

RECOMMENDATIONS FOR SAFE HANDLING OF ELECTRIC VEHICLES AFTER SEVERE ROAD TRAFFIC ACCIDENTS

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ABSTRACT

The EVERS SAFE project addressed many safety issues for electric vehicles including the crash and post-crash safety. The project reviewed the market shares of full electric and hybrid vehicles, latest road traffic accident data involving severely damaged electric vehicles in Europe, and identified critical scenarios that may be particular for electric vehicles. Also, recent results from international research on the safety of electric vehicles were included in this paper such as results from performed experimental abuse cell and vehicle crash tests (incl. non-standardized tests with the Mitsubishi i-MiEV and the BMW i3), from discussions in the UN IG REESS and the GTR EVS as well as guidelines (handling procedures) for fire brigades from Germany, Sweden and the United States of America. Potential hazards that might arise from damaged electric vehicles after severe traffic accidents are an emerging issue for modern vehicles and were summarized from the perspective of different national approaches and discussed from the practical view of fire fighters. Recent rescue guidelines were reviewed and used as the basis for a newly developed rescue procedure. The paper gives recommendations in particular towards fire fighters, but also to vehicle manufacturers and first-aiders.

INTRODUCTION

This paper is based on work performed in the EVERS SAFE project which, among other research topics, dealt with the crash and post-crash safety of electric vehicles (EVs) aiming to provide safety requirements and research needs for these (Wisch, et al., 2014). The project ran from 2012-2014 and was a collaborative project in the ERA-NET Electromobility+ programme.

EVs can be categorized into first (1GEV) and into second generation electric vehicles (2GEV), respectively. While 1GEV were defined as being solutions of electric vehicles based on existing chassis, vehicle geometries and established materials; 2GEV were defined as being developed and fabricated specifically by the car manufacturers and suppliers to best fit the users' demands of electric vehicles considering new vehicle construction concepts (including mass compensation measures regarding heavier battery weights), safety technologies and functionalities.

Motor vehicles with partial or full electric drivetrains are a small but growing component of the European vehicle fleet. An analysis of the current stock (end of year 2013) for different vehicle segments with electric drivetrains was performed based on figures for Germany (from the German Federal Motor Transport Authority) and Sweden (Trafikanalys, 2014). In both countries these vehicle types represent less than 1% of the vehicle fleet. Even in countries where government incentives are available, like Norway, the EV type is increasing faster but still is at only 1% of total vehicles (Statistics Norway, 2014). In terms of vehicle segments, in Germany around 81% of all registered passenger cars classified as battery (full) electric vehicles (BEV), range extender electric vehicles (REEV), fuel cell electric vehicles (FCEV) and plug-in hybrids have been assigned to the segments "mini" (56.7%), "small vehicle" (18.7%) and "compact class" (24.6%). The remaining share of around 19% contains larger vehicles. Due to this bias towards smaller vehicle sizes the target vehicles for investigating safety issues in EVERS SAFE (and in this paper) were superminis and small family cars.

Accident Data

The penetration of electric vehicles in the vehicle fleet is still low and this is reflected in the number of available analyses of electric vehicle crashes based on national data sources such as police reports. The most relevant report describing electric vehicle crash risks was that provided by Daimler (Justen & Schöneburg, 2011). Although electric vehicles could not be directly analyzed, they used conventional vehicles as a surrogate and identified deformation maps that could identify the most risky areas for battery placement in real crashes which were compared to deformation from standard crash tests. Also, given that electric vehicles will tend to operate in

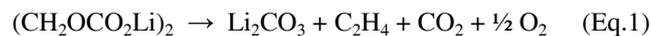
a similar manner in the road system, the accident configurations most commonly observed should also be relevant for the near future.

Marschner and Liers also discussed potential road traffic accidents involving electric vehicles based on assumptions of similarity to existing vehicles types (Marschner & Liers, 2013). For that reason, a GIDAS (German In-Depth Accident Study) analysis was carried out focusing on microcars and similar. More than 22,000 accidents were used to identify all vehicles with usage patterns close to future electric vehicles. Afterwards, numerous parameters of anticipated electric vehicles and conventional M1 vehicles were compared from which safety requirements have been derived. To characterize the expected accident scenario of urban electric vehicles, typical collision constellations, collision parameters and injury mechanisms were analyzed. Even though the analyzed vehicles were mostly small and compact cars, a significant mass difference for future urban cars was foreseen. Since the majority of the electric vehicles will be used in urban areas, it was concluded that there will be a change in the future accident occurrence. In general, lower accident severities were expected including less crashes in the longitudinal direction but with an increase in crashes at junctions while crossing and turning conflicts result in a higher proportion of side crashes. The severity of such an accident is influenced greatly by the vehicle mass and speed of the striking vehicle but the proportion of crashes with heavier vehicles was expected to remain similar to today's situation with conventional passenger cars.

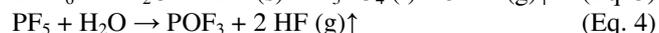
The Swedish Project "Räddningskedjan- EV Safe Rescue" reviewed 165 crashes involving hybrid vehicles based on the accident data from NASS-CDS database, the majority being the Toyota Prius and followed by Honda Civic Hybrid (Vinnova, 2014). The accident investigation team identified the primary impact direction and damage location. Of 110 hybrid vehicles with identified impact directions, 65% had a frontal impact followed by 20% with rear impacts. The car front and rear were also the two most frequently damaged areas (Vinnova, 2014), which accounted for 61% and 18% of identified damaged locations. In these 165 cases there were no fire accidents reported directly after the crash.

Lithium-ion Batteries and Potential Hazards after Crash Loads

Current Lithium-ion (Li-ion) batteries are highly developed, well balanced chemical systems. These batteries are comprised of two highly lithiated contrary charged electrodes commonly separated by an olefinic separator and filled with flammable organic solvents. The formation of a Solid Electrolyte Interface (SEI) during the first cycling of a Li-ion battery after assembly is an essential step for the function of the battery. SEI is composed of stable compounds like Li_2CO_3 and meta-stable compounds like e.g. $(\text{CH}_2\text{OCO}_2\text{Li})_2$. The SEI becomes unstable when the cell temperature rises above $70\text{ }^\circ\text{C}$ – $100\text{ }^\circ\text{C}$ with an exothermic decomposition according to Equations (1-2):



These reactions lead to the formation of ethene (C_2H_4) and carbon dioxide (CO_2). As a result, Li-ion batteries are very damageable by elevated temperatures. For example, an internal or external short circuit will raise the temperature inside the cell. An internal short circuit could arise when an external metallic part intrudes into the cell or by direct contact of battery electrodes after excessive compression of the separator. These examples may occur as a result of a car crash. Particles may also be introduced inside the cell during manufacturing process and cause an internal short circuit. Thermal and/or mechanical impact leads to the destruction of the SEI. After SEI decomposition, lithium reacts with organic electrolytes. Depending on the organic carbonates used as electrolyte components, different gaseous unsaturated hydrocarbons according to the reactions above are generated: ethene (C_2H_4), propene (C_3H_6), ethane (C_2H_6) and/or propane (C_3H_8). All these compounds are flammable and may form an explosive mixture depending on its concentration. An additional gas, hydrogen fluoride (HF), may also be produced due to reactions involving the conducting salts within the battery. Li-ion batteries can be provoked by internal or external heat sources and produce different gases that can be combustible or poisonous. The source of the heat can be fires surrounding the battery or internal short circuits of the battery cells caused by mechanical damage. High temperatures at one cell may affect adjacent cells and cause a chain reaction. With the organic solvent the conducting salt, LiPF_6 , is also emitted and reacts in contact with water/air moisture according to Equations (3-4):



If a thermal runaway occurs a large number of different kinds of chemicals are generated. Combustion reactions evolve mainly the gases CO , CO_2 from organic materials, NO_x , HF as well as low molecular weight organic acids, aldehydes, ketones etc.

Crash Safety by Regulation

Electric vehicles shall fulfill all crash safety requirements as for conventional vehicles. Thus the current prevailing homologation tests regarding crash safety are applicable to electric vehicles as well. Depending on the market, different homologation tests are required for new vehicles to be type approved. It is necessary to address potential safety risks of EVs while in use and after a crash event, including electrical shocks associated with the high voltage (HV) circuits of EVs and potential hazards associated with Li-ion batteries and/or other rechargeable energy storage systems (REESS) (UNECE, 2012). In principal, the tests shall address safety considerations regarding the HV electrical safety, safety of electrical components, and REESS whereby there shall be no evidence of electrolyte leakage, fire, or explosion.

In Europe, all new vehicles should pass crash tests as specified by the United Nations Economic Commission for Europe (UNECE). With respect to complete vehicle crash tests, required tests include UN-R94 for frontal crash, UN-R95 for side crash, UN-R12 for steering mechanisms, and UN-R32 for rear end crash. For new vehicles to be sold in USA, they need to pass crash tests specified by the Federal Motor Vehicle Safety Standards (FMVSS). With respect to complete vehicle crash tests, they should pass FMVSS 208 (frontal crash, rollover, side crash), FMVSS 214 (side crash), and FMVSS 301 (rear end crash). The homologation tests in other regions such as in China, Japan, Australia and Canada are similar to those devised by UNECE and FMVSS.

Due to the introduction of HV system and traction battery system in electric vehicles, extra demands were raised concerning high voltage safety and battery safety in crash accidents. In Europe (and especially the 1958 agreement affiliated countries), UN-R100 sets requirements for the electric powered vehicles (classes M and N) and their REESS. In UN-R100, specific requirements on the REESS performance are defined concerning vibration, thermal shock and cycling, mechanical impact, fire resistance, external short circuit protection, overcharge/discharge protection, over-temperature protection and emissions. The date of entry into force of its latest series of amendments was 15 July 2013. Basic post-crash requirements regarding the safety of electric vehicles have also been added to UN-R94 and UN-R95 (e.g. regarding the releasing of electrolyte). In USA, FMVSS 305 specifies performance requirements that specify the: allowable electrolyte spillage, retention of propulsion batteries, and electrical isolation of the chassis from the high-voltage system during the crash event. This regulation is used in conjunction with FMVSS 208 (frontal rigid barrier crash tests), FMVSS 214 (side impact), and FMVSS 301 (rear, rigid barrier and deformable barrier impact tests).

Besides these crash regulations another Global Technical Regulation (GTR) is under development which addresses the safety of EVs. The Executive Committee of the 1998 Agreement (AC.3) gave, in November 2011, its general support to a joint proposal by the United States of America, Japan and the European Union to establish two working groups to address the safety and environmental issues associated with electric vehicles (EVs). That proposal (ECE/TRANS/WP.29/2012/36 and its Corr.1) was submitted to the World Forum for Harmonization of Vehicle Regulations (WP.29) at its March 2012 session for further consideration and formal adoption. The WP29 Committee has adopted this proposal with China as one of the co-sponsors together with the United States, Japan, and European Union (UNECE, 2012). The purpose of this regulation is to avoid human harm that may occur from the electric power train. The crash and post-crash phase are addressed by measures for the protection against electrical shock; REESS crashworthiness, including the limitation of electrolyte leakage, physical battery retention, and the maintenance of essential safety performance; and REESS safety assessment and stabilization procedures (UNECE, 2014). Major results from the GTR EVS are expected in 1-2 years.

METHODS AND DATA SOURCES

Abuse Cell Tests

To study the performance of batteries under crash type loading a set of experimental abuse tests on cell level were conducted in the EVERS SAFE project aiming to understand the deformation tolerance and potential thermal and gas generated by batteries (Wisch, et al., 2014). Nail penetration is part of the standard tests being conducted on cells. In EVERS SAFE two different nail penetration test setups were conducted using pouch cells. Test setup 1 used a nail (rounded plastic punch) that had penetrations limited by the fixture back plate and did not fully penetrate the cell as specified in the standard procedures while test setup 2 had a nail penetrator according to the SAE J2464 standard (tapered conductive metallic nail) to promote internal short circuits that passed through a hole in the back plate allowing full penetration. The first case test can be considered more of a localized crush test. Another abuse test, a shear test, cleanly sliced the cells with metallic knives. Again, two different test configurations were applied. On the one hand a support plate for the pouch cell was used (test setup 3) and on the other hand the pouch cell had no support structure at the cut edge (test setup 4).

Non-standardized Vehicle Crash Tests

To study the performance of electric vehicles under crash type loading, and in particular their HV batteries, as well as and to evaluate the current protection levels of EVs and safe handling procedures for rescue services, two crash tests were conducted. Since both vehicles to be tested were already cars in serial production on the market

and successfully passed regulation and consumer program (Euro NCAP) tests, non-standardized crash test configurations have been developed to study other realistic impact conditions that are challenging for the HV battery system and which allowed studying existing and updated safe handling procedures for rescue services.

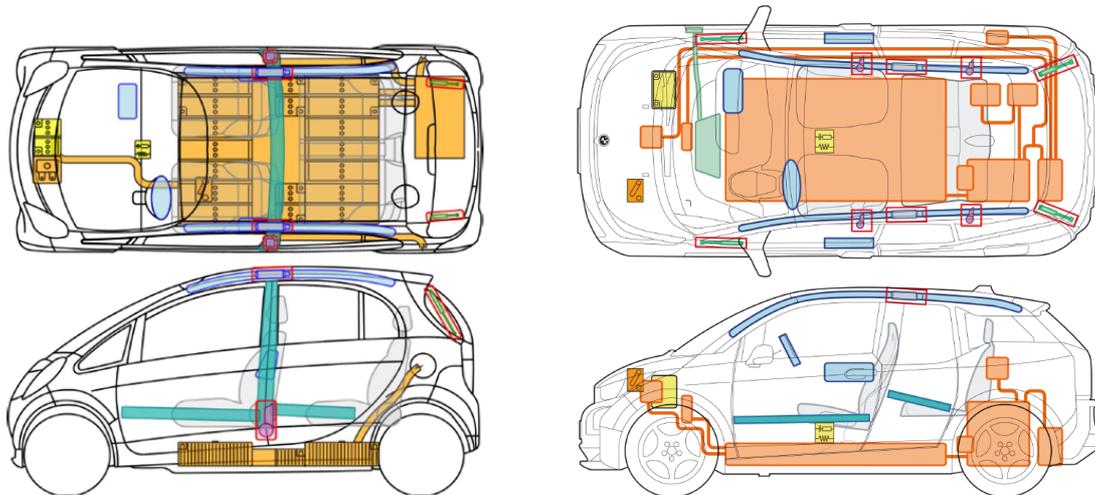


Figure 1: Left: schematic Mitsubishi i-MiEV (source: Rescue data sheet Mitsubishi) and Right: schematic BMW i3 (source: Rescue data sheet BMW)

Non-standardized Vehicle Crash Test #1 – Mitsubishi i-MiEV

As a first vehicle under test, the Mitsubishi i-MiEV (1GEV) was chosen representing a full electric vehicle with a Li-ion battery (330 V, 88 Li-ion cells, 16 kWh) that is located beneath both seat rows (see Figure 1) and two charging devices in the rear, a service-disconnect device beneath the driver seat and power electronics in the rear. As the test configuration, a 90 degree side pole impact was chosen whereby the i-MiEV was stationary (but not braked and with activated HV system) and a moving crash barrier (trolley) carried a rigid pole at its front (total mass ~2 t) approaching with 35 km/h, see Figure 2.

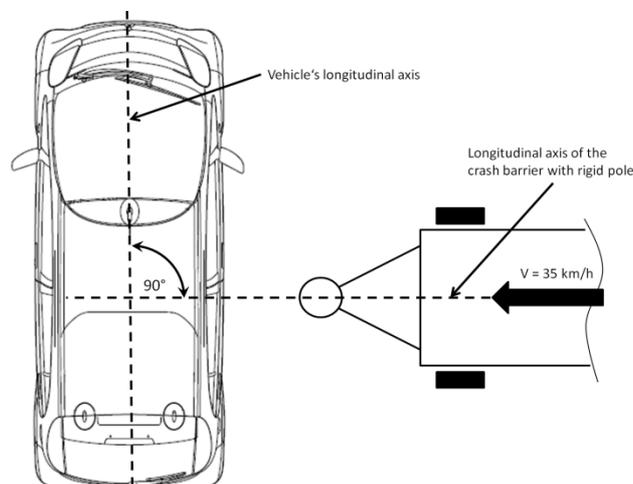


Figure 2: Scheme of test configuration side pole impact Mitsubishi i-MiEV

Non-standardized Vehicle Crash Test #2 – BMW i3

The second vehicle tested, the BMW i3 (2GEV), was chosen representing a full electric vehicle with a Li-ion battery (380 V, 96 Li-ion cells, 21.6 kWh thereof 18.8 kWh usable) that is located beneath both seat rows, see Figure 1. Further, it has one charging device in the rear, a service-disconnect device (executed as 12 V cutting line) in the car's front part and power electronics in the rear. Another peculiarity of the BMW i3 is that carbon fiber reinforced plastic (CFK) is primarily used as chassis material. However, the material used for front and rear crash structures are steel and aluminum. A crash configuration that represents both a frontal and a rear-end crash, as might occur in a traffic jam situation, was selected see Figure 3. A stationary, braked truck (weight ~10 t) was placed 2 m in front of the stationary BMW i3 test vehicle. The HV system was active and in driving readiness mode (with gear in neutral). A crash trolley fitted with a deformable barrier (total mass ~2 t) crashed then into the rear of the test vehicle BMW i3. All vehicles were centered along a common longitudinal axis. The trolley had a speed of 80 km/h. This test configuration exceeded standard crash requirements due to the fact that multiple impacts to the same vehicle were conducted.

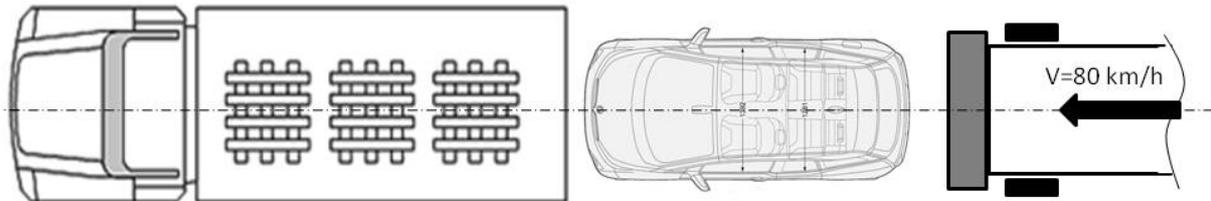


Figure 3: Scheme of test configuration front and rear-end crash with BMW i3

Rescue Procedures / Guidelines, Rescue Data Sheets and Technical Solutions

Rescue procedures vary within and between countries depending on the national, regional, and local organization of rescue services (Wisch, et al., 2014). Regardless of the location, firefighting and rescue services share common themes and technologies but there are local requirements that prohibit rigorous definition of rescue procedures. Due to the diversity of vehicles, occupants, and road conditions that will define a rescue operation, it is desirable that rescue personnel have a fundamental training that they can adapt to all possible conditions that they may encounter during their working career.

A study was performed to obtain an overview of existing rescue guidelines in Germany with special focus on information regarding the dealing with crashed electric vehicles (Wisch, et al., 2014). The information gained from the document "Accident Assistance & Recovery vehicles with high voltage systems" (German Association of the Automotive Industry (VDA), 2013) was considered to be most current and applicable. Other guidelines, as published by professional associations, do not focus sufficiently on the complete picture which is seen at a crash scene nor focused already on Li-ion battery technologies, but on organizational (mostly educational) aspects such as qualification levels or protection clothes.

Rescue data sheets have been developed to provide most important vehicle information for rescue teams in a clear and standardized way as well as in shortest time to ensure best rescue conditions for injured occupants. In Germany, the ADAC (General German Automobile Association) appealed in 2009 to the vehicle manufacturers to provide rescue data sheets for all new cars and to position them under the sun visor to provide information about cutting and pressure points, airbag zones and the location of the battery (Deutscher Feuerwehrverband e.V. (DFV), 2009). In addition to these data, rescue data sheets now include information regarding type of drive and the location of high-voltage components. Meanwhile several associations from the automobile sector and firefighting/rescue as well as vehicle manufacturers themselves and governmental entities promote the usage of these sheets in Europe. However, a legal obligation to carry a rescue card currently does not exist. The International Organization for Standardization (ISO) is developing a standard for rescue sheets (ISO, 2014). To ensure the availability of a rescue data sheet, Mercedes-Benz has introduced to the inside of the gas cap and on the opposite b-pillar QR codes that enables emergency services to access the individual sheet with a smartphone or tablet (Daimler AG, 2013).

In Germany in 2013, the Federal Ministry of Transport has set the basis to retrieve vehicle-related information directly from the database of the Federal Motor Transport Authority on software solutions on a tablet or laptop (Joint press release from von VDA, VDIK, ADAC, DAT and BMVBS, 2013). Two software solutions similar in functionality, the SilverDAT® - FRS (DAT group, 2013) from DAT (Deutsche Automobil Treuhand GmbH), and the Crash Recovery System® (Moditech Rescue Solutions BV, 2014) from Moditech Rescue Solutions use this option in the form of a license number query. Thus, it is possible to obtain directly by means of the license plate number at the accident scene information about the type of vehicle or drive and the access to the vehicle-related, digitized rescue data sheet.

In the United States, the National Fire Protection Association conducts diverse research on the handling of crashed electric vehicles and offers safety trainings as well as produces comprehensive material to be studied by firefighters. One of the basic documents, the Electric Vehicle Emergency Field Guide, provides an intuitive, quick reference guide, covering all current makes and models of hybrid and electric passenger cars drawn from manufacturer Emergency Response Guides (NFPA, 2012). Regarding the approach to a crashed vehicle, this document refers to always assume that the vehicle is some type of hybrid, electric or alternative fueled until proven otherwise.

The emergency call (eCall) is a system that in the event of a car accident automatically informs the locally responsible Public Safety Answering Point (PSAP). Technically, often the triggering of the airbag sensors initiates this automatic emergency call over the mobile network to the nearest PSAP. In addition to the position of the crashed car, vehicle-related data is transmitted, which are thus available to the emergency services even during the travel to the scene (German Federal Ministry of Transport and Digital Infrastructure, 2014). "The EC proposals for legislative acts foresaw that eCall would be seamlessly functioning throughout Europe by end of

2015. As the adoption procedure of these legislative acts by the European Parliament and the Council is still ongoing, the deadlines for implementation will most likely be the end of 2017 or early 2018.” (European Commission - Digital Agenda for Europe - A Europe 2020 Initiative, 2014)

RESULTS

In general the tested pouch cells in the EVERSAFE project were quite resistant to the abuse. Only 1 of 19 cell tests resulted in thermal events. One cell was provoked by an overloading of the cell, after an external short circuit before testing and showed no negative effect on cell integrity. Shear tests gave comparable good results with no significant thermal activity (under 30°C) but with some toxic substance release. Even after the cells had been cut, there was a stable voltage developed by the cell. The lack of reaction in these tests could confirm that a clean cut of the cell will not lead to a failure of the separator and thus no direct contact appears between the cathode and anode. Results of nail penetration tests differ according to different types of nail (test setup 1 with rounded plastic punch and test setup 2 with thin metallic nail). None of the test setup 2 nail tests produced any significant cell swelling although there were traces of toxic substances. Temperatures did not exceed 60 °C. However, test setup 1 nail penetration tests produced some cell swelling and thermal activity was observed where temperatures up to 300 °C were recorded. The nail used at test setup 1 was made of plastic and could expand during the test, resulting in a local compression of the cell compared to the full nail penetration of the cell at test setup 2. The comparison of these tests shows that a clean penetration with a thin metallic, electrical conducting nail didn't lead to a reaction of the cell, whereas an intrusion with a wider object leads to a local compression and an internal short-circuit which deems to be more realistic in road traffic accidents. A special area of concern was also the reproducibility and the robustness of these tests since it could be shown that the results of cell tests might strongly differ already due to small differences of the test conditions and test scenarios applied. Pouch cells were also tested for external short circuit and overcharge of cells. External short circuit of cells has led to a tremendous evolution of gas inside the pouch cell, resulting in an inflating of the pouch like a balloon, but did not lead to bursting. After the temperature decreases, swelling was reduced and the pouch returned to its original flat profile but with wrinkles. Even a pouch cell rigidly held to the fixture by covering with non-flammable material has shown no bursting after inflating due to external short circuit. A consecutive overcharge with 5 V led to a thermal runaway with fire. It has to be pointed out that these tests should be referred to as extreme and demonstrate the high safety level of the device under test.

The crash tests with the two electric vehicles (Mitsubishi i-MiEV and BMW i3) produced no significant battery reactions (no new or unexpected risks such as electrical hazards, chemical reactions, thermal events, release of toxic substances battery, fire or explosion) and vehicle damage was as expected for current vehicle safety levels. Figure 4 shows the BMW i3 detached from the ground shortly after crashing into the rear of the truck indicating the high crash severity. Full test reports are provided in the EVERSAFE Deliverable 3.1 (Wisch, et al., 2014). Thus, both test vehicles exhibited high levels of safety in non-standardized, but realistic experimental configurations which were shown by:

- Good mechanical protection of the battery system.
- High-voltage system disconnected automatically to safe condition.
- Shut-down times of the HV systems much quicker (< 2s) than required by crash regulations (< 60s).
- No incidents (no undue temperature increase, no release of toxic / flammable gases or liquids).
- Intact cabin; a few bruised HV wirings and small deformations to the outer battery casing but without negative consequences.
- Newer chassis materials can produce stiff structures that increase the vehicle accelerations but can provide easier access to injured occupants as the doors may not bind due to distortions of the structure.



Figure 4: BMW i3 and crash trolley have fully left the contact to the ground at ~494 ms after the first impact

The main battery requirement from vehicle safety regulations was that the high-voltage outside the HV battery should drop down quickly (below 60 V) in a crash and this situation was fulfilled. As example, Figure 5 shows the HV network shut-off of the Mitsubishi i-MiEV after crash. There was no evidence of any danger after both crash tests that could be hazardous to occupants or rescue teams, neither with regard to electrical, thermal, nor chemical hazards. However, it could not be shown which effects further handling of this crashed vehicle might have (e.g., due to pulling, cutting or distorting the vehicle) during recovery operations.

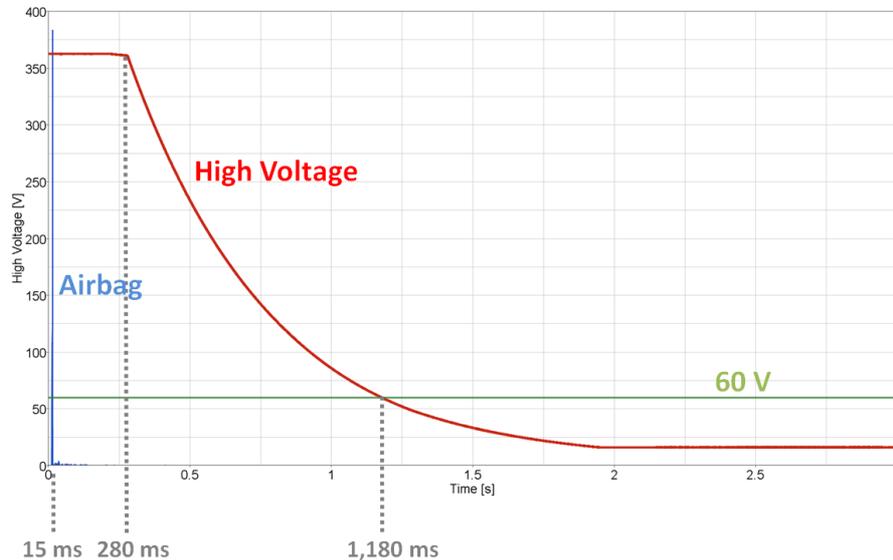


Figure 5: Airbag ignition and high-voltage network shut-off of the Mitsubishi i-MiEV after side pole impact

The severity of the full scale crash tests was chosen to be more challenging than required by the UN regulations or Euro NCAP tests, respectively. This decision was made because both test vehicles (Mitsubishi i-MiEV and BMW i3) have already successfully passed regulation and Euro NCAP crash tests and thus demonstrate a certain level of crash safety even with their new drive trains. The particular test configurations have been selected to reflect worst case, but realistic scenarios where potential hazards might occur.

Potential hazards originated from the high-voltage battery in severe crashes due to mechanical loading or fire close by during a crash are electrical shock risks, thermal events, chemical reactions and release of emissions of flammable, ignitable and/or toxic battery substances as well as fire or explosion. The main substances that can be expected from a Li-ion cell and their potential consequences are presented in Table 1.

Table 1: Table of critical emitted gases

Substance	Chemical formula	Health Risk	Toxic Concentration/ exposure time	Flammable
Hydrogen	H ₂	No		Yes
Carbon monoxide	CO	Yes	6,400 ppm / 30 minutes	No
Carbon dioxide	CO ₂	No	30,000 ppm	No
Methane	CH ₄	No		Yes
Hydrogen fluoride	HF	Yes	50-250 ppm / 5 minutes	No
Phosphor pentafluoride	PF ₅	Yes	3 ppm / 8 hours	No
Electrolyte fumes	LiPF ₆	unknown		Yes

Portable multi-gas detectors are diffusimeters by default and are appropriated to detect critical emitted gases at a crash scene. Specialized rescue vehicles have addition measurement devices with active intake (integrated pump). In general, the multi-gas detectors allow directly measuring CO, H₂S and O₂. Further the available Ex-sensor (explosion sensor) only measures combustible gases and hereby only measures exactly, when calibrated on these substances (often methane (CH₄) and nonane (C₉H₂₀)). However, gases such as H₂ can be calculated qualitatively using the explosion limit. As identified for Germany, in case of volunteer fire brigades a multi-gas detector is equipped on a vehicle specialized for measurements with a standardized configuration of the sensors and would be called subsequent to the initial vehicle arriving at the scene, whereas in case of a professional fire department this multi-gas detector is carried as standard in a vehicle of the first squad team.

A non-representative survey for available multi-gas detectors in Germany was performed in 2014 (Wisch, et al., 2014). Results have been summarized in Table 2. Although no longer commercially available the MSA “Solaris”

is still in use. There are other suppliers of portable gas detectors, but the companies MSA Auer and Dräger have largely prevailed in the fire service in Germany as standard.

Table 2: Typical multi-gas detectors used by German firefighters

Gas detector class	Label
1-5	Dräger "X-am® 5000"
	MSA Auer "ALTAIR 5X"
1-4	Dräger "X-am® 2500"
	Honeywell/ Compur Monitors "Impact (Pro)"
	MSA Auer "ALTAIR 4X"

To determine unknown liquids, a litmus paper test is standard for both volunteer and professional fire brigades. The same is true for thermal imaging cameras. In contrast, only specialized vehicles (e.g. the ABC-explorer) are typically equipped with short-time measurement tubules and need to be called subsequently by the incident commander. Water is still the standard extinguishing agent. However, additives are also used such as fire fighting foams which increase the impact of smothering a fire and cooling. Electrical measurements will be performed in most cases with a voltage tester that is present in the appropriate standardized toolbox.

An extended personal protective equipment (PPE) includes a chemical splash suit is available in several types ranging from part to full body protection in contrast to the standard PPE which contains of heat and (shortly) flame resistant jacket and trousers, helmet, leather boots (security class S3), respirator mask, special harness (incl. abseiling eyelet and hatchet).

Recommendations for Rescue Teams

In order to support rescue services when approaching road traffic accident scenes involving severely damaged electric and/or hybrid vehicles, a procedure for handling these vehicles with Li-ion traction batteries has been developed considering best practices and realistic resources. Inputs for the proposed rescue guideline (in the flow chart format of Figure 6) have come from several sources:

- Review of existing handling procedures for firefighters in particular from Germany and Sweden.
- Exchange of information and experiences with local firefighters around the crash tests conducted.
- Discussions within the EVERS SAFE consortium and external experts.
- Survey regarding gas measurement devices available at German fire departments.

The flow chart in Figure 6 is divided into three columns identified with color. The middle, light blue column represents the decision path; the left, green column gives explanations and advice for the decision path; while the right, red column gives advice for measurement devices or special personal protection equipment. In addition to the explanations, information or user warnings are provided, partly by color or pictograms.

In addition to the measures for vehicle drivetrain identification, securing and deactivation of electric vehicles and the technical possibilities of monitoring the work site, the patient's health condition plays a decisive role in the flow chart. This results in a quick assessment of the accident and selection of the three approved types of rescue "Gentle rescue", "Fast rescue" and "Immediate rescue" as made use of in Germany. This approach uses procedures familiar for accidents involving conventional vehicles and reduces additional training requirements. The monitoring of the patient and the applied measurement technology must continue following the initial patient assessment and needs to follow the procedures identified in the flowchart until the patient is rescued from the vehicle. The 'immediate rescue' is the fastest possible rescue, tolerating a possible further deterioration of the patient from immediate danger or due to medical conditions. 'Fast rescue' is the fastest possible rescue of the patient with respect to time, tactical and medical aspects. In order to minimize the travel time to the hospital, transport is to be aimed at the 'fast rescue' time window of 20 to 30 minutes. 'Gentle rescue' is a rescue, in which the time aspect moves into the background because the diagnosed injury is not sensitive to time and the time window for medical consultation may in some cases be even greater than that of 'fast recovery' (Vereinigung zur Förderung des deutschen Brandschutzes e.V., November 2011).

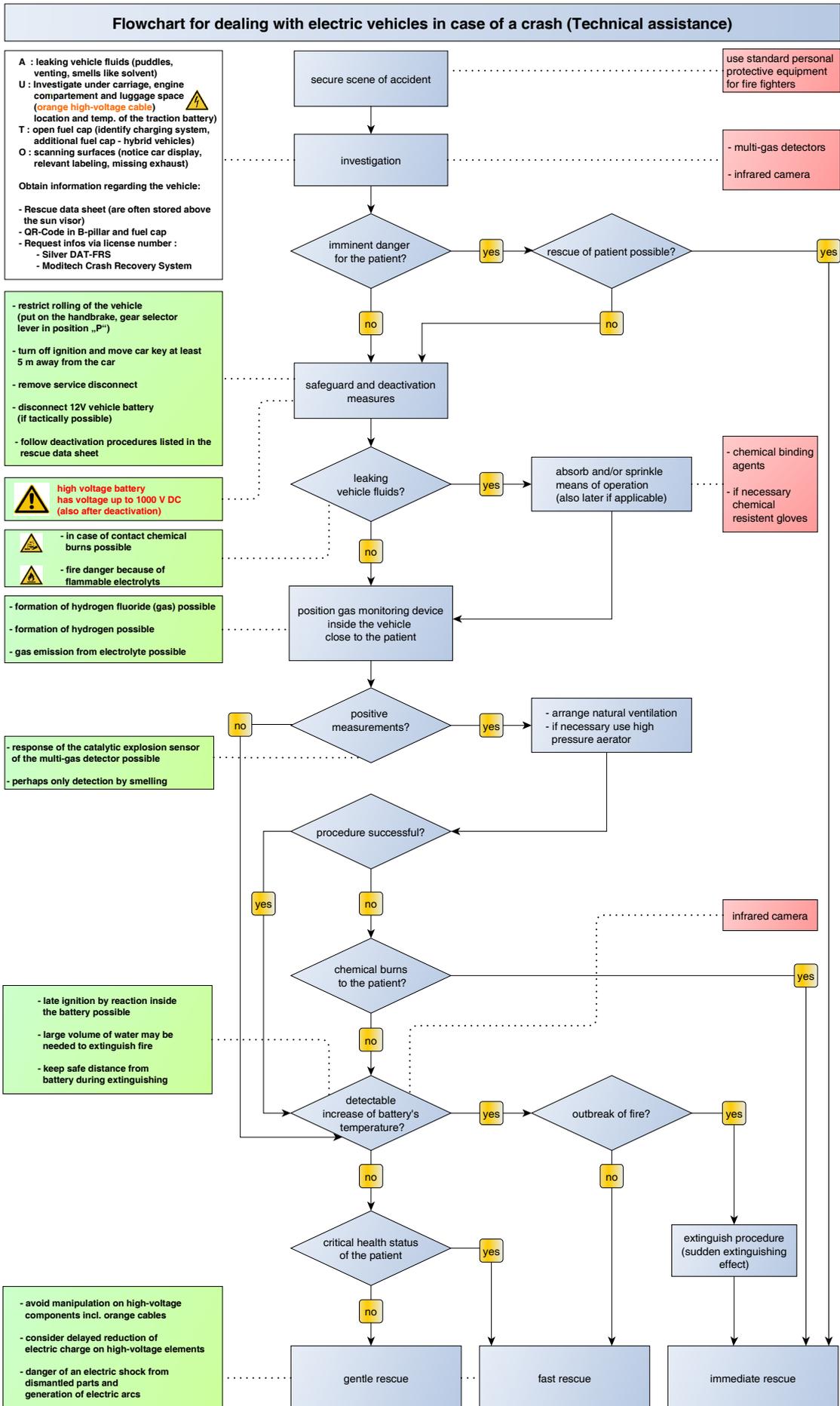


Figure 6: Updated rescue guideline

A summary of the features of the new handling procedure (see Figure 6) is provided below:

- Flow chart layout similar to best practices documentation but specialized for crashed vehicles with electric drive. The flowchart is focused on Li-ion battery technologies and not fuel cell drives.
- Clarity by three-column principle and color highlighting
- Flow chart can be used properly printed in an A4 format for use on scene
- Clear depiction that flammable, irritant and corrosive materials may be released by the HV battery and proposals for how to deal with them. For example, the explicit naming of the possible development of hydrogen fluoride (HF) could not be found in literature reviews of handling procedures.
- Procedure was optimized to maintain existing standard procedures used by (German) firefighters regarding their activities based on the patients' health states ("Gentle rescue", "Fast rescue" and "Immediate rescue") and if possible, to return rapidly to these three approved types of rescue
- Inclusion of relevant indicators for possible hazards (monitoring electrical and chemical conditions as well as temperature)
- Common measures to disable the HV system as replacement if specific rescue data sheet is not at hand.

With regard to the potential dangers that may arise due to a highly damaged electric vehicle, further recommendations and advice are provided below to complement the proposed updated rescue guidelines.

With focus on chemical hazards and fire:

- Chemical hazards exist and must be considered.
- The carbonates dimethyl carbonate (DMC), diethyl carbonate (DEC), ethylene carbonate (EC) and propylene carbonate (PC) are typical chemical substances used as electrolyte (also in mixed forms) in high-voltage traction batteries that possibly being released in case of mechanical damage to the HV battery or a cell. Therefore, these substances should be monitored using the gas detectors.
 - o If released, then check the patient's condition (see also Figure 6).
 - o In case patient should react to these carbonates (e.g. noticeable by sore throat or cough) cancel 'gentle rescue' and change to 'immediate rescue'
- Depending on the organic carbonates used as electrolyte components (see previous bullet point) and temperatures around 110 °C, different gaseous unsaturated hydrocarbons may be generated due to battery decomposition: ethene (C₂H₄), propene (C₃H₆), ethane (C₂H₆) and/or propane (C₃H₈). All these compounds are flammable and may form an explosive mixture depending on its concentration. A spark may ignite flammable gases or gas mixture.
- Hydrogen fluoride (HF) is difficult to measure on site (also costly due to required specialized gas detectors), therefore measurement of combustible gases is a suitable indicator (see previous bullet points) and is proposed by means of standard multi-gas detectors
- Multi-gas detectors should continuously measure the accident scene instead of using short-time measurement tubules which only provide a value per initiated measurement.
- Released substances are problematic in the case of Li-ion batteries because these would indicate opened (compromised) battery cells and packs which could increase the risk for gas development and resulting fire hazard.
 - o The coolant may also be hazardous (not investigated here)
 - o In case of Ni-MH traction batteries, alkaline solutions (pH 14) are used as electrolyte which leads to a risk of skin burns (not investigated here)

With focus on electrical hazards:

- Electrical hazards play a minor role due to multiple safety measures implemented by the vehicle manufacturers (no electrical hazards reported in the field known to date). However, in case of a severely damaged traction battery, extreme caution is appropriate.
- Difficulties at the scene:
 - o The voltage tester or similar equipment / measurements must be used and assessed only by authorized personnel (electrically instructed person).
 - o Difficult to determine measurement points on the vehicle as this is not described in rescue data sheets.
 - o Possibly poor accessibility
- *Important to note:* Car manufacturers have not harmonized their recommendations with regards to the mandatory or voluntary usage of high-voltage gloves for rescue services during the de-activation process of the electric vehicle's high-voltage system. Some rescue data sheets (e.g. from Nissan or from Citroen) dictate wearing high-voltage gloves. Since no electrical issues in case of crashed electric vehicles were known from the field and any research project, and even the highly-challenging crash tests conducted in EVERS SAFE did not lead to any safety issues, it is recommended that the use of HV

gloves is only warranted in case of a severely damaged traction battery and availability of specialized personnel. Latest news from the media need to be considered on this topic.

With focus on explosion:

- The risk of an explosion of the HV battery is very low.
- Ignition only occurs for high concentrations of chemical degraded products and only at high temperatures.

Monitoring the temperature change (in particular the increase of the temperature over time) of the Li-ion traction battery is probably the safest indicator for potential hazards in case of damaged electric vehicles.

- Due to available resources (in most cases only a thermal imaging camera is available) accurate measurement of the vehicle temperature is not possible and only a large increase of the temperature inside the battery is measurable from outside. The battery is often well insulated and might be difficult to be accessed for temperature measurements. Environmental influences such as high winds may exacerbate the measurement.
- If a traction battery is located below the passenger compartment, it is recommended to measure underneath the vehicle with a thermal imaging camera.
- As the temperature rises, the off gassing is amplified, which results in an increased concentration of carbonates.

Further general recommendations and advice for safe handling of EVs:

- Firefighters can approach the electric vehicle with standard PPE as approved for approaching conventional vehicles after crash. In case of any hazard (e.g. release of combustible gases) additional protection measures should be considered (e.g. wearing the respirator mask or the chemical protective clothing).
- The United States (NFPA) recommends the approach to always assume that it could be an alternatively powered vehicle (NFPA, 2012).
- The location of a vehicle's rescue data sheet may be changed and is recommended to be behind the driver's sun visor due to the severity of the crash sustained.

After the development of the new rescue guidelines, possibilities and proposals for further information and consolidation on knowledge regarding the handling of highly damaged electric vehicles involved in a crash include:

- Information and experiences with electric vehicles (and other alternatively powered vehicles) should be part of the basic training for firefighters
- Careful review of reports such as the VDA document (German Association of the Automotive Industry (VDA), 2013), from firefighting associations, research projects, service providers such as Dekra, articles in the magazine "Fire protection", etc.
- Create experience exchange forums (possibly on the Internet or in conferences)
- Firefighters are recommended to continuously browse through rescue data sheets
- Monitor current vehicle propulsion technologies and market shares

Technical solutions promising to provide important information about the vehicle in crash:

- Automatic Emergency Call (eCall) should include drivetrain information
- Query by vehicle's license number using the Crash Recovery System® of the Moditech Rescue Solutions or SilverDAT® - FRS
- QR-Codes applied to the vehicle

Finally, it should not be forgotten to ask the driver, when possible, about the type of drive and that all senses should be used in a careful manner when dealing with a crashed electric vehicle:

- Smell (e.g. released gases)
- Hear (e.g. opening of battery's safety relief valves)
- Feel (e.g. temperature increase)
- See (e.g. disrupted traction battery)

Recommendations for Vehicle Manufacturers

Vehicle manufacturers are requested to update rescue data sheets with information about chemical substances used in HV battery and possible reactions, to grant firefighters fast and simple access to (different) locations where the HV system can be shut down manually and to provide convenient, harmonized storage (positioning and attachment) for rescue data sheets inside the vehicle. Further, harmonization processes shall be reinforced with other manufacturers, automotive associations and governmental entities, e.g., to agree or not agree on the

mandatory usage of high-voltage gloves for rescue teams. Vehicle manufacturers should also promote eCall to their customers and provide as much useful information as possible within the emergency message. Finally, the communication with rescue team associations and fire brigades shall be continued and expanded.

Recommendations for First-Aiders

Based on the current results from crash tests and field experiences, persons arriving the crash scene first do not need to have specific concerns about their own safety when approaching a crashed electric vehicle in order to apply first aid to occupants. However, common sense should be applied all the times and news about this topic in media should be monitored. It is also recommended to inform other people close by about the presence of an electric vehicle if identified, including professional emergency workers. For first-aiders it is strongly prohibited to touch or modify any HV related vehicle components which are e.g. marked by an orange color or by figures.

DISCUSSION

In general and to the current state of the art technology, the batteries of electrically propelled mass production cars of the M1 category are well protected on standardized tests (e.g. according to UN-ECE R 94/95, Euro NCAP etc.) and even beyond. Nevertheless, in very severe crashes or unfortunate circumstances, the battery can be damaged severely causing hazards. Simulations in the EVERS SAFE project and electric vehicle crash results showed that some current cell abuse tests, e.g. SAE J2464, might not be representative of what may happen in a vehicle crash as the intruding object would probably be wider as a thin nail.

Fuel sources for vehicles are becoming more individualized to the vehicle type and manufacturer. Additionally, the diversity of fuel types for vehicles sharing the same platform can lead to different rescue operations for vehicles with identical appearances. It is in regards to this point that electric vehicles impose new, and currently undefined, training needs for firefighters. Manufacturers can offer internal combustion, hybrid, or fully electric variants of the same vehicle model. Each has specific features that influence the rescue procedures. The documented rescue training materials for Swedish and German firefighters were summarized and compared in (Wisch, et al., 2014). Information provided is based on basic instructions that is under constant review and not every document is covered. Interviews with fire fighters were also conducted to capture the formal and informal knowledge of electric vehicles. A general outline of rescue operations for crashes involving electric vehicles was identified to facilitate the analysis. A general approach to rescue operations can be considered as:

- 1) Information on the way to the scene
- 2) Appraisal of the vehicle on the scene, identification of vehicle
- 3) Securing/stabilizing the vehicle
- 4) Fire control
- 5) Chemical hazard control
- 6) Shut-down electrical systems (to cut the vehicle)
- 7) Occupant extraction
- 8) Post crash issues

The review of Swedish and German rescue procedures and training materials indicate that there are many similarities that can be exploited when adapting existing methods for new vehicle technologies. The main point to be aware of is that the basic structure for approaching and acting at a accident scene are similar between countries and that the only issues that need to be addressed are related to the battery and its connections to the electric drivetrain. From the testing and simulation activities in the EVERS SAFE project, there does not seem to be significant differences between EV and conventional vehicles in terms of fire and occupant extraction procedures.

The crash tests have also been used as training for firefighters. In particular, existing and alternative post-crash guidelines were considered and checked for their viability under realistic conditions. Different portable multi-gas detectors have been utilized to identify combustible gases (diffusion devices MSA Auer Altair 4X and devices with active intake MSA Auer Altair 5X and MSA Auer Sirius PID). Since hydrogen fluoride (HF) is the worst case result of possible chemical reactions, a special gas detector (Dräger X-am 5100 with HF/HCL sensor) was rented to directly measure HF (which did not emerge). Due to the high acquisition costs (around 1,500€) and maintenance costs of such a specialized gas detector it was considered to be not economical to propose the purchase for general application by rescue services. This conclusion was strengthened by consideration of the difficulties to measure under real conditions (e.g. wind) and the order of emergence of combustible gases due to a damage of the HV battery which can be detected with usual multi-gas detectors.

Following the crash test of the BMW i3, the work of the fire brigade was analyzed and discovered the following:

- Finding the rescue datasheet proved difficult, as this was thrown by the impact from the original position behind the sun visor in the back seat area and was discovered only in the further course of the training by the fire department. The firefighters were then able to act purposefully.
- The orange color of the 12 V rescue disconnect point and the resulting suspected high voltage danger were misleading so that the deactivation measures were carried out with high voltage gloves. Since the pulling of the plug required a detailed manipulation and took too long, the decision was taken to cut all connecting wires. However, it has to be noted that an adaptation of the color of the rescue disconnecting point was already provided at the time by BMW.
- Subsequent to the firefighter training performed at the BMW i3 crash test, the firefighters indicated that it is of high importance for them to recognize early in time the presence of an alternatively propelled vehicle. Therefore, the firefighters considered it advisable to consistently mark electric vehicles, e.g., similar to the license plate marking used in Norway (Balzter, 2013).

The training also confirmed the theoretical assumption that many firefighters are not yet adapted to the dangers of electric cars. Further, flowcharts of the procedure for accidents involving electric vehicles are largely unknown in the fire service. There is little distinction in the use of measures between conventional and electric vehicles.

There are some common actions observed in the rescue guidelines that need to be developed into rescue service education programs or better information is needed for rescue workers. The main points of interest are:

- How can EVs be readily identified at a crash or rescue scene? It is desirable that the vehicle identifies itself by eCall information or are there standardized identifications visible on the vehicle itself?
- How can a high-voltage system disconnect be confirmed? There is no visible indicator on the vehicle exterior that readily shows the high voltage circuit has been disconnected. This information can remove one step (Item 6) in the rescue process.
- Can there be a requirement (such as a UNECE regulation) that requires the HV system to disconnect when the 12V is disconnected? As rescue services routinely disconnect the 12 V system to eliminate pyrotechnical safety systems from inadvertently deploying, this interlock would also eliminate one step (Item 6) in the rescue process.
- How are batteries affected during extreme manipulation of the vehicle during occupant extrication? For example, the extension of the car from two winch points involves tension and bending loads on the vehicle floor, particularly if any of the pillars have been cut. This may induce internal deformation in the battery that may not have arose in the original crash, or accentuate existing damage in the battery caused prior to the extrication procedure.

In addition to the need to address the issues raised above, there is a lack of standardized or legislated procedures outlining the towing and storage of electric vehicles after a crash. Vehicle manufacturers develop their own product recommendations but there should be universal procedures to eliminate the risk of mistreatment of an EV due to a diversity of handling procedures.

The need for firefighters and other rescue workers to use specific protective equipment for EVs needs further investigation. Rescue operations should not require high voltage electrical repairs or investigation by individuals without appropriate training. It is desirable that standard protective equipment is sufficient and the vehicle systems are designed to ensure electrical isolation from rescue workers under foreseeable rescue operations.

One additional issue that requires further investigation is the influence of battery aging. Li-ion batteries are still a new technology with few years of service and thus experience with older batteries is lacking. There is a need to monitor EVs and identify if batteries and their structures exhibit degradation in their mechanical tolerance to failure.

The battery protection was achieved by very stiff protective structures using new materials as carbon fiber reinforced carbon (especially in 2GEV). This may lead to less overall vehicle deformations and higher acceleration loadings for occupants during crashes and thus increases the risk for severe, internal injuries. With regard to future user patterns, it has to be noted that other vehicle categories than the often discussed passenger vehicles (M1) will enter the markets. Especially in urban areas, smaller electric vehicles such as quadricycles and microcars are alternatives. Many of these small electric vehicles will be certified as vehicles of categories L6e or L7e which do not have to fulfill any legal crash requirements in Europe by now. This may result in less performing vehicle crash structures and other safety issues as tests of Euro NCAP have shown in 2014 (Euro NCAP, 2014). However, it has to be noted that most of the full-electrified small vehicles will run on low voltage networks that reduce the electrical hazards but depending on the cell chemistry thermal and chemical potential hazards may remain existent.

