwithstanding the difficulties inherent in simulating propulsion batteries through on-board testing, the prevailing approach to validation is to conduct physical testing to ascertain that different cell chemistries meet performance requirements and that safety standards are met under varying conditions. The training of artificial intelligence applications used in battery management systems in propulsion batteries is primarily based on three types of data: typical measurement data from batteries, live data from electric vehicle fleets, and offline data from battery packs. The

algorithms in question employ a combination of signal processing techniques to extract insights from measurement data, which are then subjected to machine learning models in order to extract diagnostic and thermal runaway-related risk information from these insights. This innovative approach has the potential to significantly reduce thermal risks to drive batteries and is regarded as an effective method for integrating battery expertise and modern machine learning (Thermal Hazard Technology,2024).

### Analysis and Case Studies of Electric Vehicle Fire Incidents

In October 2013, on a highway in Washington State, an incident occurred that was to become known as the first mass-produced electric car fire in the world. A piece of metal came into direct contact with the modules in the battery pack, resulting in the vehicle being completely burned. It is confirmed that no fatalities or injuries were sustained by any of those involved in this incident. The inaugural fatality resulting from an electric vehicle fire occurred in May 2018. It has been documented that this fire occurred subsequent to an incident in Florida, wherein an electric vehicle that was exceeding the speed limit veered off the roadway (NTSB, 2020).

As reported by the International Energy Agency, approximately 14 million new electric vehicles were registered globally in 2023, resulting in a total of 40 million electric vehicles on the road. A total of 511 confirmed, officially recorded electric vehicle fires have occurred worldwide between 2010 and 2024 (as of June 2024), according to data from Australian government fire agencies. In consequence, 117 fires were documented in underground or enclosed garages, 173 fires occurred in outdoor settings with vehicles parked, and 155 fires occurred while individuals were operating motor vehicles. Furthermore, no documentation was available for 67 fires. Furthermore, the report indicates that 489 fires were initiated by sparks or jet-like directional flames, while 22 fires commenced with the presence of dense smoke, followed by an explosion and subsequently by intense flames. The available records indicate that 80 fires occurred during the charging process of electric vehicles, while 10 fires occurred at the maximum of 60 minutes after the end of the charging process (Austalia Defence Department, 2024).

This study also considers electric buses, with a particular focus on those with high battery capacity and used in public transportation systems. By 2022, the number of electric buses in use in public transportation systems worldwide had exceeded 800,000, representing more than 3% of the total number of buses. In 2022, approximately 66,000 electric buses were sold worldwide, with China accounting for 54,000 of these, representing approximately 4.5% of all bus sales. It is projected that the number of electric buses in operation will reach 1.4 million in 2025 and 2.7 million in 2030, with one in ten buses expected to be electric (BloombergNEF, 2023).

Accordingly, a review of official records from around the globe revealed that at least 27 high-voltage drive battery fires occurred in electric buses utilized in public transportation systems between 2010 and 2024 (June 30). As evidenced in the aforementioned records, one fire originated in the maintenance and repair workshop, while 12 fires occurred in garages during the act of parking. Similarly, it is stated that 7 fires occurred during the charging process (while the plug was connected), and a further 7 fires occurred by spillover from other fires that were affecting each other. (Austalia Defence Department, 2024).

From the perspective of emergency response to fire situations on electric buses, this significant challenge also pertains to the location of the batteries. The drive batteries of low-floor buses, particularly those designed for disabled access, are often mounted on the roof rather than inside the chassis, as is the case with electric vehicles of the M1 class. This design approach allows for the integration of roof-mounted batteries into conversion projects involving existing diesel buses, while also reducing the need for cooling due to natural air circulation while driving. In the event of thermal runaway in the drive batteries of electric buses, there are no issues with delivering water for cooling, as is the case with chassis-integrated drive batteries in electric vehicles.

It is not possible to obtain specific official records on electric vehicle fires in Türkiye. However, according to the information reflected in the visual and written media, the most prominent cases of electric vehicle fires in Türkiye over the past year have been those occurring during charging in Gaziantep, while the vehicle was being towed by a tow truck on the highway in Adana, and in Istanbul, where a total of six electric vehicles were burned on a truck trailer. In addition, there was one death in the city of Kayseri.

Some of the details of the electric bus fires that were mentioned above are included in this section.

As shown in Figure 1, in accordance with the aforementioned, a fire occurred in the area where electric buses are stationed for charging in Shenzhen, China, where the use of electric buses is the most prevalent. It has been stated that the charging process did not take place. The incident in question is understood to have occurred in a warehouse parking lot that is enclosed on three sides.


**Figure 1** Electric bus fire in Shenzhen, China (EVfiresafe,2024)

It has been reported that in Düsseldorf, Germany, in 2021, in the garage where a total of 40 electric and diesel buses were deployed, all of the buses were burned and extensive damage occurred in the fire. Figure 2 illustrates the visual representation of the incident as it was presented in the press. The cause of the fire is currently unknown.

**Figure 2** Electric bus fire in Düsseldorf, Germany (EVfiresafe, 2024)

In a further incident that occurred in Hannover, Germany in 2021, it is documented that five electric buses, two hybrid electric buses and one diesel bus caught fire in the garage where the buses were located. Figure 3 indicates the manner in which the incident was represented in the press following the fire. Also there is no data available to indicate whether the buses were undergoing charging at the time.

**Figure 3** Electric bus fire in Hannover, Germany (Sustainable Bus Magazine, 2023)

In the incident that resulted in the burning of 25 electric buses (Mercedes eCitaro) in Stuttgart, Germany in 2021, it was stated that the charging centre and garage were completely burned along with the buses in the fire that broke out due to a technical malfunction during the charging process. In Figure 4, the visual presented in the aftermath of the fire event.

**Figure 4** Electric bus fire in Stuttgart, Germany (Sustainable Bus Magazine, 2021)

It has been reported that 149 electric buses of the same make and model operating in Paris have been taken out of service for safety reasons due to the successive fires in 2021 in two electric buses (Bolloré Bluebus) operated by RATP in Paris, France and used since 2016. The image of the bus engulfed in flames during the trip is shown in Figure 5. In consequence of these incidents, the entire fleet has been withdrawn from service.

**Figure 5** Electric bus fire in Paris, France (Ile-de-France, 2023)

In Türkiye, electric buses, which have been supplied by different local governments in various specifications since 2016, are currently being utilised in the public transportation system. In accordance with the aforementioned, in Türkiye, contracts have been concluded for a total of 241 electric buses, with a length ranging from 6 metres to 25 metres. The fires that occurred in 3 electric buses at disparate times were recorded. Two of the fires were reported to have occurred in garages. The fires occurred in electric buses operated by ESHOT in Izmir. In total, there were five electric buses involved in the incidents. Figure 6 illustrates the use of The combustion of electric buses in public transportation in Izmir, as reported in the local press.

**Figure 6** Electric bus fire in İzmir, Türkiye (Yeniasır, 2021)

In Guangxi, China, in 2021, it was reported that four buses had been completely burned down due to an unidentified fire in one of the electric buses that had been parked in an entirely open area. Figure 7 presents a visual representation of the incident.

**Figure 7** Electric bus fire in Guangxi, China (South China Morning Post, 2021)

In the City of London, England, it was reported that a total of six electric buses were damaged in a fire that broke out in electric buses operated by Transport for London (TfL) in 2022. In the City of London, England, it was reported that a total of 6 electric buses were damaged in a fire that broke out in electric buses operated by Transport for London (TfL) in 2022. It was reported that as a result of the investigation into the causes of the fire at Potters Garage, operated by Metroline, a decision was taken to withdraw 90 electric buses from operation as a precautionary measure. Also It was reported that, following a fire on a double-decker electric bus operated by Transport for London (TfL) in London, electric buses on the affected route were removed from service as a precaution in January 2024. The visual representations of both events are presented in Figure 8.

**Figure 8** Electric bus fires in London, England (BBC News 2022,2024)

## Assessment and Conclusions: Key Insights and Implications

The findings of the statistical analysis and literature review indicate that there is no clear indication that the charging of electric vehicles in parking garages will increase the probability of fire. In consideration of the extant regulations pertaining to electric vehicle charging points, it is determined that the fire risk associated with the charging of electric vehicles in parking garages is within an acceptable range. A series of tests conducted by NFPA in 2023 revealed that electric and internal combustion engine vehicles exhibit comparable combustion temperatures (Brandt & Glansberg, 2020). It is additionally observed that fires in electric vehicles do not result in a considerable enhancement in heat dissipation when compared to conventional vehicles, which utilise diesel or gasoline engines. It is thus concluded that the necessity for fixed water-based fire extinguishing systems in parking garages will be adequate for those where electric vehicles can be charged. However, the potential for fires caused by electric vehicle drive batteries in parking garages should be taken into consideration. Such fires are likely to spread more rapidly. It is thus concluded that the necessity for fixed water-based fire extinguishing systems in parking garages will be adequate for those where electric vehicles can be charged. It is important to note that fires occurring in parking garages tend to spread at a faster rate than fires caused by electric vehicle drive batteries.

In this context, it is important to distinguish electric vehicle fires from fires in electric vehicle traction batteries. As electric vehicle fires have similar characteristics to fires in conventional motor vehicles, the extinguishing and intervention methods for such fires are also similar. If a fire in an electric vehicle starts at a location other than the traction battery, taking into account the time it takes for the fire to reach the temperature to cause thermal runaway in the battery, technical intervention methods such as fire extinguishing works or automatic extinguishing systems should be applied in the same way as for conventional vehicle fires. On the other hand, the fire-fighting measures are different if the fire starts directly in the battery pack or if the battery is exposed to high temperatures for long enough for the fire to spread to the battery pack. In M1 class vehicles, the battery packs are generally located inside the vehicle and under the chassis to provide effective isolation from the external environment. This makes it difficult to access the batteries from the outside and prevents water from entering the pack due to the insulation provided in accordance with the battery standards, which makes it difficult to intervene directly in the fire. It is very difficult to stop the chemical reactions that cause thermal runaway in the cells inside the pack without physically opening the pack. It may be possible to achieve adequate cooling of the cells in question using methods of intervention that require the use of large quantities of water. In this context, if the temperature inside the battery is not reduced sufficiently, it may lead to a re-ignition, even if the fire appears to have been extinguished.

It is recommended to monitor the battery pack with a thermal imager to check the temperature of the traction battery in electric vehicles. However, thermal cameras are only able to detect the temperature of the surface of the battery. Therefore, in order to check that the surface temperature has not risen again, the cooling process should be interrupted, a certain period of time should be allowed to elapse, and then the intervention process should be continued with the following check.

The most appropriate fire-fighting scenario for electric vehicles, even in cases where the traction battery temperature is high, is to ensure the safety of the surroundings before moving the vehicle, to intervene where the vehicle is located and, if possible, to extinguish the fire. In the next stage, it may be preferable to allow the vehicle to burn out or to continue cooling the battery pack until the temperature of the battery pack has reached a sufficiently low level in a position where the safety conditions of the vehicle are met. In the case of fires in enclosed car parks, this will depend on the layout of the car park (e.g. multi-storey or multi-pillar structures), the location of the vehicle in the car park, the availability of the necessary equipment to remove it and the availability of competent emergency response personnel to carry out this activity. The most important case is to start work as soon as possible and to prevent the spread of fire from the fire engine to other vehicles.

In the case of uninterrupted water flow in electric vehicle fires, the research reports state that the risk of electric shock from electric vehicle high-voltage batteries is very low and there are no global case records for emergency services. However, given that electric vehicles may always be live during the operations to be carried out, maximum care must be taken to ensure that appropriate personal protective equipment is used and that the body of the vehicle does not come into contact with high-voltage cables and other basic high-voltage components, which are coloured orange according to the standards.

In addition, the rotation of the wheels, particularly when transporting an electric vehicle with a partially burnt-out traction battery after an accident, can cause the regenerative braking system to be activated and power to be supplied to the traction battery. This situation should be considered as an important issue that represents a risk of battery re-ignition. Tow-truck operators, especially for electric vehicles, should be specially trained in emergency procedures and, if possible, the vehicle should be transported on a vehicle (e.g. a flatbed) rather than towed.

As a result, the existing regulations for electric vehicle charging points are considered sufficient to keep the fire risk that may arise from charging electric vehicles in car parks at an acceptable level. In this context, the need for fixed water-based fire extinguishing systems in indoor car parks where electric vehicles can be charged is assessed at a similar level to other car parks. In addition, it is essential that charging stations and their installations comply with applicable legislation and that the use recommendations of vehicle and charging station manufacturers are followed. For this reason, it should be noted that wall sockets and, in particular, extension cords that are not designed for vehicle charging should be avoided.

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