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Abstract

The demand of environmental and sustainable thinking, concerning global warming, has not surpassed the car industry, which have started to develop the electric vehicle. When developing this new type of vehicle, new issues regarding passive safety arise. The battery and related technology implemented in the electric vehicle, has to be made safe for the occupants. This report provides an in-depth investigation of the structural behaviour in electric vehicles, from a passive safety perspective. By researching state of the art technologies within the electric vehicle area, including batteries, battery placement, battery safety, sensors and upcoming technologies, this report gives conclusions and recommendations for different safety solutions, which could be implemented in future electric vehicles.

Keywords: passive safety, electric vehicle, structural behaviour, battery
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1 Introduction

1.1 Background

Through the European Project Semester (EPS), which was started in 1994 by Dr. Arvid Andersen in Helsingør, Denmark, engineers from different fields and backgrounds are given the opportunity to develop team working, innovation, sustainability and many other project related skills. In an all more internationalized world of Engineering, team work over country and cultural boundaries is essential to maintain a consequent development in the industry.

The project presented in this report, called “Passive safety in electric vehicles from a structural perspective” is done in School of Engineering of Vilanova i la Geltrú (EPSEVG) for the car manufacturer SEAT.

Of all the different fields, one of the biggest and most important industries is transportation. This field makes it possible to transport people and goods all over the world. Starting of by inventing the wheel and carriage several thousands of years ago, we are nowadays accustomed to vehicles using internal combustion engines (ICE), making transportation a real pain free experience. Having said that, one would think that our need has been satisfied and this means of transportation works out well for us, but as everything else that is invented, it won’t be cutting edge technology forever.

One main cause of today’s constant development within different fields is environmental and sustainable reasoning, not the least in the field of car technology. Because of this, all major car manufacturers are forced to develop new vehicles with reduced Carbon dioxide emissions which are involved with global warming, and fuel consumption due to the diminishing oil reserves. A solution, which could solve both earlier stated problems and which many car manufacturers believe in today, is the electric vehicle (EV).

1.2 Topic

The cutting edge technology implemented in today’s EVs, in forms of i.e. battery, wiring, sensors and an electric motor, have to be safe from a passive safety point of view. There are several new risks to take in to account that were not needed before with internal combustion engine vehicles (ICEVs). For instance, there is an up to 500 volt electric current inside the battery and it’s wiring system and a battery pack that may be possible to leak, burn or even explode.
Furthermore, big parts of the car’s structure are reinforced or changed due to its new type of drive train. These changes need comprehensive safety solutions implemented with them in the EVs to keep both the drive train and thereby also the occupant safe from hazard in case of a crash.

1.3 Scope

This project is limited to the structural behaviour of an EV, from the perspective of passive safety. We will not go in on active safety or emphasize on other parts outside passive safety. This means searching, concluding, and recommending different safety solutions that could be used in future SEAT EVs. Because the main focus is placed on keeping the battery packs safe, the recommendations include e.g. placement and fixing of the battery packs, different sensor technology implementations and new battery technology. The focus lies on the battery compartment because it is the heart of the EV. The battery pack, with its big mass and high electric current, is the part making the EV stick out compared to the mainstream ICEV. The battery pack also forms the most valuable part of the EV, with a cost of thousands of Euros. Other tasks given to the project team consists of searching and comparing different battery technologies. This comparison could help SEAT choose the most appropriate battery type for their future EVs.

1.4 SEAT

SEAT is a Spanish car manufacturer founded May 9, 1950 by the Instituto Nacional de Industria, a state owned industrial holding company. Since 1990 it is a fully owned subsidiary of the German Volkswagen Group and marketed with a sporty youthful profile. The brand SEAT is further divided into a subsidiary, SEAT Group and a parent company, SEAT, S.A. It’s headquarters are situated in Martorell, an industrial complex just outside Barcelona in Catalonia, Spain. The industrial complex in Martorell also hosts the facilities of SEAT Sport, SEAT’s Technical Centre (where our project is managed), Research and Development Centre (R&D), Design Centre, Prototypes Centre of Development, SEAT Service Centre, as well as the Genuine Parts Centre for SEAT, Volkswagen, Audi and Skoda brands.
Since the beginning of 1950, more than 16 million SEAT cars have been produced and SEAT nowadays is the only major Spanish car manufacturer with the ability and the infrastructure to develop its own cars in-house with a personnel of around 10 000 and with a production capacity of around 500 000 units per annum. The following table shows sales figures for SEAT during the last six years. [1]

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual production</td>
<td>405,019</td>
<td>422,67</td>
<td>412,946</td>
<td>380,575</td>
<td>307,502</td>
<td>345,027</td>
</tr>
</tbody>
</table>

*Table 1 Total units produced per year by SEAT. Source: SEAT*

The project presented in this report was carried out in collaboration with SEAT´s Technical Centre, which also contributed with two supervisors, Jorge Barreló and Sven Winter. They were able to give the project team instructions and assist with substantial information when needed during the development of the project.

### 1.5 Project Management

Managing a project is essential, not only for the end results to be successful, but also for the project to develop in a functional way. Therefore this project team used certain guidelines when working on the project.

First of all, decisions concerning the project were taken by those attending agreed meetings if not otherwise agreed. Second, tasks were brainstormed and divided amongst team members, so that everyone could participate and have their voices heard. Third, everyone was responsible for their given task and got assistance if necessary from team members or supervisors from the school or the company.

Meetings were tried to be held every other week with SEAT. In these meetings the current state of the project was discussed. Meetings concerning the team only, or with the school supervisor, were arranged when needed, this was decided within the team. As a gathering point for all project
related documents a web site was established on http://teambox.com, which also gave an overview of the project development.

2 Active and passive safety

Before the recommendations and assumptions connected to passive safety in EVs can be presented, automobile safety has to be defined. Usually when speaking about “safety” in the car industry, the expression is divided into two categories; active and passive safety. Safety solutions that try to avoid crashes are known as active. Active safety works before the collision has occurred. Passive safety solutions help secure vital car parts and passengers while the collision is happening. Safety generally is important issue from beginning of car industry. First elements of safety in cars were seat belts and padded dashboards. General Motors was the first company which performed crash test. Safety cage was firstly used by SAAB in model 92, it was a big step towards improving safety. In 1958, international standards in car safety were established. In the same year three-point lap and shoulder seat belts were invented and developed over next few decades. In 1979 National Highway Traffic Safety Administration (NHTSA) began crash testing of cars and publishing the results. Thanks to this action manufacturers were encourage to improve the safety of their vehicles. In 1997, European New Car Assessment Program (Euro NCAP) was established to test vehicles. The NHTSA is nowadays a U.S. branch of the NCAP. Together with technological development new safety systems are developed. Due to this fact cars are becoming safer. [2] Active safety is a complex of factors influencing the reduction in the risk of collision or accident. Including the following set of characteristics of the vehicle; The design of the vehicle that provides visibility from the vehicle (lights, windows, mirrors, wipers) and the vehicle (colour, lighting) as well as providing ergonomics (which helps the driver to focus on the road) and has the aerodynamic properties to ensure stability. The braking system with supporting systems, as well as, traction control systems in vehicle, such as: [2]

- **ABS** (Anti-Lock Braking System) - system used in motor vehicles in order to prevent the wheels from blocking during braking, as part of the braking system. This system is classified as a group of systems Advanced Vehicle Control Systems (or Automated Highway Systems).
ABS prevents the phenomena occurring after blocking the wheels, such as spinning the car or losing control of car driving. Braking distance of a vehicle equipped with ABS as compared to an identical vehicle without the system depends on several factors, such as external conditions and driving skills. [2]

• **BAS** (Brake Assist System) - system works in cooperation with ABS. The system detects situations where the driver wants to brake quickly. Then the system responds by increasing maximum pressure in the brake system to get as much braking power. In some vehicles, during the operation of the BAS also include emergency lights to warn another drivers about sudden braking. [2]

• **ASR** (Anti-Slip Regulation) - main task for this system is to prevent excessive wheel spin during acceleration of the vehicle. Indirectly, such systems may also contribute to improve the traction properties of the vehicle. [2]

• **ESP** (Electronic Stability Program) - an electronic control system that stabilizes the car when cornering, to take control of interconnected systems like ABS and ASR. This system is activated automatically, by braking one or more wheels, once the appropriate sensor detects a tendency to slipping the car from the corner. [2]

Passive safety- set of characteristics of the vehicle to reduce the effects of the collision or accident from the viewpoint of all participants. Elements improving passive safety are shown below. [2]

**Pretensioners and webclamps**

Seatbelts in many newer vehicles are also equipped with "pretensioners" and/or "Webclamps". Pretensioners preemptively tighten the belt to prevent the occupant from jerking forward in a crash. Mercedes-Benz first introduced pretensioners on the 1981 S-Class. In the event of a crash, a pretensioner will tighten the belt almost instantaneously. This reduces the motion of the occupant in a violent crash. Like airbags, pretensioners are triggered by sensors in the car's body, and most pretensioners use explosively expanding gas to drive a piston that retracts the belt. Pretensioners also lower the risk of "submarining", which is when a passenger slides forward under a loosely worn seat belt. An alternative approach being looked at by major car companies is the CG-Lock technology whereby the occupant is held in position via the lap belt in order to prevent the passenger from coming out of position in the event of a crash. [2]
Webclamps clamp the webbing in the event of an accident and limit the distance the webbing can spool out (caused by the unused webbing tightening on the central drum of the mechanism) these belts also often incorporate an energy management loop ("rip stitching") which is when the lower part of the webbing is looped and stitched with a special stitching. The function of this is to "rip" at a predetermined load, which reduces the load transmitted through the belt to the occupant, reducing injuries to the occupant. [2]
Headrest

When travelling in an automobile, a properly adjusted headrest can reduce the severity of neck injuries such as whiplash in the event of a collision. The top of the headrest should be in line with the top of the occupant's head. The headrest should not, however, be placed behind the occupant's neck. Maintaining an adequate separation from the vehicle in front while driving and pressing your back against the seat while facing forward if a collision appears imminent might also be advisable. This helps prevent the neck being forced backwards, and decreases the risk of whiplash. [2]

Collapsible Steering Columns

Collapsible steering columns still consist of a long shaft that connects the steering wheel to the steering gear box. However, the collapsible design is composed of an inner and an outer sleeve, pressed tightly together with a number of steel bearings in between. These steel bearings are pressed into the metal sleeves, and are held in place with a strong safety resin, which is designed to harden and then shatter when a specific level of pressure is applied.
In the event of a frontal impact, the steel bearings between the sleeves break free, allowing the inner sleeve to be moved further into the outer sleeve in telescopic fashion before enough pressure is achieved to ram the whole steering column into the driver. In this manner, the energy received through a frontal impact is completely absorbed by the steering column's collapsing parts, allowing most modern drivers to remain completely unaware of the danger they have avoided. [2]

**Figure 4 Idea of how the collapsible steering column works. Source: www.gracetoyota.in**

**Crash sensors for the airbag system**

When the crash sensor in the car detects a collision, it sends a signal to the control module which deploys the airbag. There are various types of crash sensors, like the older ones which were placed in the front of the car (in the crash zone area), and the latest micromachined accelerometers that are installed inside the control module or the airbag brain. The micromachined accelerometers actually measure the speed and severity of the collision. There are also sensors placed in the doors, for deploying the side airbags. The front and the side sensors only work with the front and the side airbags, respectively. [2]

The control module is a small computer that receives data of the crash from different sensors, and then decides which airbag is to be deployed. It is unable to deploy an airbag, if it receives only one pulse. It would need two or more pulses from the sensors to do so. The second pulse comes from the arming sensor that is located inside the car, which senses a sudden decrease in speed. When
the control module is certain about a severe crash, it signals the squib inflator, also known as the igniter, which is an electrical device that has a thin bridge wire. [2]

**Frontal airbag**

Depending on the severity of the crash, frontal air bags inflate to prevent occupants from hitting the steering wheel, dashboard, and windshield. Frontal air bags for both drivers and passengers have been standard equipment in all vehicles since 1998. Frontal air bags do not eliminate the need for safety belts and typically do not offer protection in rollovers, side-impact, or rear-end crashes. Air bag effectiveness depends upon the proper use of safety belts, which help keep you in place should a collision occur. Occupants who are unbelted or out-of-position can end up being seriously injured or killed if they are too close to the air bag when it deploys. [2]

![Figure 5 Picture showing the frontal airbags. Source: www.bodyautorepair.org](image)

**Advanced (Frontal) Air Bag Systems**

Advanced air bag systems are a next-generation frontal air bag system designed to further reduce the likelihood of serious injury or death to occupants, whether adults or children, who may be too close to the air bag when it deploys. Most advanced air bag systems use sensors that automatically detect the severity of the crash, the occupant’s size, safety belt use, and/or seating position, and deploy the appropriate level of power to the driver’s and passenger’s frontal air bags. [2]
Side torso airbag

Side-impact airbags or side torso airbags (side thorax/abdomen airbags) are a category of airbag usually located in the seat, and inflate between the seat occupant and the door. These airbags are designed to reduce the risk of injury to the pelvic and lower abdomen regions. Some vehicles are now being equipped with different types of designs, to help reduce injury and ejection from the vehicle in rollover crashes. More recent side airbag designs include a two chamber system; a firmer lower chamber for the pelvic region and softer upper chamber for the ribcage. [2]
Side tubular or curtain airbag

This is an industry's first in offering head protection in side impact collisions. This airbag also maintained inflation for up to seven seconds for rollover protection. However, this tubular shaped airbag design has been quickly replaced by an inflatable 'curtain' airbag for superior protection. Roll-sensing side curtain airbags found on vehicles more prone to rollovers such as SUV's and pickups will deploy when a rollover is detected instead of just when an actual collision takes place. Often there is a switch to disable the feature in case the driver wants to take the vehicle offroad. Curtain airbags have been said to reduce brain injury or fatalities by up to 45% in a side impact with an SUV. These airbags come in various forms (e.g., tubular, curtain, door-mounted) depending on the needs of the application. Many recent SUVs and MPVs have a long inflatable curtain airbag that protects all 3 rows of seats. [2]

![Figure 8 Curtain airbag. Source: www.zodiacautomotive.com](image)

Knee airbag

The airbag is located beneath the steering wheel. There has been much effort to protect the driver's knees and legs and a knee airbag worked well. Since then certain models have also included front passenger knee airbags, which deploy near or over the glove compartment in a crash. Knee airbags are designed to reduce leg injury. The knee airbag has become increasingly common in the 2000s, with a large minority of cars featuring them on the driver side by 2010. Passenger knee airbags remain extremely rare. [2]
Sensors for accident detection

The main task of the sensors it is to provide immediate data on the probable type and seriousness of a collision:

- **Frontal impact**: In addition to the central sensor in the airbag control unit, the luxury coupé is equipped with "up-front" sensors. Because of their exposed position in the front module, they detect the anticipated strength of an impact even earlier and with even more precision, so that the time between the crash and the activation of airbags and seat-belt tensioners can be reduced even further. [2]

- **Side impact**: pressure sensors relay rapid, precise information to the control unit in the event of an impact from the side in the area of the doors. These sensors react when the air between the doors' outer skin and inner lining is compressed on impact. Additional side sensors are installed in the lower (not visible) B-pillars. [2]

- **Rear end collision**: if the central crash sensor in the interior detects a rear impact, it triggers the pyrotechnic front and rear belt tensioners to fix the occupants securely in their seats. [2]

- **Rollover**: in side rollovers, a rollover sensor integrated into the airbag control unit can activate the seat-belt tensioners and window bags. [2]
Body structure

When a vehicle crashes against another object, its structure is involved in a hard acceleration which is transferred to the passengers. The main purpose of the structure design is to reduce the consequences of a crash on the passengers and essential car parts. The vehicle structure is designed with areas that absorb and distribute the crash energy through the whole structure. [2]

Figure 10 See through model showing structural safety enhancements. Source: www.3.bp.blogspot.com
3 The electric vehicle

3.1 Differences between EVs and ICEVs

The EV differs from conventional ICEVs in several ways. These differences include lack of an ICE in the front compartment, lack of a fuel canister in the back but the addition of battery packs in the rear, middle or front. Also the total weight of the car usually increases mainly due to the heavy weight of the battery packs. Because of these new additions, the structure of the car body has to be strengthened or changed to comply with the new basis. These changes in the cars structure and it’s inside, changes how the car behaves on the road while driving it but also what happens during and after a crash.

3.2 Legislation and safety regulation

As with all other types of vehicles, there are also laws and legislation for the EV. The EV market is still young and under development. This means that there is probably going to be a lot of new laws and requirements in the field in the near future.

In March 2010, United Nations Economic Commission for Europe (UNECE) presented a new regulation called Regulation No. 100. This regulation concerns not only EV’s but also hybrid vehicles. This safety regulation is today applied in 41 countries. Apart from the 27 states of European Union, Azerbaijan, Belarus, Bosnia and Herzegovina, Croatia, Malaysia, Montenegro, Norway, Russian Federation, Serbia, Switzerland, The Former Yugoslav Republic of Macedonia, Tunisia and Turkey are also applying the new regulation. [4]

Regulation No. 100 covers “Uniform provisions concerning the approval of battery electric vehicles with regard to specific requirements for the construction and functional safety”. The following topics are dealt with in the regulation: [4]

• Compliance of the vehicle manufacturer to all applicable technical requirements
• Testing by a certified technical service
• Approval by the national Approval Authority
• Conformity of production by the manufacturer in agreement with the Approval Authority
• Certificate of conformity issued by the manufacturer to the end-user

In order to get approved by UNECE, a car manufacturer must send a vehicle to a so called "contracting party". An administrative process will follow and the contracting party will perform several tests and verifications. If the vehicle fulfils the demands that are required by the regulation, the vehicle will get an approval mark. See figure 11. [3]

![Image](https://www.greencarcongress.com)

Figure 11 Picture of the Regulation No. 100 approval mark. Source: www.greencarcongress.com

3.3 Crash tests

A large portion of the time spent with a car prototype is devoted to crash tests. The goal of this testing is to learn about the structural behaviour in EVs in different crash compositions. Different kinds of common crash tests are presented below.

**Frontal-impact tests**

This is what most people initially think of when asked about a crash test. These are usually impacts upon a solid concrete wall at a specified speed, but can also be vehicle-vehicle tests. SUVs have been singled out in these tests for a while, due to the high ride-height that they often have. [5]
Offset tests

In offset tests only a part of the front of the car impacts with a barrier. These are important, as impact forces remain the same as with a frontal impact test, but a smaller fraction of the car is required to absorb all of the force. These tests are often realized by cars turning into oncoming traffic. [5]
Side-impact tests

These forms of accidents have a very significant likelihood of fatality, as cars don't have a significant crumple zone to absorb the impact forces before an occupant is injured. [5]

![Side-impact test diagram](image)

*Figure 14 Shows how the side-impact test is done with a "carriage". Source: www.euroncap.com*

Rollover tests

During a rollover test, a car's ability (specifically the pillars holding the roof) to support itself in a dynamic impact is tested. More recently dynamic rollover tests have been proposed as opposed to static crush testing. [5]
Roadside hardware crash tests

Roadside hardware crash tests are used that crash barriers and crash cushions will protect vehicle occupants from roadside hazards, and also to ensure that guard rails, sign posts, light poles and similar appurtenances do not pose an undue hazard to vehicle occupants. [5]

Computer model

Because of the cost of full-scale crash tests, engineers often run many simulated crash tests using computer models to refine their vehicle or barrier designs before conducting live tests. [5]
4 State of the art battery

4.1 Battery Benchmarking

Batteries for EVs are because of their relatively high power-to-weight ratio, energy-to-weight ratio and energy density; smaller and lighter batteries exposed to high demands. So the right choice of a battery is very important. To find the state of the art battery type, we have made several investigational steps. [6]

Our first step was to select a particular kind of battery e.g. lead battery, lithium battery or Nickel-cadmium battery. To make this decision easier we created a benchmarking table. In this table we evaluated the different criteria for batteries e.g. life span, charge efficiency, energy density, power density and operating temperature. We used an excel table to benchmark the different battery types. This table can be found in the appendix. We recommend taking a closer look at the table for further details. After comparing the metrics of the different battery types we came to the conclusion that the lithium battery (marked with green colour in the table), suits our needs the best. By this conclusion, we had a made the first step in the benchmarking.

Benchmark of Lithium Battery

The following step was to choose between different types of lithium batteries. The term "lithium battery" refers to a family of different chemistries, comprising many types of cathodes and
electrolytes. Lithium-ion is a low maintenance battery, an advantage that most other chemistries cannot claim. There is no memory and no scheduled cycling is required to prolong the battery’s life. In addition, the self-discharge is less than half compared to nickel-cadmium, making lithium ion well suited for modern fuel gauge applications. Lithium ion cells also cause little harm when disposed. To make this huge topic a bit clearer we created a benchmarking table for the section, comparing different types of lithium-batteries against each other for e.g. Lithium iron phosphate, Lithium-iron sulphide battery, Lithium-ion battery and the Lithium-Metal-Polymer Battery. We came to the conclusion to choose the Lithium iron phosphate battery, because the battery shows very good returns. The battery also has a positive effect on safety, which we appreciate really high. [7] [8]
Lithium iron phosphate

As one can see from the comparison table, the lithium iron phosphate battery looks really promising. The lithium iron phosphate battery, also called LFP battery, is a type of rechargeable battery, specifically a lithium ion battery. Basically the lithium-ion battery is the further development of the lithium iron phosphate battery. The lithium-ion battery uses a lithium-ion-derived chemistry and shares many of its advantages and disadvantages with other lithium ion battery chemistries. However, one key advantage over other lithium-ion batteries is the superior thermal and chemical stability, which provides better safety characteristics than lithium-ion batteries with other cathode materials. Due to significantly stronger bonds between the oxygen atoms in the phosphate (compared to the cobalt), oxygen is not readily released, and as a result, lithium iron phosphate cells are virtually incombustible in the event of mishandling during charge or discharge, and can handle high temperatures without decomposing. [8] [9] [10]

<table>
<thead>
<tr>
<th>Type of Battery :</th>
<th>LiFePo4 (lithium-ion phosphate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance/ Energy Throughput</td>
<td>90–110 Wh/kg (320–400 J/g)</td>
</tr>
<tr>
<td>Safety</td>
<td>no explosion, will not catch fire under collision, over charged, or short circuit, high thermal stability up to 500°C</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>2000-3000 times</td>
</tr>
<tr>
<td>Remaining capacity after high discharge rate</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Depth of Discharge</td>
<td>100,00%</td>
</tr>
<tr>
<td>Time durability</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td>Working Temperature Range</td>
<td>-20C to 70C</td>
</tr>
<tr>
<td>Specific power</td>
<td>&gt;3 W/g</td>
</tr>
<tr>
<td>Energy density</td>
<td>220 Wh/L (790 kJ/L)</td>
</tr>
<tr>
<td>Environment</td>
<td>Non-toxic, very environmental friendly</td>
</tr>
<tr>
<td>Maintenance</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2 table shows a summary of the basic specifications for li-on phosphate [8] [9]
Few disadvantages: While LiFePO4 cells have lower voltage and energy density than LiCoO2 Li-ion cells, this disadvantage is offset over time by the slower rate of capacity loss (aka greater calendar-life) of LiFePO4, also when compared with other lithium-ion battery chemistries. [8]

4.2 Political impacts of Lithium

After selecting Lithium batteries as the best one in our opinion, we have to consider political and economical impacts connected with Lithium. World’s reserves of Lithium are quite big and should be sufficient for some time. But as we can see in the table presented below, different sources present various amount of Lithium. However, based on this table we can say that the largest deposits are found in the Lithium Triangle (Argentina, Bolivia and Chile), China and the United States. Taking all factors into consideration, we can say that source number three is most similar to the real state. [11] [12]
<table>
<thead>
<tr>
<th>Country</th>
<th>Source 1</th>
<th>Source 2</th>
<th>Source 3</th>
<th>Source 4</th>
</tr>
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<tr>
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<td>262,800</td>
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<td>5,400,000</td>
<td>5,500,000</td>
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<td>123,000</td>
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<td>255,600</td>
<td>1,073,000</td>
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<tr>
<td>TOTAL</td>
<td>11,400,000</td>
<td>13,500,000</td>
<td>28,500,000</td>
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</table>

*Table 3 The table shows the size of the world’s Lithium reserves in tons*

There is also new research conducted on places where lithium could be found. In 2010, the New York Times reported that American geologists were conducting ground surveys on dry salt lakes in western Afghanistan believing that large deposits of lithium are located there. Those researches were finished with success because the New York Times presented an official stage of Pentagon: "Pentagon officials said that their initial analysis at one location in Ghazni Province showed the potential for lithium deposits as large of those of Bolivia, which now has the world’s largest known
lithium reserves." However, Afghans denied this information, because they fear that U.S. forces will stay there for a long time to protect the sources of Lithium. [12]

In the meantime different companies and universities are carrying out studies on the recycling of lithium-ion batteries on a massive scale. The company Chemetall estimates that by recycling, one will be able to recover about 50% of lithium from a spent lithium-ion battery. This means that after about 15 years of use, battery packs (first in the vehicle, and later as stationary energy storage) will be able to recover half of the lithium contained there. [12]

**Lithium in Bolivia**

Bolivian President Evo Morales did not allow investments by foreign corporations interested in metal mining. They are only interested in the extraction and preliminary purification of raw materials, and they want to produce batteries outside the country. This is not enough for Mr. Morales, because he is interested in the construction of refineries and assemblers of lithium batteries. [13]

Bolivia announced a plan to build a large refinery, which is to eventually produce 30,000 tons of lithium per year, accounting for 30 percent of current world production. The plant will be ready in the year 2013/14. Its projected cost is 250-300 million dollars. In addition to the cost of construction of the plant the government will have to find an additional 500 million dollars to cover expenses related to the modernization of infrastructure. Plans to build assembly plants accumulate are associated with additional costs of a billion dollars. Bolivia cannot afford at this time to allow for such an investment, therefore the Bolivian government would have to borrow money. [13]

Even if a huge company will invest in Bolivia, there is huge risk of money being wasted by the local government. Looking at the political scene or any financial news around the world, it will bring to the conclusion, that huge amounts of money pumped in to these kinds of projects, can have a bad impact on the situation in the country. Without a good plan, prepared by the best economists, the situation could easily fall into chaos. [13]

The three largest companies known for Lithium extraction, called "Lithium trinity" (Sociedad Química y Minera de Chile (SQM), FMC Technologies (FMC) and Chemetall), are in general not interested in deposits in Bolivia, because according to Paul J. Norris of the FMC, they may still increase production themselves, with a lower cost. [13]
Lithium in China and Chile

Another place where mining of Lithium is difficult because of political aspects is Chile. According to the Chilean Constitution Lithium is state property and companies have to apply for a concession. What’s more nowadays Government investigate the concessions awarded to SQM and SCL for Lithium extraction under previous Governments (they might be illegal). [14]

In South America, people are demanding a much greater financial return from the exploitation of their immense mineral wealth by foreign companies and protection of the environment, and companies must meet their demands in order to have benefits from the resources located there.

Also in China, there are problems with Lithium because of their geographical location. [14]

China’s Lithium deposit is located in Tibet, as we now this place is a politically sensitive region, due to activists fighting for independence of theirs region. However, this shouldn’t be a problem for the supply of Lithium from the region. [14]

Lithium in the future

There are reports on the potential risks associated with the increased demand for lithium, although experts are not unanimous here. Meridian International Research organization presented in its study “The Trouble with Lithium”, that global reserves of the element, concentrated in Chile, Bolivia, Argentina and China, are just 6.2 million tons. They came to the conclusion that the broad expansion of the electronics industry, as well as the development of the sector of EVs, will lead to an increased demand and may result in worse relations between the United States and South America. [15] [16]

In 2015 (around the time of completion of the Bolivian refineries) demand for lithium in the automotive sector is estimated at just 10,000 tons. In 2020, however, it may jump to 81 thousand tons. [16]

4.3 Battery technology

As mentioned several times in this report, one of the major problems with EVs is the batteries and the recharging (and discharging) problems of them. Ever so often one can read about new battery technologies being developed, promising more power or lower weight or faster recharge time, and
so on. Sometimes though, you stumble upon some research papers that look more promising than others. In this section we are presenting one new technology that is being developed as we speak. Note that this technology is being developed with the aim at improving performance in EVs.

**Battery technology that allows recharging within a couple of minutes**

Professor Paul Braun from the University of Illinois along with fellow researchers Huigang Zhang and Xindi Yu, have designed a new 3D film battery that looks very promising for the EV industry. It has been shown that batteries which are equipped with a 3D film can be charged up to 100 times faster than regular counterparts. The battery that Braun and company are developing is using a nano-structured 3D film in the cathode of the battery. The design of the cathode gives the battery several specifications that will greatly benefit an EV. The most important specification being the recharge and discharge benefits. This technology is not just for Lithium-ion. It can also be used for NiMH and other types of batteries. In the research paper they give an example of recharging a big (as in EV-size) battery 90% in 2 minutes. This is clearly a great and interesting achievement. Let us continue with looking more into details of the design process of the cathode. [17]

*Figure 18 The figure shows the three-dimensional construction of the cathode in Braun's battery (left) and a scaled up picture of the nanostructure (right). Source: Paul Braun, University of Illinois*
In order to achieve the previously mentioned specification, the group of researchers had to design a three dimensional film for the cathode. To keep it brief, they produced a film full of nano-scaled spheres with a metal coating. They created films for both Lithium-ion and NiMh batteries. Finally the research group states that this technology can be implemented in the fabrication process and that it is suitable for both large- and small-volume manufacturing. [17]

5 Battery safety

As we mentioned earlier we selected the lithium-type batteries as the best option for an electric vehicle. Although lithium might have a bad reputation concerning safety issues, one must understand that there are many different types of lithium batteries and some of them are safer than others. One problem with lithium batteries has been the risk of battery cell overheating that could - in some rare cases - lead to an explosion within the battery. This scenario has been solved though by using different kinds of materials both inside and outside the battery cell.

In this section we will present three basic steps that should be taken into consideration when working with battery safety. [18]

Step 1; Make sure to choose a reliable battery manufacturer

Car manufacturers who are developing EVs usually don’t produce the batteries them self. For this matter they rely on external manufacturers. This is a critical matter and it’s important for the car manufacturer to closely inspect and analyse what supplier to buy from. Things to take into consideration are for example; Safety tests, reputation of the company (i.e. experience, capacity and quality) and of course the price. Apart from these rather obvious points, there are some more battery specific criteria’s to look into as well. A good battery cell is constructed in a steel case. Steel is the best material considering the price-weight-durability ratio. The steel case should have a solid and high quality finish. There are several tests that should be conducted on the case, for example a Vickers hardness test, a nail penetration test, a vibration test and an impact test. Further the steel case should be equipped with a pressure valve, a positive temperature coefficient resistor (PTC) and a high temperature separator. A short explanation will follow about the previous mentioned specifications. [20] [23]
Pressure valve, a pressure relief valve is used to protect a system from taking damage if exposed to too high pressure. Every system has a maximum allowable working pressure (MAWP). Since pressure valves are safety components, there are several standards available to control the manufacturing process. It would be a good idea to make sure the battery supplier meets these criteria’s. [19] [20]

Positive temperature coefficient resistor (PTC), a PTC is a passive electronic component that acts as a resistor with specific resistance depending on the temperature. In a battery cell this means that the resistance will increase when the battery gets warmer. This way you can control the current flowing trough the cell package. [19] [22]

High temperature separator, this type of separator is used in lithium batteries to prevent the electrodes from short-circuiting in case of a meltdown inside the battery. The separator is formed as thin film that surrounds and separates the anode from the cathode. The separator film is made out of a material that has a higher melting point than the electrodes. [19] [24]

![Figure 19 The figure shows a cross section of a Lithium Ion battery including a valve, PTC and separator. Source: DuPont](image)

Using the previously mentioned methods will prevent thermal runaway within the battery pack. Last but not least the battery cells should meet the UL 1642, the standard for lithium ion batteries. [19] [24]
Step 2; Using sensors to protect the batteries

There are several sensors that could be used to monitor and protect the battery package. As discussed earlier in step 1, protecting the battery cell from overheating is of utmost importance. Using PTC’s and separators is one way to control the temperature inside the batteries, but using external sensors to monitor the battery package is also recommended. [22]

In case of an accident, it’s impossible to protect the battery package from every thinkable scenario, but using some basic sensors can go a long way. Using sensors to monitor acceleration, tilting, temperature, humidity, voltage and over current, will aid in protecting the battery in quite a few car accident scenarios. If the sensors pick up some unusual activity the will simply unplug the batteries and await further orders. See “Sensor technology” chapter for more details. [19]

Step 3; Protecting the battery pack from physical impacts

When all above fails, it’s important that the battery pack is strategically placed in the vehicle. This topic is being covered in more detail in the “Placement of the battery” chapter.


5.1 Passive safety aspects

When the EV is in a collision, the battery is exposed to large forces. These forces can harm the battery in different ways. To be able to keep the battery and the occupants free of harm, several scenarios need to be avoided. Below is a list of the scenarios, which need to be avoided for the battery packs. The listed scenarios are not in any particular order.

- Overheating
- Fire breaking out
- Explosions
- Large deformation
- Leakage of high voltage current to unwanted areas
- Leakage of fluids and gases

Some of the listed scenarios could be able to cause the other. And even if one of these scenarios would occur, there is no guarantee for the occupant or any other person within certain proximity, to feel confident of their security.
5.2 Placement of batteries

A very important aspect connected to passive safety in EVs, is the placement of the batteries. Due to the fact that the battery pack is the most sensitive and expensive element of an EV, it must be well protected in case of crashes. Generally there are few places where the battery can be mounted: middle part of the car (under the floor), underneath the rear seat, between the rear wheels, below the cargo floor or almost everywhere in the car (in front of the car, in the middle part and in back), such a solution is used in new BMW EV, which will be explained later.

Middle position is currently used in Mitsubishi i-MiEV:

![Figure 20 Battery placement in Mitsubishi i-MiEV. Source: www.mitsubishi.com](image)

The engine is located in the rear part of the car and Lithium-Ion batteries in the middle part. The battery pack is located far from the front and rear parts of the car and thanks to this it is well
protected from destruction during a crash. However this position has some disadvantages, due to the size of the car, it can easily be exposed to deformation in case of a side impact. [25]

Another location is under the rear seat. Such a position is presented below in the Lexus RX 400h.

![Battery placement in a Lexus RX 400h](source: www.Lexus.com)

*Figure 21 Battery placement in a Lexus RX 400h Source: www.Lexus.com*

In Toyota Prius the battery pack is located between the two rear wheels. This solution is similar to the one used in the Lexus. That is why all advantages and disadvantages of those two solutions are presented together below, in the picture of a Toyota Prius. [26] [27]
The solutions proposed in the two figures above are better than the first one presented, with the battery only in the middle part. One of the main advantages is that the battery pack is located far from the front part of the car and thanks to this it is well protected from destruction during a front or side crash. Furthermore, the engine is located in the front part of the car to provide a good weight distribution. However, this solution is not the best one. Placing of the battery in such a position exposes it to deformation in case of a rear impact. [27]

The next idea is to put the battery below the cargo floor like in a Ford Escape Hybrid:
The advantages and disadvantages of this solution are similar to the ones with the placement of the battery underneath the rear seat or between the rear wheels. But such a position is not the best solution for a small EV, because the battery pack would probably completely fill the trunk compartment. [28]  

Another placement solution for the battery pack is used in the new BMW ActiveE, which is presented below.

![Figure 24 BMW ActiveE battery pack position. Source: www.bmw.de](image)

In this situation the battery pack is placed almost everywhere in the car (in the front of the car, in the middle part and in the back). Such a solution is great for cars in which the engine is located in the rear part of the car. Thanks to this position, well weight distribution is achieved. However, the battery pack protection in case of a front or rear crash is not very good because of the compartment being located close to the front and rear of the car. [29]
Battery placement and shape

After comparing different positions for the battery packs, a conclusion can be made about where it is best to place the battery pack. The “T-shape” option looks most promising. This configuration is some kind of a combination of the first and second placement options presented above (in the middle and also underneath the rear seat). The name of it, “T-shape”, derives from its appearance. Such a positioning is used in Chevrolet Volt, Nissan Leaf and Volvo C30 BEV. [29] [30]

Figure 25 Battery placement in Volvo C30 BEV. Source: www.topspeed.net
All this information concludes that the batteries should be placed in a place where they are well protected from deformation. Some high tensile steels should also be used to ensure maximum crash protection from the front, side and rear. Even if the batteries are placed in the middle of the car, front, rear and side-door impact bars have an important role in protecting the batteries. The battery packs should be put in a place where they can be easily removed if it would become necessary to replace them. The best way to place the batteries is in a “T-shape” configuration (in the middle and also underneath the rear seat). Thanks to putting the batteries in this configuration, there is equal weight distribution (if not equal, similar to a Front Wheel Driven Vehicle (FWDV)).
5.3 Fixing of batteries

Software

The prototype of the battery compartment was drawn in SolidWorks (3d-drawings) and AutoCAD (2d-drawings). SolidWorks and AutoCAD are CAD (Computer-aided design) software applications, developed by Dassault Systemes and Autodesk, for professional modeling and designing. We decided to use SolidWorks and AutoCAD because we all had previous experience with the CAD applications.

Measurements

The measurement used in the following drawings is not based upon a specific car model. However, the measurements are realistic and the battery compartment is estimated to store between 200-250 kilograms of Li-ion batteries. The main purpose of the drawings is to show the idea behind the design of the battery compartment.
Figure 27 2D drawing showing the measurements of the battery pack.

Figure 28 2D drawing showing measurements of the belt fixing.
Figure 29 The battery belt fixing illustrated in a 3D environment.

We decided to design a battery pack in the before mentioned “T-shape” configuration. Inclined sides in the front and rear parts allow the battery to slide down when it is involved in a hard crash.

Figure 30 The sketch shows the direction of the battery pack in an end collision.

In this way the entire battery configuration gets displaced in a crash and the structure of the car is able to absorb more energy than before. This shape of the battery also allows easier installation of the battery in to the EVs, because of less sharp edges.
Belts to fix the batteries

One of the belts fixing the rear part of the battery pack.

One idea how to fix the batteries to the vehicle is by using rubber capsulated steal belts over the top of the battery packs. Because of the thickness of the belts they can easily deform in hard accidents, which is necessary for easy releasing of the batteries. This solution also reduces vibrations towards the battery pack because of bigger energy absorption. Please see appendixes for more detailed (high-resolution) drawings.
5.4 Sensor technology

To keep the EV safe in crashes, different sensors are implemented in the electronic systems of the vehicles. Because EVs have high-voltage electrical systems, for safety reasons all major car manufacturers use isolated electric busses to prevent any electric current through the car body in case of loss of isolation between the positive and negative electric busses. For this reason occupants do not have to worry about getting electric shocks. On the contrary, regular cars’ electric wiring solutions do not need this due to the vehicle frame or chassis works as a negative buss. This is possible due to the low 12V DC in these cars, which is not lethal to humans. Furthermore, all electric vehicles from the largest car manufacturers use combinations of automatic disconnect functions like ground fault monitoring, a pilot circuit or an inertia switch. Along with the high-voltage electric cables runs a pilot cable. The function of the cable is to disconnect the battery pack from the electrical circuit in the case that the electric cable breaks. This is possible due to the integration of the pilot circuit in to the electric cable itself. [31]
Ground fault monitoring systems stop operation if a current leak is found within the high-voltage electrical system. This principle works the same way as in usual household electrical wirings.

Inertia switches cut the current between the battery and the rest of the EV and are mostly used in case of abrupt deceleration, like in accidents. The switch can be either manually or automatically reset and can be adjusted to react even on the smallest impact. [31]

Beside these disconnecting solutions due to safety, there are also manual disconnecting points in the vehicle for maintenance or rescue purposes. These can be accessed both in- and outside the vehicle. One must not forget that disconnecting the electrical wiring does not remove the electric current from the battery itself and therefore it must be treated almost like a fuel tank in regular ICEVs. [31]

Omni-directional crash sensor

The omni-directional crash sensor comprises a piezoelectric film, partly made out of polyvinylidene fluoride (PVDF). It works as a stress wave sensor, detecting acoustic waves which propagate through the vehicle structure. By being attached in three places on a vehicle structure, at the same distance from each other, the sensors are able to determine both origin and severity of an impact. It does this by measuring both amplitude and rise time of each sensor’s output. By using the PVDF sensor more accurate information can be sent even faster to the central unit, which handles collision data. [32]

To avoid the sensor from activating any restraint system in wrong moments, a vehicle could comprise several of these PVDF systems, placed in different sections of the vehicle. Thus the sensor is very thin (25µm), it can easily be fitted on to the windshield, which is advised in the patent for the sensor. [32]
The evSAT sensor

Figure 33 Picture of an evSAT sensor. Source: evSAT

Continental, the international automotive supplier, has developed a sensor (satellite) called evSAT for electric and plug-in hybrid vehicles which will immediately shut off the high-voltage battery in the event of a collision while the vehicle is in charge mode. This means that emergency service personnel can recover vehicles without running the risk of suffering an electric shock. [33]

The evSAT acceleration sensor is active in charge mode; it detects an accident and passes this information on to the battery management system which then shuts off the high-voltage battery. One benefit of this sensor is that it prevents fire and rescue service personnel sustaining high-voltage injuries when coming into contact with vehicle metal parts or if they have to cut through the vehicle to recover accident victims. [33]

Essentially this sensor consists of an independent, tri-axial sensor with a CAN interface. During the charge phase, the other vehicle electronics, including the airbag system are not operational. So as to avoid the considerable expense of adapting the airbag system to meet new requirements, Continental has also developed evSAT for the vehicle's charge mode. [33]

The accelerator sensor employs an algorithm to detect a frontal, rear or side collision with another vehicle and immediately transmits a signal via the CAN interface to the battery management system which then switches off the battery within half a second. [33]

The sensor evSAT reacts in the same way if it detects a rollover in driving mode. In this case, the battery is deactivated within four seconds at most. In the event of other types of driving accident,
evSAT remains inactive. In such cases, the airbag system assumes the task of cutting off the battery. If the electric or plug-in hybrid vehicle has been switched off and is not being charged, the evSAT moves to a standby mode to prevent the battery discharging. As such, evSAT represents an additional passive safety system function for electric and plug-in hybrid vehicles. [33]

![Figure 34](image-url)

*Figure 34: The figure shows where the evSAT sensor can be mounted in an EV. Source: Continental*

Possible applications and advantages of the sensor evSAT is that it can be installed in a number of different places in the vehicle; it should, however, be placed sufficiently well inside the vehicle (beneath the front passenger seat, for example) to avoid being damaged in an accident. The advantages of using evSAT are that there is no need for the conventionally powered vehicle variants within a model series to be modified. [33]

The sensor evSAT can be also integrated into the existing systems of electrically powered vehicle variants without redesign work. This benefit also increases flexibility as regards installation space, customer-specific requirements and development time. Savings can be made due to lower system development costs and by avoiding placing greater demands on the airbag system. [33]
Delphi High Voltage Battery Pack Electrical Center

Figure 35 Picture of Delphi unit

Delphi’s High Voltage Battery Pack Electrical Centers help provide safe operation of a battery in vehicles requiring high voltage and also during servicing, collisions or fault conditions. Delphi High Voltage Battery Pack Electrical Centers incorporate the following: [34]

- Main contactors for connection and disconnection of the high voltage battery pack to the inverter, DC/DC converters, and auxiliary high voltage loads
- Battery isolation for safety and maintenance
- Current monitoring of the battery pack for state of charge
- Auxiliary high voltage circuit protection
- Pre-charging function for large capacitors, supporting the inverter and DC/DC converters

Specialized, high voltage contactors provide isolation of the battery from loads when the system is off. When engaged at power-up, the contactors initially perform a pre-charge operation, which safely charges the capacitors in the inverter and DC/DC converter sections. This is necessary to protect the main contactors from switching directly into a high current load (charge capacitors).
The pre-charge function can also be performed using solid state components instead of electromechanical contactors, such as high voltage Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) or Insulated Gate Bipolar Transistors (IGBTs), replacing large, costly high voltage contactors. The current sensor provides monitoring of current flow during battery charging, regenerative braking, electric propulsion motor and high voltage auxiliary load operations. The applications of the Delphi High Voltage Battery Pack Electrical Centers are engineered for any high voltage battery (<750Vdc) application for the transportation market. [34]

6 Summary

Passive safety in EVs is a very wide field and therefore needs a lot of attention. One part of passive safety is the structural behaviour, which has been handled in this project.

First of all, the shape of the battery compartment directly affects the behaviour of the EVs structure. The design of the compartment must absorb as much energy as possible incurred to the EVs structure to protect the passengers in a crash. Secondly, it is important to keep the compartment water proof by adding a layer of some kind of rubber material to the shell. This also keeps the battery more stable and less exposed to vibration. Furthermore the battery has a higher tolerance to move when fastened with belts than with usual bolt fixing points to the EVs body, making the compartment absorb more energy in a crash.

New interesting technologies have been presented to SEAT with this project, which hopefully will be of good use in their future development of the EV. There is the sensor solution by Continental, the patented PVDF sensor which could be further developed by SEAT and new battery technology solutions.

Further doings within the field handled, which did not fit in to this project, could be e.g. to answer the questions how to keep passengers safe in case of the battery getting flooded, which is the best way to keep the batteries at the desired temperatures and what improvements can be done to the restraint system.
7 References

[12] The Trouble with Lithium - Implications of Future PHEV Production for Lithium Demand
[16] Lithium Alliance www.lithiumalliance.org/about-lithium/lithium-sources/85-broad-based-lithium-reserves?showall=1
[18] Battery University http://batteryuniversity.com/