ELECTRIC MOBILITY AND ROAD TUNNEL SAFETY
HAZARDS OF ELECTRIC VEHICLE FIRES

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ABSTRACT

This experimental study illustrates that severe damage of electric vehicle batteries can immediately lead to uncontrollable fires with high-energy release, strong smoke generation and so far untypical smoke emissions. The experiment was conducted in a real tunnel environment and investigated the effects of a lithium-ion battery used in a full electric vehicle approved for traffic – there were no crash tests with vehicles nor were there any analyses on the probability of such damage. Since potential causes for electric vehicle fires in road tunnels are mechanical (e.g. crash) and thermal (e.g. fire) damage to their batteries, four different scenarios were tested, each following a worst-case approach. The study concludes that the thermal fire hazards of electric vehicles are comparable to those of conventional vehicles. In the immediate vicinity and in unfavourable ventilation situations, however, electric vehicle fires may lead to new and potentially more severe chemical hazards. Analyses point to critical concentrations of heavy metals such as cobalt, lithium and manganese in form of aerosols. These pollutants do not occur in such high concentrations in conventional vehicle fires and are toxic for both humans and the environment. It is assumed that the existing operational and safety equipment in road tunnels is sufficient to cope with these new threats – therefore, no technical adjustments are recommended. Overall, increasing electric mobility will not lead to a reduction of tunnel safety, but in certain aspects, it will change the hazard situation in road tunnels and ultimately will have an impact on incident management in particular.

Keywords: electric vehicles, lithium-ion batteries, experimental measurements, tunnel safety

1. INTRODUCTION

Technical development and the intentional promotion of low-emission vehicles have led to an increasing electric mobility in many European countries. New registrations of electrically powered vehicles are rising steadily in Switzerland, even though their share of the entire motor vehicle fleet remains small (ca. 2%). Virtually all forecasts imply a significant increase of all sorts of electric vehicles; for Switzerland, it is expected that the number of electric vehicles will grow continuously in the years to come, ultimately leading to a penetration rate of over 40% in the year 2050 ([1]). Even though the effective numbers might vary between countries, a high proportion of electric vehicles on European roads and in tunnels must be considered very likely in the future.

1.1. Research questions and project goals

Electric vehicles are defined as vehicles that are powered by electrical energy, encompassing pure battery as well as hybrid electric vehicles. Typically they obtain their energy from high-capacity batteries which, due to their high energy content and highly reactive chemical components, are associated with fire hazards and other chemical or electrical risks ([6];[8]). With increasing urbanisation ([9]) and the observable tendency to shift traffic underground ([2]), the safety question for these new technologies is now being voiced. For special traffic infrastructure with limited ventilation, escape or rescue possibilities, as is typical in road tunnels, two questions arise regarding the specific hazard situation:

- Do electric vehicle fires in road tunnels cause different hazards compared to conventional vehicle fires?
- Is there a need to adapt technical safety equipment or future operations of road tunnels?

To answer these questions, the characteristics of electric vehicle fires need to be investigated in the real environment of a road tunnel. From literature, only limited information can be derived. Although the safety of electric vehicle batteries is subject to controversial debate in research as well as the media in general, the hazards emanating from such fires in road tunnels have not been examined comprehensively so far ([3];[4]). With respect to road tunnels, possible fire hazards of electric vehicle batteries (e.g. gas emission, smoke development, etc.) are discussed primarily theoretically or with the aid of models and have only been investigated in isolated experiments – and then not in the real environment (see [3];[6];[7]).

In order to close this knowledge gap, the present research project was launched with the support of the Swiss Federal Roads Office (FEDRO) and the French Centre d' Études des Tunnels (CETU). The study was to examine experimentally whether the increasing share of electric vehicles will lead to changing hazards in road tunnels due to their different energy storage systems. Since the majority of electrified vehicles will be passenger cars, the experiment concentrated on these; electrified heavy vehicles and motorcycles were intentionally excluded from the considerations. The project had the following objectives:

1. Experimental analysis of the effects of a typical electric vehicle fire in a road tunnel
2. Description of the different fire consequences of an electric and a conventional vehicle in a road tunnel, due to their energy storage systems
3. Identification of possible impacts on road tunnel operations, and adequate mitigation measures

1.2. Approach and hypothesis

The main difference between a conventional vehicle with an internal combustion engine (ICE vehicle) and an electric vehicle (EV) is, apart from the electrified motor, their energy storage. While the energy of the former is mostly stored in the form of liquid fossil fuels (e.g. gasoline, diesel), the latter uses rechargeable batteries made of highly reactive chemical components. Since the superstructure of both vehicles may be assumed as mainly comparable, the experiment concentrated on the root cause of the hazard differences: the battery.

With this approach, crash and fire tests with complete vehicles were deliberately excluded from the study. Such experiments have already been described in literature, although without special regard to road tunnels ([7];[10]). The main goal, now, was to analyse the greatest possible effects of damaged EV batteries from a passenger car in a road tunnel, hence a worst-case approach. To get significant conclusions, various test scenarios had to be conducted, each maximally damaging a high-capacity battery of a typical EV in a different way. The whole project was grounded on the hypothesis that "*compared to conventional vehicles, electric vehicles lead to increased fire hazards in road tunnels due to their energy storage*".

2. METHOD

The experimental situation had to be established in such a way that the relevant parameters could be recorded correctly. Because influencing factors, such as product-specific protective measures on the battery systems had to be eliminated, individual modules of an EV battery were investigated in the experiment. There was no battery management system to ensure chemical and electrical safety of the modules, and no protective battery housing to guarantee its mechanical safety. The results were then scaled up to the battery level.

2.1. Test material

As rechargeable energy storage systems for EV, the most promising technologies currently are lithium-ion batteries. This term generally refers to batteries, in which the element lithium is used as active material in pure or bound form and where lithium ions move from the anode to the cathode during discharge and back when charging. Because of their high reactivity, lithium-ion batteries tend to develop a thermal runaway when damaged mechanically, thermally or electrically ([11]). The battery then heats up automatically and very quickly (>10 °C/min) through chemical processes, and leaves its stable operating range. Battery fires with large energy release, leakage and gas venting are the consequences. The main goal of the experiment was to investigate these effects of a lithium-ion battery in a road tunnel environment. The battery modules used in the experiment were fully usable and new components of a fully EV that is approved for traffic (see Table 1); they were completely charged (>95%) for the experiment.

Table 1: Characteristics of the investigated lithium-ion battery system

Characteristic	**Description**	
Number of cells	96 cells in 8 modules	
Electrode active material	Anode: Graphite	Cathode: $LiNiMnCoO_2$
Electrolyte	Lithium hexafluorophosphate ($LiPF_6$)	
Energy (gross/net)	33.182 / 27.2 kWh	
Specific energy (gross/net)	0.14 / 0.12 kWh/kg	
Thermal runaway	From 210 °C typical. High charge promotes thermal runaway.	

2.2. Measurement concept

In the event of a fire involving EV, apart from the conventional combustion gases (e.g. CO, CO_2 etc.), the formation of new, highly toxic pollutants is of special interest. Because of this theoretically expected difference to conventional vehicle fires, the experiment focused specifically on gas analysis. Pollutants and aerosols were measured in the test tunnel 160 m downstream of the test site at approx. 1.5 m above road level. In addition, thermal parameters were measured and visual characteristics of the provoked battery fires were recorded on video. The experiment was conducted in the test facilities of VersuchsStollen Hagerbach AG (VSH), which offer a real and safe environment for large fire tests with a reference to road tunnels. The site had a varying cross-section, being 56 m^2 at the test site and 43 m^2 at the measuring site.

The test area had to be constantly ventilated throughout the entire experiment for safety and measurement reasons. In order to control air flow and to prevent dilution by added fresh air after the test site, the bypass (pink) to the main ventilation duct (blue) shown in Figure 1 was closed with a gate during all tests. The measurements of the pollutant concentrations and the flow velocities in the main ventilation section could thus be determined conclusively and reliably.

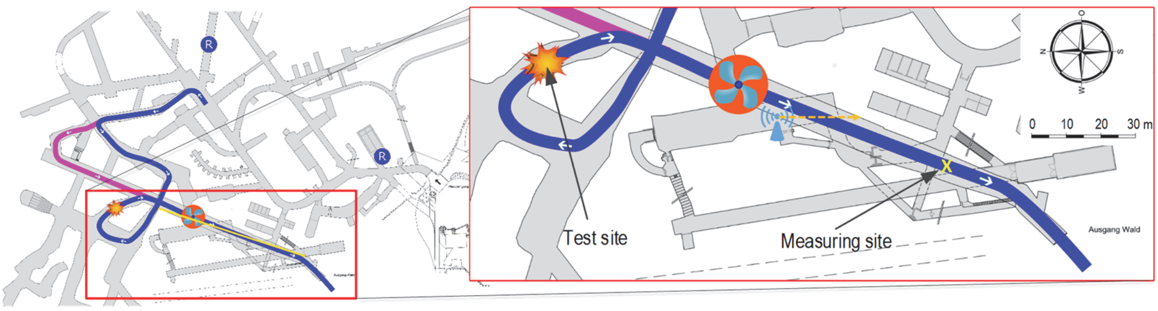


Figure 1: Layout of the test area: test site (fire), main ventilation section (blue) with closed bypass (pink), fan and measuring site (yellow)

The driving fan was located in the fire tunnel downstream of the test site (see Figure 1 and Figure 2). It was placed in the centre of the fire tunnel and provided a constant, homogenised air flow with an average speed of 1.0 - 1.5 m/s. All kinetic, thermal and chemical risks for the test personnel arising from the experiment were mitigated with appropriate safety precautions.

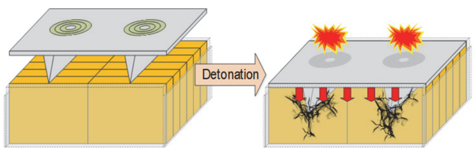
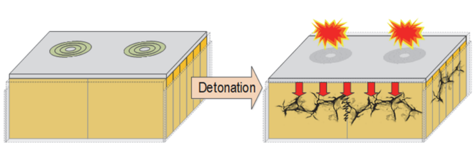
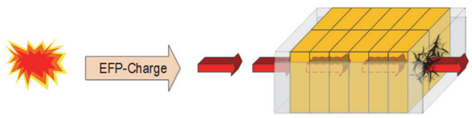
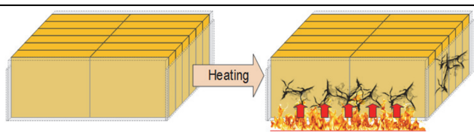
Figure 2: Test site (left) and subsequent fire tunnel where samples were taken (right)

2.3. Test scenarios

Possible fire scenarios in road tunnels involving an EV are mechanical damage (e.g. crash, object impact) and thermal stress (e.g. fire in a road tunnel, fire of EV itself) of its battery. These main scenarios were used as a basis for the experiment; in total, four identical modules were damaged in different ways, ultimately leading to a thermal runaway (see Table 2). The exact cause of the battery damage and its probability of occurrence in reality were not defined: The aim of all test scenarios was to achieve the maximum damage to the battery modules and ensure the resulting thermal runaway.

The forces required for the mechanical damage of the battery modules were generated by explosive methods – but the batteries themselves were not blown up. Depending on the test, the force was applied via a steel plate on which a sufficient explosive charge was mounted for acceleration in the direction of the battery module or through a penetrating projectile. Ideal quantities of explosives for the scenarios were determined in specific preliminary tests.

Table 2: Test scenarios of the experiment

#	Scenario	Illustration
1	**Wedge-shaped penetration**: Detonation of explosive charges accelerated a steel plate in the direction of the battery module. As a result, the wedges on the underside penetrated evenly into the two cell rows of the battery module, where they remained and caused electrical short-circuits.	
2	**Blunt impact**: Detonation of explosive charges accelerated a steel plate in the direction of the battery module. The module thus suffered a blunt impact over its entire surface so that all cells were structuraly damaged without penetration.	
3	**Central puncturing**: Battery module was shot at centrally with an explosively formed projectile (EFP) from a distance of 10 cm. As a result, both cell rows were to be damaged with a continuous penetration of all 12 cells.	
4	**Thermal stress**: Battery module was evenly underfired with a propane gas fire until the module caught fire. The fire source was then removed and the thermal runaway of the battery observed.	

3. RESULTS AND DISCUSSION

The tests were carried out on 27 and 28 November 2017 in the Hagerbach test tunnel according to a test concept drawn up beforehand. All measurements started at the time of damage and ended after the battery modules had completely reacted. The results shown in Table 3 are mean values over the listed test durations.

Table 3: Freight / release quantities (measurement uncertainty of ±10%)

Parameter	Test 1 («wedge»)	Test 2 («plate»)	Test 3[1] («puncture»)	Test 4 («fire»)
PH_3 [g]	< 0.4	---	< 0.4	---
F^- as HF [g]	1.1	3.1	< 1	< 0.5
PO_4-P as H_3PO_4 [g]	< 1.5	< 1.5	11.3	< 1
Co [g]	457	567	190	364
Li [g]	107	124	42	92
Mn [g]	445	536	184	349
F^- Aerosol [g]	152	160	68	126
NO [g]	< 1	1.1	< 1	1.5
NO_2 [g]	< 1	< 1	< 1	< 1
CO [g]	76	181	97	141
CO_2 [g]	8’500	6’000	2’000	7’800
TVOC [g]	20	196	93	32
∑ Aromate [g]	1.6	8.6	3.2	3.1
Benzene [g]	1.1	3	1.6	1.7
Toluene [g]	0.2	1.1	0.5	0.4
Xylene [g]	0.1	0.6	0.3	0.2
Styrene [g]	0.1	3.0	0.5	0.6
Duration	*16 min*	*21 min*	*16 min*	*26 min*

At the beginning of all scenarios, the damaged battery modules emitted large amounts of black and very dense smoke. It rose directly to the tunnel ceiling and drifted in stable layers from the test site to the ventilation fan in the subsequent fire tunnel, where turbulence destratified the smoke layers. Growing combustion processes gradually reduced the smoke emissions in all scenarios. In addition to typical combustion gases, other pollutants were detected, which are relevant because they do not occur in conventional ICE vehicle fires. The measurements indicate increased amounts of the toxic heavy metals Cobalt, Manganese and Lithium (dust-bound aerosols). It is noteworthy that the cause of damage has no significant influence on the released quantities of pollutants: in a worst-case, the whole chemical potential of a battery is set free. Contrary to expectations, no large quantities of HF were found[2].

Whereas the different mechanical damaging scenarios led to almost simultaneous thermal runaways of all cells, thermal stress did not result in a uniform reaction of the whole module: in this scenario, a distinct chain reaction from one cell to another could be observed, ultimately leading to the longest test duration (see Table 3). After the tests, the modules had no voltages left. It was shown that severe mechanical and thermal damages to EV batteries instantly lead to uncontrollable fires with high-energy releases. However, the general hypothesis that the fire

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[1] In test 3, the measurement encompasses only the time during which 50% of the module was destroyed.

[2] It is assumed that considerable quantities of HF were formed in the experiments, but due to its highly hygroscopic properties it very quickly reacted with moisture from the environment and presumably deposited somewhere in the tunnel on the way from the test site to the measuring site (approx. 160 m).

hazard in road tunnels will generally increase as a result of high-capacity traction batteries in EV cannot be confirmed. The experimentally derived findings illustrate that EV batteries do not lead to an aggravation, but to changing hazards in road tunnels.

Will thermal hazards change in road tunnels?
No. The battery fires were characterized by their rapid development, their high-energy release in a short period and, in some cases, by spectacular thermal processes (deflagration, flash flames) with strong smoke formation and high temperatures. Despite these effects, however, no explosions or other thermal effects could be observed that would differ significantly from conventional ICE vehicle fires. The measurements indeed show very high temperatures of up to 750 °C within the batteries, but at a distance of 2 m practically no temperature rises were registered. It is not possible to make a reliable statement on the heat release rate (HRR) of the battery fires based on the present measurements. However, within this context, the HRR of the battery fires is not decisive. The observed temperatures (>700 °C) during the experiments suggest that lithium-ion batteries are indeed extremely energy-rich fire sources and that a battery fire will spread through the surrounding body parts and ultimately lead to a complete vehicle fire. As soon as a full EV fire has occurred, its thermal characteristics will not differ from those of a conventional ICE vehicle fire: Experimental studies with complete vehicles prove that comparable EV and conventional ICE vehicles have similar HRR (approx. 5 MW) and heats of combustion (approx. 7'000 MJ) ([3];[5];[7]).

Will chemical hazards change with regard to potential effects on humans in road tunnels?
On the small-scale: Yes. Like conventional vehicles, completely burning EV emit pollutants that result from the exothermic decomposition of the vehicle. However, due to the chemical components of lithium-ion batteries, the flue gases of an EV fire contain additional substances that are very reactive and pose a considerable health risk to humans. In the immediate vicinity and in unfavourable ventilation situations, therefore, EV fires pose new and potentially greater chemical hazards to people than fires of conventional ICE vehicles. On the large-scale however, it can be assumed that the chemical hazard situation for tunnel users will not change with increasing distance from the fire: the natural air flows in road tunnels and the ventilation systems lead to fresh air supply and dilutions and thus to increasingly lower pollutant concentrations.

Is there a need for technical adaptation in road tunnels?
No. Due to the experimental results, no adaptation of the existing operating and safety equipment seems necessary. Ventilation systems in road tunnels are central facilities to enable appropriate self-rescue for road tunnel users in the event of an incident. In Switzerland they are generally designed for major fires (30 MW) with considerable pollutant emissions (e.g. heavy vehicles). It is therefore assumed that EV fires can be adequately managed with the existing technical equipment in state of the art road tunnels.

Is there a need to adjust the management of incidents with regard to firefighting?
Concerning the choice of the extinguishing agent – No. Water is considered the best coolant for lithium-ion battery fires, although the chemical properties of the batteries practically prevent a complete fire extinguishment. Firefighting with water has the advantage that undamaged cells of a battery may be cooled and hence protected against a thermal runaway. However, for effective cooling of EV fires, very large quantities of water are required, potentially more than with conventional ICE vehicle fires. Hence, sufficient water supply is a critical factor at the site during an incident.

What about chemical hazards in other underground infrastructure?
The findings of this study point to potential relevant consequences for other, smaller underground infrastructure (e.g. car parks). To estimate the chemical fire hazards of a complete lithium-ion battery in a passively ventilated room, the experimental pollutant data can be expressed in terms of the maximum concentration values at which an exposed person suffers serious or

permanent damage after 30 minutes (immediately dangerous to life or health, IDLH[3]). For this, the following scenario is assumed: The complete battery (8 modules) as described in Table 1 is completely burnt off within 30 minutes in a volume of 1,000 m^3 (e.g. car park with 20 x 20 x 2.5 m). The room is ventilated passively with an air exchange rate of 3/h. The calculated concentrations are then compared with the IDLH values of the respective substances. Table 4 only lists the substances where critical concentrations could be detected (all other substances show concentrations that lie below the IDLH-values).

Table 4: Chemical hazards in a room with 1000 m^3 (≠ road tunnel)

Substance	Concentration (mg/m^3)	IDLH-Value (mg/m^3)	Q
Co	1'100	20	55
Li	300	0.5	600
Mn	1'100	500	2.2
F^- Aerosol	400	250	1.6
CO_2	121'000	72'000	1.68

These thoughts illustrate that heavy metal emissions are of particular importance, as they do not occur in such concentrations in conventional ICE vehicle fires. In this example, the calculated concentrations of cobalt are 55 times higher than the maximum IDLH-value; lithium is 600 times higher and manganese 2 times higher than the maximum value at which serious or lasting damage is to be expected after 30 minutes. From a scientific point of view, these findings must be verified; it is therefore recommended that heavy metal emissions from EV fires in infrastructure with restricted ventilation as well as possible contamination should be investigated in greater depth. In the context of changing mobility, these findings support emergency forces in coping with future incidents. They are also able to sensitize operators of other underground traffic infrastructure (e.g. car parks) to changing hazards.

4. OUTLOOK

Even if the original hypothesis about the increased risk from EV fires in road tunnels could not be proven, new topics were uncovered, which have to be scrutinised in further research steps.

Potential contamination

Burning lithium-ion batteries form the highly toxic, gaseous hydrogen fluoride (HF) due to the fluorine contained in the electrolytes. Being highly hygroscopic, it tends to bond very rapidly with water. In contact with firefighting water, hydrofluoric acid can form, which is a powerful contact poison that is immediately absorbed by the human skin. If contaminated firefighting water with HF or with the heavy metals Co, Li and Mn drains off uncontrolled after a fire event and is released to the environment, additional hazards arise that cannot be estimated at the present time. Since no measurements were carried out on this aspect in the study at hand, further investigations are recommended to assess the potential hazard posed by contaminations of damaged EV batteries (e.g. firefighting water, building structures, vehicle parts, equipment of emergency personnel).

Disposal of damaged traction batteries

In contrast to the test material of this research project, EV batteries are in most cases not completely reacted and chemically inert after a real mechanical or thermal damage event. This means that damaged but not completely destroyed cells of a lithium-ion battery can repeatedly emit harmful substances or even flare up again. From the emergency personnel's point of view, it is therefore important to be able to assume that damaged traction batteries no longer pose any

[3] https://www.cdc.gov/niosh/idlh/intridl4.html

chemical or electrical hazards. At present, however, there are no uniform procedures for limiting risks in this respect. In the course of the present experiment, a number of explosive methods have been revealed that might be suitable for efficiently neutralising damaged traction batteries after an incident on-site. Based on this practical experience from the experiment, further studies are to be carried out to get an effective, practicable and economic method to ensure a safe disposal of damaged EV batteries after a fire.

Effectiveness of high-pressure water mist systems in underground infrastructure
Investigations for ocean ferries have shown that the use of high-pressure water mist appears particularly suitable for EV fires, as the extinguishing agent is distributed effectively in a room and has the property of penetrating concealed places as well. The risk-based effectiveness of these firefighting systems in relation to EV fires in road tunnels and other underground infrastructure (e.g. car parks) has not been investigated thoroughly yet. A risk-oriented study on the alleged effectiveness of high-pressure water mist systems for EV fires seems recommendable.

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