SAFETY OF LITHIUM ION BATTERIES IN VEHICLES – STATE OF THE ART, RISKS AND TRENDS

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ABSTRACT

The safety of lithium ion batteries in vehicles is a priority of the automotive industry. The focus of the development activities are the reduction of the risks and the improvement of the safety concepts and systems.

In the last few years some incidents and accidents have taken place; a short overview about the state of the art of lithium ion battery technology on cell and battery level with focus on safety features, the risks, the statistical relevance and occurred incidents or accidents will be given.

An overview about dangerous events (worldwide) with lithium ion batteries for vehicles will be given (for cars as well as for test facilities); this overview is limited to data that is publicly available. A statistical significance based on this data will be shown; it includes the total number of vehicles in the relevant markets and an outlook for the future. In conclusion, the absolute number of safety relevant events is low because of the low number of electric and hybrid vehicles on the market. The absolute risk is low as well. The risk of safety-related incidents per electric or hybrid vehicle is much higher. Ultimately it depends on the used trigger; if vehicle accidents are seen as the trigger for battery incidents, the risk is low.

Using a bottom-up safety assessment approach in which the estimated risks for the cell, module, and battery are described, and the hazard levels and risk levels for their use in vehicles are determined will give an excellent overview. A description of additional and possibly future relevant safety features like changes in cell chemistry (additives, improved separators or flame retardant electrolytes) will be included. Furthermore, an assessment of these additional relevant safety features will be given. This main finding of this assessment is that the safety level of a lithium ion battery depends mainly on the cell chemistry and its capacity. The use of additives can improve the safety, but will lead to lower capacity and performance and result in higher prices. Other additional features won't have any impact regarding battery safety.

From this it is possible to define requirements for the safety of vehicles regarding: package, crash behaviour, and functional safety. The current safety level of electric and hybrid vehicles (concepts and characteristics) will be shown and discussed.

Finally information about new technology and trends for lithium batteries will be given, including information about relevant safety characteristics.

This study is limited to lithium ion batteries used in electric and hybrid vehicles.

INTRODUCTION

According to the sales numbers of hybrid electric vehicles and electric vehicles (in sum XEV's) as well as the attention given by the public, the hype of the e-mobility seems to have died down. Despite this, car manufactures continue to develop these kind of vehicles.

Lithium ion batteries are used in drive trains for these vehicles for energy storage reasons. Of the various technologies available, lithium ion technology is the preferred technology (power and energy density) despite any negative concerns regarding cost and safety.

For this reason it is necessary to know the real risk, challenges, and countermeasures to resolve any problems and to ensure safe mobility.

STATISTICAL RELEVANCE – INCIDENTS AND ACCIDENTS

In 2012, there were 42.9 million passenger vehicles recorded in Germany (according to the data of the German departure for statistics).

Currently 52,183 HEV's and EV's are in use in Germany. The market share of XEV's is 0.09% in 2011 and 0.12 % in 2012 (according to all vehicles in Germany). The goal to have 1 million EV's by 2020 still stands. [1]

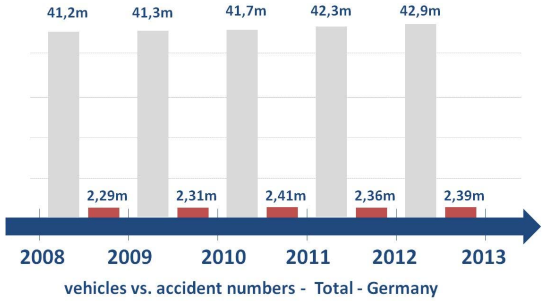

Figure 1: Vehicle numbers [1]

The expected number of accidents for cars in Germany is 2.390.000; out of this 303.000 are accidents with injuries of persons. That is of about 12,68%. [1]

From a former study done in 2011, the share of accidents involving XEV's with injured persons is about 0.05% to 0.08% (2007 to 2011) of all accidents with injuries.

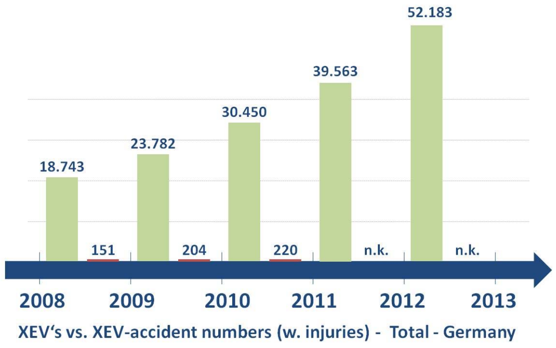

Figure 2: Accidents w/o XEV's [1]

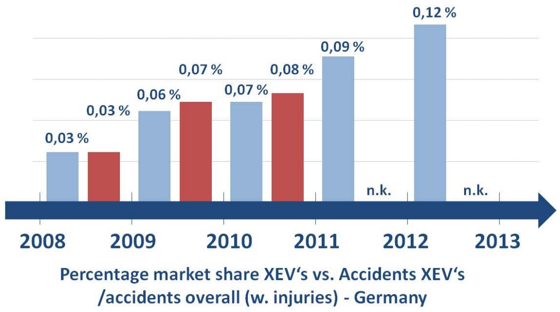

Figure 3: Accidents w/o XEV's according to market share [1]

This shows a strong, yet unsurprising correlation between the total numbers of cars and XEV's, and the accident numbers. The crash severity could seem a little bit lower due to the preferred use of XEV's in urban areas.

The overall risk for an incident due to a battery problem seems to be quite low. This is a result of the low numbers of existing vehicles.

It is important to distinguish between incidents that were the result of technical malfunctions and incidents that were a result of crashes involving vehicles.

According to several studies, the amount of technical reasons that cause accidents in Germany is below 10 % (most of which are tire defects), while accidents due to human error are over 85%. The implication of this is that, in the case of an accident, the protection of a battery in a vehicle is of utmost importance.

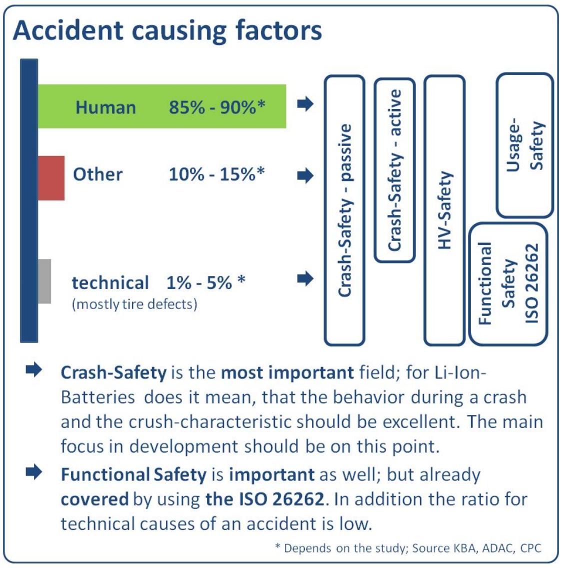

Figure 4: Accident causing factors [2]

The functional safety to avoid incidents due to technical reasons is covered by the development activities and processes of the car manufacturers. This includes different safety fields, like functional safety and the requirements outlined by ISO 26262, high voltage safety and the safety during use and during repairs or maintenance.

If we consider actual accidents involving batteries (both lithium Ion and NiMH), we find that the absolute number during transport and use didn't increase, while the number of vehicle accidents and incidents due to battery problems is increasing. This is from the increased number of XEV's in the field, but it is not above the expected numbers from the current market share of XEV's.

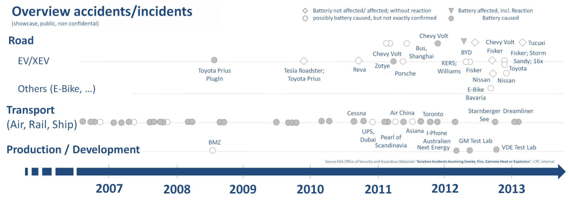

Figure 5: Accident and incidents with batteries involved (public available data only) [3]

The rate of accidents with involved battery but without any dangerous reaction of the battery is of about 25%. This shows that the implemented safety systems of the vehicle and the protection of the battery system worked very well.
In approximately 66% of the accidents the battery probably caused the event. Out of this the safety system of the battery doesn't seem to work properly; this shows that the risk can be reduced by improved safety systems as well as risk assessment processes.
This seems to be opposite to the statistic overview given above with just 1% to 5% of the accidents because of technical issues. It just shows the actual state of the art and the risks of the battery technology and gives a direction for the main focus for future developments.

Noteworthy is that the absolute number of accidents didn't increase with respect to the absolute number of battery cells produced during the past few years, or with respect to the increase in market share. Considering these statistics, it seems that the safety level of the batteries produced and quality of the batteries are not only getting better, but also that the safety systems and requirements are working very well.

ASSESSMENT METHOD FOR THE SAFETY OF ELECTRIC AND HYBRID VEHICLES

To get an idea of the safety level of vehicles, especially vehicles with an electric power train, it is necessary to understand what the triggers for dangerous situations are as well as the reaction of the vehicle and its occupants.

For this, the methodology of the ICE 61511 is used and adopted to the vehicles. As shown in figure 5 the system is split into several (technology driven) levels; for an electric vehicle, there is the cell chemistry level, the cell level, the battery system level, and the vehicle level, as well as the environment influences by the infrastructure (safety lanes, charging stations) and the rescue and first responder level.

For each of these levels, the risks need to be evaluated. Some of the risks are mentioned below:

- electrical risk (short-cut)
- fire and explosion
- danger due to chemical reactions
- chemical risk due to toxic liquids and gases
- thermal danger due to high temperatures
- mechanical risk because of the higher weight of the battery components

Several technologies to improve the safety of the whole system can be used and are already implemented. Some of these will be discussed below.

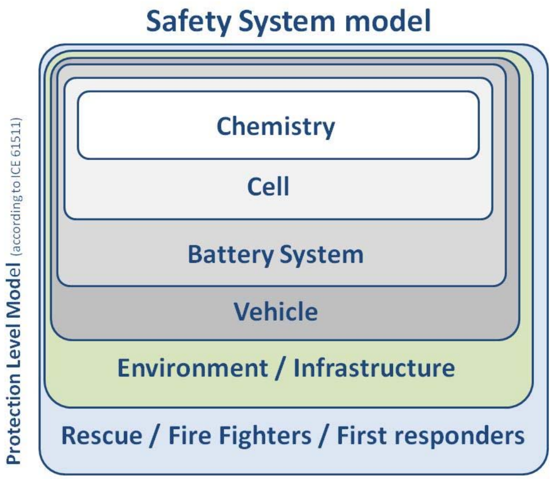

Figure 5: Safety model for XEV's with the different safety levels

On the level of the cell chemistry, it is important which kind of material is used for the cathode, the anode, the separator and the electrolyte. The combination of materials used dictates the thermal stability, the lifetime, the charging- and discharging characteristics, as well as the reaction during an external physical impact.

For the cathode, $LiFePO_4$ and $LiMn_2O_4$ are the most safe chemistries, while $LiCoO_2$ is known as less safe. This is based on tests regarding thermal stability. These tests simulate the reaction of the cell chemistry during an increase in temperature, and in the event of a thermal runaway. Usually heating (external and self heating) is triggered by internal or external short-circuits. The choice of the material chemistry is the basis for the overall safety of the whole system.

Another important aspect of overall safety is given by the anode chemistry used, the electrolyte and the type of the separator.

For the separator currently ceramic, semi ceramic and membranes (mostly polyethylene or polypro-pylene) are in use. The ceramic separator type seems to be better out of the safety point of view because of the higher resistance according to physical and thermal influences. On the other hand it's not possible to fold it (doesn't work for cylindrical or prismatic cells with folded layers) and it shows a lower performance according to energy and power.

On the cell level, the cell form that is used is important. Common cell designs are: pouch cells, prismatic cells, and cylindrical cells. The cell form is important because the cell housing is what protects against impacts and intrusions.
The prismatic and cylindrical cells show more mechanical stability than the pouch cells. Using a pressure safety vent makes it possible to avoid a burst or explosion of the cell by reducing the internal pressure. For the pouch cells, overpressure can be reduced via defined cut lines; this helps to guide the gas flow.

For the battery system, the design of the housing is also important. The battery management system controls and checks the performance (temperature, current, voltage, isolation etc.) of the battery during the use.
Another important feature is the choice of the cooling system. In general, air cooling and liquid cooling systems are most common. However, some systems work without cooling devices. Additionally, the cooling system can be used as heating device for low temperatures areas.
The choice of the cooling system depends on the expected use (power batteries for hybrid vehicles or energy focused applications for pure electric vehicles) as well as the expected local weather and temperatures (tropical climate, arctic climate …).

The positioning and the packaging of the battery, as well as integrated additional protection and deformation elements are part of the vehicle level. Deformation of the battery housing should always be avoided.
In the case of a deformation of the housing and the cells an explosion (because of gas leakage) or fire can take place.

An example for this explanation is the Chevy Volt incident after a crash test in 2011. Besides the handling with the battery (which was not according to the guidelines of the manufacturer; the battery should be secured after a crash and shouldn't be in the vehicle for a lot of days afterwards) the intrusion of the battery caused the following reactions like the leakage of coolant and the short circuits with the result of a vehicle fire.

Sometimes the battery housing is integrated into the vehicle structure and has to fulfill other functions. This might be a little bit concerning, especially in this case where it is crucial that the interface between vehicle and battery be designed properly.

The positioning of the battery is also important for Emergency responders. This is part of the outer-most safety level according to the used methodology.
If the battery is packaged under the hood, it is relatively easy to extinguish a fire. It is much more difficult if the battery is positioned in the rear part of the vehicle or directly in the middle under the vehicle.
Lastly, it should be noted that it is necessary to provide emergency responders with information about the vehicle, the position of the emergency disconnect device, the position and type of the used

battery, as well as information about the position of the high voltage harness.

For a realistic assessment of the safety of a battery system in an electric vehicle (XEV) the risk of each system level should be figured out.

The first step involves an analysis of each parameter and the main influencing factors must be indentified.

By using the definition for risks from the ISO 26262, the final risk is the product out of severity, probability and controllability. The following values for the different factors for the levels cell chemistry, cell and battery system are adopted by ISO 26262 and are proposed in this study for the use of the assessment:

Severity:

S0 EUCAR -Level 0-3

S1 EUCAR -Level 4-5

S2 EUCAR -Level 6-7

S3 EUCAR -Level not predictable

Probability:

E1 Very low probability (≤ 0,001)

E2 Low probability (≤ 0,01)

E3 Medium probability (≤ 0,1)

E4 High probability (≤ 1)

Controllability:

C0 controllable in general

C1 Simply controllable

C2 Normally controllable

C3 Difficult controllable

As example an assessment for a 5kWh battery system like described below will be shown.

The system characteristics are:

- prismatic cells with safety vents and $LiFePO_4$ at the cathode side, hard carbon for the anode and an ceramic separator
- liquid cooling system
- BMS; controls temperature and voltage, able to balance the cells
- stabile metal housing with safety vents
- passing all tests according UN transportation requirements on cell and safety level
- production of more than 1 million cells with a failure rate in the range of 6□
- used in prototype applications without any incidents or failures

The worst case scenario is S1 (it is the goal for future lithium ion systems); the probability for an incident is low (E2) and might be very low basing on the information about the history and the controllability can be assessed as C2.

The overall risk can be defined by using a matrix adapted according to the ISO 26262 matrix. An example of this is shown in figure 6.

		C1	C2	C3
S0	E1	Level 1	Level 2	Level 2
	E2	Level 2	Level 3	Level 3
	E3	Level 2	Level 3	Level 4
	E4	Level 3	Level 3	Level 4
S1	E1	Level 3	Level 3	Level 4
	E2	Level 3	Level 3	Level 4
	E3	Level 3	Level 3	Level 4
	E4	Level 3	Level 3	Level 4
S2	E1	Level 3	Level 3	Level 4
	E2	Level 4	Level 4	Level 4
	E3	Level 4	Level 4	Level 4
	E4	Level 4	Level 4	Level 4

Figure 6: Assessment matrix

The final definition of the risk leads to requirements for the sample application, wherein the battery will be used. For example, a level 3 system needs to be positioned in a safe part of the vehicle there is no risk for intrusion. Furthermore, it might be needed to pass additional crash test.

The same methodology can be used for the definition of safety requirements for transport, application in aircrafts or ships, for prototype applications, as well as for the identification and the safety of testing facilities.

The main point is that the risk depends on several factors. It cannot be figured out just by knowing that a lithium ion battery is used in an electrical car. The overall risk depends on more factors that have to be taken into account.

TECHNICAL TRENDS

For the future in cell chemistry level, lithium-air and lithium-sulfur systems might be very interesting. With both systems it is possible to store more energy than what is currently possible. This is the reason further developing this. The hope is to get more range, but more energy means less safety on the cell level. Because of the higher risk on cell level, it is important to improve the safety of the battery system and the vehicle system.

Another very interesting topic is the research on flexible cells; this might work very well if high accelerations or intrusion of the battery housing occurs and the flexible cell doesn't break.

For cooling systems, it seems that air-cooling for an electric vehicle might work well. Some reduced systems cool only the outside of the cell housing or only the top or bottom.

In general, the strategy should be developed according to the following [4, 5]:

1. Cell and battery level
   - Pre-emption – avoid thermal runaway
   - Detection – warning of potential failure
   - Intervention – stop thermal runaway
   - Containment – minimize damage

2. Vehicle Level
   - Safe driving
   - Preventive Protection
   - Adaptive Protection
   - Secure and rescue

The strategy is in general the same; safe use, prevention by detection, reaction if needed and securing after an incident by minimizing the damage.

CONCLUSION

The use of lithium ion batteries in vehicles is not only important for the e-mobility future, it is the key to any future success for electric vehicles. It doesn't matter for which kind of vehicles it will be used.

There are several risks that exist, such as chemical risk or electrical risk. It is important to understand the technology and the reactions of the material, and the cell and the cell system during an accident. With this knowledge, it is possible to design a safe system.
An approach for a method to assess risks and to define requirements for the safety levels is outlined within this paper.

From statistical data of actual accidents, it seems that the risk for electric and hybrid vehicles to be involved in an accident is similar to that of conventional vehicles. There have yet to be found any studies that are focused on the crash safety of batteries because of the high number of non-technical reasons for accidents. It is important to focus on the accelerations and intrusions, but the reaction of batteries according to acceleration is not known completely; especially when it is combined with aging and different states of charge.

The technical risks are covered by developing according to ISO 26262.

The technical trends are gravitating toward higher energy and power densities; but in general, more energy means less safety.

Despite any potential drawbacks, it is possible to design safe battery applications and safe electric and hybrid vehicles if the risks are taken into account and the systems are designed properly.

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