UDC 614.8

Comparative Analysis of the Fire Hazard of Electric Vehicles

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At present, the issue of the active introduction of electric vehicles — as well as their hybrid variants — into the global automobile market in general and the domestic market in particular has become highly relevant. One of the main reasons for the development of the electric-vehicle market in Kazakhstan is economic feasibility. The explanation is simple: electricity is cheaper than gasoline. The following data illustrate this point.

Passenger cars with gasoline engines in a combined city/highway driving mode consume on average 7–10 liters per 100 kilometers. Popular crossovers already consume 10–12 liters per 100 kilometers. Large SUVs, even diesel ones, use about 11–14 liters of fuel per 100 km, while powerful luxury vehicles consume 15–20 liters. If we take the average national fuel price at the beginning of 2024 as 200 tenge per liter, then every 100 kilometers traveled by an internal combustion engine vehicle costs approximately 2,000–4,000 tenge, depending on the vehicle class.

The average electricity consumption of a typical electric vehicle in mixed driving conditions is about 20 kWh, costing approximately 1,000–1,600 tenge per 100 kilometers depending on the type of charging station.

The simplicity of the electric-vehicle design results in simpler and therefore less expensive maintenance.

Another important reason for the intensive adoption of electric vehicles in Kazakhstan is environmental concerns of a global nature. People observe the impact of traditional transport on air pollution and recognize the importance of introducing green technologies not only in the energy sector but also in transportation, seeking more environmentally friendly alternatives. Electric vehicles meet these requirements well.

Electric vehicles offer a cleaner and more environmentally friendly mode of transport, attracting consumers concerned about environmental protection. In addition, rising fuel prices and society's movement toward decarbonization have also contributed to growing demand for electric vehicles in Kazakhstan.

The absolute number of electric vehicles in Kazakhstan remains small. According to [1], in 2023 the share of electric vehicles amounted to only 0.11% of the vehicle fleet, whereas during the same period of the previous year the figure was only 0.01% of all registered passenger cars. Figure 1 shows the ratio of the total number of vehicles to electric vehicles in Kazakhstan for 2022–2023.

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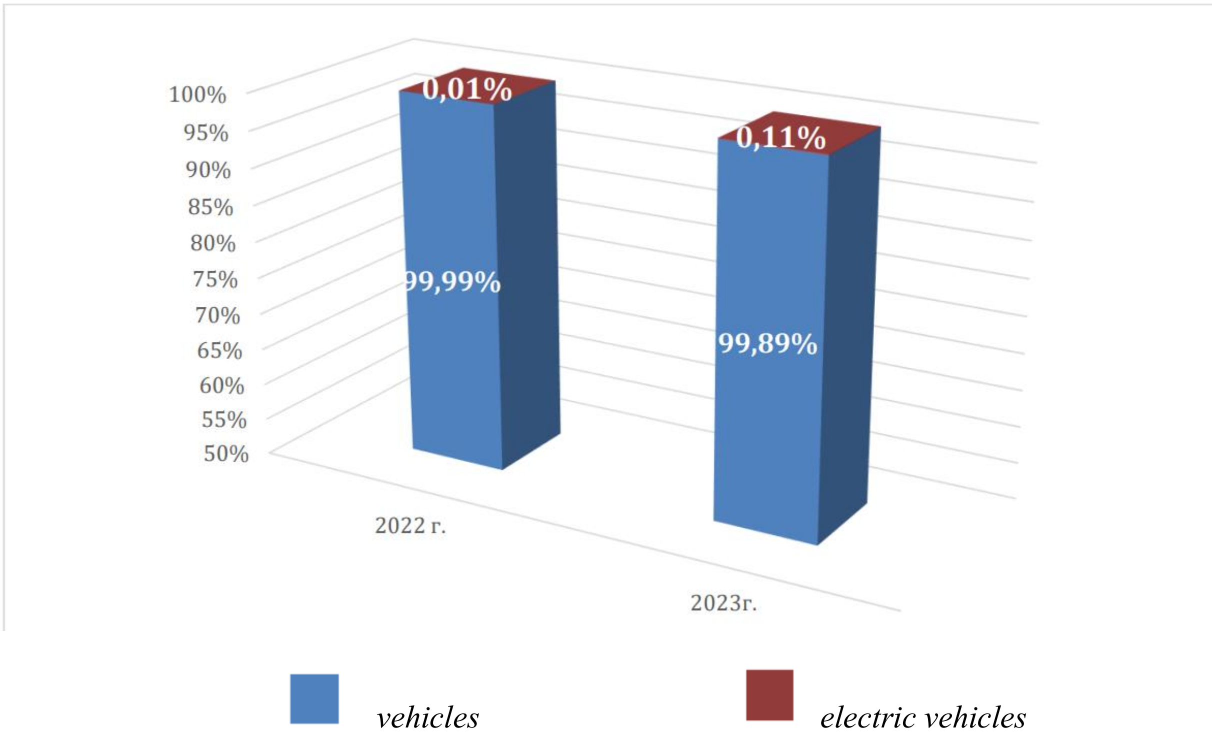

Figure 1 – Ratio of the number of vehicles and electric vehicles in Kazakhstan in 2022–2023.

In regional terms, in 2023 the largest number of electric vehicles was registered in the city of Almaty: 2.8 thousand units, compared with only 40 vehicles a year earlier, representing a 68.8-fold annual increase. The share of such vehicles in Almaty amounted to 59 per cent of the national total, compared with 8.9 per cent in the previous year.

Second and third positions were occupied by the city of Astana (550 electric vehicles, compared with 12 units a year earlier) and the Almaty Region (208 vehicles, compared with only one electric vehicle a year earlier).

The smallest numbers of electric vehicles were registered in the Abai Region (8 vehicles), the North Kazakhstan Region (14 vehicles) and the Zhetysu Region (21 vehicles).

As of 1 August 2023, a total of 4.4 million passenger cars were registered in the country. The majority operated on gasoline (3.9 million vehicles). In addition, 83.2 thousand vehicles used diesel fuel, 5.4 thousand used compressed gas fuel, 4.7 thousand were powered by electricity, and 366.4 thousand operated on mixed fuel (gasoline, compressed gas and electric propulsion). For 90.8 thousand vehicles, the type of fuel was not specified at registration. Figure 2 presents the distribution of motor vehicles in the Republic by engine type.

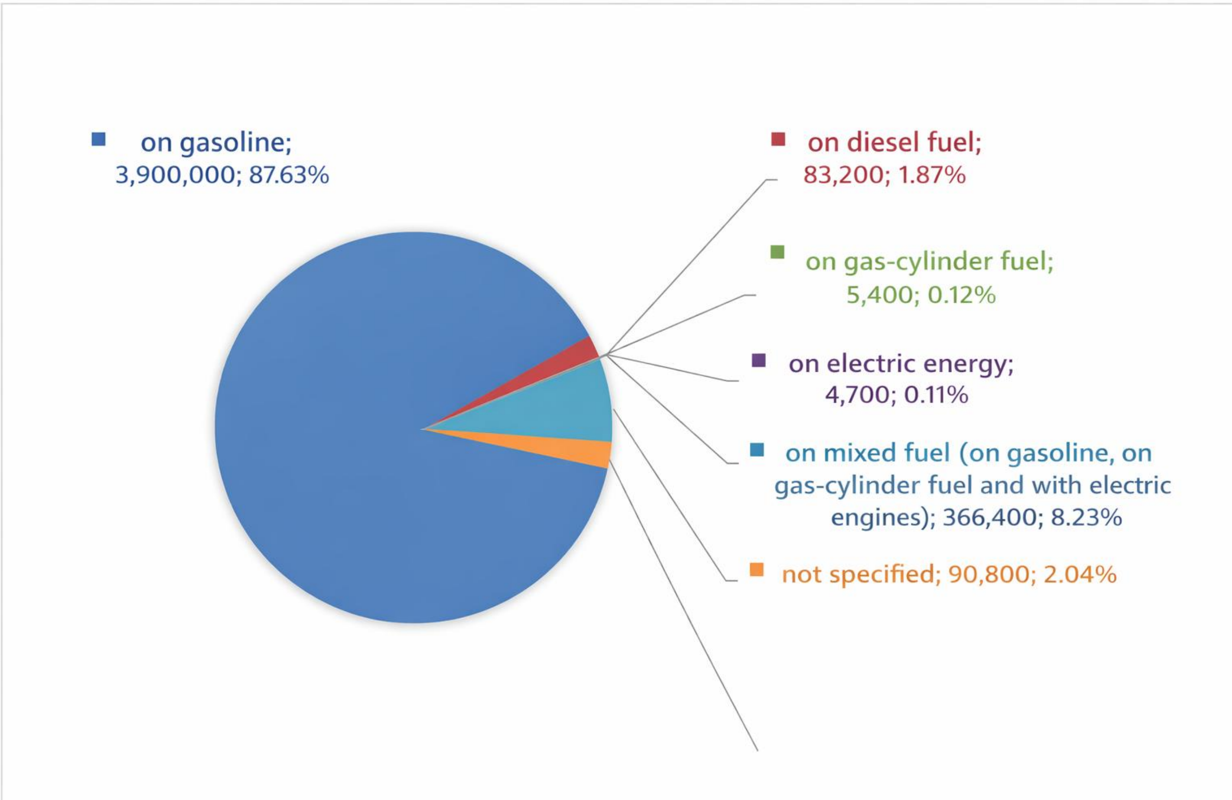

Figure 2 — Number of motor vehicles by engine type as of 1 August 2023

The number of gasoline-powered vehicles increased by 14.9%, diesel-powered vehicles by 12.2%, gas-fueled vehicles by 38.2%, and mixed-type vehicles by 19.3%.

According to the Bureau of National Statistics, as of 1 June 2024 the number of electric vehicles in Kazakhstan tripled compared to the same period of the previous year, increasing from 3,229 to 9,906 units [2].

To stimulate and regulate the use of electric vehicles in Kazakhstan, the Law of the Republic of Kazakhstan dated 18 July 2024 No. 126-VIII ZRK "**On Amendments and Additions to Certain Legislative Acts of the Republic of Kazakhstan on Transport and the Development of Infrastructure for Electric Vehicles**" [3] was adopted. As follows from its title, the law is aimed at the development and regulation of infrastructure for electric vehicles. However, issues related to ensuring the safety of this type of transport were not directly addressed in the document. At the same time, general approaches to fire safety established in regulatory legal acts oblige the entities of the State Fire Safety System to take all necessary measures to eliminate this regulatory uncertainty.

At the initial stage, the Ministry for Emergency Situations of the Republic of Kazakhstan studied the experience of foreign countries in the operation and placement of electric vehicles and charging stations (USA, Canada, Mexico, the Netherlands, Switzerland, Germany, the United Kingdom, and Russia).

Based on proposals developed by the Ministry for Emergency Situations, the Ministry of Industry and Construction introduced amendments to construction codes and regulations concerning the placement of electric vehicles and charging stations (Order of the Committee for

Construction and Housing and Utilities of 19 April 2024 No. 68-нк). Amendments were also made to the Firefighting Organization Rules (Order of the Ministry of Internal Affairs of 26 June 2017 No. 446) regarding firefighting methods (water and dry powder) and rescue operations involving electric vehicles and electric buses (Order of the Ministry for Emergency Situations of 7 June 2024 No. 217). Furthermore, by Order of the Ministry for Emergency Situations dated 15 August 2024 No. 321, amendments and additions were introduced to the Fire Safety Rules (approved by Order of the Ministry for Emergency Situations of 21 February 2022 No. 55), allowing the charging of electric vehicles in garages, parking structures, vehicle storage premises, industrial garages, under canopies, and in open areas, subject to compliance with state regulatory requirements when placing electric vehicles and charging stations in parking facilities. These measures were urgent and priority steps to eliminate regulatory gaps concerning fire safety and the extinguishment of electric vehicle fires.

To determine the main directions for further research necessary to update regulatory documents in the field of fire safety at all key stages of electric vehicle operation — namely operation, storage, and charging — it is essential first to examine the design features and operating principles of electric vehicles, analyze data on recorded fires, and, based on this, develop possible fire scenarios. This will make it possible to conduct a comparative analysis of the fire hazard of electric vehicles versus vehicles equipped with internal combustion engines.

From a fire safety perspective, a vehicle is a mobile object in which a significant fire load is concentrated within a relatively small volume. This load includes flammable and combustible liquids, solid synthetic materials, and substances that, when burning, may release highly toxic compounds comparable in danger to chemical warfare agents. The development of fire safety measures and firefighting methodologies is based on an analysis of fire hazards. To understand the specific features of electric vehicles within the framework of this study, a comparative analysis of the fire hazard of electric vehicles and internal combustion engine vehicles is conducted. It is evident that both identical and specific key systems and components influencing overall vehicle fire risk will be present. For clarity, Table 1 presents data on the presence of the main systems and components of these vehicles.

Table 1 — Units and Systems of a Passenger Vehicle

№	Name of unit or system	Internal combustion engine vehicles	Electric vehicles
1	Body	+	+
2	Cabin	+	+
3	Wheels	+	+
4	Fuel System	+	-
5	Lubrication System	+	+
6	Cooling System	+	-
7	Internal Combustion Engine	+	-

8	Power Electric Motor	-	+
9	Traction Battery	-	+

For the analysis of fire hazard, we use a well-known methodology [4], slightly optimized for vehicles.

Obviously, the fire hazard of a car is determined by the large amount of combustible materials it contains. GOST 12.1.044-89 [5] provides the normative definition of flammability of substances and materials, as well as a detailed methodology for their experimental study depending on their physical state. In a car, combustible materials are present in gaseous, liquid, solid states, and as dust. The characteristics of ignition and combustion of substances and materials in gaseous, liquid, solid states, and as dust are well known and described in the literature [6].

The fire hazard of materials for body parts and equipment located in the functional compartments of a car is shown in Table 2.

Table 2 – Fire hazard indicators of materials used in all passenger cars

Material Name	*Flammability Group*	*Temperature, °C*				
		Autoignition	*Ignition*	*Melting*	*Brittleness / Frost resistance*	*Softening*
Low-density polyethylene	Combustible	417	306	120	-180	80-90
High-density polyethylene	Combustible	349-422	340	138	-249	120-125
Polypropylene	Combustible	325-388	325-343	165	-23	150-155
Polyvinyl alcohol (PVA)	Combustible					
Vinyl Plastic	Combustible	580	580	-	-	-
General Purpose Polystyrene (GPPS)	Combustible	486	343	-	-40	85
Artificial Leather	Combustible	-	165	-	-	-
PVC Linoleum	Combustible	410	330	-	-	-

Getinax	Combustible	480	285	-	-60	-
Textolite	Combustible	491-500	358	-	-60	-
Rubber	Combustible	350	-	-	-	-
Fiberboard	Combustible	345	222			
Bitumen	Combustible	380-397	300-351 (auxiliar y 240-299)	-	-	40-100
Polyurethane foam	Combustible	480	440			
Flexible polyurethane foam	Combustible	480	440			
Artificial leather	Combustible					
Artificial leather on a knitted base	Combustible					
Upholstery vinyl leather TR	Combustible					
Car tire rubber	Combustible	440	270			

Table 2 shows that, regardless of the type of passenger car, a wide range of flammable substances and materials is used in their construction

Based on the study and analysis of fire hazards in vehicle parking areas and methods of extinguishing them, carried out as part of the development of Special Technical Conditions, the following was established. The main fire load of a vehicle consists of rubber, fuel, lubricating oils, synthetic polymers, and other flammable materials. According to collected empirical data, the average quantities of these materials in a civilian SUV are Rubber – 100 kg, Gasoline fuel – 64 kg, Lubricating oils – 8 kg, Polyurethane foam – 8 kg, Polyethylene – 1.8 kg, Polyvinyl chloride – 10 kg, Artificial leather – 9 kg

The total mass of combustible materials is 200.8 kg, or up to 15% of the vehicle's total weight

The fire hazard of a vehicle is significantly increased by various operational fluids and lubricants. Table 3 lists the most common working fluids used in both internal combustion engine vehicles and electric vehicles.

Table 3 – Indicators of fire hazard of operating fluids and lubricants typical for all types of vehicles

Material Name	Flammability Group	Temperature, °C		
		Flash	Ignition	Autoignition
Greases				
Litol TU 38-101207-75	Flammable, viscous, light-brown liquid	221 (Open Cup) 185 (Closed Cup)	231	364
FIOL-2M TU 38-101233-75	Flammable, viscous, silvery-black liquid	259-322 (OC) 183 (CC)	304 - 346	402
FIOL-2U TU 38USSR 201266-79	Flammable, viscous, dark-gray liquid	225-269(OC) 191(CC)	261 – 280	395
FIOL-4, Grade A TU 38 401.68-78	Flammable, viscous, dark-gray liquid	186(OC) 164(CC)	250	396
Solidol (Synthetic) GOST 4366-76	Flammable, viscous liquid	185(OC) 184(CC)	208	385
Transmission Oils				
TRANSELF TYPE B 80W90 (ELF)	Combustible	220	290	
Brake Fluids				
Brake fluid (BSK type)	Highly flammable liquid	40	46	345
«NEVA»	Combustible	97-102	102	242
«ROSA»	Combustible	112-128	131	315
«ROSDOT-4 Super», TU 2451-004-36732629-99	Combustible	139	140	

(manufactured by Tosol-Sintez, Dzerzhinsk)				
«ROSDOT-4 Super» TU 2451-004-36732629-99 (manufactured by ТОСОЛСИНТЕЗ, Dzerzhinsk)	Combustible	140	142	
Castrol RESPONSE DOT-4	Combustible	150	155	
Hydraulic Fluids (Selected)				
Power steering oil A 001 989 24 03 10	Combustible	155	160	
Automotive Anti-Corrosion Agents and Preservatives				
Bituminous anti-corrosion coating	Highly flammable liquid	16	31	433
Exhaust anti-corrosion coating (TU 6-15-07-12-74)	Highly flammable liquid	21	30	463
Auto-preservative (TU 6-15-1045-77)	Highly flammable liquid	12	25	264
Movil (rust-preventive oil / rust inhibitor)	Highly flammable liquid	42	43	-
Auto-preservative (TU 6-15-07-9-74)	Highly flammable liquid	52	66	355

From Table 3, it is evident that all of them are generally flammable liquids, and some even belong to highly flammable liquids.

Obviously, the main distinction between different types of vehicles is the presence of engine fuel and, accordingly, coolant in one case, and a power battery in the other, as seen in Table 1.

Table 4 presents data on the fire hazard of engine fuel and coolant, taking into account the volume stored in vehicles. These are the most fire-hazardous components, especially since fuel also poses an explosion risk. All indicators presented in Tables 2–4 are taken from reference literature [7].

Table 4 – Indicators of fire hazard of liquids typical for vehicles with internal combustion engines

Vehicle Fuel Type	Flash Point (°C)	Autoignition Temperature (°C)	Flammability Limits (%)		Temperature Limits (%)	
			Upper Limit	Lower Limit	Upper Limit	Lower Limit
Gasoline						
A-76	-37	320	5,6	0,78	-7	-35
AI-93	-37	360	6,14	0,79	-6	-37
Diesel Fuel						
DZ DL DS DT-1 DT-2	59 65 92 110 110	237 225 231 370 350			98 116 146 135 155	54 64 76 99 91
Coolants						
«Tosol-A»	108	117				
«Tosol»	142	148				

The fire risk of electric vehicles is predominantly linked to the characteristics of their power batteries, particularly lithium-ion cells. Deviations from normal operating conditions of battery cells can result in overheating, damage, and subsequent ignition. The principal factors contributing to battery failure are as follows:

- **Environmental Exposure:** Exposure to high ambient temperatures or charging under cold conditions can degrade battery performance. Additionally, contact with saline water, such as during flooding, may cause component corrosion and short circuits.
- **Mechanical Damage:** Damage to battery cells resulting from accidents or high mechanical loads (e.g., off-road driving) may compromise structural integrity and lead to separator failure, thereby increasing the risk of short circuits and overheating.
- **Electrical Overcharge:** Exceeding the permissible charging voltage can trigger exothermic reactions at the cathode, leading to overheating and potential hazardous events.
- **Electrical Over-Discharge:** Voltage dropping below the allowable limit may dissolve the ion-conductive protective layer on the anode, creating conditions conducive to short circuits.
- **External Short Circuits:** Short circuits in external electrical circuits of the vehicle can heat battery cells to levels that initiate thermal runaway.
- **Manufacturing Defects:** Poor assembly, electrode defects, or contamination may result in internal short circuits, triggering a thermal runaway process.

- **Aging:** Gradual degradation of lithium-ion cells due to natural wear and improper operating conditions increases the likelihood of hazardous events.

Any of the factors listed above may initiate a thermal runaway process in a battery cell, potentially leading to ignition of the entire battery pack through a chain reaction.

For an assessment of the relative risk associated with different vehicle types, the following statistics on vehicle fires are presented:

Vehicle Fire Statistics by Fuel Type

According to data from AutoinsuranceEZ.com [8], widely cited in related studies and publications, fire incidence per 100,000 vehicles is distributed as follows:

- Hybrid vehicles – 3,474.5 (~3.5% of 462,000 units)
- Internal combustion engine vehicles – 1,529.9 (~1.5% of 13,000,000 units)
- Electric vehicles – 25.1 (~0.025% of 207,000 units)

Furthermore, media reports from the People's Republic of China indicate that 640 electric vehicles caught fire in the first quarter of 2022 (~0.01% of 7,000,000 units).

Figure 3 illustrates the ratio of vehicle fires relative to the total number of vehicles by type.

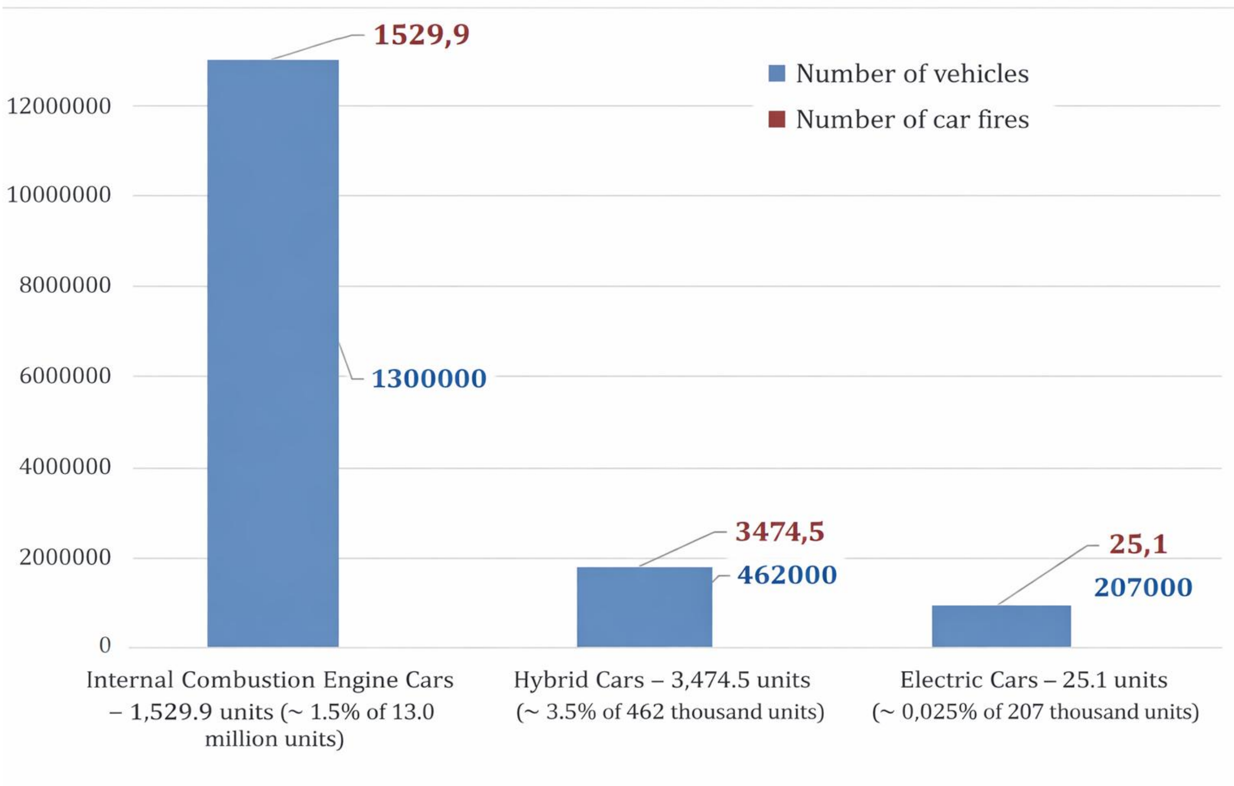

Figure 3 – Number of Vehicle Fires by Type

Despite favorable statistical data indicating a comparatively low incidence of electric vehicle fires relative to other types of transport, it should be noted that the vast majority of electric vehicles in operation as of 2024 have a service life of no more than 3–4 years. This is significantly shorter than the typical operational lifespan of conventional internal combustion engine vehicles.

Experts predict that, with the increasing age of the electric vehicle fleet, its widespread adoption, and a growing number of cases of unqualified repair and maintenance, the relative frequency of electric vehicle fires is expected to rise substantially.

The physico-chemical processes leading to the phenomenon of thermal runaway (hereinafter "TR") occur within battery cells when they fail.

Following an initiating event in a battery cell, a heating process begins. At temperatures of 70–90 °C, the ion-conductive protective layer on the anode starts to decompose, resulting in the reaction of embedded lithium with the electrolyte and the release of volatile hydrocarbons such as ethane, methane, and ethylene. Despite the presence of an explosive mixture, ignition does not occur due to the absence of oxygen within the cell.

As the reactions with the electrolyte are exothermic, temperature and pressure within the battery continue to rise. When the temperature reaches 180–200 °C, disproportionation of the cathode material—often composed of transition metal oxides with lithium inclusions—occurs, releasing oxygen. This triggers self-ignition of the battery cell and a further rapid temperature increase. Simultaneously, thermal decomposition of the electrolyte occurs at 200–300 °C, producing additional heat.

In the final stage, graphite reacts with the electrolyte, and at approximately 660 °C, the aluminum current collector melts. Temperatures within the cell generally do not exceed 900 °C. Once thermal runaway begins in the electric vehicle's battery pack, the process is extremely difficult to halt, as each cell contains all components necessary for combustion: an oxidizer, fuel, and heat transferred from adjacent cells already in advanced stages of TR.

The specific characteristics of electric vehicle battery fires render traditional firefighting methods, developed for internal combustion engine vehicles, largely ineffective. During TR, combustible gases are released intensively, exiting early through pressure relief valves or due to cell rupture from rising internal pressure. In confined spaces, these gases can accumulate, and their ignition typically results in flash fires.

Although publicly available data on such incidents is limited, the accumulation of combustible gases in enclosed spaces can reach explosive concentrations, with explosion pressures potentially exceeding 5 kPa, which may compromise load-bearing reinforced concrete structures.

The toxicity of certain chemical by-products generated during TR in lithium-ion cells poses a significant threat to human health and life during electric vehicle fires in enclosed spaces. These toxic substances also tend to dissolve in water used for firefighting, rendering it hazardous and requiring careful consideration of environmental and sanitary safety during disposal.

The jet-like nature of combustion (high-temperature burning of gases expelled under pressure from the battery pack) increases the impact on nearby objects, such as adjacent vehicles, substantially raising the overall fire load.

The placement of electric vehicle battery packs within sealed, fire-resistant enclosures under the vehicle floor considerably limits the accessibility of firefighting agents to the ignition source, complicating rapid fire containment.

Studies indicate that the time required for initial containment of an electric vehicle fire averages 30–60 minutes. The risk of re-ignition remains high due to the characteristics of thermal runaway in individual cells, which can result in subsequent fires occurring hours or even weeks after initial containment. In some documented cases, the number of re-ignitions reached six to eight instances.

The average duration of emergency and rescue operations, typically ranging from 6 to 8 hours, raises concerns regarding the effectiveness of current fire safety regulations for buildings and existing methods for extinguishing electric vehicle fires. For instance, the maximum fire resistance of buildings according to the standards of the Republic of Kazakhstan is 2.5 hours, which is significantly shorter than the time required to manage an electric vehicle fire.

Residual battery charge constitutes one of the primary causes of re-ignition and poses a direct threat to the safety and health of firefighters due to potential contact with high-voltage electric vehicle cables. A particular challenge is the inability to determine the residual charge level of the batteries in a damaged vehicle without the involvement of the electric vehicle manufacturer's specialists, introducing additional unpredictability into emergency operations and increasing risk for firefighting personnel.

The absence of specialized extinguishing agents with enhanced effectiveness against electric vehicle fires creates substantial operational difficulties for fire departments. This is primarily because the combustion of lithium-ion cells does not require atmospheric oxygen, significantly limiting the efficacy of conventional firefighting methods. Currently, the standard recommendation from researchers in this field, as well as electric vehicle manufacturers, is the use of large volumes of water—up to 30 tons per vehicle—for cooling the battery and suppressing the thermal runaway (TR) reaction. However, this approach is not optimal, as it does not guarantee prevention of subsequent re-ignitions.

Widely used extinguishing agents such as gas, powder, aerosol, or finely atomized water, which have proven highly effective in other types of fires, have demonstrated limited effectiveness in electric vehicle fires. The development of more effective methods for combating electric vehicle fires is currently the subject of active discussion among professional firefighters and manufacturers of specialized fire-fighting equipment. Nevertheless, proposed solutions so far lack sufficient evidence of effectiveness based on large-scale testing.

The situation is further complicated by the diversity of technical solutions employed by different electric vehicle manufacturers, including variations in the chemical composition of lithium-ion cells, cell sizes and configurations, and the placement of battery packs within the vehicle structure. This considerably complicates the systematization of accumulated global experience and poses additional challenges in developing universal approaches to electric vehicle fire suppression.

At present, large-scale studies aimed at producing specific guidelines and recommendations for building design that account for electric vehicle fire risks remain at an early stage. This applies to research conducted by major professional organizations such as the National Fire Protection Association (NFPA) [10], the Fire Safety Research Institute (FSRI), and the National Transportation Safety Board (NTSB).

Figure 4 – Highlights from the International Scientific and Practical Conference on “Firefighting and Emergency Rescue Operations in Response to Electric Vehicle Traffic Accidents”


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This article was prepared following consultations with representatives of the Fire Safety Committee of the Ministry of Emergency Situations of the Republic of Kazakhstan and represents the first in a planned series of studies in this field. We hope to engage the domestic community of specialists to foster a deeper understanding of this issue, the resolution of which is possible only through a consolidated approach that integrates our scientific and creative capacities.

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Almaty, October 2024