Detection of Fires in Heavy Duty (HD) Vehicles

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ABSTRACT

Detection of fires in the engine compartments, toilet compartments, baggage bays and sleeping cabins of Heavy Duty (HD) vehicles is arduous. The elevated air flows, concentration of pollutants and wide range of surface temperatures in the engine compartment together with the complicated geometries of the latter spaces complicate the operation of all types of detectors. These lead to difficulties defining the optimal type of detection technologies to be used as well as the adequate location of each detector.

This paper presents research for understanding the challenges and necessary characteristics of detection systems in compartments with high air flows, large temperature variations and complicated geometries. In particular, this work reports about literature surveys of existing standards, legislations and research in the field as well as experimental findings.

INTRODUCTION

Fires in the engine compartments of surface and underground non-rail heavy duty (HD) vehicles are unfortunately still common around the world [1]. For instance, fires in the media drift and distribution level sections of Swedish non-coal mines and German potash and rock salt mining are predominantly caused by service vehicles, drilling rigs and loaders [2–4]. Furthermore, statistical data indicates that nearly one percent of the buses registered in northern Europe will suffer an incident related to fire during a one year period [5]. Although this quantity is alarmingly high, it does not necessarily denote that all these fires lead to fatalities or total property loss. However, statistical data do indicate that almost two thirds of the reported fires commenced in the engine compartment and that these fires were, in most cases, not promptly detected by the drivers. Late detection causes that nearly one in five of the aforementioned fires spread outside the firewall of the engine compartment putting in risk the security of its occupants [6, 7].

Engine compartments of heavy duty vehicles are, in general, spaces where detecting fires with inexpensive and simple detection systems is arduous. High air flows and large amounts of suspended pollutants in the compartment, together with the complicated geometry and the wide range of surface temperatures typically occurring during the normal operation of the vehicle, complicate the operation of all types of detectors. The deposition of pollutants on the components of optical detectors can impair their operation as well as obstruct the channels of aspirating systems, thus hindering their operation or shortening their service interval. In addition, thermal point detectors can have an extremely limited effectiveness under high air flow conditions unless these are located in the vicinity of an eventual fire where these can be effectively heated by the ensuing smoke and fire plumes [8].

UNECE Regulation No. 107 regulation stipulates that engine compartments of buses and coaches with rear mounted engines must be equipped with a fire detection system and that coaches should have fire detectors in the toilet compartments and sleeping cabins, but the regulation is unfortunately not specific about the performance and effectiveness of the employed detection system. This inaccurateness allows the employment of detection systems which would be incapable of detecting fires under high air flow conditions, providing a vague improvement regarding fire protection [9].

Although the engine compartment is the most common place of origin of fires in these types of vehicles, toilet compartments, baggage bays and sleeping cabins are not excepted of this problem. Although detecting fires in these compartments is not as difficult as detecting fires in engine compartments, the differences in geometries among vehicle fleets may lead to difficulties defining an optimal detection

technology and location of a detector to be installed in these compartments. Even though the mandatory implementation of detection systems is a fact, the effectiveness of the detectors will be highly suspected to their correct selection and placement.

Research for understanding the challenges and necessary characteristics of detection systems in compartments with high air flows, large temperature variations and complicated geometries is necessary. SP Fire Research conducts active research in the field of detection of fires in HD vehicles where different detection technologies and strategies are evaluated and compared. This paper reports experimental findings, a literature study about the existing standards and legislations in the field, and a study of bus fires in Sweden.

BUS FIRE STATISTICS FROM SWEDEN

Data was collected from the Swedish Civil Contingencies Agency's (MSB) database on fires occurring in Sweden, which is based on incident reports from the emergency services. The study was confined to reports from 2005-2013, due to that before 2005 bus fires had no separate category in the incident reports. The study includes a total of 1255 records spread over this nine-year period. The data material was processed in a repetitive process in order to obtain relevant information. Loss of the records was 26 %, partly due to the study's limitation to commercial traffic as well as number of incidents being registered incorrectly in the bus category.

The average number of incidents per year related to fire between 2005 and 2013 was 104, which corresponds to 0.73 % of the buses in the commercial traffic. The highest number of incidents was recorded in 2006 with 130 cases; and fewest in 2012 with 88 cases and in 2013 with 81 cases. However, studying the whole period it is difficult to make a definitive conclusion on a decreasing trend regarding fire-related bus incidents.

In 61 % of the cases the incident originated in the engine compartment and in 20 % of the cases the incident originated in the wheel well. In 14 % of the cases the data was too flawed to obtain the information regarding origin area; in the remaining 5 % the incident originated inside the bus or in other area, see Fig. 1.

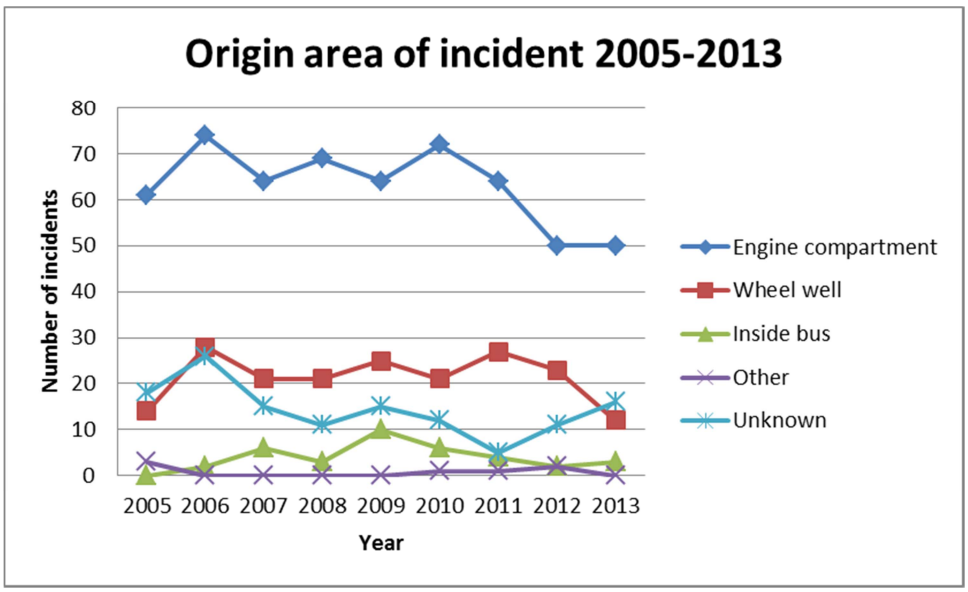

Figure1. Origin area of incident 2005-2013.

Flashover occurred in 7 % of all the registered incidents. The highest number of cases was registered in 2009 with 13 cases and in 2012 with 10 cases. There is no indication that the number of flashover fires is decreasing.

Fire and Rescue Service (FRS) carried out fire-fighting action in 55 % of the call outs between 2005 and 2013. In 73 % of these cases the FRS had to perform extinguishing action and in 27 % of the cases FRS conducted only cooling of the affected area.

The study shows that the bus drivers and staff have a very significant role in the initial stage of the fire-related incidents. Bus drivers extinguished the fire in 26 % of the cases prior to FRS arrival to the accident site.

STANDARDS AND LEGISLATIONS

To our knowledge, there are no approval standards or test methods in use for fire detection in HD vehicles. There are some standards that point out minor requirements or risk assessment methods, but no approval test methods. E.g. the Australian Standard AS 5062 is a comprehensive standard regarding fire protection in vehicles, focused on risk analysis, and the Swedish Fire Protection Association publishes two guidelines, SBF 127 and SBF 128, which include minor requirements on fire detection in HD vehicles. Also a new standard from Israel for fire suppression systems in buses, I.S. 6278, includes a few tests for detection systems. Regarding environmental tests requirements, such as resistance to vibration, ambient temperature variations, and corrosion, EN 14604 and UL 217 set out requirements for recreational vehicles. Also the NATO standard STANAG 4317 have some relevant environmental requirements for main battle tanks.

For general use, the main standards for fire alarm systems in Europe and in the US are EN 54, ISO 7240, NFPA 72, FM (3210, 3230, 3232, 3260), and UL (268, 521). All of these, except NFPA 72, include approval test programs for different types of detectors. However, these should not be used for approval of detectors for use in e.g. the engine compartment of vehicles. There are several important parameters that are not adapted for vehicle application in these standards, such as ambient temperature, vibrations, high airflow, fire sources, and false stimuli/background level.

The European automotive legislation has very vague requirements on fire detection. For buses and coaches, UNECE Regulation No. 107 sets out some minor requirements, but the regulation is not specific of the performance or installation of the system.

The following two sections present fire detection tests conducted in the toilet compartment and in the engine compartment of buses. This and future work will be the basis for new improved standards of fire detection in HD vehicles.

FIRE DETECTION IN BUS TOILET COMPARTMENTS

For the toilet compartment tests [10] a mockup was built, see Fig. 2, based on input from 26 different buses from a variety of suppliers. The most important influencing parameter was the ventilation condition, which may differ between buses. However, most buses have a fan positioned in a concealed space under the sink that extracts air from the compartment. The air enters the concealed space via air vents and in some cases also via the trash can opening (the largest hole to the left in Fig. 2). Gaps around the toilet door works as air inlet to the compartment and in the mockup these gaps are summed up in a larger gap at the upper right corner of the toilet door. Some real toilet compartments also have a feed from the air conditioning system.

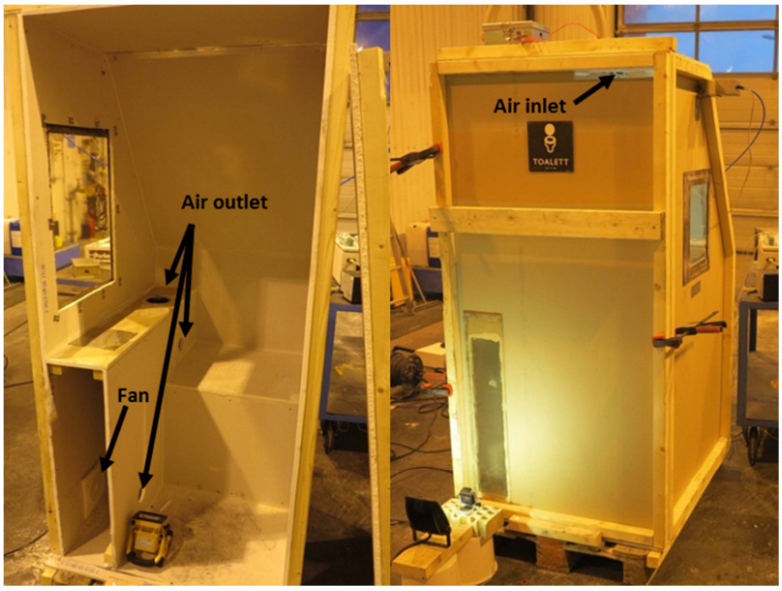

Figure2. Mockup of bus toilet compartment.

Five different fire detection systems were tested in different positions. The detectors included linear heat detection, point heat detection, point smoke detection, and aspirating smoke detection. Seven fire tests were conducted in accordance with Table1. The heptane pool is not a realistic fire source in the toilet compartment, but was used because of good repeatability compared to the other fire sources. The rubber and plastics were placed in the concealed space of the fan representing a pump, cables and other electronics normally contained there.

Table1. Test scenarios.

Test	Fire source	Fire position	Ventilation condition
1	Cigarette	Seat level	Low fan speed
2	Paper	Trash can	Low fan speed
3	Paper	Trash can	High fan speed
4	Heptane pool	Floor level	Low fan speed
5	Heptane pool	Floor level	High fan speed
6	Plastics/rubber	Above fan	Low fan speed
7	Plastics/rubber	Above fan	High fan speed

The main conclusions from the tests were:

Smoke detectors are generally much faster than heat detectors. Heat detectors should only be used in narrow spaces where the detector is close to a potential fire source, e.g. above the trash can.
The impact of the ventilation fan was very large. In several fire scenarios a detector in the ceiling of the toilet compartment would not give a fire alarm in the early stage of a fire. Fig. 3 shows the trash can paper fire, and no smoke entered the toilet compartment in this test.
Because of the impact of the fan, it is recommended to have fire detectors also in the concealed space of the fan, why aspirating systems may be considered due to their capability to sample air from several spaces. Another advantage of aspirating systems is that the detector is hidden and protected.
Aspirating smoke detectors were not affected as much as point smoke detectors by high air flows.
It was only the most sensitive aspirating smoke detector that was activated by cigarette smoke.

Figure3. Trash can paper fire.

FIRE DETECTION IN ENGINE COMPARTMENTS

As part of an evaluation of fire detection systems for HD vehicles testing has been performed in the engine compartment of a city bus (See Fig. 4). Several systems were tested and compared regarding detection time, including heat, smoke and flame detectors.

Heat detection is the most used fire detection method in engine compartments of HD vehicles today. Flame detection is used to some extent, while smoke detection has until now not been much used in engine compartments of HD vehicles. Three widely used linear heat detectors were tested, two with fixed activation temperature of 170°C and 180°C respectively and one responding on the average temperature of the detector, with 139°C as activation temperature if the full length of the detector is heated. Also one IR/IR flame detection system and one aspirating optical smoke detection system were tested. The detection systems were installed in the engine compartment of the bus as it could have been installed in a real case with the aim of covering the entire engine compartment. Three fire scenarios were designed to simulate realistic fires and consisted of both slow developing electrically generated fires as well as a fast developing fuel leakage fire. Fig. 5 shows a fast propagating fuel spray fire. In all cases the air flow through the engine compartment was representing a stationary bus on idle speed. The rear hatch of the engine compartment was replaced with a glass window for increased visibility into the engine compartment as seen in the figures.

Figure4. City bus prepared for performing fire detection tests

Figure5. Fast developing fuel spray fire

The detection ability varied between the systems and between the fire scenarios. While the flame detector gave extremely fast response on the quickly developing fuel spray fire, it did not respond at all to the small and slow propagating electrically generated fires. The flame detector used in the test was designed to automatically adjust its detection alarm level to avoid false alarms, i.e. the detector does not respond if the radiation level increases too slowly. The results from the linear heat detectors shows that the tested systems has to be close to an open flame in order to activate, which may considerably delay the alarm time for small fires far away from the detection system. Moreover, the air flow from the engine compartment fan had a great impact on the heat transport by removing the heat from the fire area. It underlines the importance of covering the entire fire hazard area with the detectors and taking into account the heat transport direction. The tests did not show any significant differences in detection times between the different fixed temperature heat detectors. The results from the aspirating smoke detection system showed that the tested system was able to detect the fire at an early stage, i.e. already at small amounts of smoke. The test results show the importance of appropriate fire detection system design in order to avoid unwanted consequences in case of engine compartment fires.

OUTLOOK

The work presented in this paper is part of the project "Fire detection & fire alarm systems in heavy duty vehicles – research and development of international standard and guidelines". The aim of the project is to develop an international test method for fire detection systems in the engine compartment of buses and other heavy duty vehicles. Most work packages in the project are mainly focused on producing background material for the overall goal of defining an international test standard for engine compartments, but the project also includes work leading to recommendations on what type of fire detection system that is most suited in e.g. toilet compartments on buses and how the systems should be installed.

The remaining work consists of more testing, both full scale and small scale testing, more studies of background noise and fire causes in vehicles operating in different environments, e.g. in urban, in mines, or at construction sites, and in the end the development of an international test method.

ACKNOWLEDGEMENTS

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High-Risk E-Vehicle Battery Sled Testing

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ABSTRACT

Crash testing of E-Vehicles (electrified vehicles, e.g. electric and hybrid electric vehicles) is required to assure compliance with global safety regulations and standards as well as the even higher requirements set by the car manufacturers themselves. The introduction of E-Vehicle battery systems of as much as 200 to 600 Volt dc presents new safety considerations when performing crash tests. At a crash test, safety by regulations, standards and ratings as well as the limits of durability are investigated. If investigating the limits of durability, scenarios such as release of harmful gases and thermal events must not be disregarded. In order to ensure safe testing conditions, regardless of the severity of impact to be evaluated, new risk analysis, routines and laboratory designs need to be assessed when a new technology, such as high voltage (HV) battery systems, are introduced to the vehicle market.

Autoliv has a long experience in crashworthiness testing and offers car manufacturers assessments of crash safety in laboratories and crash tracks available on all continents. E-Vehicles are being crash tested as well, and for that reason Autoliv have established research and testing capabilities for HV batteries as well as updated routines and laboratory designs. Besides Autoliv's full size crash tracks around the world a new laboratory facility for battery sled testing is now available in Sweden for high-risk durability-limit testing.

INTRODUCTION

Range anxiety is often defined as one of the key limitations of E-Vehicles. It is often considered that the limited range can be extended by means of research on more energy dense battery chemistries. Currently, the Li-ion chemistry is the predominant battery on the market because it currently presents the highest energy density. A great deal of successful research on the constituent materials and molecules have contributed to the introduction of the current Li-ion battery technology. Although this family of battery chemistries have proven to be the key to the present global launch of E-Vehicles, the importance of system and structural design achievements cannot be underestimated.

Another key for the global launch of E-Vehicles is the battery safety. Traditionally the crashworthiness of a battery system installed in an E-Vehicle is solved by locating it in the "safe zone" where mechanical damage from a crash is limited according to crash statistics. Additionally, battery systems are equipped with rigid

housings and other means of structural protection in order to prevent intrusions upon the battery. Crashworthiness testing is a vital part of the safety research that in the years to come will assure that the range anxiety issue will become less of a hurdle. New designs of HV battery systems will permit them to be located closer to frequent deformation zones rather than restricted to the safe zone. The risk that any vehicle crash could reach a worst scenario consequent continuous to diminish as capabilities and routines for safe crash testing and mechanical abuse testing on cars and components are constantly being developed. However, in the world today, there exist only few laboratories for dynamic mechanical abuse testing on HV battery systems, which offers a complete methodology and testing experience in order to replicate the crash environment suffered by such a battery system in a full vehicle crash. The key issue is the concern for the safety of the testing personnel, the facility and the testing equipment since the structural and chemical response of a battery under dynamic sled tests and crash test is not common knowledge. Such a safe testing environment is now offered by Autoliv in Sweden.

Issues to be anticipated when performing high-risk battery testing

The influence of battery material and chemistry

As mentioned Li-ion batteries offer an out-standing energy and power density in comparison to other battery chemistries (e.g. NiMH and lead acid). The key is the high nominal voltage per cell that is a consequence of the large difference in standard reduction potential between the material of the anode and the cathode. Because of this high nominal voltage water cannot be used as electrolyte solvent in Li-ion batteries. Instead, organic solvents are used together with a salt to form the required electrolyte. Commercial Li-ion batteries use a mixture of alkyd carbonates as solvent and the $LiPF_6$ as the salt to form their electrolyte. This salt is completely predominant because of its extraordinary performance in comparison to other salts. If the battery cell is exposed to elevated temperatures (commonly starting within the range from 80 to 170 ºC), the material of the two electrodes have a tendency to start reacting with the components of the electrolyte (Huang, Yan, & Jiang, 2008). Under such conditions, the pressure will build up inside a battery cell because of those reactions as well as the gradual vaporization of the organic solvents.

In order to prevent rupture at higher pressures Li-ion cells are designed with soft-spots or venting mechanisms that will release the gases from the cell at a prefered lower internal pressure. This is a safeguard feature which in many scenarios mitigate further escalation of a cell failure. Another safeguard feature is the characteristics of the separators that ensure that only Li-ions can move from one electrode to the other. Commonly, the separator constitutes of a multilayer structure of polyethylene (PE) and polypropylene (PP) with a thickness between 10 to 40 µm. The two polymer melts at 135ºC (PE) and 165ºC (PP) and the 30ºC buffer allow the PP to retain the separator structure while the PE melts and make the separator impenetrable to Li-ions which consequently prevents Li-ion transport at the location of the damage and thus impedes the current in the circuit (Zhang, 2007). Therefore, they are named shutdown separators. Many battery cells are equipped with additional safeguard systems that intend to prevent an escalation of a cell failure, such as Current Interrupt Devices (CID) or poly-thermal switch (PTC).

Nevertheless, all these safeguard systems have an upper limit of operation at which they are overridden. A common cause for a safeguard system to be overridden is when the thermal exposure onto, as well as inside, a battery cell lead to a temperature increase at a rate that is higher than those safeguard systems are capable of handling. Under such circumstances, a battery cell risk to reach a second stage of critical failure that is defined as thermal runaway. Among conventional Li-ion batteries, this may occur at temperature ranging between 170 to 250ºC depending on the constituents of the cathode material (Yang, Amiruddin, Bang, Sun, & Prakash, 2006). As of 2014, the two predominant Li-ion chemistries are denoted NMC (based on the use of a cathode material composed of Nickel Manganese and Cobolt) and LFP (based on the use of a cathode material composed of iron phosphate). At best, a thermal runaway remain isolated to the original cell but it is not

unlikely that the heat-up of the first cell increases several hundreds of degrees rapidly that then provokes the neighboring cells into thermal runaway. If propagation of thermal runaway starts between cells it becomes nearly impossible to extinguish until the fuel, (i.e. the cell material) is consumed. This scenario will generate large quantities of gases, as presented by the picture of a faulty battery module in Figure 1a. In the presence of a sufficient source for ignition, the electrolyte vapor might ignite (Figure 1b).

Figure 1. **Under tough crashworthiness testing conditions, an E-Vehicle battery may experience thermal runaway. Such a critical cell failure cause the faulty cell to heat up rapidly, which may lead to propagation of the failure to neighboring cells. The first indication of a damage battery cell is gas ventilation (a) and the worst scenario of a fire might occur if the organic electrolyte vapors get access to a sufficient ignition source (b).**

<u>A simplified fault tree analysis for a Li-ion battery cell</u>

Three major abusive conditions can be illustrated with a simplified fault tree diagram (Figure 2). Those three conditions are:

- Mechanical Abuse
- Electrical Abuse
- Thermal Abuse

A worst-case scenario, in the event of a traffic accident or as a consequence of tough durability testing the mechanical abuse generated onto the battery, would be that the whole failure sequence described above is not impeded. In such a scenario, the mechanical abuse could result in a fault current(s) that heat up the internal components of the battery cells. If the rate of heat-up exceeds the shut-down capacity of the safeguard systems,

thermal runaway might start and the quantity/pressure of electrolyte vapor and gaseous species, which are generated by the decomposition of the cell's material, cause the cell to rupture. At that point, large quantities of gases are emitted to the surrounding and in the presence of a sufficient ignition source; a battery fire might start (Figure 1b).

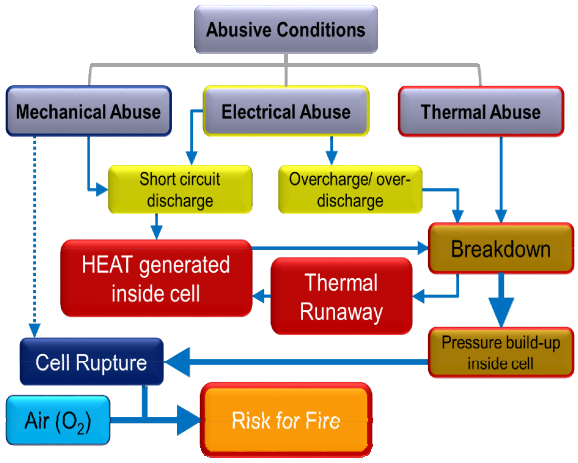

Figure 2. **Fault tree analysis for a battery cell. There are three major abusive conditions – Mechanical, Electrical and Thermal Abuse. When thermal runaway have started the cell-internal pressure quickly increases and the cell soon rupture and gases are emitted to the surrounding. (Sturk, 2011) Autoliv ©.**

There is of course no fire without a fuel. For the internal breakdown of Li-ion cells, the fuel is the mix of organic electrolyte and the active materials of the electrolytes, while a battery cell external fire is fueled by the electrolyte vapors emitted by a critically damaged battery.
The internal breakdown can progress without visual flames but it will generate much gases. Predominant species is carbon dioxide and carbon monoxide. However, it has been documented that lesser quantities of more toxic species such as hydrogen fluoride or other fluoro-organics are generated. (Hammami, Raymond, & Armand, 2003) (Sturk & Hoffmann, 2013) (NIOSH, 1996) (AFS, 2011)The toxic fluoro-species derive from the breakdown of the salt $LiPF_6$. (Yang, Zhuang, & Ross Jr., 2006) (Wilken, Treskow, Scheers, Johansson, & Jacobsson, 2013) Hence, extensive ventilation of gases from a critically damaged Li-ion battery must be anticipated when preparing for a crash test of an E-Vehicle or a battery component test.
In the event of a battery fire, the composition of gases emitted may alter somewhat, but the risk for harmful fluoro-organics and hydrogen fluoride remains. (Sturk, Hoffmann, & Tidblad, 2015)

METHOD

Autoliv's battery abuse testing facility is designed for dynamic mechanical abuse testing, i.e. separate acceleration or deformation tests, or a combination of the two. The specifications defining how to perform such a battery test are developed by means of full vehicle crash test with dummy/inert batteries and/or CAE crash simulations on E-Vehicle and battery pack or subsystem in order to assure the best possible replication of the target crash conditions.

The characteristics and safety feature of the battery sled track

As for all types of crash related testing, sensors and cameras are used to provide qualitative data acquisition during and after test so as to fulfill customer specifications and maintain high level of post-crash safety. In order to offer customers a high-end sled track for battery systems, the 15 meter of track utilize up to 9 meters

for acceleration of the sled that can be propelled, by up to 10 bungee ropes, to a maximum velocity of close to 100 km/h. An empty sled weight 196 kg and the maximum added weight of battery unit is 200 kg. In comparison to regular crash tests some extra sensors and monitoring equipment is added to this test setup because of the need for monitoring the temperature and electrical properties of the battery unit to be tested. (Figure 3)

Additional requirements when performing high-risk battery abuse tests involves a stringent FMEA and routines that ensures that:

1) No test operators or other people are exposed to potentially harmful situations or substances caused by the test.
2) No collateral or unforeseen damage should be caused to the facility or neighboring facilities or property.
3) Any damage to test equipment shall be kept to a minimum.

Based on these priorities Autoliv has equipped the new facility with a test chamber by the barrier-end of the track. This test chamber is surrounded with transparent removable walls that will ensure that no physical parts of the test setup or object will be expelled from the chamber. The chamber offers an enforced environment for fire suppression and forced cooling measures as it limits the air volume, and restrict the area where any critical battery failure may occur. For flame suppression a stationary CO_2 system is dedicated, and for fire suppression and forced cooling water spray is used. Water (with or without additives) is the preferred cooling and fire suppression medium according to research published by (Egelhaaf, Wolpert, & Lange, 2014) and (Sturk, et al., 2014). Besides sensors for electrical characteristics and temperature monitoring a gas-detection warning system ensures an early alert for emissions of species such as carbon monoxide, organic vapors, hydrogen and hydrogen fluoride. All liquids released or leaked during or after a test will be collected and safely handled. For the safety of test operators, multiple cameras allow visual monitoring of the track and test chamber to be viewed from a separate control room with no direct air-contact with the testing room.

Figure 3. **Autoliv's laboratory for high-risk sled testing of E-Vehicle batteries offers a testing environment with multiple layers of safety. A key safety feature is the enforced test chamber, at the barrier-end of the sled track, which is equipped with gas detection warning, fire suppressions, forced ventilation and collection of liquids. (Autoliv ©)**

Defining specifications for physical testing

Regardless of the choice of preferred physical testing setup – i.e. separate acceleration or deformation tests, or a combination of the two – the customer specification, upon which the final battery sled test is designed, can be derived from one out of two alternatives:

A. Battery crash environment characteristics acquired by complete E-Vehicle crash testing with low state of charge (SOC) battery, dummy battery or inert battery system. Tests performed by either Autoliv or the customer.
B. Battery crash environment characteristics acquired by CAE simulations on complete E-Vehicle crash model. Simulations performed by either Autoliv or the customer.

Alternative A is preferred when a comprehensive simulations model of all relevant parts of the E-Vehicle, the battery system and electronics are not yet fully validated. It shall offer the characteristics of the mechanical abuse that a battery system and its subcomponents experience under the complete vehicle crash. The necessity of replacing the active battery with dummy or inert battery, or using a low SOC is analog to the procedures of conventional crash testing where all liquids, which possess a fire risk (e.g. petrol and diesel), are replaced by inert liquids in prior to crash testing.

Alternative B is preferred when a validated simulation model with sufficient details of the E-Vehicle as well as the battery system is available. This offers a cost effective and fully risk free investigation of the mechanical abuse that may compromise the battery integrity.

Either way, Autoliv will utilize the data acquired to establish a best possible replication of the battery system and/or the subcomponents and run the corresponding simulations with the object to be tested in a detailed model of the battery sled track in order to ensure a high-end of equivalence between the crash scenario and final physical battery sled test (Figure 4). Autoliv's methodology behind this has been publicly presented through the OSTLER project that was cofunded by the European Commision through the 7th Framework Programme. (Funcke, et al., 2014)

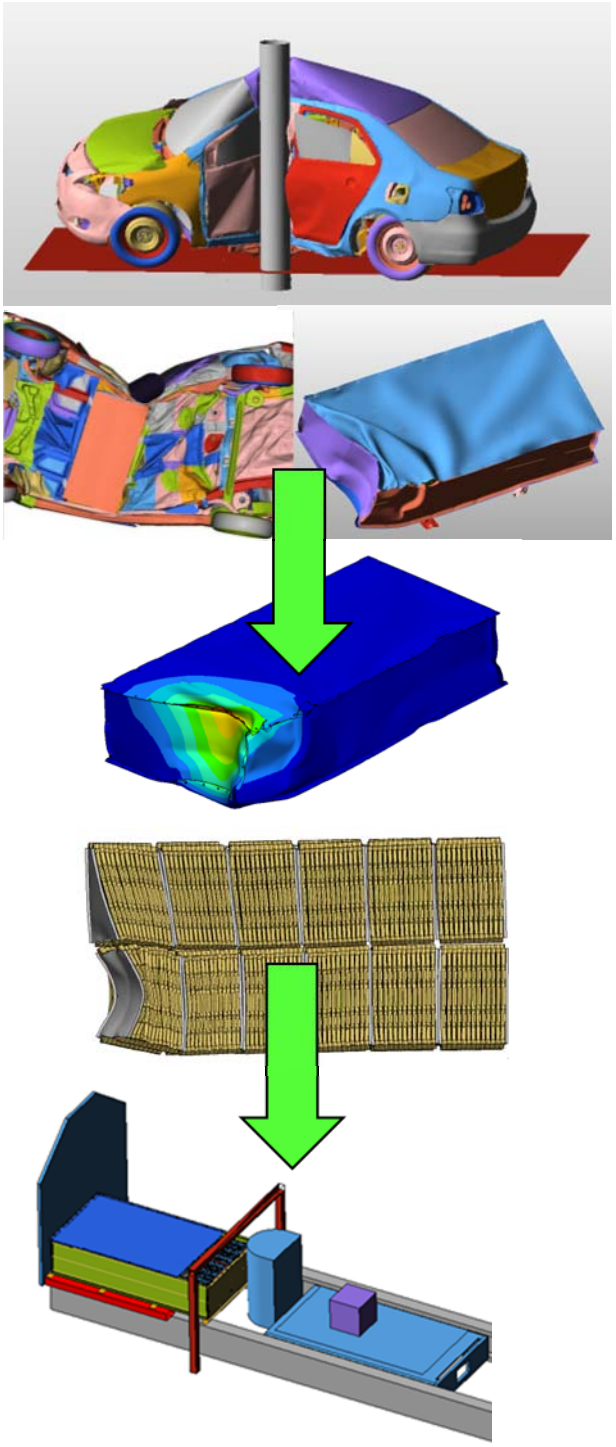

Figure 4. **CAE simulations on the crash scenario to be investigate offers a more cost effective alternative than complete E-Vehicle testing when the crashworthiness of the battery system and its subcomponents are to be physically tested. (Funcke, et al., 2014)**

RESULTS

As mentioned, when performing a replication of the crash environment experienced by the battery pack in an E-Vehicle crash scenario or when plainly investigating the crashworthiness limits of a battery system, the physical test setup can be optimized for either battery deformation tests or acceleration tests. A combination of them both is also possible. However, it will involve a larger physical setup in order to provide the correct synergy effects of testing the acceleration and deformation characteristics simultaneously. Hence it may put restrictions as to the size of the battery object to be tested.

Battery Deformation Test

In the OSTLER project a scenario of an E-Vehicle crashing into a pole (sideways) at 50 km/h plus the corresponding damage to the "floor-battery" was investigated (Figure 4). For this physical test setup of the battery sled track, the battery pack was mounted to a rigid barrier and a pole-impactor was mounted on the moving sled. The conversion from the complete E-Vehicle crash characteristics to the physical test setup proved successful and a satisfying match of the compared crash environments was achieved. Figure 5 show the setup prior to testing as well as the arcing-event that occurred during the intrusion of the pole. It is also possible to mount the battery pack or its sub-components on the sled and the impactor or deformation element onto the barrier.

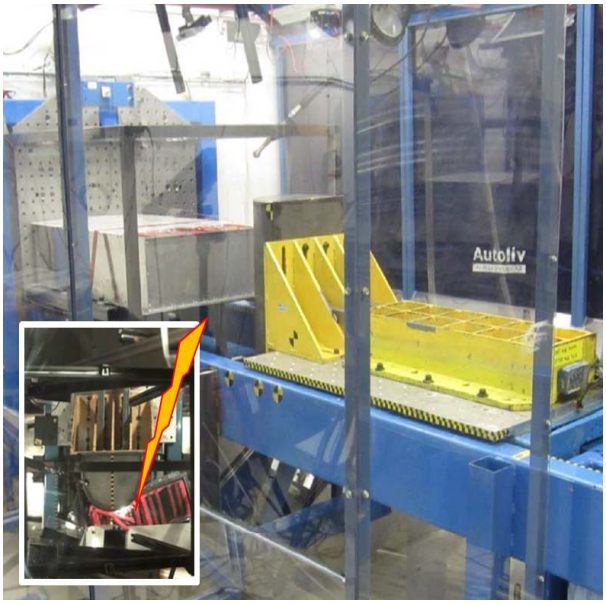

Figure 5. **A battery deformation test with a pole impact. After the characteristics that a battery experience in a specified vehicle crash have been simulated in a CAE model of the track, the physical setup is constructed to offer a crash-matching environment for the battery system and its subcomponents to be tested. (Autoliv ©)**

Battery Acceleration Tests

Conventional E-Vehicles are traditionally designed to assure the battery system integrity by means passive protective structures. Figure 6a presents a successful FMVSS 305 rear end collision (FMVSS 305, 2015) where the integrity of the battery system proved tough enough to prevent any intrusions. Consequently, in this example a deformation test on battery subcomponent proved not to be needed. In the research project E-Vehicle Safe Rescue, Autoliv performed the corresponding acceleration exposure onto battery modules in order to visualize the high level of robustness of a conventional battery system to the project's target group of first responders. (Sturk, et al., 2014)

At an acceleration test the battery or sub-component to be tested is mounted on the sled and the dedicated acceleration pulse is achieved by means of different types of breaking elements, such as tubes, bending bar or honey-comb structures.

Regulation UN ECE 100 requires that battery systems are tested for “Mechanical Shock” and show complience with a set of specifications. In its Annex 8C, figure 1 presents an accelration pulse corridor with nodes defined by the tables 1-3. (Economic Commission for Europe, 2014) Such a regulatory pulse requirement is physically possible to perform at Autoliv’s battery sled track facility.

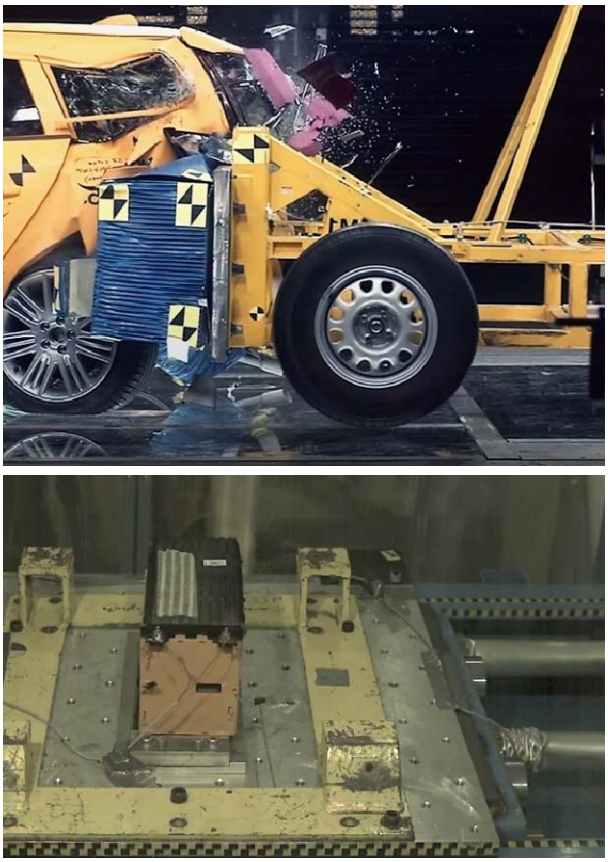

Figure 6. **A battery acceleration test. FMVSS 305 rear impact is a tough test that US market E-Vehicle must comply to; in order to avoid over-engineering of protective structures, the battery and its subcomponents can be tested separately to offer more precise testing feedback on the design. Picture from a video available at (Swedish Civil Contingencies Agency, n.d.).**

SUMMARY

Conventional E-Vehicles of today present a high level of safety but at a cost of range and battery weight since the structural integrity of their battery systems are commonly ensured by passive protection and its location is often restricted to the “safe zone”. Continuous efforts to develop lighter batteries and protective structures demand for dynamic abuse testing that is capable of replicating any foreseeable crash scenarios of future E-Vehicles in order to modify the battery system design without compromising battery crashworthiness.
Moreover, regulations, standards and ratings are adressing battery safety more precisely by every subsequent amendment process. The need for test facilities that are prepared for the increase demand of battery crash testing and all the safety concerns related thereto, are not always fully anticipated by current laboratories on the testing market.

For this reason, Autoliv have developed its new battery laboratory for dynamic mechanical abuse tests on E-Vehicle battery systems and their subunits.

General risk factors when testing battery systems

When performing durability and crashworthiness tests on battery systems and their sub-components it is of outmost importance to have updated routines and fully understand the potential risks associated with provoked batteries in order that any critical battery failure may not compromise the safety of test personnel, the facility and test equipment.

The constituent material of a battery cell influence its failure response in the event of a critical battery failure. As of 2014, the two most common Li-ion chemistries are denoted NMC and LFP based on their respective cathode material. However, all commercial Li-ion battery cells use the salt $LiPF_6$ together with alkyd carbonates solvents in their electrolytes. As the electrode materials have advanced to higher levels of stability the electrolyte is often considered as the weak link as it starts to decompose when being exposed to temperatures above 80ºC and risk to start reacting exothermally with the electrode materials if the temperature becomes even higher.

Depending on the choice of active materials in a Li-ion battery, the onset temperature of thermal runaway can be experience in the range from 170 to 250ºC for most of the commercial battery cells. At elevated temperatures (i.e. starting at 80ºC) the cell-internal pressure of these batteries rapidly increases and if the heat-up rate is too fast for the safeguard systems to comply, extensive ventilation of electrolyte vapor and other gases risk to be emitted to the surrounding of the battery. If there exists a sufficient ignition source, a fire could be the worst-case scenario. The gases released during ventilation and the gases during battery fire have proven to be unhealthy to people since they may constitute of species such CO_2, CO, various organics, fluoro-organics, and possibly hydrogen fluoride.

Efficient and Safe Methodology

In order to reduce the number of unknown parameters related to a battery system of an E-Vehicle that is exposed to a crash test, it is beneficial to study a smaller system (i.e. the battery system or sub-components) than the complete E-Vehicle. The mechanical interaction between the battery and its surrounding can be extracted from either, complete E-Vehicle crash tests with dummy/inert batteries or low SOC batteries, or stringent CAE simulation models of the vehicle and the battery. By avoiding complete E-Vehicle tests with active high-SOC battery systems, safety during testing is enhanced. This is analog to the requirements of conventional vehicle crash testing when all flammable liquids such as fuels are replaced with inert liquids prior to crash tests. The mechanical characteristics that is extracted from complete (electrically inactive) E-Vehicle crash tests are subsequently transferred into CAE models of the battery sled track together with the model of the battery and/or its sub-components. After optimizations have been done with these models, a physical test setup can be constructed. The final test can be either deformation tests or acceleration tests, or a combination of the two.

Autoliv's methodology, in combination with the new battery-sled-track laboratory, ensures that the unit to be tested experience a good representation of the dedicated crash environment while the risk factors associated with critical battery failure are safely anticipated.

FINAL REMARKS

Autoliv's battery-crash test facility in Sweden can provide dynamic crashworthiness investigative testing on E-Vehicle battery systems and its sub-components in a dedicated laboratory environment. Severe mechanical abuse testing can be pushed beyond the limit of critical battery failure without compromising the safety of test operators as

well as neighboring facilities. Testing beyond this limit is key to develop lighter battery designs for further extension of the range of future E-Vehicles without compromising battery integrity and crashworthiness.

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