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CAUSES OF BATTERY FIRES IN RAILWAY VEHICLES AND CHALLENGES OF EXTINGUISHING

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Abstract. The aim of this article is to introduce an issue that has not yet been addressed in our region – the fire hazards of BEMU units. The methodology of the Fire Rescue Service of the Czech Republic vehicles was used to establish the basic procedure for extinguishing batteries in railway passenger coaches.

Keywords: Rail transport, environment, alternative drives, BEMU units, battery, fire.

1. Introduction

The railway network of the Czech Republic can be considered one of the densest in Europe. At the end of the year 2023, the total length of public tracks was 9 349 km in our country. It means, that there were 118.5 km of tracks per 1 000 km^2 of the territory of our state. The impulse, why the aforementioned network was built in this length, was the industrial revolution and mankind's effort to simplify and speed up individual jobs. The discovery of the steam engine showed, that the animal power used for decades could be replaced. Gradual development and above all the discovery of fossil fuels and the use of their energy caused the gradual abandonment of steam traction. But it is necessary to realize that nothing has only positive sides. Human activity was simplified, but the consequence is an environmental damage. In order to prevent damage to our planet in the future, emphasis is placed on so-called sustainable development. This means that human needs are fulfilled, but not at the expense of future generations.

Although railways can be considered one of the most ecological modes of transport, it also has weaknesses. The biggest problem is represented by independent traction vehicles using a combustion diesel engine for the mentioned fossil fuels (representing primary energy) for their movement. The mentioned fuels are converted into secondary energy by burning, which is then used for the movement itself. During combustion, the carbon contained in fossil fuels is converted into carbon monoxide (in the case of incomplete combustion in internal combustion engines) and carbon dioxide, these gases are subsequently released into the atmosphere.

The goal of our society is to replace vehicles with combustion engine on railways. There are two options how to achieve this replacement. The first option is to electrify the line, meaning to build a overhead line traction system. The second approach involves deploying vehicles with alternative power sources, specifically hydrogen-powered vehicles and battery-powered vehicles. Given that the Czech Republic does not have sufficient production and infrastructure for the distribution of hydrogen, it is more advantageous to consider the operation of battery-powered vehicles, specifically BEMU (Battery Electric Multiple Unit) units, in the Czech Republic [1].

In addition to the issues related to deploying vehicles into regular operation – such as range, battery capacity, energy recovery options, and others – it is necessary to consider safety. For BEMU units, beyond the standard safety measures applicable to other vehicles, special attention must be given to the battery itself.

This article focuses on the safety of BEMU units on Czech railways. Since there are currently no guidelines on how to proceed in the event of a BEMU fire in our country, key points are highlighted here that should be addressed to prevent complications during emergencies.

2. Emergency exits

Before this article addresses battery fires, it is important to understand the options passengers have to escape from a vehicle in the event of an emergency. Since the early days of railway operations, passenger safety has been the highest priority, and significant resources are dedicated to ensuring their protection.

Some of the first railway safety measures were introduced in response to a railway accident, often referred to as the greatest railway disaster of the 19th century. The accident occurred in 1842 on the line between Versailles and Paris. The train consisted of three locomotives and several carriages. Near Meudon, the wheelset of the first locomotive broke. The second locomotive collided with the first (the third locomotive was positioned at the end of the train as a banking locomotive. At the same time, hot coal and steam were released from all engines, which caused the passenger carriages to catch fire. Passengers were unable to escape from the burning carriages because, at that time, the doors could only be opened from the outside.

As a result, 157 people were killed or went missing out of the 1 530 passengers. This accident led to safety measures being introduced across Europe, including in Austria. Emperor Ferdinand I himself ordered a ban on locomotives with two axles and prohibited the use of pushers in all circumstances. The maximum speed for passenger trains was set at $30\,\mathrm{km\,h^{-1}}$, and for freight trains at $23\,\mathrm{km\,h^{-1}}$. It was also forbidden to lock carriages that did not allow passengers to escape on their own in case of an accident (this applied to first- and second-class carriages), or measures had to be taken to ensure that passengers could easily unlock the doors if needed [2].

Due to various emergency situations, vehicles have been improved and equipped with several safety features to help passengers escape in case of an incident. Additionally, there are units within the Integrated Rescue System that are designated not only for evacuating people but also for handling other potential dangers, such as fires [3].

The simplest way to evacuate passengers is when no new escape routes need to be created, and the prescribed ones can be used. This method is called self-evacuation. In this case, the escape routes must be clearly marked with signs placed along the expected escape path. In a train carriage, a safety hammer is located near the window along with a pictogram that clearly explains the window as an emergency exit. Conversely, near the doors, a properly marked handle is placed to unlock the doors, which should then open [3].

However, it is not always possible to use the prescribed escape routes. That is why rescue teams are trained to determine the most suitable, least demanding, and quickest way to create an escape route. For example, they may use doors that have become deformed due to the emergency, making it impossible to enter. In such cases, special equipment is required, which the rescue teams have. This may include hydraulic rescue tools with spreaders, which are now battery-powered to make firefighters' work easier. Additionally, motorized cutting tools or saws can be used. In the event of a derailment or overturning of the carriage, emergency exits can be created through the roof. The roof is one of the easiest areas to create escape routes, as it is made of sheet metal. However, electrical wiring, which is usually routed under the roof, can cause complications [3].

The specific method of evacuation is always determined by the commander of the rescue team, as they are specially trained and prepared for such operations, such as in the case of firefighters. Firefighters are trained for common situations they encounter regularly. However, they do not have detailed knowledge of railway vehicles, unlike specialized railway firefighters.

3. Fires in E-mobility

Fires are a part of daily life. However, we have been encountering a new trend: fires involving electric cars, trains, scooters, and other vehicles in recent years. This does not refer to traditional vehicle fires, which firefighters frequently handle, but rather to the growing category of battery fires, most commonly involving lithium-ion batteries.

3.1. What is battery

Before discussing the issue of fire outbreaks, it's important to define what a battery is. In Czech terminology, a "battery" refers to a cell that can only be used once. In contrast, an "accumulator" (referred to as a battery in English) can be repeatedly charged and discharged during its lifespan.

A battery is an electrochemical galvanic cell, where a chemical reaction generates voltage. Inside the battery, there are two half-cells, which are electrodes immersed in an electrolyte. These electrodes are separated by a separator to prevent the battery from short-circuiting. During the movement of the vehicle, energy is depleted. This means that one electrode becomes a negative anode, releasing electrons that move towards the positive cathode. During recharging, the cell is connected to an external power source, causing electrolysis, which switches the electrodes' functions – this is referred to as the electrolytic mode [4].

The battery itself is composed of individual cells. A group of cells is called a module, and these modules are then assembled into packs. In practice, we often encounter various types of batteries, each differing in their chemical composition. Some examples include [4]:

- **Li-ion battery** – cathode: $LiCoO_2$, anode: LiC_6 or C, electrolyte: $LiPF_6$,
- **Li-polymer battery** – cathode: $LiCoO_2$, anode: LiC_6 or C, electrolyte-separator: solid polymer, polymer battery casing
- **Lithium iron phosphate battery (LFP)** – cathode: $LiFePO_4$, anode: Li or LiC_6
- **Lithium titanate battery (LTO)** – cathode: $LiMn_2O_4$ or $LiFePO_4$, anode: $Li_4Ti_5O_{12}$

The most commonly used types of batteries are Li-ion and Li-polymer batteries.

3.2. Fires involving lithium-ion batteries

As mentioned in the introduction to Chapter 3, the most common energy source in electric vehicles is the lithium-ion battery. This technology is crucial for energy storage, not only in transportation but across almost all industries. However, along with these batteries comes a new risk: their potential to catch a fire.

When batteries are damaged, unwanted reactions can occur inside the battery itself. These reactions cause a rise in temperature and the release of gases, which can ignite and lead to a fire. It is important to note that during the burning process, it is not the material itself that burns, but the released gases.

Although battery fires are not very common, they present dangers that are significantly different from other fire hazards in terms of initiation, spread rate, duration, toxicity, and suppression [4, 5].

Among the most common types of damage are mechanical stresses. A typical example can be an incident where, for instance, a railway vehicle derailment causes damage to the separators and subsequent short-circuiting of the battery, leading to the release of a large amount of energy. One example, actually not related to transportation, is a house fire where insulation work led to a worker's walkie talkie falling into a blowing machine. This caused damage to a battery, which subsequently ignited and as a result the fire consumed the entire house. Another cause can be electrical stress, such as using an inappropriate type of charging for the battery or resulting from a malfunction. Thermal stress is another factor, such as the consequence of exposure to fire. Additional causes can include manufacturing defects, intentional damage, and so forth [4, 5].

The technology of lithium-ion batteries is advancing rapidly. This leads to a significant increase in the use of these batteries not only in industry but also in transportation. Given the incidents involving batteries, the question of how to ensure safety is becoming increasingly relevant. The most common issue is exceeding the operational temperature limits. This relates to the concept of "thermal runaway". This is a state that occurs when the temperature of battery reaches a critical value. As a result, the rate of the exothermic reaction increases the temperature, which in turn accelerates the reaction rate further. This temperature rise poses a risk of ignition and related fire hazards. As mentioned earlier, a battery consists of cells or a collection of cells. If one cell is damaged, it can lead to a heat release affecting neighboring cells, resulting in a chain reaction that can impact the entire battery. This can lead to a substantial release of gases, which are difficult to suppress or extinguish [4, 5].

3.3. Issues with batteries and their placement on vehicles

Nowadays, there are two approaches to dealing with battery fires. The first approach involves developing a safe chemical composition or a secure battery design that prevents thermal runaway or the subsequent spread of fires. It is generally agreed that some chemical cathodes are safer than others. Additionally, preventative measures include using so-called shutdown separators that stop the transport of lithium ions once a set temperature is reached. The second approach assumes that thermal runaway will occur and focuses on implementing reliable lightweight elements that concentrate on detecting and mitigating the spread of fires. Currently, there is no specific approach to fire suppression, so manufacturers combine various methods for fire detection and mitigation. Among the most well-known detection methods are terminal voltage and temperature detection.

One of the major issues today is the lack of a globally established regulation for testing and ensuring the safety of batteries. Regulations are issued by the relevant governments and are legally enforceable. On the other hand, batteries are tested only under static conditions and not under dynamic movements that are typical for accidents. Generally, testing a battery is both physically and financially demanding. From a physical point of view, there is no reliable method to induce thermal runaway in a battery to represent failure modes during operation [5].

Although battery-powered railway vehicles have been in operation since the last century, it could be said that the regular operation of these vehicles is still in its early stages. While the vehicles and their individual parameters must comply with fire safety regulations, there has not yet been any major incident involving the ignition of a battery. Thus, it can be said that there has not yet been a direct testing of all safety features in action, but only in a laboratory setting.

One of the first questions regarding fire safety is the placement of the battery on the vehicle. The current trend is towards low-floor vehicles. This implies that the battery cannot be placed in the lower part of the vehicle (due to maintenance advantages, centre of gravity, etc.). Usually manufacturers today place batteries on the roof of the vehicle, where the structure must be reinforced to support the weight, or the battery can be placed in a separate module within the vehicle, where the area for passengers could be located. As mentioned, the first safety measure is prevention; however, if ignition occurs, the primary safety measure for passengers is that the compartment containing the battery should withstand at least 15 minutes before failing. This should be the time required to safely evacuate passengers from the vehicle. But what if there is a derailment or another emergency situation and passengers are trapped inside the vehicle? It must be recognized that there can be a delay between reporting the incident and the arrival of rescue services (which must arrive on-site within 7 minutes of the report). During a fire, it is also necessary to properly direct gases away from passengers. This raises questions about which direction the vent hole should be positioned. If the battery is located on the roof of the vehicle and the vent is directed downward, the heat from the device might affect the roof structure and cause damage. The most common placement is on the side. However, the vehicle could cover the vent and prevent safe gas removal from the fire in the event of a derailment and subsequent side fall.

3.4. Methods for extinguishing fires in battery-powered railway vehicles

In the Czech Republic, there is currently no methodological guideline for the localization and extinguishing of fires in battery-powered railway vehicles, specifically for the battery itself. The Fire Rescue Service of the Czech Republic developed a document on electric mobility insights in the Czech Republic from 2019 to 2020. This chapter compares whether this document regarding fire extinguishing procedures could be applicable to BEMU units as well.

The first piece of information for firefighters is to understand what they are dealing with on-site, so they know the appropriate procedure for extinguishing the fire. For example, in modern road vehicles equipped with the eCall system, a message is generated and sent to the operational center. Railway vehicles are not yet equipped with this system, so there must be a way to mark or distinguish these vehicles from others. In the case of the first BEMU unit operating in the Czech Republic (BEMU RegioPanter), the presence of the battery used as an energy source for propulsion is indicated by an orange triangular warning sign with a battery pictogram. Apart from the colour coding of different regions in the standard RegioPanter electric units (e.g., the Prague integrated transport colour), the battery-powered unit is marked with green at the front of the unit, as opposed to the blue colour of the standard electric units with the same commercial designation [4].

In passenger coaches, the battery is most often stored above or close to the rear axle. As described in the previous chapter, due to the requirement for low-floor trainset, the battery is placed on the roof or in a separate vehicle section, known as a so-called PowerPack. Upon rescue services arrival to the site of intervention, it is necessary to assess whether standard extinguishing agents can be used, considering the risk of electric shock. It is important to recognize that during a fire, a BEMU unit may be standing under or even be connected to fixed traction power lines. In such a case, immediate intervention is not possible; the traction power lines must first be shut off and isolated. This differs from electric cars that move freely on roadways. A similar problem arises when electric vehicles are charging, but the difference lies in the power requirement, which is lower compared to trains [4].

After locating and extinguishing the fire, it is essential to continuously cool the battery. This is to prevent the transfer of heat between individual cells and sections of the battery. During the fire, some cells may have ignited but not completely burned out. Water, without any additives, is used as a cooling agent and is applied directly to the battery cover for 10 minutes. Following this, the battery should be monitored for 5 minutes to check if it continues to heat up or emit smoke. If the battery does, cooling should be repeated for another 10 minutes, and this process should continue in a cycle. To determine if the battery is still overheating, it is advisable to use a thermal camera. After successfully cooling the battery, it is recommended to monitor its condition for an additional 45 minutes. If no self-heating or smoke is observed during this time, the scene can be handed over with post-fire measures established. Subsequently, a thorough inspection of the battery is necessary. One effective cooling solution in automotive transport is to submerge the vehicle in a water tank (Figure 1). However, this would cause total damage to the vehicle and is not feasible for rail vehicles. Therefore, the battery should be designed to allow connection to a fire hose for cooling. It should be noted that this would require the fire truck to be present for several days. Additionally, the fire truck's tank would need to be cleaned afterward, as the water used for cooling will be contaminated with battery fumes [4].

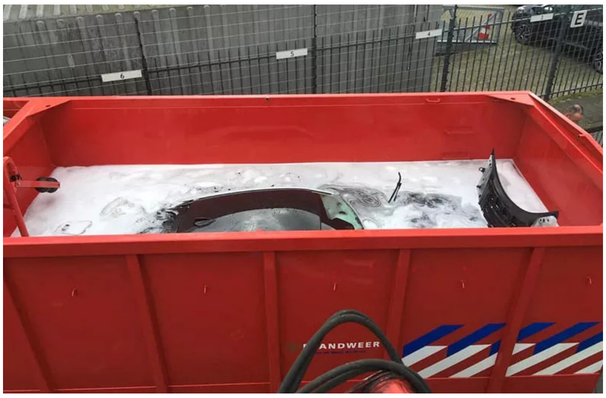

Figure 1. Submerged electric car in a container of water [6].

3.5. Possibility of using modern technologies for locating batteries

With the gradual development of firefighting technology, there are systems that may improve the management of battery fires. One of these is the COBRA device (Figure 2). This device equipped on some fire trucks, can cut through the battery cover and apply water directly between the battery cells, thus effectively cooling them. However, the fact that the battery cover is breached during the intervention is not in accordance with manufacturers' recommendations. In cases where this system might be effective, it could lead to damage to other battery components by the water jet, potentially disrupting internal electrical wiring or disabling safety elements designed to prevent electric shock. The water jet may also disturb battery cells that have not been affected by the fire, unnecessarily releasing chemicals into the extinguishing water. Additionally, there is a high likelihood of a violent reaction between alkaline metals from damaged cells and water. However, this system might be used, in the case of a derailment where access to the battery

Figure 2. Firefighters using COBRA equipment [7].

is needed, as it is generally not recommended unless specified otherwise by the manufacturer [4].

Swedish company Dafo is now introducing a revolutionary system for extinguishing battery fires. This is achieved using a special substance called Forrex, which is a battery component. Forrex is designed to prevent oxygen from reaching the battery, thereby stopping the fire. The advantage of Forrex is that it is applied immediately after fire detection. As mentioned, the substance quickly extinguishes the fire while also beginning to cool the battery. The lifespan of this substance is approximately 10 years, which corresponds to the typical lifespan of a battery. However, the biggest issue is its acquisition cost. At the required amount of 200 to 300 litters, the cost constitutes about 1 % of the acquisition price of a BEMU unit [8].

3.6. How to prepare for future fires in BEMU vehicles

As previously mentioned, the regular operation of BEMU vehicles is still in its early stages. Although manufacturers assume that emergency situations will be rare, it is essential to be prepared for such events. It is important to note that the railway vehicle is not always the cause of the emergency. An example is the incident at a railway crossing in Olomouc that occurred in November 2023. At that time, a train collided with a truck. A fire broke out immediately due to the flammable fuel, and passengers had only a few minutes to escape.

The first step in ensuring the safety of battery-powered trains is to familiarize emergency responders with the vehicle's structure. In regions where BEMU vehicles will be introduced into regular service, integrated rescue units should be briefed on the specifics of these vehicles. For example, when new passenger cars are launched, some units are provided to firefighters for training purposes, allowing them to practice various rescue techniques and familiarize themselves with the vehicles. However, this approach is not feasible for railway vehicles due to the high costs involved. With the advancement of modern technology, it would be possible to conduct training in virtual reality. There are already applications, such as FLAIM Trainer, that allow firefighters to practice emergency response procedures in a virtual environment. Another common practice today is equipping fire trucks with tablets that store structural plans of different vehicles [9].

Another solution is the labelling of vehicles. Currently, there is no prescribed system to indicate that a vehicle is a BEMU unit. As previously mentioned, some vehicles have an orange battery label, but this label was placed by the vehicle manufacturer, not because of the regulation. Additionally, it was noted in the previous chapter that BEMU units differ in colour from standard EMU units. However, the current trend is to standardize the colours of vehicles in integrated transport systems, making it difficult to distinguish between EMU and BEMU units. Therefore, the goal is to establish a clear labelling system for BEMU vehicles.

In the event of an emergency where the battery catches fire, it would be beneficial for the battery to disconnect from the vehicle itself. This would only be feasible if the battery were located on the roof of the vehicle. Firefighters could handle the battery separately from the vehicle. However, a concern arises regarding whether the disconnection process might cause additional damage if not executed properly. This method would require a series of tests on various mechanisms. One clear advantage is that the battery could potentially be submerged in a container of water for cooling.

Another possible solution that exists today and can be used for extinguishing battery fires is a new innovation from the Austrian company Rosenbauer, specifically the piercing spike. This device is capable of penetrating the battery casing and spraying water directly from the spike to cool the internal parts of the battery. Similar devices are currently used by airport firefighting vehicles to extinguish fires inside airplanes [6].

As previously mentioned, there is currently no established system for extinguishing BEMU vehicles. Therefore, it is necessary to address this issue to prevent emergencies and potential loss of human lives.

4. Conclusion

This article was created to outline the issue of fires in BEMU units within our country, where there is currently no specific procedure for handling fires in battery-powered trains.

First, the article discusses the issue of harmful substances produced on the railway network in the Czech Republic. This is related to the replacement of internal combustion engine vehicles with those using alternative propulsion systems.

Second, the article describes the battery and the possibilities related to its ignition. Preventive measures for battery fires were then considered, including the placement of the battery on the vehicle and the location of safety vents.

In the subsequent sections, the methodological guidelines of the Fire Rescue Service of the Czech Republic were reviewed and compared to determine if these procedures could be applied to BEMU unit fires. Finally, the article discusses devices that could be used for fire extinguishing and earlier intervention.

Acknowledgements

References

[1] J. Krejčí. Principle of testing the operational capability of dual-power railway vehicles (trolley/battery electric multiple units) on regional passenger rail transport lines. *New Railway Technique* (3):21–22, 2024.

[2] Vagony.cz. Neotvírejte dveře, dokud vlak nezastaví [In Czech; History of doors in rail vehicles], 2024. [2024-09-05]. https://www.vagony.cz/historie/dvere.html

[3] O. Šilhavá. *Evakuace osob z vlaku [In Czech; Evacuation of Passengers from Trains]*. Bachelor thesis, Tomáš Bata University in Zlín, Faculty of Logistics and Crisis Management, 2024. [2024-09-05]. https://digilib.k.utb.cz/handle/10563/56487

[4] Z. Malkovský, J. Karl, O. Suchý, P. Thin. Aktuální poznatky z elektromobility pro potřeby HZS ČR [In Czech; Current knowledge on electromobility for the needs of the Fire Rescue Service of the Czech Republic], 2020. Ministry of the Interior of the Czech Republic, General Directorate of the Fire Rescue Service of the Czech Republic – Technical Institute of Fire Protection, [2024-09-05]. https://www.hasici-vzdelavani.cz/sites/default/files/download/soubory/201007%20Komentovan%C3%BD%20v%C3%BDklad%20k%20MU%20s%20EV-H_0_0.pdf

[5] L. Bravo Diaz, X. He, Z. Hu, et al. Review – meta-review of fire safety of Lithium-ion batteries: Industry challenges and research contributions. *Journal of The Electrochemical Society* **167**(9):090559, 2020. https://doi.org/10.1149/1945-7111/aba8b9

[6] Auto.cz. Rakouská společnost představila speciální zařízení pro hašení elektromobilů [In Czech; The Austrian company has introduced a specialized device for extinguishing electric vehicle fires], 2021. [2024-09-06]. https://www.auto.cz/rakouska-spolecnost-predstavila-specialni-zarizeni-pro-haseni-elektromobilu-141654

[7] HASICIVO. Hasiči se účastní výcviku s hasicím zařízením CCS Cobra [In Czech; Firefighters participate in training with CCS Cobra firefighting equipment], 2022. [2024-09-06]. https://www.hasicovo.cz/cs/zpravy/hasici-se-ucastni-vycviku-s-hasicim-zarizenim-ccs-cobra

[8] Dafo.cz. Forrex, 2024. [2024-09-05]. https://dafo-czech.cz/

[9] FLAIM Trainer, 2024. [2024-09-06]. https://flaimsystems.com/products/trainer