GRADO EN INGENIERÍA EN TECNOLOGÍAS DE
TELECOMUNICACIÓN

DIPLOMA WORK

DESIGN OF A HIGH VOLTAGE BATTERY ACCUMULATOR FOR A FS VEHICLE

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UNIVERSIDAD PONTIFICIA COMILLAS
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA EN TECNOLOGÍAS DE TELECOMUNICACIÓN

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TRABAJO FIN DE GRADO

DESIGN OF A HIGH VOLTAGE BATTERY ACCUMULATOR FOR A FS VEHICLE

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DISEÑO DE UNA BATERÍA DE ALTO VOLTAJE PARA UN COCHE DE FS

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Entidad colaboradora: Univerza v Mariboru

RESUMEN

1. Introducción

La formula-student es la versión Europea de la F-SAE (Society of Automotive Engineers) que se formó en EEUU en 1981 de la mano de Mark Marshek. Tras su éxito inicial, se cerró un acuerdo para organizar eventos también en Reino Unido. Poco a poco se fue extendiendo por países de todo el mundo.

La competición está dividida en dos partes principales. La primera la conforman el business, el cost y el design. En el business y el cost se evalúa la dinámica de grupo (estructura interna y organización) y el proceso de toma de decisiones ejecutivas. En el design se juzga todo lo relacionado con el proceso de toma de decisiones desde un punto de vista más ingenieril, en definitiva las decisiones que llevaron a materializar la idea inicial del proyecto.

El subsistema de baterías trata de abordar uno de los principales problemas de los coches eléctricos; el almacenaje de la energía. Las baterías deben ser lo más ligeras posibles pero también lo suficientemente potentes como para satisfacer la demanda del inversor y todo ello garantizando la seguridad mediante relés, fusibles BMS y un sistema de shutdown circuit.

2. Metodología

En la competición, el accumulador tiene dos partes principales que serán examinadas por los scrutineers: La parte eléctrica y la mecánica. Ambas deben ser diseñanas respetando cada norma del 2020 FS-EV rulebook, y ofrecer pruebas de ello mediante la documentación pertinente.

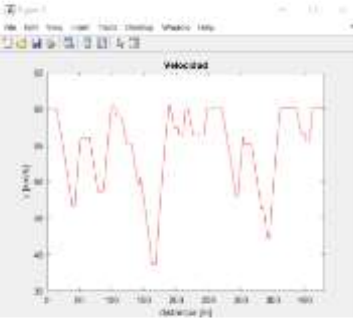
- Diseño Eléctrico: Esta parte incluye el esquema eléctrico, la selección de la química y todos los elementos de seguridad con sus características para que el acumulador sea seguro y se desactive en caso de que hubiese algún incidente con cualquier subsistema si el coche se encuentra encendido. La configuración elegida debe aportar el voltaje necesario para el inversor y la energía necesaria para acabar la endurance sin problemas. El lap time simulator (Matlab) simula el comportamiento del coche a lo largo de una vuelta de la endurance generando las curvas de intensidad, torque, aceleración y velocidad. También calcula la energía total consumida. Estos resultados se obtienen mediante una serie de parámetros eléctricos y mecánicos como las características del motor, la transmisión, las ruedas o la aerodinámica.

- Diseño mecánico: Cuando la configuración está clara y todos los elementos del acumulador han sido escogidos, se diseña un modelo 3D del acumulador con todos los componentes en el que se puede comprobar gran parte de la normativa. El acumulador y los enganches deben de ser lo suficientemente robustos para resistir cualquier percance en carrera. En este caso el acumulador será fabricado en Kevlar y el diseño debe ser comprobado en ANSYS. Para comprobar que las simulaciones son correctas, se realizarán varias con distinta malla para comprobar que efectivamente los resultados coinciden. Todas las simulaciones tendrán que presentarse ante los scrutineers el día de la competición junto a los reports de los tests y dos muestras de Kevlar.

3. Resultados

Las celdas serán de Li-Ion. El criterio para su selección se centra en las características más beneficiosas para un coche de competición y su comportamiento en pista. Éstas características son la C-rate y la densidad energética. Las celdas seleccionadas son peligrosas pero el BMS controlará que nada ocurra desactivando el acumulador si algo no funciona correctamente.

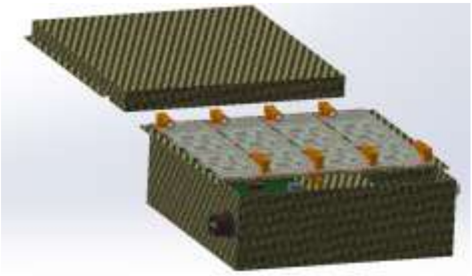
El Lap Time Simulator es la herramienta básica para cualquier equipo de FS. En este trabajo se ha desarrollado uno centrándose en las baterías pero con elementos mecánicos para dictar el comportamiento del coche en la pista. Dichos factores son la fricción, la aerodinámica y la transmisión. El objetivo principal es averiguar la cantidad energía que será necesaria.

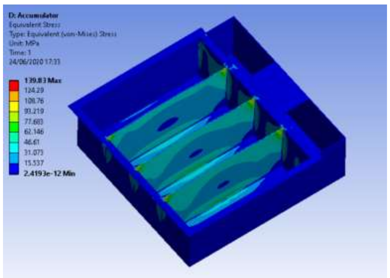


En la figura anterior, se muestra la velocidad del vehículo en una vuelta. El LTS también registra la intensidad integrándola en el tiempo para calcular la capacidad total necesaria (6.8332KWh). El LTS permite al usuario cambiar ciertos parámetros para ver cómo ello afectaría al comportamiento general del coche.

Una vez conocida la capacidad, se procede a diseñar la seguridad y a seleccionar los componentes. El fusible escogido es de 90A y los dos GIGAVAC AIRs de 200A/800V son de tipo normally open. El BMS controla la temperatura y el voltaje de cada celda y mantiene los AIR cerrados si no detecta ningún problema. El IMD comprueba que no haya ninguna desviación a masa.

La competición facilita los grosores que los acumuladores de aluminio o acero deben tener. Éste acumulador está fabricado en Kevlar y ha sido ensayado en ANSYS de forma satisfactoria. Las simulaciones (20g en la dirección vertical y 40g en las otras dos) han sido realizadas con mallas distintas y resultados convergentes.





4. Conclusiones

- Las características electroquímicas de la celda se reproducirá a escala en el acumulador. Para una competición de vehículos priman parámetros como la C rate o la densidad energética sobre valores como la self-discharge rate o el n-factor.

- Un lap time simulator es una herramienta que todo equipo de FS debe desarrollar en algún momento. Permite hacer estimaciones de antemano sobre cambios futuros y ayuda a entender cómo dicho cambios influirán sobre el comportamiento del coche en pista. Aunque el modelo sea muy aproximado a la realidad, los resultados solo serán tan buenos como los inputs por ello es recomendable medir los parámetros a introducir en el laboratorio.

- Un archivo detallado de SOLIDWORKS incluyendo el assembly de todas las piezas permitirá comprobar gran parte de la extensa normativa de la competición y agilizará la selección de la mejor distribución de los componentes. Muchas de las normas (como el aislamiento) tendrán que ser comprobadas una vez esté fabricado el acumulador con los elementos ya situados dentro.

- El Kevlar Tiene las propiedades perfectas para construir el acumulador al ser ligero y resistente. Las simulaciones muestran que el grosor elegido es más resistente que el mínimo dictaminado por la competición si estuviese fabricado en aluminio o acero. Aun así, en una plancha de Kevlar del grosor seleccionado se debe ensayar un three point bending test y un shear test para respaldar las simulaciones.

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ABSTRACT

1. Introduction

The formula student is the European version of the F-SAE (Society of Automotive Engineers) that was born in the US in 1981 moved by Mark Marshek. After the success of this competition the F-SAE accepted the European venture as a partnership to organize the events in the UK. And it has spread throughout Europe since.

The competition has two main different sides. One of them is the business, the cost and the design. It measures the dynamics of the team (the inner structure and organization) and the process behind the decision making (executive and engineering decisions). The other part analyzes the engineering behind the decisions that lead the team to materialize the idea at the beginning of the project.

The battery subsystem faces the main issue of electric cars; the energy storage. As a competition car the batteries should be as light as possible but still powerful enough to respond the motor demands. Apart from this, the dispositive must operate under guaranteed safety systems like the shutdown system, the IMD, fuse and relays and the BMS.

2. Methodology

In the competition, the accumulator has two main parts from a scrutineering point of view: The electric part and the mechanical part. Both of them should be designed respecting every single rule of the 2020 FS-EV rulebook, providing reports and documentation to back up the design

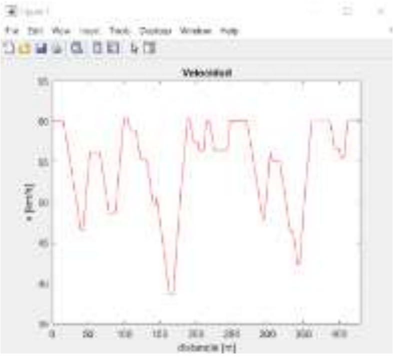
- Electric design: This part includes the electric scheme, the selection of the chemistry of the cells and safety elements and their characteristics in order to provide a safe accumulator that deactivate if any subsystem fails when the car is in a dynamic event. Also the configuration of the chosen cells in order to meet the requirements of the inverter and provide just enough energy to finish the endurance. The lap time simulator (Matlab) represents one lap of the car around a circuit generating information about the intensity, torque, velocity, acceleration and energy consumed. These results are obtained taking into account a number of mechanical parameters such as the transmission, the aerodynamics or the wheels characteristics and the electric parameters that relate the energy consumption with the torque generated

- Mechanical design: Once the configuration is clear and all the elements are chosen, a 3D model of the accumulator and its components will be designed. This will improve the distribution of the components inside and confirm that the design does not have any mistakes before the fabrication. The accumulator and its eight attachments must also be robust enough to resist any incident safely. In this case, the accumulator is made out of Kevlar. The design must be backed up by ANSYS simulations. These simulations test the resistance of the accumulator in the three main directions. In order to make sure that these simulations are valid, they will be performed with different meshes with convergent results. The simulations must be presented to the scrutineers along with the results of a three point bending test and a shearing test with two pieces of Kevlar plates in order to pass the scrutineering.

3. Results

The cells are going to be Li-Ion based. The criteria in the selection of a chemistry for the batteries focuses on the characteristics that benefit the performance of the car in the dynamic tests. Those values are the specific energy and the discharge rate. These cells are more dangerous than the rest but all the security systems in the accumulator will prevent something to happen.

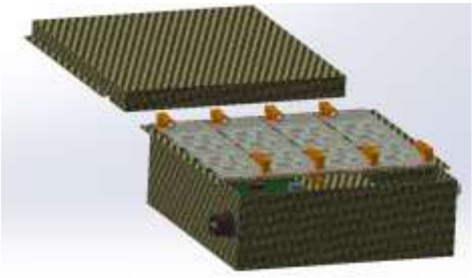
The Lap Time Simulator is the basic tool that any team must develop and build year over year. In this diploma work, one is included having the batteries as the main focus. The friction with the asphalt, the aerodynamics the transmission and the motor are going to dictate the behavior of the car in the endurance test to find out the minimum energy required to complete it.

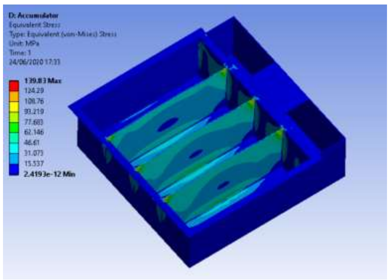


In the figure 1, the velocity of the vehicle during one la pis displayed. The LTS also integrates the intensity along the way to get the minimum capacity (6.8332KWh). The LTS allows the user to change parameters and see how will those changes will impact on the performance.

Once the capacity is known, the electric design should be carried out. The safety is provided by a 90A fuse and two GIGAVAC AIRs normally open type. The BMS monitors the temperature and voltage of the cells and keep the AIRs closed if no errors are detected. The IMD keeps track of the grounding of the car; if a derivation is detected, it will send a signal to the BMS to open the AIRs.

The competition provides the data for steel and aluminum accumulators. This accumulator is made out of Kevlar and the design (lower right figure) was tested in ANSYS with positive results, as shown in the lower left figure. The simulations (20g in the vertical direction and 40g in the other two) were made with different kind of mesh generating similar results both for the accumulator and the attachments, meaning that they are correct.





4. Conclusions

- The electrochemical characteristics of the cell are going to be reproduced in the accumulator. For a competition car a high discharge rate or a high energy density are the most important factors while the self-discharge rate or the number of cycles are a minor issue.

- A lap time simulator is a tool that every team must have. It allows to make estimations beforehand about future changes in the car and information on how will they impact the performance in the dynamic events. Taking care of good data for the inputs (measuring and testing in the laboratory) will have a direct impact in the quality of the outputs.

- A detailed SOLDWORKS assembly can provide with useful information for the distribution of the components in the accumulator. Plenty of the rules of the competition can be checked one by one beforehand with the 3D design. Some of them such as the isolation should be taken care of after the fabrication.

- Kevlar has good properties for building an accumulator (light and resistant). It is also electrically isolating with the proper resin. The simulation shows that with the chosen width is far more resistant than an accumulator built of Steel or aluminum with the same width. However, three point bending test and shear test should be performed and reported to show the jury of the competition along with two pieces of kevlar similar to the ones used in the accumulator.

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FIGURES

TABLES

1. INTRODUCTION

1.1 FORMULA STUDENT

The formula student is the European version of the F-SAE (Society of Automotive Engineers) that was born in the US in 1981 moved by Mark Marshek. The first competition was held at the University of Texas. In the first place, the organization gave the teams few rules, and the motor was chosen by the organizers. This did not let the students enough room to practice as much engineering as they do today in these kinds of projects.

The competition kept evolving and it started being appealing also to European engineers to the point that in 1998 a demonstration competition was held in the UK. After the success of this competition, the F-SAE accepted the European venture as a partnership to organize the events in the UK spreading throughout Europe.

The competition has two main different sides. One of them is the business, the cost, and the design. It measures the dynamics of the team (the inner structure and organization) and the process behind the decision making (executive and engineering decisions). The other part analyzes the engineering behind the decisions that lead the team to materialize the idea that started the project [1].

1.1.1 STATIC EVENTS

The competition has four main different parts [2] that have a different weight in the total scoring of the competition as it is shown in the table 1.

Table 1: Static events points

TEST	POINTS
Engineering design	150
Cost and sustainability Analysis	100
Business presentation	75
Technical inspection	no points

- **Engineering design:** The team members have to discuss with the jury all the engineering behind the decision making that lead to the finished car. The students will also be asked theoretical questions about every subsystem. The documentation and all of the reports including the simulations can also be asked.

- **Cost and sustainability analysis:** In this event, each team has to defend the way the entire budget has been spent during all the different phases of the organization. It is important to explain the arguments followed in the decision making financially speaking.

- **Business presentation:** The objective of this event is to convince a jury that the project could have a proper acceptation in the market, explaining the business plan and how the car as a product is going to be targeted to a certain consumer.

- **Technical inspection:** The security is vital for the competition. Due to this every single subsystem inspection is going to be carefully carried out. Every single detail must respect the rules; otherwise the car will not proceed to participate in the dynamic events.

1.1.2 DYNAMIC EVENTS

The table 2 shows the different dynamic events; each one of them tests different aspects of the car.

Table 2: Dynamic events points

TEST	POINTS
Skid pad	50
1 Km autocross/Sprint	150
75 m acceleration	75
22 km endurance	300

- **Skid pad:** The goal of this event is to test the behavior of the car in curves. The track is shaped in an 8 and the pilot must complete two laps in each direction. Each pilot has 2 tries.

$$\boldsymbol{P.skidpad} = 71.15 \times \left(\frac{\left(\left(\frac{Tmax}{Tteam}\right)^2 - 1\right)}{0.5625} \right) \tag{1}$$

Tmax: 1.25 times the time of the fastest team in the skidpad.

Tteam: team's best run in this event including the penalties.

- **1 Km autocross/sprint:** The circuit in this event is about 1km long. In this circuit the dynamic behavior and the maneuverability of the car is put to test.

$$\boldsymbol{P.Autocross} = 95.5 \times \left(\frac{\left(\frac{Tmax}{Tteam}\right) - 1)}{0.25} \right) \tag{2}$$

Tmax: 1.25 times the time of the fastest team in the autocross.

Tteam: team's best run in this event including the penalties.

- **75m acceleration:** This event consists in completing 75 meters as fast as possible. The unofficial speed record for an electric FS car is held by AMZ (0-100Km/h in 1,513 seconds).

$$\boldsymbol{P.Acceleration} = 71.15 \times \left(\frac{\left(\frac{Tmax}{Tteam}\right) - 1)}{0.5} \right) \tag{3}$$

Tmax: 1.5 times the time of the fastest team in the acceleration

Tteam: team's best run in this event including the penalties.

- **<u>22Km endurance:</u>** In this event, the electric car has to proof how well they do in long distances showing their efficiency. The competitors must complete 22km.

$$\boldsymbol{P.Endurance} = 300 \times \left(\frac{\left(\frac{Tmax}{Tteam}\right) - 1)}{0.333} \right) \quad (4)$$

Tmax: 1.333 times the corrected elapsed time of the fastest team.

Tteam: team's best run in this event including the penalties.

1.1.3 TEAM CLASSES

- **<u>Class A:</u>** Formed by teams that have a complete car in which every subsystem is thought to be able to successfully pass the scrutineering. Once the car enters passes the scrutineering and participates in the dynamic events, the team is considered an A class team. That car can only be used un the competitions held in that season.

- **<u>Class B:</u>** Teams that have at least a physical chassis. These kind of teams don't aspire to participate in the dynamic events but their main focus is to learn as much as possible from the feedback of the scrutineers and from the other teams in order to be an A class team next year.

- **<u>Class C:</u>** In this class the teams just bring the design to the competition. Not every team decide to go through this class. The teams show the design to the jury and the scrutineers in order to get advice very useful when finally building the car and spending the money. It is very prudent to go through this class before actually building a car and teams that decide to do it like the one from the Lisbon University, usually have better results in the first car.

1.1.4 PROJECT GOALS

- As this project will be used for the design of future cars, it should respect a certain budget. This means that certain parts of it will be reused from previous accumulators.

- The design must also focus on weight. The battery accumulator of the formula student of 2018/2019 weighted around 10% of the car. A big reduction in the weight of the accumulator will have a big impact on the car.

- In the competition, the dynamic tests are as important as the static ones. In the last ones, all the simulations have an important role in the punctuation. The more simulations backing up our design, the more chance the design will have of getting higher punctuation.

1.2 BATTERIES FOR ELECTRIC MOBILITY

The first electric vehicle was built by Sirbrandus Stratingh with the help of Christopher Becker. This antecessor of the electric car was designed using the principals developed by Michal Faraday and created a big expectation at that time, even the King Wilem I visited Stratingh's laboratory and often read reports about his investigations. The battery used in this prototype was a copper-zinc one filled with sulphuric acid that generated two volts.

The electrochemical principals of the Cu-Zn battery are based in a REDOX reaction. On the one side, the zinc acts as a reductor agent releasing electrons in the reaction with the sulphuric solution. On the other side, the copper behaves as the oxidator agent tending to capture the electrons from the connection of the terminals in the reduction that happens in the cathode.

$$Zn + Cu^{2+} \rightarrow \ Zn^{2+} + Cu \tag{5}$$

The breakthroughs in battery technology allowed the design of better electric vehicles. In 1860 Gaston Planté invented a lead sulfur accumulator formed with two lead plates rolled and separated with rubber from each other.

In his accumulator, each cell provided around two volts and he tried to solve the problem of the inner resistance of the battery. His battery accumulator had a much lower inner resistance and this way, higher currents were able to be reached. Also the battery was able to stay unused much longer because of that smaller inner resistance.

Twenty years later, Camille Faure coated the lead plates with a paste of lead oxides. This way the paste reacts with the sulphuric acid diluted in water creating lead sulfates adhered to the lead plates. This made the plates more electrochemically active so the accumulator was able to stay healthy during more cycles.

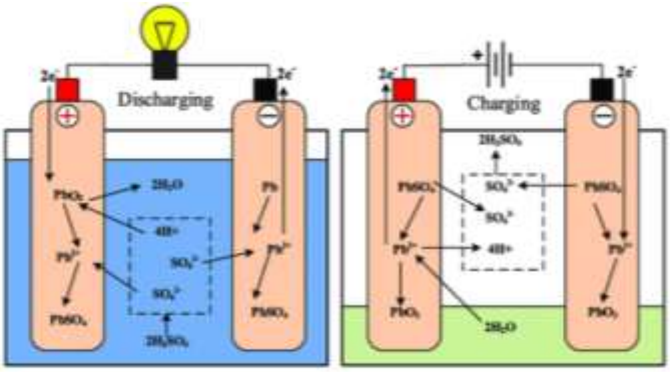


Figure 1: Lead sulfur battery

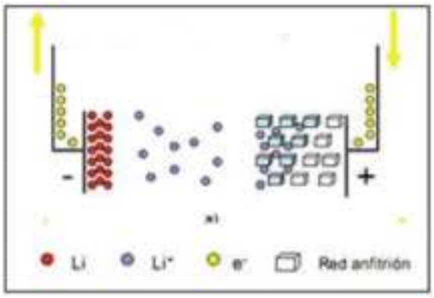
$$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e \qquad (6)$$

$$PbO_2 + HSO_4^- + 3H^+ + 2e \rightarrow PbSO_4 + 2H_2O \qquad (7)$$

From then on new inventions and designs implemented in electric mobility made the industry grow and turn the electric car into luxury specially in the US. It was easy to maneuver, very smooth and silent. Some cars in the early 20th century could break the 100Km/h barrier.

Figure 2: American car in the 20th century

Nowadays, electric mobility represent a strong tendency in the evolution of the automobile with companies like Tesla or new divisions in the traditional companies. These cars have autonomy for up to 600Km and with quick charging in about 20 minutes batteries can be charged up to an 80%. These newer batteries accumulator can be formed by different types of cells. One of them are the lithium ion cells. In the cathode there is lithium working as the oxidizing agent while working as a reducing agent there is FePO4. These kind of cells usually present a big maximum current.



$$Li \rightarrow \ Li^{+} + 1e \qquad (8)$$

$$FePO_4 + 1e \rightarrow FePO_4^{-} \qquad (9)$$

1.3 PRINCIPAL AND MAIN CHARACTERISTICS

A battery is an electrochemical device formed by a reducing agent, an oxidizing agent and an electrolyte. The reducing agent, also known as anode, tends to release electrons in an oxidation reaction. On the other hand, the oxidizing agent, also known as cathode, captures electrons in a reduction reaction. Both reactions take place in an electrolyte which is a fluid with a high density of ions making possible the REDOX reaction. Those are also known as electrodes which are typically semiconductor materials that connect the terminals of the battery with the electrolyte. The different characteristics of the battery depend entirely on the electrochemical reactivity of the electrodes with the electrolyte that holds them. The figure 3 includes a simple representation of a battery scheme [4].

Figure 3: Copper-silver battery scheme

When both terminals are connected, the electrons go from the anode to the cathode releasing the chemical energy stored in the cell. The electrons go in the opposite direction in which the current is represented. When the battery is being discharged the anode is negative terminal and the cathode is the positive one but the opposite happens when the charging process is taking place [4]. The main characteristics are:

- **Voltage:** Usually referred to the difference of potential between the terminals of the battery in open circuit. There is also the theoretical voltage that depends on the chemistry of the battery. It is the first characteristics of a battery.

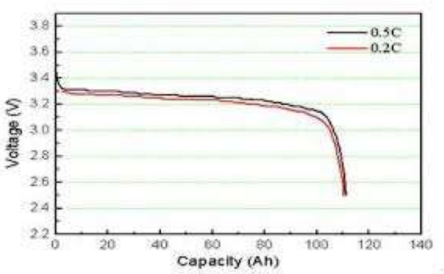


Figure 4: Voltage-Capacity curve

- **Capacity:** Measured in Ah indicates how much energy the battery is able to store. For instance, a battery with 1Ah is able to hand a current of 1A during 1 hour. It is the second of the three main characteristics of a battery.

Maximum discharge/charge current: Every battery has a certain maximum current that is able to resist without causing permanent damage. This current is usually different when charging or discharging. It is measured in Amps.

Energy: while the capacity mentioned before is defining some constant current that the battery can offer for a certain amount of time, the energy defines the chemical energy that the battery is able to transform into electricity. It is measured in Wh.

- **C rate:** Could be refer to the charging or the discharging curve. It determines the current in which the batteries can be charged or discharged without being damaged.

$$Amax = C \times Ah \tag{10}$$

- **Resistance:** The electric resistance of the battery against the current flow. Nowadays it is usually around a few milliohms.

- **Shelf-discharge rate:** The amount of energy that the batteries lose when they are not being used.

- **Specific parameters:** These parameters take the weight of the battery into account. As this project is about a competition, they are going to be very important especially in the electric division in which efficiency is one of the most important characteristics of the car. The more power the car has per kilogram the better scoring. Firstly, the specific energy is the energy that the cells are able to store divided by the weight. Secondly, the specific power is the energy that the accumulator is able to provide divided by the weight.

- **Efficiency:** The energy that the battery is able to hand divided by the energy needed to charge the battery expressed in a percentage.

- **n factor:** Number of cycles in which the batteries are able to perform in a healthy way. Nowadays they can stay healthy for thousands of them.

For an F-SAE accumulator, the design should be done taking into account every single point of the formula student rules. If any of the parts of the car doesn't make the scrutineering, the car will not compete in the dynamic tests. In the competition, the accumulator has two main parts from a scrutineering point of view: the electric part and the mechanical part. Both of them should be designed respecting every single rule of the 2020 FS-EV rulebook, providing reports and documentation to back up the design:

- Electric design: this part includes the electric scheme, the selection of the chemistry of the cells and safety elements, and their characteristics in order to provide a safe accumulator that deactivates if any subsystem fails when the car is in a dynamic event. Also, the configuration of the chosen cells in order to meet the requirements of the inverter and provide just enough energy to finish the endurance.

- ·Mechanical design: Once the configuration is clear and all the elements are chosen, a 3D model of the accumulator and its components will be designed. This will improve the distribution of the components inside and confirm that the design does not have any mistakes before the fabrication. The accumulator and its eight attachments must also be robust enough to resist any incident safely. In this case, the accumulator is made out of Kevlar. The design must be backed up by ANSYS simulations. These simulations test the resistance of the accumulator in the three main directions. In order to make sure that these simulations are valid, they will be performed with different meshes with convergent results. The simulations must be presented to the scrutineers along with the results of a three-point bending test and a shearing test with two pieces of Kevlar plates in order to pass the scrutineering.

2. CELL SELECTION

The particular electrochemical properties of the batteries electrodes and electrolytes define each and every aspect mentioned at the beginning of the diploma work, being especially important the specific values as they also take into account the weight efficiency in them [5].

Weight is a crucial factor in any vehicle but even more important in a competition one. The specific energy is the amount of energy that a cell can store when charged per kilogram of weight and it is going to be one of the most important characteristics in the selection.The business part of the project contemplates that 1000 cars will be sold in order to make the company profitable. Durability is an important aspect in this sense as it would make the car more appealing to a possible buyer.

The motors used for this kind of purpose offer great torque in order to accelerate as fast as possible therefore the batteries should be able to hand out a great current (big discharge rate). The inner resistance of the cells has an important role in the current that can be charged or discharged from them but also in their efficiency, an aspect that can give a team up to 100 points making it decisive in the competition. The current meets the inner resistance of the cell, power is released in the form of heat. The maximum temperature allowed by the competition is 60 degrees Celsius; otherwise the BMS should open the AIRs. Having a big inner resistance in the cells not only will make the car less efficient but also more susceptible of reaching that critical temperature and stopping during the endurance test.

The chosen cells should be chosen respecting the budget of the project. The economic dimension is the celling for any engineering project and the cell selection should be coherent with this idea.

2.1 LEAD ACID

The electrolyte used is usually a diluted solution of sulfuric acid. There are newer versions that rely on different gels made. The chemical reaction of these batteries is the following:

$$PbO_2 + HSO_4^- + 3H^+ + e \rightarrow 2H_2O + PbSO_4 \quad (11)$$

$$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e \quad (12)$$

They are widely used in the automotive industry as the power supply for low voltage systems. They can perform around 1000 cycles with a charge-discharge efficiency of an 80% until critical damage occurs. As the main component is plumber, a heavy metal, the specific energy is around 30 to 40Wh/Kg which puts in the worse part of the spectrum.

These batteries tend to shelf discharge a 5-10% per month when unused, an aspect that usually is not a problem as in private cars they get constantly recharged when driving. The temperature range considered safe for this chemistry is up to 45 degrees Celsius.

The nominal voltage per cell is 2.05V and the discharge rate is around 1C being very noticeable the elongation of the healthy life when this parameter is respected.

The biggest advantage of lead acid batteries is the great offer and supply. As the technology is simple and reliable it has been used for many decades making its industry grow optimizing manufacturing processes and lowering the prices.

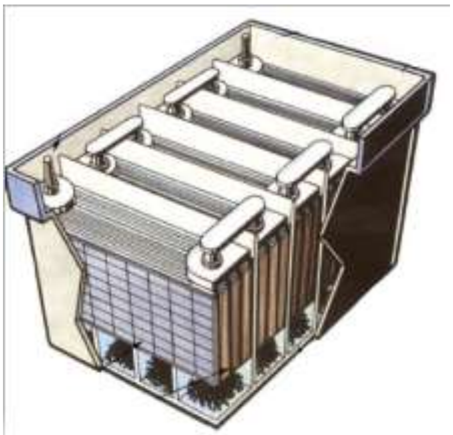


Figure 5: Lead acid battery

2.2 NICKEL METAL HYDRIDE

The chemical reaction of these batteries is the following:

$$H_2O + M + e \rightarrow OH^- + MH \qquad (13)$$

$$Ni(OH)_2 + OH^- \rightarrow NiO(OH) + H_2O + e \qquad (14)$$

The electrolyte is usually potassium hydroxide but other alkaline electrolytes can be used as well. Nickel Metal Hydride batteries were the first ones used for electrical cars that were offered in the market (General Motors). They have a much higher specific energy than the lead acid; around 80Wh/Kg but in some cases, they can reach up to 120Wh/Kg. Batteries relying in this technology can stand over 350 deep discharges without suffering severe damages but under controlled circumstances, their n factor is around 4000 cycles.

About the efficiency in relation to the charge-discharge cycle, the age of the batteries plays an important role. The newer ones can present up to a 95% and decrease with the use to a 70% over time.

The nominal voltage of a single metal hydride nickel cell is 1.2V and the current discharge rate is 2C and up to 3C in some cases for the newer generations of NiMH cells.

Figure 6: Nickel metal hydride battery

2.3 NICKEL CADMIUM

These cells also use an alkaline electrolyte and like the previous ones and the most used one is also potassium hydroxide. The chemical reaction of these batteries is the following:

$$Cd + 2OH^{-} \rightarrow Cd(OH)_2 + 2e \tag{15}$$

$$2Ni(OH)_3 + 2e \rightarrow 2Ni(OH)_2 + 2OH^{-} \tag{16}$$

Batteries that rely on this technology have a wide range of different uses. From portable tools to toys or the power source for vehicles, mostly hybrid cars but their use has been decreasing over the last years because of environmental reasons.

The versatility of Ni-Cd cells comes from the different shapes and sizes in which they can be presented. Shapes like-gum stick are used for toys or tools while cylinder shapes are more commonly used for automobiles or RC control devices that need to drag bigger currents.

The capacity for these cells is usually around 40-70 KW/h with an efficiency of up to an 80%. The memory effect can also affect these parameters negatively. A correct use of these cells can prolong their life considerably. After a full charge, they lose around a 5% of the energy stored monthly, in some cases up to a 10%.

Figure 7: Nickel cadmium battery

2.4 LITHIUM POLYMER

The chemical reaction of these batteries is the following:

$$Li_xC_n \rightarrow C_n + xLi^{+} + xe \tag{17}$$

$$Li_xMO_2 + xe + xLi^{+} \rightarrow LiMO_2 \tag{18}$$

This technology was developed in the 70s and 80s and mastered by SONY. Nowadays the company is the main provider of Li-Po cells worldwide. These cells are used for many different purposes, from RC devices to cars or even light aircrafts. In the electric vehicle industry, the most common design of battery accumulator is a multiple cell configuration but more recently bigger cells in pouch shape are being developed for this process [7].

They are widely used for mobile purposes because their energy density is around 200KW/h which is relatively high value and their efficiency levels, up to a 99% in some cases which makes them perfect for these tasks.

They can perform around 1000-1500 cycles in an acceptable SOH however after 400/600 cycles their capacity can be noticeably reduced down to an 80%. These damage can be aggravated by deep discharging or overcharging the batteries.

Overcharging Li-Po batteries can be especially dangerous and can make them burst into flames. The temperature can deeply affect the too. They should work over 45 degrees Celsius also for that reason. Below 10 degrees Celsius they cannot longer perform with the same efficiency and below 0 degrees the performance is too poor.

The nominal voltage for a single cell is 3.6V and the Discharge rate is 1C or 2C in some cases.

Figure 8: Lipo battery

2.5 LITHIUM ION

The chemical reaction of these batteries is the following:

$$CoO_2 + Li^+ + e \rightarrow LiCoO_2 \quad (19)$$

$$LiC_6 \rightarrow C_6 + Li^+ e \quad (20)$$

Among all the different technologies, this is the one that offers a higher energy density with 250 Wh/Kg. It is the most recent of all of them to enter in the marked as their production started growing during the 90s. The high energy density makes it perfect to heavy duty or automobilistic purposes.

Li-Ion cells are also the most inestable ones and if they are not handeled and used properly they can burst into flames or even explode. It is very important to use and store them paying attention to the temperature as this is the main factor that an lead to problems. Using them over 45 degrees celsius can deteriorate their properties but in any case they must be used over 60 defrees celsius.

The average Li-Ion ell can perform around 800 cycles during its healthy life but recent developments in the technology lead to the design and production of more professional cells that can perform up to 2500 cycles.

Their efficiency is slightly lower than the than Li-Po cells, around a 90 percent, a characteristic that can be sustained over time if the temperature and use recommendations are respected over time.

The main drawback of Li-Ion cells is the price. They are by far the most expensive ones in the list as their technology is newer with production methods that are more expensive and also because both Li-Po and Li-Ion present important improvements in different aspects.

A Li-Ion cell has a nominal voltage of 3.2 V and a great discharge current. Some cells can fully discharge in just a few minutes. Some cells can reach 6C discharge rate [6].

Figure 9: Li-Ion battery

2.6 TABLE AND CONCLUSION

Table 3: Comparison table for batteries chemistry

CHEMISTRTY	SPECIFIC ENERGY	EFFICIENCY	DISCHARGE RATE	CYCLES	DANGER	COST
LEAD-ACID	40	80%	1C	1000	🟩	🟩
Ni-M-H	120	95%	1C	4000	🟩	🟧
Ni-CD	70	80%	4C	1500	🟩	🟩
Li-PO	200	99%	2C	1500	🟥	🟥
Li-Ion	250	90%	6C	2500	🟥	🟥

The criteria in the selection of the chemistry for the batteries focus on the characteristics included in table 3 that are going to benefit the performance of the car in the dynamic tests. Those values are the specific energy and the discharge rate. Both of them are led by Li-Ion chemistry.

These batteries are more dangerous than the rest but all the security systems in the accumulator will prevent them to happen. Even though that they are not as efficient as the Li-Po cells the difference in the specific energy is big enough to surpass this characteristic.

The n-factor is not going to be a relevant aspect in these criteria as during testing and competition any value of the table is far from being reached.

In the project, there are things that are going to be reused from other years and this lets room to spend a greater amount of money in better cells. Therefore, the chemistry of the cells used is going to be Li-Ion. The 18650 SAMSUNG cell will be the chosen one.

3. LAP TIME SIMULATOR

3.1 DESCIPTION AND HYPOTHESIS

A Lap Time Simulator is a basic tool for any FSAE team that models the car behavior during one lap. In this model, there are many things that should be taken into account such as aerodynamics, the transmission, the Tractive System parameters, etc. The more things included in the model, the better it is going to be however the output of the simulation is going to be just as good as the input; a very descriptive model that manages accurately to describe the behavior of the car will not offer good output if the input is not accurate. For instance, the characteristics of the wheels or aerodynamics that are crucial elements in the car must be as accurate as possible because provided that the model is good, the conclusions will be mistaken if that is not the case. Testing the materials in the university lab is a good option to back up the datasheet of the elements. The autocross, the acceleration, and the skidpad don't have any speed limit or an efficiency component in the classification. The endurance test has a speed limit (maximum and average) and also analyzes the energy consumption during the 22Km. Therefore, even though all the dynamic tests should be simulated, for the battery department the simulation of the endurance test has a greater interest because this test is made to evaluate the efficiency and behavior of them.

The elements included in the model are:

- **Aerodynamics:** The aerodynamical design of the car defines the interaction of the vehicle with the air. There are two main forces involved in this behavior. The first one is the drag, a force that is opposite to the direction of the car and that grows with the square of the velocity. The second one is the lift, a force that pulls down the car due to the difference of pressure formed by the different speeds of the air surrounding the moving car. Having a big negative lift will allow the car to stick to the ground and turn faster but will increase the drag limiting the top speed.

- **Wheels:** In this program, there are five parameters that can be adjusted. The rolling coefficient, which is the opposition of the wheels when moving, The friction coefficient, which relates the normal force to the ground with the maximum force that the wheels can stick to the ground without friction, the radius, the weight, and the moment of inertia.

-

- **Power train:** the interest elements of the power train are the transmission rate that relates the velocity of the wheels with the velocity of the motor and the efficiency of this mechanical mechanism.

-

- **Motor:** The motor used is an axis flux motor. The parameters are the maximum torque and the relation of the torque and the intensity required to obtain it.

The behavior of the car in one lap is:

The car starts the circuit at a certain speed, it should be the same as the one in which it ends the lap. Facing a straight segment of the circuit the car accelerates at the maximum torque allowed until it reaches the top speed or until the breaking moment starts. When the maximum speed is reached, the torque remains constant and enough to keep that speed.

The deceleration of the car is fixed and higher than the one generating from the wind weight plus the rolling friction with the ground but smaller than the one the breaks can withstand saving energy (the motor is not consuming while breaking) without compromising the speed to an unacceptable point.

The program reads the shape of the next curve and comes up with the maximum speed that the car can stand in it without surpassing the friction limit. The car starts breaking the precise moment that the deceleration allows it to be at the right speed at the beginning of the next curve.

During the curve, the velocity of the car stays the same with the proper torque that can sustain it. The bigger the radius of the curve is, the greater that velocity will be. The model must respect the maximum speed.

The circuit for endurance:

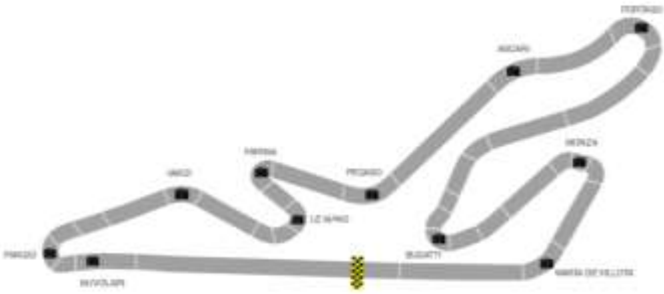


Figure 10: Circuit layout

The circuit should between 200 and 500m long. In each competition the circuit varies. For the simulation a scaled down version of the Jarama circuit was used which layout is the one displayed in figure 10. The car must complete enough laps to reach 22Km. In this case the circuit is 406m long so each car must complete 54 laps (27 laps per pilot).

3.2 GRAPHS AND RESULTS

The right graph describes the velocity curve. It can be seen how the car accelerates and decelerates in the straight segments while in the curves the speed remains constant. The effect of the drag is not very noticeable because the range of velocities is not very wide. The left one describes the acceleration. It is greater at the beginning of the straight segment and as the velocity increases the drag force is greater so the acceleration drops. The deceleration is constant.

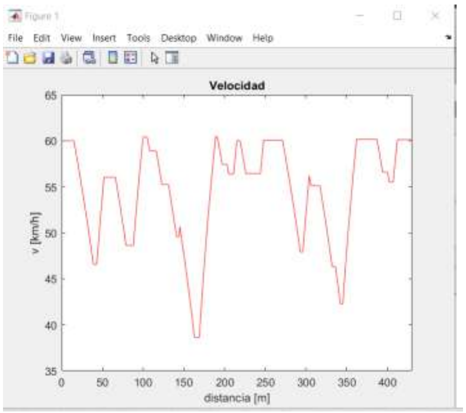


Figure 11: Velocity during one lap

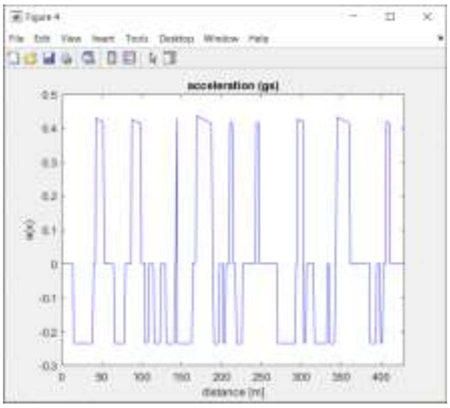
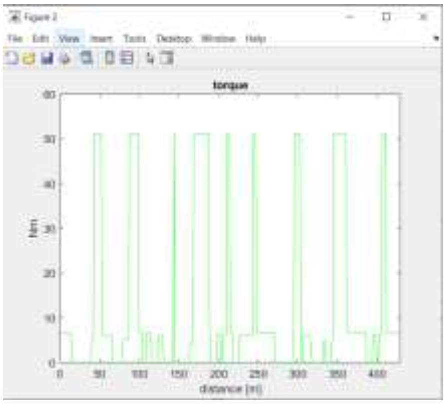


Figure 12: Acceleration in one lap

On the right graph, there is the torque curve generated by the car through the circuit. The torque is maximum when accelerating and the proper one to sustain the adequate top speed when needed and the right one in the curves. On the left one, there is the Intensity used by the motor during the lap. In these kinds of motors, the torque generated and the energy consumed can be approximated by a constant [Kt].

The main goal of the simulator is to find out the capacity that the batteries should have. It is calculated by integrating the intensity along the time during the 22Km. With these conditions, the capacity should be greater than **6.84KWh.**



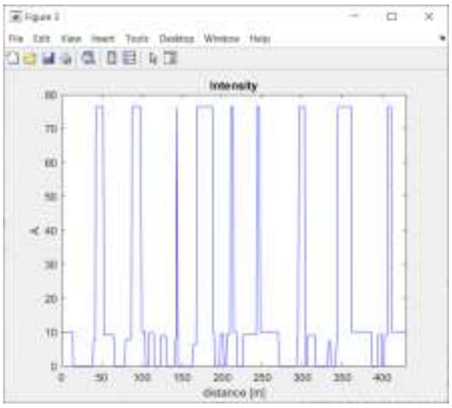


Figure 13: Torque during one lap

Figure 14: Intensity during one lap

According to the LTS, the accumulator should provide the car with over 6.84 Kwh. The Samsung 18650 cells the configuration 100s 6p will offer 360 nominal Volts and 6.9Kwh.

4. ACCUMULATOR COMPONENTS

Some elements of the TS (Tractive System) and the accumulator must be included. These elements are included in the electric layout schemed in the next figure.

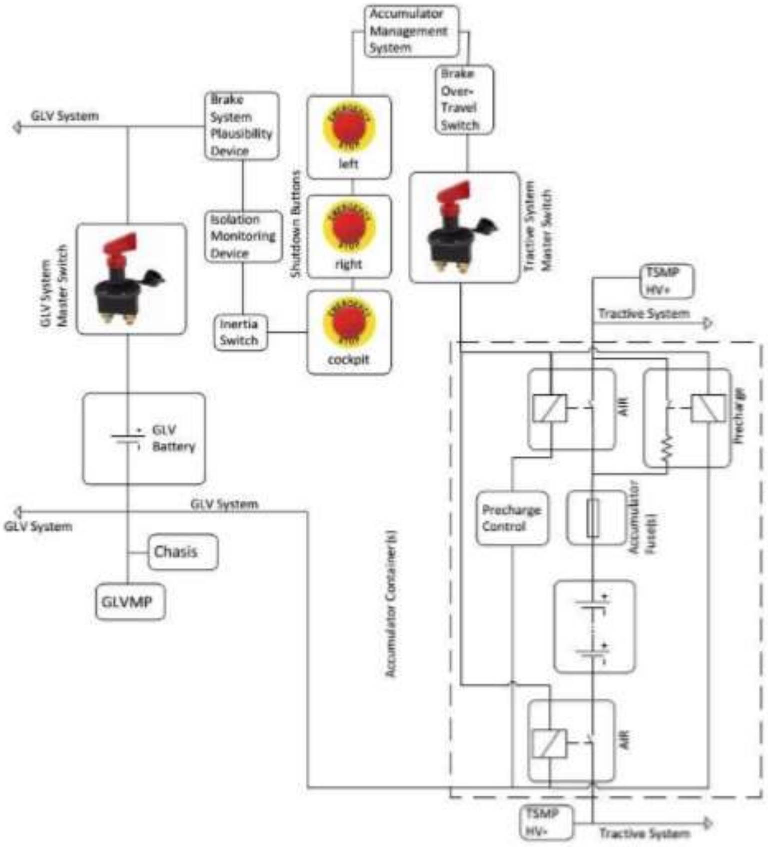


Figure 15: Layout of the TS and the shortcut circuit

4.1 BMS

The battery management system monitors the cell´s voltage, temperature, SOC, current and voltage, and IMD. It also controls the AIR, the pre-charge, and balances the cells. There are many different kinds of BMS with different configurations [8] but the team is going to use the one from previous projects in order to respect the budget.

The chosen BMS is the LITHIUMATE PRO model, powered by Elithion. It is specially designed for lithium batteries.

The rules to follow are that the temperature sensor must be 10mm away from the anode of the cell, the voltage of every cell must be monitored, and also at least the temperature of at least 20% of the cells. Those cells in which the temperature is measured must be evenly distributed in the accumulator as usually, the cells in the middle of the configuration tend to heat more [9]. The maximum temperature allowed is 60 degrees Celsius even if the fabricant of the cells guarantees that they can safely perform at higher temperatures. The configuration selected measures the temperature of every single cell.

There are different ways of setting up the BMS central (figure 16 below). As all the cells must be monitored in some way, the easiest configuration is the fully distributed one [10]. This configuration uses one cell board per building block.

BMS: https://www.elithion.com/battery_management_systems.php

Figure 16: BMS master

4.2 BMS

The battery management system monitors the cell´s voltage, temperature, SOC, current and voltage and IMD. It also controls the AIR, the pre-charge and balances the cells. There are many different kind of BMS with different configurations but as in the team is going to use the one from previous projects in order to respect the budget.

The BMS in powered by ELITHION and the model is LITHIUMATE PRO. It is especially designed for lithium batteries.

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There are different ways of setting up the BMS central. As all the cells must be monitored in some way, the easiest configuration is the fully distributed one. This configuration uses one cell board per building block.

BMS: https://www.elithion.com/battery_management_systems.php

4.3 LITHIUMATE GUI

USB disconnected: looking for a BMS in all ports

Now trying port COM

NEED HELP? CONTACT ELITHION DIRECTLY.
Elithion knows its products better than anyone else.
Only Elithion offers direct support through remote access.

Call 1-720-488-7000 x2
or use the Help menu to go to Elithion's tech support page

Note:
Presets are operations, not settings.
Hover over this for more

(*) Cycle BMS power off and on
or reset BMS (Ctrl+Shift+R)
for changes to take effect

Figure 17: BMS gui

The program must be downloaded to the BMS central. All the parameters of the battery accumulator must be introduced about the cell description the parameters to introduce are chemistry, voltage (nominal, maximum and minimum), capacity, inner resistance and also the accuracy of the cells balance. About the accumulator parameters it is important to set the maximum intensity allowed, the number of cells per pack and the number of packs.


USB disconnected: looking for a BMS in all ports

Figure 18: Elithion main menu

In this screen it can be seen the number of packs that are connected, the value of the voltage, of the temperature with the different limits. If one of this limits is not respected the BMS will activate the failure procedure. The BMS also must detect that every single cell board is working properly. There is a light code that every cell board follows specified in depth in Elithion's GUI.

All the different coils can be activated or deactivated in order to work with the batteries out of the car for testing purposes.


USB disconnected: looking for a BMS in all ports

Figure 19: Elithion time information

Elithion also offers the chance to keep track of the some values (cell voltage, temperature, cell resistance, pack voltage, pack current, SOC and loads) of the accumulator. These graphs can be seen not only when the BMS central is connected to the computer while testing but a new graph will be generated and saved as the central receives load or source voltage. Therefore, the user can download valuable info after a dynamic test in the car too.

4.4 COMPONENTS, CONNECTIONS AND LAYOUT

Each connection [10] with the BMS central is explained in tables from 4 to 7.

4.4.1 CONTROL

Table 4: BMS main connector description

#	name	utility	notes
1	GND	Signal ground	Use a separate wire from power ground, to avoid errors in analog readings
2	V+	Full voltage utility supply	Voltage present when BMS powered through either V+L or V+S line. May be used to power equipment such as loggers, remote controllers
3	V+L	P. from load	The BMS is powered by voltage at either terminal (uses isolating diodes). V+L must be powered whenever the load is on, and only then. V+S must be powered whenever the source is on, and only then. For example, in a BEV or PHEV application, V+L is powered by Ignition, V+S is powered whenever the vehicle is plugged into AC power. In a HEV application, V+S is powered by the ignition. In a UPS application, V+S is powered whenever there's AC power, and V+L is powered all the time. If only one power source is possible, use V+S.
4	V+S	P. from source	
5	C.R.	Contactor request	For vehicle applications, connected to the ignition line (the TSMS). off when pilot turns the car off or the shutdown circuit opens.
6	SRC	Source current	Analog input to measure current from the source / charger
7	5V	5V supply	
8	CANL	Can bus low	
9	PGND	P. common	Return for high current loads (contactor coils, fan, HLIM, LLIM and Fault outputs). Use a separate wire from the signal ground
10	LLIM	Low lim.	Open collector, polarity selectable in software. Activated when the most charged cell's voltage is too high (HLIM) or when the most discharged cell's

			voltage is too low (LLIM).
11	HLIM	High lim.	Open collector, polarity selectable in software. Activated in case of alarm.
12	FLT	Fault	Analog voltage: 5 V = 100 % full, down to 0 V = empty
13	SOC	SOC output	Analog voltage: 5 V = no limit, down to 0 V = no current allowed.
14	DCL	Dis. current limit	
15	CCL	Ch. Current limit	
16	CANH	Can bus high	

4.4.2 COILS

Table 5: BMS coils connector description

#	name	utility	notes
1	K+	Coils common	Same as V+ on the control connector: voltage present when the BMS is powered through either V+L or V+S line.
2	K1	precharge	
3	K2	Air+	
4	K3	Air-	

4.4.3 FAN

Table 6: Fan connector description

#	name	utility	notes
1	+15V	Pos. supply	Same as V+ on the control connector: voltage present when the BMS is powered through either V+L or V+S line.
2	-15V	Neg. supply	
3	SIG	signal	
4	GND	Signal common	

4.4.4 CELL BOARDS

Table 7: Cell board connection description

#	Name	utility	notes
1	TX	Tr. Out	To positive end
2	GND	TX return	
3		ommon for both	
4		RX return	To most negative end
5	RX	Rec. In	

The BMS central connections layout is represented in the following figure.

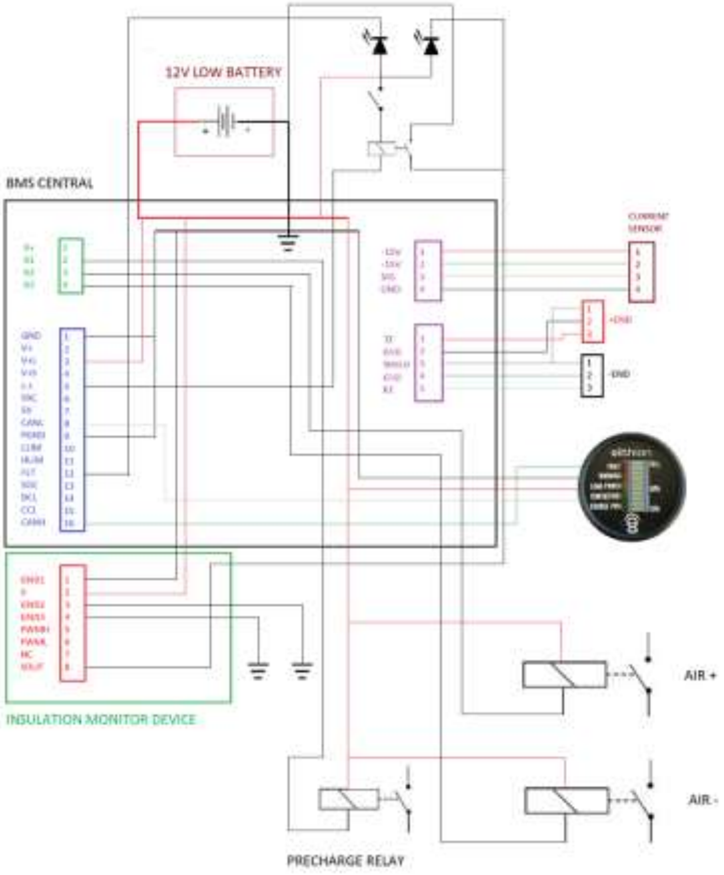


Figure 20: LV Layout in the accumulator

4.5 PRECHARGE

When a DC source such as a battery accumulator is connected to a capacitive device, a high intensity peak current takes place. The connections can resist a high transitory current but the batteries can be seriously damaged. Because of that, a precharge circuit must be used in a battery powered car. This circuit is very simple, just a resistance to dissipate the energy, as shown in figure 21.

In this case, the capacitive is the inverter. According to its datasheet, it behaves as an 800uf capacitor from the precharge circuit behavior. That capacitor should be charged in less than five seconds.

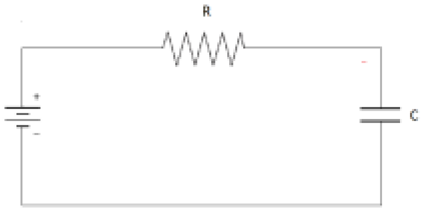


Figure 21: Precharge circuit

$$Vbat = Vres + Vcap \tag{22}$$

$$Vbat = I * R + \frac{q}{C} \tag{23}$$

$$R * \frac{dq}{dt} = Vbat - \frac{q}{C} \tag{24}$$

Integrating both sides of the equation and:

$$q = C * Vbat * (1 - e^{\frac{-t}{R*C}}) \tag{25}$$

Divide by the capacity to get the voltage:

$$\mathrm{V} = \mathrm{Vbat} * \left(1 - \mathrm{e}^{\frac{-\mathrm{t}}{\mathrm{R*C}}}\right) \tag{26}$$

- Vbat = 360V
- R = Resistance value
- Vres = voltage drop in the resistance.
- Vcap= Voltage of the capacitor

- q = charge of the capacitor
- V = 0.98x360V (the voltage of the capacitor taken as fully charged).
- t=2.5s (time to reach the voltage)

Substituting the values in the equation, the resistance value is around 800ohm.

For the precharge, the elements required are the resistance and the relay. The maximum current will be $\frac{Vbat}{R} = 0.45A$.

The relay used must be able to resist big voltage differences but not a big amount of power. The GIGAVAT G85C245 will be perfect for this purpose **[306 USD].** The resistance used is going to be an LPS 800. **[65 USD].** The rest of the components are explained in table 8.

Table 8: Components of the accumulator

ELEMENT	NOTES	IMAGE
AIR	-At least two isolation relays must be installed -The relays must open both poles of the accumulator -When they are opened, no high voltage should be present outside the accumulator container. -Their maximum switch off current must have a rating over the fuse working current The AIRs selected is the GIGAVAT GV220 from a very well recognized company and able to open at 200A and 800V **[108 USD each].**	

FUSE	It should work when the intensity is higher than the maximum expected current during the dynamic tests but lower than the current that might damage the batteries or other element of the HV circuit. Under these premises the fuse should be less than 100A. The chosen fuse is the BUSSMANN 100FEE. It stands up to 90A and has a quick fusing velocity.	
DC/DC	The rules of the competition oblige the teams to have some led indicating that the TS is charged. This indicator should be hard wired, not programmed, and to do this a led is going to be connected to the outer side of the AIRs through a DC/DC converter; a chopper. It should be from 400 to 12V. The DC/DC converter is a 400/12V with internal isolation from the brand VICOR.	
INTERLOCK	The different battery packs must be connected in a certain way. They should be easy to connect and disconnect in order to work in the accumulator. Some kind of positive locking should prevent them from getting loose. The selected ones are the 5.2mm in F, able to handle 100A currents. One male-female pair per battery pack. **[45USD]**	

TS CONNECTOR	The connectors out of the housing must also have some kind of positive locking feature. They must have an interlock connected to the shutdown circuit so if by accident they disconnect while the vehicle is on, the BMS will open the AIRs. The chosen ones are the AS 22-24320 from the ASHP series of Dutch. These connectors are widely used in the competition as they fulfill every rule. They can stand up to 200A. **[70 USD]**	
LV CONNECTOR	There are some signals that have to go in and out of the accumulator. For this a low power with multiple intakes easy to disconnect should be installed. D38999/24FF11SD a male and TWO females will be required. **[45.5 USD]**	
IMD	The Insulation Monitoring Device's purpose is to detect any failure in the shutdown circuit. Also detects if any failure is happening in the insulation, any kind of and in the own IMD at all times. If somehow any of these failures is detected, the device sends the signal to the BMS central through the contactor request port to open the AIRs and stop the car. The IMD must be a Bender A-ISOMETER ® iso-F1 IR155-3203 or -3204 or a similar one approved by the competition. **[80 USD].**	

4.6 CHARGING

The charging cart must have certain characteristics as well as the charger. A security circuit must also be located on the charging cart with the signals waning about a failure and a simple shutdown circuit to guarantee the security. The BMS must be working during the charging too. Every team should have a hand cart to transport the accumulator container. During the competition, the accumulator can only be transported on the cart. The cart must have a dead man´s switch. This kind of break is always on except when released by pushing and holding the mechanism.

The graph in figure 11 was made by Elithion showing the best compatible charger options with the BMS Lithiumate pro organized by voltage and power. The charger used will be the Kingpan KP9000Q because is the only one that has a charging mode suited for lithium batteries. The charging curved must be asked to be programmed in the device by the company before being sent to the team. The company also guarantees that all of their charges have the CE certificate, a quality certificate necessary to pass the scrutineering.

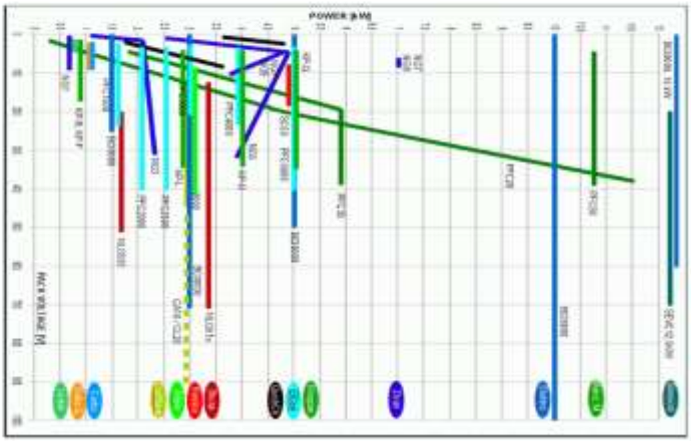


Figure 22: Charger grouping for different batteries

The charging curve has two main phases; the first one with constant intensity until the voltage is reached, and the second one with constant voltage until the charge is completed. There are other curves available for lead acid batteries but the one in figure 22 is the best suited for lithium cells.

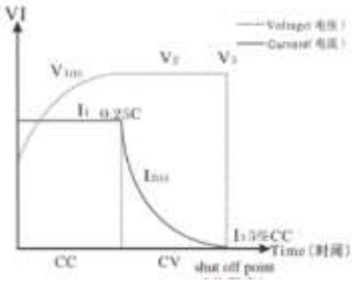


Figure 23: Charging curve

During the charge, there must be certain mechanisms to stop the process if anything goes wrong. The BMS must be working at all times monitoring voltage, temperature, and current and balancing the cells too. A shutdown circuit must be installed in the charging cart with the HV connector interlock and with two signs. The first one will be activated through the contactor if the emergency button is pressed for some reason, and the second indicating the BMS failure. The figure 24 represents the circuit on the charger´s cart.

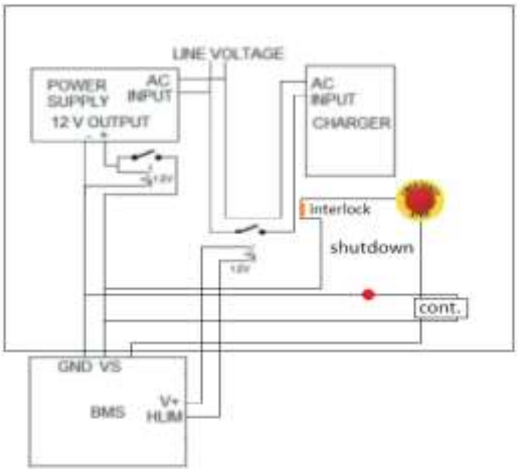


Figure 24: Protection circuit of charger

5. MECHANICAL

5.1 SOLIDWORKS

The accumulator must be also presented to the mechanical scrutineering along with the rest of non-electric/electronic pieces. As it contains the battery cells, there are certain structural rules that must be fulfilled.

The configuration of the battery pack must be designed so that each segment weights less than 12Kg. Every segment over 8kg must be attached to the accumulator with three fasteners and separated with isolating inner walls of at least the 75% of the total height of the accumulator. If the walls are made from conductive materials, there are ways to isolate them, such as kapton foil.

These segments, that should have 6MJ maximum should be able to be removed easily, therefore the connection between them must be safe and easy to dismantle (surlock plus). They must be connected in a particular configuration so that no short circuits can happen by mistake. There must be a top isolation in each segment that prevents any tool from falling on top of the building blocks dangerously short-circuiting a segment. This isolation will be tested with a 6mm diameter plastic tool that shouldn’t be able to reach any cell connection.

Every conductive part of the accumulator should be connected to the GLV including bolts and other elements. This will be strictly measured before the competition and should be less than 300mOhms. There should be a resistance over 6MOhms between segments.

The holes made to the accumulator must be only performed for connections and for ventilation purposes. In case that the accumulator doesn’t have ventilation, there must be a valve in order to release possible inner pressure.

According to the LTS, the accumulator should provide the car with over 6,8 Kwh with a DC voltage of 360V using the Samsung 18650 cells the configuration 100s 6p will offer 360 nominal Volts and 6.9 Kwh.

5.1.1 ACCUMULATOR

The following image (figure 25) shows a battery pack formed by the cells, the copper plates, the building blocks, the surlock plugs and the support and protector. As it weighs less tan 8kg, only two attachments would be required. This design allows extracting and introducing the packs in an easy and safe way.

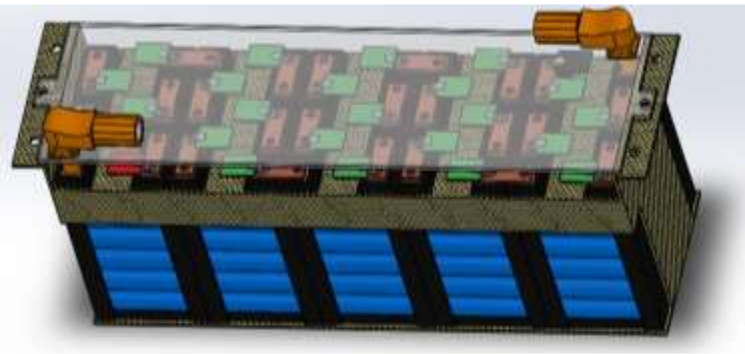


Figure 25: Battery pack assembly

The next image illustrates the Kevlar fiber accumulator. With a simple design in order to have a cheap an easy construction with enough space for all the different elements disposed in a simple and accessible way.

Figure 26: Accumulator(kevlar)

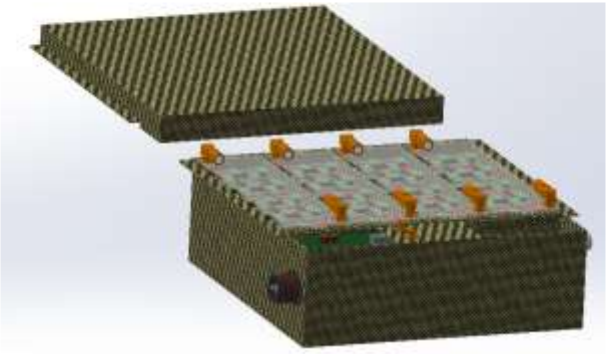


Figure 27:Accumulator assembly

Figures 26 and 27 show the accumulator with the top and its components, it is important to have a detailed assembly before fabricating anything as this will show some mistakes that could be solved before even starting its fabrication.

5.1.2 ATTACHMENTS

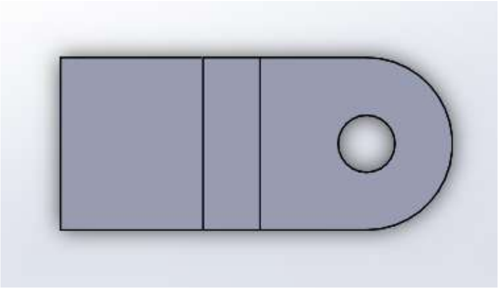


Figure 28: Attachment top view

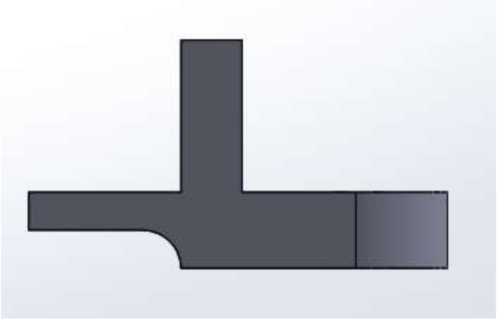


Figure 29: Attachment side view

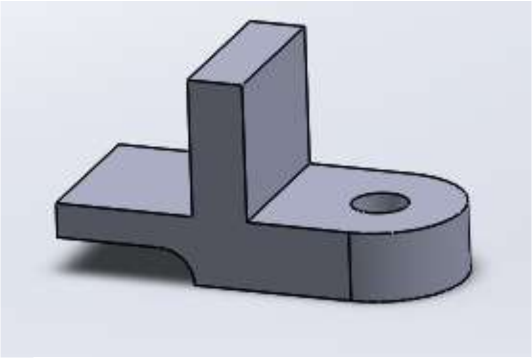


Figure 30: attachment

The attachments are made simple to economize fabricating processes, as shown in figures 28, 29 and 30. They are made of aluminum in order to lighten the pieces. They will be glued to the accumulator with epoxy resin usable for these surfaces. These kinds of resins can stand great forces.

5.2 MATERIALS

Table 9: Material comparison

	DENSITY g/cc	YOUNG'S MODULUS GPa	POISSON COEFF.	YIELD STRENGTH MPa	PRICE
ALUMINUM 2024 T4	2.78	73.1	0.33	324	3 USD/Kg
STEEL 304	7.80	193	0.25	215	1.6 USD/Kg
KEVLAR 29	1.44	70.3	0.36	890	30 USD/m^2

The accumulator must be made of a robust material for protection. The competition provides a certain width that the accumulator should have if it is made of steel or aluminum. In case that the accumulator is made from a different material such as Kevlar or carbon fiber, the team must proof itself the toughness with computer simulation and reports of a three-point bending and a shearing test performed to samples of the chose composite similar to the one used in the accumulator. In this case Kevlar was selected because it is even lighter than aluminum and more resistant too. The main characteristics of the materials needed [11] in order to make an ANSYS study are included in table 9.

5.3 ANSYS

5.3.1 ACCUMULATOR

The accumulator must be analyzed with ANSYS in order to provide detailed information to the scrutineers. The piece must resist 40g in the x and y axis and 20g in the vertical one.

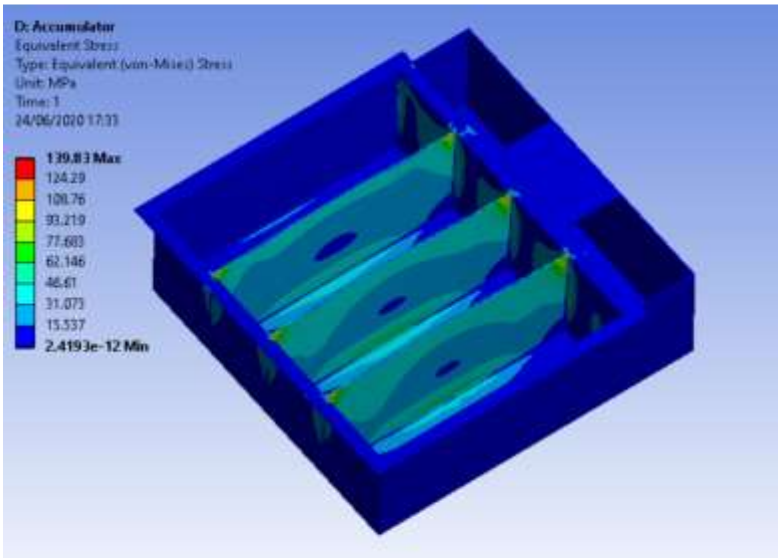


Figure 31: Stress suffered by the accumulator

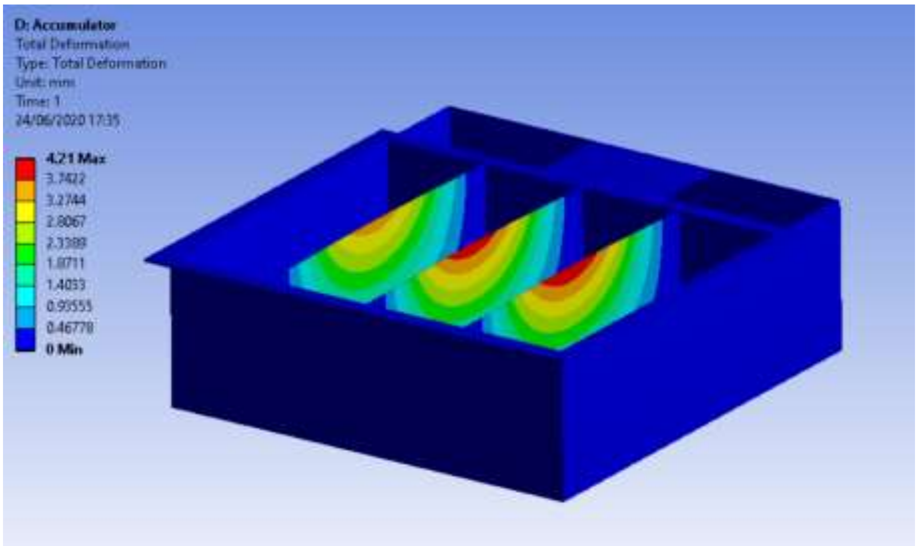


Figure 32: deformation when maximum forces are applied

For this case, a 5mm mesh was used. All the different forces were applied at the same time over the structure. The accumulator resisted all the stresses successfully (figure 31) and the deformations were acceptable, as seen in figure 32.

5.3.2 ATTACHMENTS

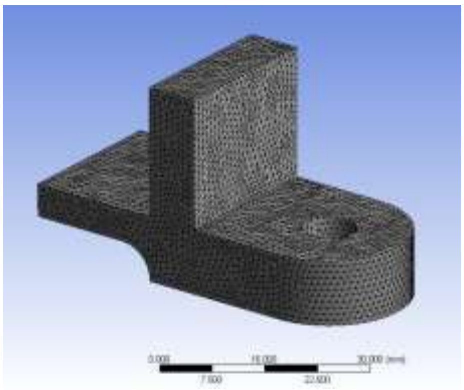


Figure 33: Attachment mesh

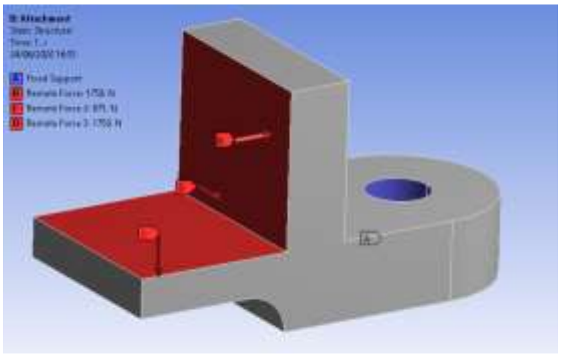


Figure 34: Representation of the forces

The attachments must resist the same stresses as the accumulator. They were applied over the surfaces attached to the accumulator and held by the bolt hole, the directions of the arrows in figure 33. The mesh has more elements around the critical elements such as sides or intersections as can be seen in figure 34.

In figures 35 and 36 the stress and deformation can be seen. The aluminum piece successfully stood all the stress and the deformation is minimal (less than 0.09mm in the critical point) even thought that all the forces (20g in the vertical direction and 40g in the other two) were applied at the in the same simulation in order to reach the worst-case scenario.

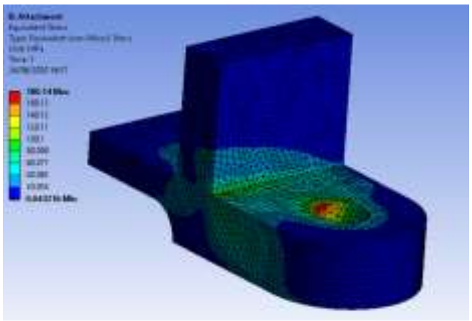


Figure 35: stress in the attachment

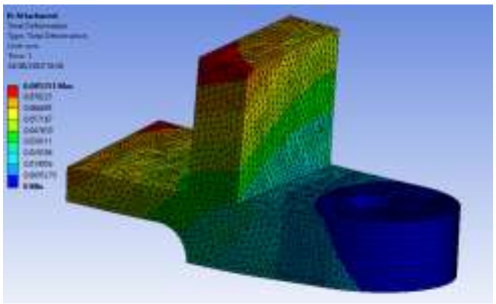


Figure 36: Deformation in the attachment

6. SUSTAINABLE DEVELOPMENT

There are over 24 million cars in Spain, including all kind of combustion cars (gasoline, diesel, liquated gas butane and electric). This constitutes an important percentage of the negative impact that the Spanish society has on the environment as most of the cars rely on hydrocarbons as the main source of energy releasing to the atmosphere damaging residual gases such as CO2 or the NOx.

In the past years the concern of the population about the environment and the importance of the respect of the natural resources and the preservation of the planet and nature has drastically increased. Signs of this are the support of the citizens for renewable sources of energy that has had as a result the promotion of them to a point that Spain is in the top countries that produce renewable energy.

Figure 37: Energy generation by technologies

Another big concern of the population is the efficiency of combustion cars and the transition of the Spanish fleet of personal cars from combustion to electric cars. The government has forbidden the entrance of combustion cars to the main cities and there are different prices depending of the car in the parkimeters. The debate about forbidding combustion cars (2030-2040) has already started. The main drawbacks are the difficulty of the electric energy transport to such a big amount of cars and the infrastructure for it but this is not the point of the topic.

It is obvious where the main impact of the combustion cars come from but the electric cars are not completely clean. The energy used to charge them comes from different sources and not all of them are clean. Also their batteries are made of rare materials that are difficult to obtain with a certain usable life being after that difficult to reuse and to recycle.

The main goal of this paper is to analyze the different impacts of different types of cars taking into account the projection of the technologies (Combustion cars are more efficient and so are the batteries of the electric cars) and to compare them. Also how would the batteries that are not efficient enough for electric mobility could be used for another purpose, in this case the improvement of the lifestyle of people in need.

6.1 COMBUSTION CARS

Combustion cars use different hydrocarbon compound extracted from oil with a different series of escalated processes and to this day it is also the main source of energy for transport as the vast majority of lad vehicles use its great chemical power as a source of energy. In the combustion there are different gasses as a result some of them are inoffensive such as water steam, Hydrogen but others can be extremely harmful for the environment and humans.

- **Hydrocarbon gasses:** They are poisonous alone such as benzene that can cause different symptoms depending on the concentration from irritation in the mucosa of the eyes and the lungs to nausea, vomits and dizziness. The exposure to benzene is highly correlated with different kinds of cancer as well as with some other hydrocarbon gasses from the combustion of diesel of gasoline like aldehydes od fentanols. They react with the nitric oxides with devastating consequences for the environment in form of acid rains.

- **PM:** These are suspended particles in the air of different kinds. They are smaller than 10 micrometers and the bigger ines can be seen with the naked eye. The dangers behind them are very different and involve lung problems such as difficulty of breading, irritation and asthma aggravation. They also may cause hart and circulatory problems being a considerable risk factor for heart attacks.

- **CO:** This gas is caused by a wrong mixture of gasses in the motor. It is formed when there is not enough oxygen during the combustion to form CO2. This gas is not considered as an important contributor to the global warming because even though it can capture radiation warming up, these molecules have a short life as they are very dilutive and reactive. However it is very harmful for humans and animals that have hemoglobin in their blood as the CO can irreversibly react with it causing dangerous saturation levels in the blood.

Table 10: CO concentration vs harm to humans

Concentration	symptoms
0-229 mg/m3 (0-200 ppm)	Head pain
10 mg/m3 (8,7 ppm)	Acceptable carboxihemoglobine after 8h of activity
30 mg/m3 (26 ppm)	Acceptable carboxihemoglobine after 1h of activity
34,4 mg/m3 (30 ppm)	Equivalent to smoking 20 cigarettes a day
40,1 mg/m3 (35 ppm)	Risk for people with cardiovascular problems
60 mg/m3 (52 ppm)	Acceptable carboxihemoglobine after 30 minutes of activity
100 mg/m3 (87 ppm)	Acceptable carboxihemoglobine after 15 minutes of activity
115 mg/m3 (100 ppm)	Cases of angina pectoris reported as

	a result
229-458 mg/m3 (200-400 ppm)	Nausea, vertigo and mental problems after 5h of exposure
458-802 mg/m3 (400-700 ppm)	Vomits, nausea and discoordination after 4h of exposure
802-1260 mg/m3 (700-1100 ppm)	Vomits weakness and faints after 3h of exposure
1260-1832 mg/m3 (1100-1600 ppm)	Coma after 1,5h of exposure
1832-2290 mg/m3 (1600-2000 ppm)	Death after 1,5h of exposure
5726-11452 mg/m3 (5000-10000 ppm)	Death after 15 minutes of exposure

- **NOx:** They are very harmful by themselves causing irritation in the mucosa and hurting the lungs. They are gasses that take a big role on the global warming but nitrogen oxides have also other harmful consequences. When they react with the hydrocarbon or the smog and the water steam of the air forming acids diluted in the air that cause acid rain with harmful consequences to the environment. These rains can occur miles away from the city.

Table 11: NOx concentration vs harm to humans

concentration	symptoms
4 µg/m^3 (0,01 ppm)	Breathing symptoms in kids
190 µg/m^3 (0,1 ppm)	Increase in respiratory infections with prolonged exposure
200 µg/m^3 (0,11 ppm)	Slight respiratory irritation in some individuals after 1h of exposure
210 µg/m^3 (0,112 ppm)	pain
400 µg/m^3 (0,2 ppm)	Slight respiratory irritation in more individuals after 1h of exposure
µg470 µg/m^3 (µg0,25 ppm)	Slight inflammation in some non-asthmatic individuals

470-900 µg/m^3 (0,25-0,50 ppm)	considerable inflammation in some asthmatic individuals
560 µg/m^3 (0,3 ppm)	Decrease in the lung capacity in some individuals
600 µg/m^3 (0,32 ppm)	Bronchospasms for asthmatic individuals
900 µg/m^3 (0,5 ppm)	Symptoms for some healthy adults
1.080 µg/m^3 (1 ppm)	Problems for healthy adults
18.800-37.600 µg/m^3 (10-20 ppm)	irritating
37.600 µg/m^3 (20 ppm)	IDHL
≥282.300 µg/m^3 (≥150 ppm)	Deaths reported
327.400 µg/m^3 (174 ppm)	50% of mortality after 1h

6.1.1 GASOLINE

In February of 2020 there were over 11 million gasoline cars in Spain, 3.5 million of them were built before 2000. As the technology improves the cars also turn more efficient with a better ratio of fuel litres per 100 Km and also the combustion process is improved with a better mixture of the gasoline and the air in the motor that generates less damaging gases.

The EURO standard is the norm that regulates the allowed emissions in a fabricated car during the period the law is active. Every few years, the norm is changed as the technology improves allowing the design of more efficient cars.

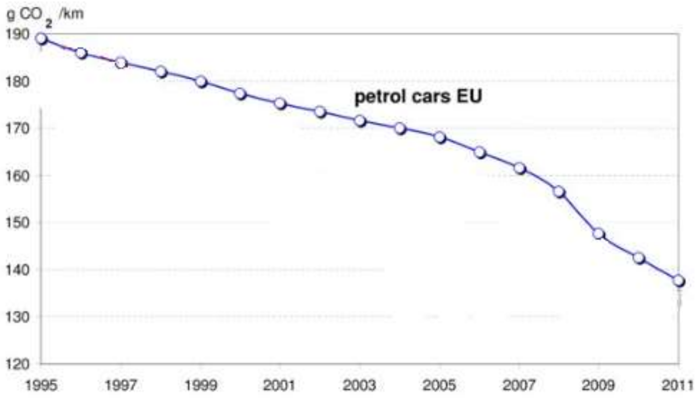


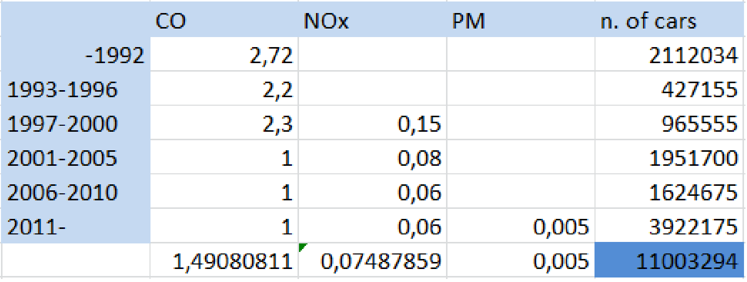
Figure 38: Gasoline cars pollution

Table 12: EURO standard

Tier	Date (Type Approval)	Date (First Registration)	CO	THC	NMHC	NO_x	$HC+NO_x$	PM	PN [#/km]
Petrol (Gasoline)									
Euro 1†	July 1992	January 1993	2.72 (3.16)	-	-	-	0.97 (1.13)	-	-
Euro 2	January 1996	January 1997	2.2	-	-	-	0.5	-	-
Euro 3	January 2000	January 2001	2.3	0.20	-	0.15	-	-	-
Euro 4	January 2005	January 2006	1.0	0.10	-	0.08	-	-	-
Euro 5a	September 2009	January 2011	1.0	0.10	0.068	0.060	-	0.005**	-
Euro 5b	September 2011	January 2013	1.0	0.10	0.068	0.060	-	0.0045**	-
Euro 6b	September 2014	September 2015	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}***
Euro 6c	-	September 2018	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}
Euro 6d-Temp	September 2017	September 2019	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}
Euro 6d	January 2020	January 2021	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}

An average can be obtained from the data of the table with the data from the DGT knowing the number of active cars. This average is the average top limit of the emissions for passenger cars up to 2.5 tons.

Table 13: Allowed emissions for gasoline cars



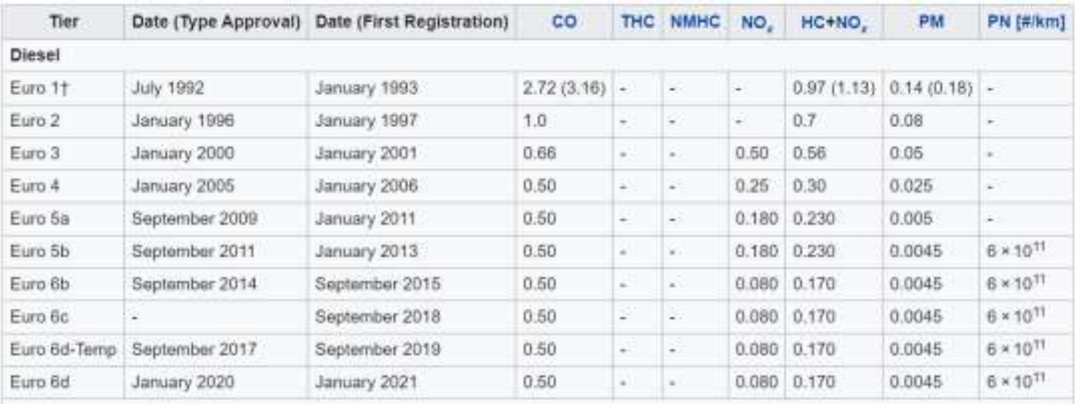
	CO	NOx	PM	n. of cars
-1992	2,72			2112034
1993-1996	2,2			427155
1997-2000	2,3	0,15		965555
2001-2005	1	0,08		1951700
2006-2010	1	0,06		1624675
2011-	1	0,06	0,005	3922175
	1,49080811	0,07487859	0,005	11003294

6.1.2 DIESEL

In February of 2020 there were over 13,5 million diesel passenger cars. The number of new diesel cars has been reduced considerably year due to the different laws that will limit the usage of them in the future.

The difference of the fuel and the kind of motor has a result a difference in the emission particles. The higher temperature has a result a lower CO emission but a higher NOx and PM ones. This is the cause of the harder laws involving diesel cars that lower the sales in the sector.

Table 14: EURO standard



Tier	Date (Type Approval)	Date (First Registration)	CO	THC	NMHC	NO_x	$HC+NO_x$	PM	PN [#/km]
Diesel									
Euro 1†	July 1992	January 1993	2.72 (3.16)	-	-	-	0.97 (1.13)	0.14 (0.18)	-
Euro 2	January 1996	January 1997	1.0	-	-	-	0.7	0.08	-
Euro 3	January 2000	January 2001	0.66	-	-	0.50	0.56	0.05	-
Euro 4	January 2005	January 2006	0.50	-	-	0.25	0.30	0.025	-
Euro 5a	September 2009	January 2011	0.50	-	-	0.180	0.230	0.005	-
Euro 5b	September 2011	January 2013	0.50	-	-	0.180	0.230	0.0045	6×10^{11}
Euro 6b	September 2014	September 2015	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6c	-	September 2018	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6d-Temp	September 2017	September 2019	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6d	January 2020	January 2021	0.50	-	-	0.080	0.170	0.0045	6×10^{11}

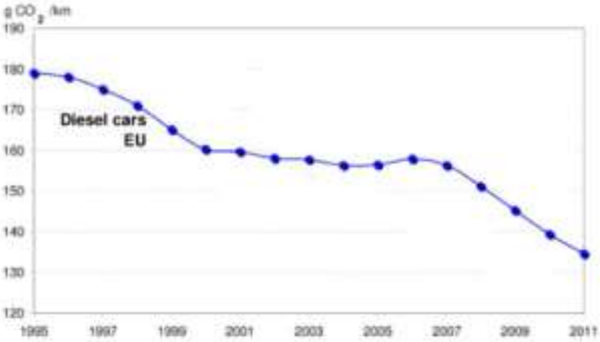
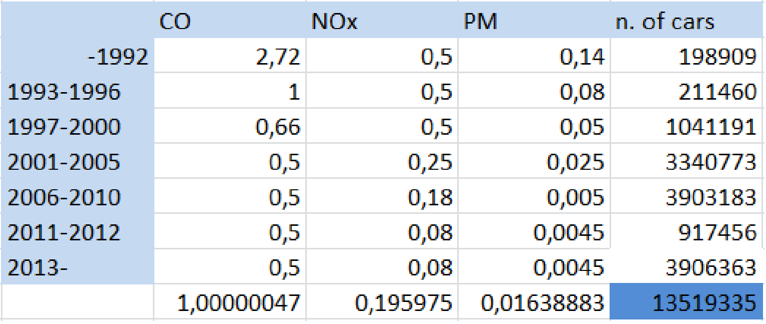


Figure 39: Diesel cars pollution

Table 15: Allowed emissions for diesel cars



	CO	NOx	PM	n. of cars
-1992	2,72	0,5	0,14	198909
1993-1996	1	0,5	0,08	211460
1997-2000	0,66	0,5	0,05	1041191
2001-2005	0,5	0,25	0,025	3340773
2006-2010	0,5	0,18	0,005	3903183
2011-2012	0,5	0,08	0,0045	917456
2013-	0,5	0,08	0,0045	3906363
	1,00000047	0,195975	0,01638883	13519335

6.2 ELECTRIC CARS

In February 2020 there were 42242 electric cars in Spain, half of them produced in the last two years as it can be seen in the following graph there is a strong growing tendency in the electric cars market. There are many reasons behind this fact such as the increasing number of charging points on the roads, the improvement of batteries capacity and charging velocity, fuel savings or the benefits the user gets from using an electric car. Another reason is the bigger concern in the environment but electric cars pollute in many different ways. The batteries are usually made of rare materials with a difficult extraction having a big impact on the environment and they are very difficult to recycle as it is going to be studied in the following points.

The electric cars represent the 0,15-0,2% of the total Spanish car not having a significant impact on the harmful gasses and PM emissions. There are also many logistical challenges in order to sustain a national electric based car fleet. The most important one is the amount of energy that should be produced and transported from the generation point to the charging points as the actual Spanish electric network is not ready for that at this point.

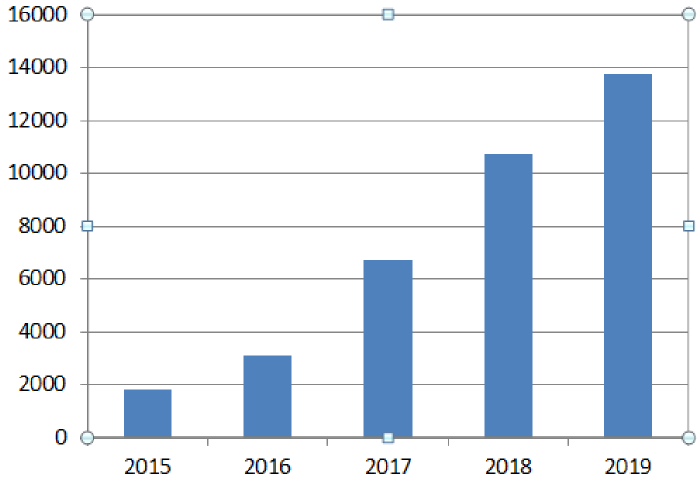


Figure 40: electric car park in Spain

6.2.1 BATTERIES

The main environmental impact of electric cars comes from the fabrication of their batteries. The materials needed for their fabrication are not vey abundant in the earth crurust and must go through many different process prior to their incorporation. These processes take a considerable amount of energy causing emission of CO2 and other harmful gasses. In the following graph it is shown the distribution of energy divided in the different processes and parts of a battery.

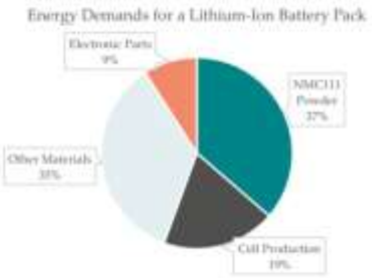
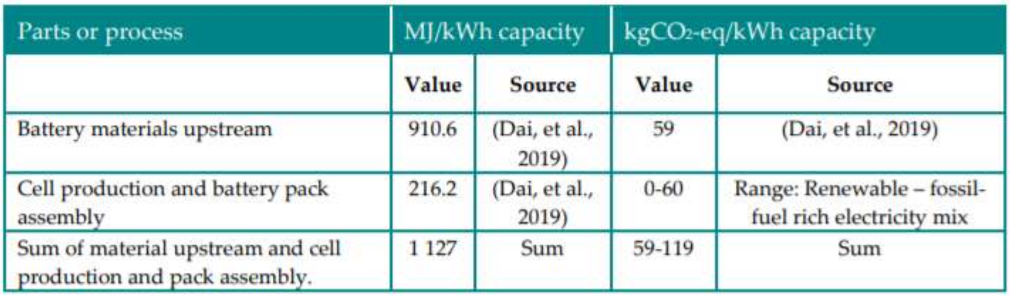


Figure 41: energy percentage by parts

The energy used for a battery accumulator varies depending of the capacity of it. A battery pack consist on a certain distribution of cells that take a certain amount of energy to build so the more cells a battery pack has, the more energy will be needed for its fabrication. As the technology evolves, these cells will have a bigger energy density and fewer of them will be needed to feed the car.

Table 16: KgCO2 in battery manufacture by parts



Parts or process	MJ/kWh capacity		kgCO₂-eq/kWh capacity	
	Value	**Source**	**Value**	**Source**
Battery materials upstream	910.6	(Dai, et al., 2019)	59	(Dai, et al., 2019)
Cell production and battery pack assembly	216.2	(Dai, et al., 2019)	0-60	Range: Renewable – fossil-fuel rich electricity mix
Sum of material upstream and cell production and pack assembly.	1 127	Sum	59-119	Sum

A battery accumulator takes between 59-119KgCO2/Kwh, this means that an average accumulator able to store 100Kwh of energy will release from 5900 to 11900 Kg to CO2 to the atmosphere.

The average healthy life of a battery accumulator is around 320000 Km. the total emissions of a car using a 100Kwh battery pack is 9200-13200 Kg of CO2. A 65-72% of total emissions of these kind of cars come from the production of their batteries.

6.3 ENERGY FOR CHARGING

Electric cars use the energy stored in their battery accumulators. In the process of releasing this electrochemical energy there is no kind of emissions. All the energy is used to move the vehicle with a high efficiency ratio and the rest is dissipated in heat.

Electric machines have already reached a high efficiency; electric motors for some cars can reach up to a 95% of efficiency while combustion motors are around the 25%. This means that almost all the energy used to recharge the batteries is used for its purpose.

The emissions generated from electric cars come from the generation of the energy in the power plants. In Spain around a 26% of electricity comes from renewable sources and the percentage coming from nonrenewable sources has a much higher efficiency than the usable energy from combustion motors.

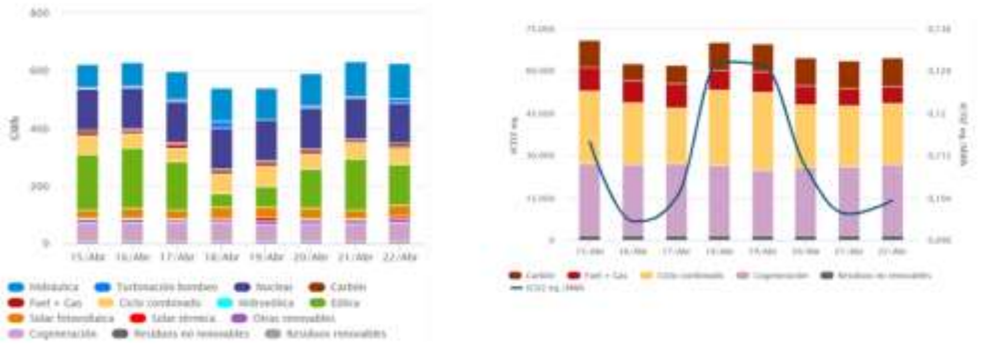


Figure 42: Energy generation by technologies

The CO2 emissions in the Spanish generation system generates around 0.1 tCO2/MWh or 100g/Kwh but the plans for the future is reduce this value increasing the percentage of renewable sources up to a 40% between 2030-2040. The average electric car uses between 7-13 Kw/100km depending on the year it was fabricated. This means that the average electric car`s CO2 emissions are around about 7-13gCO2/km. Around 10 times less than a combustion car built this year.

As the countries are having a clear tendency in transitioning towards clean sources of energy, this will have a direct impact on the emissions that derivate from electric vehicles.

6.4 COMPARISON AND CONCLUSION

An electric car does not emit any damaging gasses for the environment or the human as the energy is generated in power plants. These power plants are much more efficient than any combustion car which has an efficiency of around a 25%. An important part of the energy sources generating energy for the cars are a renewable energy power plant (26% in Spain) which does not generate emissions in the process. This makes the electric car pollute around 10 times less than a combustion car.

Providing that all the components of the car but the batteries have a similar energy usage, the batteries are the part that pollutes the most (59-119kgCO2/Kwh) this considerable amount is even bigger that all the CO2 generated during the life of the car (around 320.000Km).

Both amounts of CO2 emissions, the energy generation and the battery fabrication ake the electric car release around 25g/Km, a fifth of a regular diesel or gasoline cars.

The CO2 emissions of a both diesel and gasoline cars has drop since the EURO standard norm was active incredibly also powered by the pursuit of better efficiency but the last years it has even slightly increased. It is a technology with a lot of years and engineering optimization and even thought that there is still room for improvements, the electric technology and the batteries for personal cars has not had all those years to mature. Every year the electric vehicles offer battery accumulators with better energy density and cells able to perform a greater number of cycles. Right now they are already more sustainable but the developing of actual technologies and the discovery of new ones plus while the energy coming from renewable sources take over the nonrenewable ones will enlarge this difference.

The main issues involving a big electric car park are the charging due to the amount of energy that should be generated and transported to the charging points and the recycling of the batteries.

6.5 REUSE AND RECYCLE

Once the cells for an electric car reach a point of SOH (state of health) they compromise the efficiency of the electric vehicle. However, they still have a considerable amount of cycles that they can perform under suboptimal conditions for other purposes.These cells are distributed in a particular way inside the accumulator aiming for the optimal functioning of the vehicle but they can easily be dismantled and rearrange in order to fulfill other purposes. An electric car needs high power for a shorter time but a but a water pump to water a medium or small corn field using a water deposit needs less power but longer working periods.

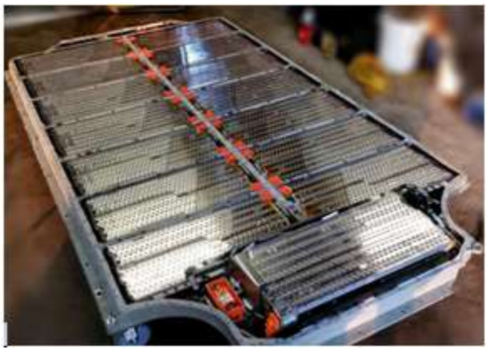


Figure 43: Tesla accumulator

Those cells can be connected either in series or in parallel. The voltage of a battery accumulator will grow as more cells in series are connected while the capacity will be increased as cells are connected in parallel. Any configuration can be made to adapt a design for a certain electric machine.

For example with a solar panel that meets the right characteristics, a battery accumulator can be charged in order to power a submergible water pump to fill a water tank. A relatively cheap and simple mechanism can ensure a constant water supply for a small village in places known for having a climate that divides the year in rainy and dry seasons making the agriculture viable also during the dry season.

There are countless projects like this one that could make the lives of people that does not have access to the electrical network using renewable sources of energy.

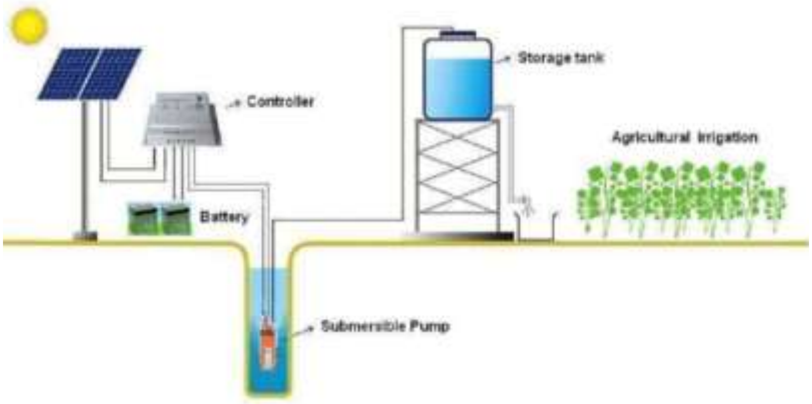


Figure 44: Solar powered pump for crops scheme

These kind of initiatives can prologue the life of cells while helping people in need in the process but a scenario that contemplates a majority of electric cars faces challenge of the recycling of millions of cells per year (letting aside other logistic problems).

In the case of regular 12V car batteries there is a big infrastructure that reuses most of the materials. First of all the batteries are destroyed into pieces that are submerged in water. The plastic parts float and they are retired and melted to build more batteries. The metals particles are solved in the sulfuric dilution, kept in pools until precipitation occurs. The water with acids is properly threatened while the metallic paste is melted. Plumber melts faster than the rest of the materials solving the problem of their separation. That plumber is going to be used to form lead ingots.

The European legislation says that only about 50% of the materials use for these lithium batteries must be reusable but mechanical process for the batteries mentioned before has being adapted for lithium batteries making it the best option. The main materials (graphite, lithium, cobalt and nickel) are almost completely saved.

Both processes do not generate emissions directly to the atmosphere. The only ones are the ones generated in the energy production for the installations. The amounts of materials kept in the cycle are close to an 80% according to FORTUM, the Finnish company in charge of a great part of the battery recycling business in Spain. This is relatively high percentage; higher than the average one for most of different elements but as the aim of the electric car is to reduce drastically the emissions that come from particular mobility, companies keep investing in increasing this percentage.

7. CONCLUSION

- The electrochemical characteristics of the cell are going to be reproduced in the accumulator. For a competition car, a high discharge rate or a high energy density are the most important factors while the self-discharge rate or the number of cycles are a minor issue.

- A lap time simulator is a tool that every team must have. It allows to make estimations beforehand about future changes in the car and information on how they will impact the performance in the dynamic events. Taking care of good data for the inputs (measuring and testing in the laboratory) will have a direct impact on the quality of the outputs. The LTS developed provides the needed information to dimension the batteries and also important information about the car performance during the endurance.

- A detailed SOLIDWORKS assembly can provide useful information for the distribution of the components in the accumulator. Plenty of the rules of the competition can be checked one by one beforehand with the 3D design. Some of them such as the isolation should be taken care of after the fabrication. All the geometric rules were checked successfully in the assembly.

- Kevlar has good properties for building an accumulator (light and resistant). It is also electrically isolating with the proper resin. The simulation shows that with the chosen width this accumulator is far more resistant and lighter than an accumulator built of Steel or aluminum with the same width. However, the three-point bending test and the shear test should be performed and reported to show the jury of the competition along with two pieces of Kevlar similar to the ones used in the accumulator.

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9. APPENDICES

APPENDIX 1: MATLAB

```
clc
clear all
close all
%% circuit
%circuito = xlsread('Trazados.xlsx','JARAMA');
circuito = xlsread('Trazados.xlsx','MOTORLAND');

%% Parameters
mm = 200;    %Kg
mp = 70;     %Kg
Rr = 0.165; %Radius [m]
Ir = 2.95*0.2159^2+3.9*Rr^2+0.35*0.1^2; %moment of inertia wheel [kgm2]
Im = 0.009; %moment of inertia motor [kgm2]
N = 5.5;     %transmission
Cd = 0.7;    %drag coefficient
Af = 1.2;   %frontal area [m2]
roair = 1.2;     %air density [kg/m3]
g = 9.81;
mrod = 0.03;   %rod coefficient
decel=2.3; %decceleration
% suspended and non suspended weight
m = mm + mp + 2*Ir*(1/Rr)^2 + Im*(1/N/Rr)^2;

%% Powertrain
%efficiencies
rendTr = 0.98;
rendME = 0.98;
rendInv = 0.95;
RT=rendTr*rendME*rendInv;
%Parameters
Imax = 150;      %peak intensity [A]
Vbat = 360;      %accumulator voltage [V]
Pmax = 68000*rendME;   %Potencia maxima en [W]
Parmax = 64*0.8;     %Par motor en [Nm]
wmax = 6500;     %Velocidad angular máxima del motor [rpm]
mu = 1.9;
K=0.67;
```

```
%% Simulación:
tramos = size(circuito);
syms vel;
syms inct;
preva = 60/3.6; %initial speed
vmax = 60/3.6;
tvuelta = 0;
nvuelta = 1;
r=10;
l=0;

for i=1:34
    if i<=34;
Rc_c = abs(circuito(i+1,2))/r;
long = round(circuito(i,3))/r;
pend = circuito(i,4)/r;
Rc = abs(circuito(i,2))/r;

if Rc == 0
            va(i,1) = preva;
            v_end=sqrt(mu*g*Rc_c);
            if v_end >= vmax
               v_end=vmax;
            end
     for j=1:long
                l=l+1;
                tdel= (preva-v_end)/decel;
                lbreak=preva*tdel-0.5*5*tdel^2;
                rest=long-j;
             if rest > lbreak %acceleration
                if va(i,j) >= vmax % max speed
                    axa(i,j) = 0;
                    F2=0.5*Af*Cd*roair*va(i,j)^2;%Fdrag
                    F3=(mm+mp)*g*mrod;%Frod
                    Par(i,j)=(F2+F3)/(N*rendTr/Rr);
                    I(i,j)=Par(i,j)/K;
                else
                    Par(i,j)=Parmax;
                    F2=0.5*Af*Cd*roair*va(i,j)^2;
                    F3=(mm+mp)*g*mrod;
                    F4=Par(i,j)*N*rendTr/Rr;
```

```
                    axa(i,j)=(F4-(F2+F3))/(m+mp);
                    I(i,j)=Par(i,j)/K;
                end
            else %deceleration
                Par(i,j)=0;
                if va(i,j) >= v_end % speed limit
                    axa(i,j) = -decel;
                    I(i,j)=0;
                else
                    axa(i,j) = 0;
                    I(i,j)=0;
                end
             end %accel/decel

                va(i,j+1) = sqrt(va(i,j)^2 + 2*axa(i,j)); %
ax = cte

                if axa(i,j) ~= 0
                    dta(i,j+1) = (va(i,j+1)-
va(i,j))/axa(i,j);
                else
                    dta(i,j+1) = 1/va(i,j+1);
                end

     end
     preva=va(i,j);
else%curve
    for j=1:long
        l=l+1;
        va(i,j) = preva;
        axa(i,j) = 0;
        F2=0.5*Af*Cd*roair*va(i,j)^2;%Fdrag
        F3=(mm+mp)*g*mrod;%Frod
        Par(i,j)=(F2+F3)/(N*rendTr/Rr);
        I(i,j)=Par(i,j)/K
        vd(i,j+1) = va(i,j); % ax = cte
                if axa(i,j) ~= 0
                    dta(i,j+1) = (vd(i,j+1)-
va(i,j))/axa(i,j);
                else
                    dta(i,j+1) = 1/vd(i,j+1);
```

```
                end
    end
    preva=va(i,j);
end%curva
    else
    end
end
n=1;
b=1;
vt=0;
%GRAPHS
    for uno=1:i
        d=round(circuito(uno,3))/r;
   for dos=1:d
    v(b)=3.6*va(uno,dos);
    vt=vt+v(b);
       b=b+1;
   end
    end
figure(1)
plot(v,'r')
xlim([0 b])
title('Velocidad');
ylabel('v [km/h]');
xlabel('distancia [m]');
b=1
for uno=1:i
        d=round(circuito(uno,3))/r;
   for dos=1:d
    p(b)=Par(uno,dos);
       b=b+1;
   end
    end
figure(2)
plot(p,'g')
xlim([0 b])
title('Par');
ylabel('Nm');
xlabel('distancia [m]');
b=1
for uno=1:i
```

```
        d=round(circuito(uno,3))/r;
   for dos=1:d
    p(b)=I(uno,dos);
       b=b+1;
   end
    end
figure(3)
plot(p,'b')
xlim([0 b])
title('I');
ylabel('A');
xlabel('distancia [m]');
b=1
for uno=1:i
        d=round(circuito(uno,3))/r;
   for dos=1:d
    p(b)=axa(uno,dos)/9.81;
       b=b+1;
   end
    end
figure(4)
plot(p,'b')
xlim([0 b])
title('G');
ylabel('a(x)');
xlabel('distancia [m]');

Capacidad = 0;
l=0;
    for i=1:33
        long = round(circuito(i,3))/r;
        for j = 1:long
                Capacidad = Capacidad + 
I(i,j)*dta(i,j)/3600;
                l=l+1;
        end
    end
    vt/l
    Capacidad*22000/l
```

APPENDIX 2: COMPONENTS

Low power: https://www.mouser.es/ProductDetail/Amphenol-Aerospace/D38999-24WC35SB-LC?qs=YIxVbm6S2%2FMCHhl0wYba1w%3D%3D&vip=1&gclid=CjwKCAjw5Ij2BRBdEiwA0Frc9bczirDu3-NL4hBzJ2_Z3DzZgxU0LFc_I0sOuqKfroJMn8cTgC6rThoC7EYQAvD_BwE

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