Master's degree Course in Energy and Nuclear Engineering

Renewable Energy Engineering

Master's Degree Thesis

Fire risk of electric vehicles in confined spaces

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Abstract

Electric machines and batteries are crucial components of modern technology, powering everything from smartphones to electric vehicles. However, they also present a potential fire hazard, particularly in the case of lithium-ion batteries which are widely used in many electronic devices. Nowadays, the study of the evolution of fires with the use of Fire Safety Engineering methods is going to be more and more important In Italy and in all the developed countries.

To address this issue, researchers and engineers have been working to develop better fire prevention and suppression systems. Pyrosim is one such system, which uses computational modeling to simulate and analyze fires in enclosed spaces such as tunnels or buildings. By using FDS alongside Pyrosim as a simulation method, it is possible to gain a more comprehensive understanding of fire behaviour.

In this thesis, it has built upon the work done by previous researchers in the field of fire safety for electric vehicles and batteries. Using Pyrosim's and thus FDS modelling capabilities, it has been developed a simulation model of a tunnel with an anti-fire system, as well as a vehicle using methane or electricity.

By running simulations with varying parameters, such as the type of fuel used and the position of the car, it was possible to analyze the behaviour of fires in enclosed spaces and identify potential weaknesses in fire suppression systems. Additionally, the temperature and heat released during the simulated fires are investigated to gain a better understanding of the specific risks associated with electric vehicles.

In conclusion, the results support the importance of continued research and development of fire prevention and suppression systems. By utilizing advanced modelling tools like Pyrosim, it is possible to better understand the behaviour of fires in enclosed spaces and work towards improving the safety of these technologies.

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Spero di dare a voi almeno una piccola parte di quello che voi date a me.

Vi voglio un bene immenso.

Vostra Silvia.

Inscription

Alle donne della mia famiglia:
mia mamma Rina,
mia nonna Ida
e mia nonna Gina,
che, con il loro esempio, mi hanno insegnato
che i limiti non esistono.

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Nomenclature

EU -European Union
FDS - Fire Dynamic Simulator
CO_2 - carbon dioxide
IPCC - Intergovernmental Panel on Climate Change
GHG - green-house gases
CCS - carbon capture and storage
EV - electric vehicle
BEV - battery-powered electric vehicle
PHEV - plug-in hybrid electric vehicle
NiMH - nickel-metal hydride
$NaAlCl_4$ - molten sodium chloroaluminate salt
CC - constant current
CV - constant voltage
PU - polyurethane
PE - polyethylene
PP - polypropylene
LIB - lithium-ion battery
SEI - solid electrolyte interphase
ICEV - internal combustion engine vehicle
H_2 - hydrogen
CH_4 - methane
CO - carbon monoxide
HF - hydrogen fluoride
TR - thermal runaway
Cd - compressibility factor
SOC - state of charge
SOD - state of discharge
HRR - heat release rate
PHRR - peak heat release rate
HCN - hydrogen cyanide
HRRPUA - heat release rate per unit area
CNG - compressed natural gas
NMC - nickel-manganese-cobalt
EMF - electromotive force
NFPA - National Fire Protection Association
BMS - battery management system
VOC – volatile organic compound

Chapter 1

Introduction

Nature is calling for help. It was clear from the Kyoto protocol in 1997 that involved 180 countries of the world. Starting from that moment there was the awareness that climate was changing in bad, mainly caused by human pollution. Nowadays the European Union, seems to be the leader of the change. With the EU Green Deal they declared a path toward the decarbonization of society in 2050. The transportation sector is a significant contributor to greenhouse gas emissions, accounting for around 14% of global emissions [1].

As a result, the adoption of electric vehicles is regarded as an essential step in lowering transportation-related emissions and lessening the effects of climate change. As battery technology advances and the availability of charging stations grows, electric vehicles are becoming more and more popular since they emit much fewer pollution than conventional gasoline-powered vehicles.

Electric cars have advantages beyond just lowering pollution. In comparison to conventional vehicles, they also provide cheaper maintenance costs, quieter operation, and increased energy efficiency. The need for fossil fuels will decline as more people move to electric vehicles, which will result in lower greenhouse gas emissions and better air quality.

Nevertheless, there are still obstacles preventing the widespread use of electric vehicles. In addition to cost and charging accessibility, fire risk is a phenomenon to take under consideration and control.

The focus of this report will be to look closer in to specifically lithium-ion batteries. In particular after a brief discussion about climate change and its drivers in Chapter 1, a detailed study of electric vehicles and batteries will be discussed in Chapter 2. Chapter 3 will examine the general phenomenon of fire and the fire risk of lithium-ion batteries present in electric vehicles. The model is then developed in Chapter 4 using Pyrosim and FDS, providing results for a methane car and an electric vehicle. Conclusions will be reported in Chapter 5.

1.1 The problem: climate change

1.1.1. Main drivers

Studying the temperature evolution of the world over the years it is possible to notice a dramatic increase.

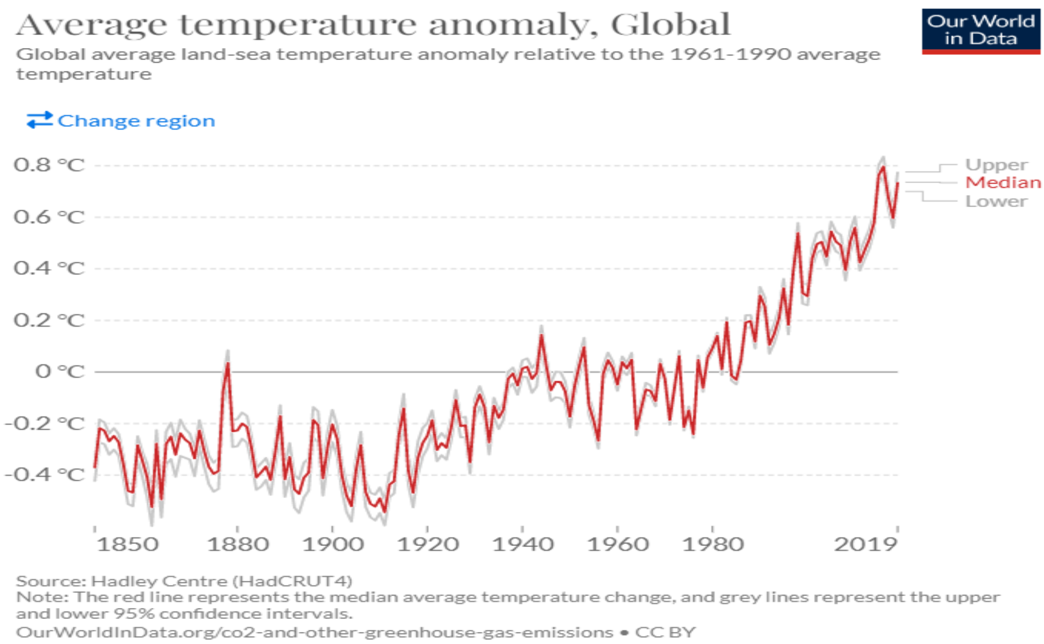

Figure 1. Global average temperature in the years

Human emissions of CO_2 and other greenhouse gases are a primary driver of climate change and present one of the world's most pressing challenges. In Figure 1, the average yearly temperature trend through time is represented by the red line with the upper and lower confidence intervals given in light grey. In the previous two decades, the global temperature increased reaching a level that is 0.7°C higher than the period between 1961 and 1990. However the overall increase in temperature is between 1 and 1.2°C [2].

Since 1850 almost all the warming can be attributed to the human emissions. This is evident from the Intergovernmental Panel on Climate Change (IPCC) which states in its AR5 assessment report: "Anthrpogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800000 years. Their effect, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century" [3].

1.1.2 Most dangerous sectors

Climate change can seem like a problem that's either too difficult, or too far off in the future, to solve. However, it is well known which are the primary contributions to today's global greenhouse gas emissions. They are five and listed from the most pollutant to the lowest [4]:

1. Industrial manufacturing (concrete, steel and plastic materials);
2. Electricity production;
3. Agriculture and breeding;
4. Transportation;
5. Heating and cooling of buildings.

The percentages are reported in Figure 2.

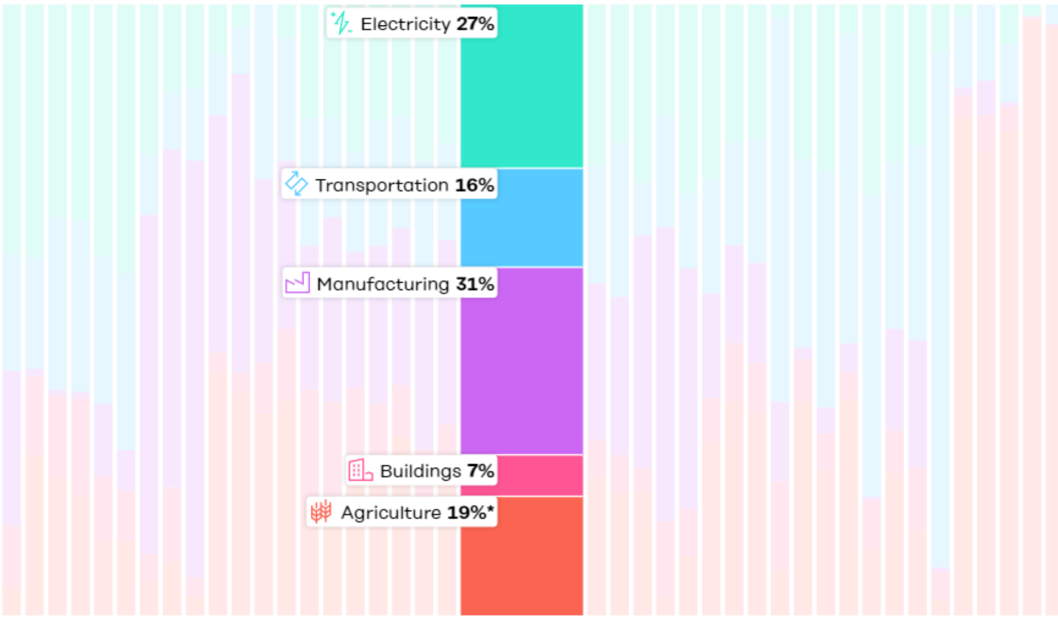

Figure 2.Major sectors involved in global greenhouse gas emissions

Counties today are concentrating their strengths in particular on the electricity production since it influences also the transportation, heating and cooling systems of buildings and energy intensive industries.
Industrial manufacturing represents the highest contribution on greenhouse gas emissions. With up to 5% of all CO_2 emissions produced by humans in the cement business, it is one of the two greatest producers of this gas in the world [5]. The CO_2 emission from the manufacture of concrete is directly proportional to the cement content utilized in the concrete mix [6]. Several approaches to reducing emissions related to concrete from both the academic and industrial sectors have been suggested.
For what concerns the agricultural sector, it is responsible for non-CO_2 emissions generated within the farm gate. Some of the sources of air pollution from agriculture include:

1. Livestock emissions: the rearing of livestock for meat, dairy, and eggs can lead to the emission of large amounts of methane, which is a potent GHG. Methane is produced by the digestive process of ruminant animals such as cattle and sheep, as well as from mature management. Livestock emissions can also contribute to the formation of smog and other air pollutants.
2. Field burning: in some agricultural practices, the crop residue is burned in the field after harvest. This can release large amounts of particulate matter

and other pollutants into the air, which can be harmful to human health and contribute to air pollution.
3. Pesticides and fertilizers: their use can also lead to air pollution. Pesticides can drift from the intended target and contribute to the formation of ozone ad other air pollutants. Fertilizers can release ammonia and other gases into the air.
4. Dust and particulate matter: agricultural practices such as tillage, planting, and harvesting can also lead to the release of dust and particulate matter into the air. These particles can be harmful to human health [7].

Due to an increase in inland freight volumes and passenger transport between 2013 and 2019, domestic transportation emissions climbed steadily closely related to economic growth trends. As it is possible seen in the Figure 3, road travel accounts for three-quarters of transport emissions. Most of this comes from passenger vehicles such as cars and buses. Even though it frequently receives the greatest attention when discussing how to combat climate change, only 11,6% of transport emissions come from aviation [8].

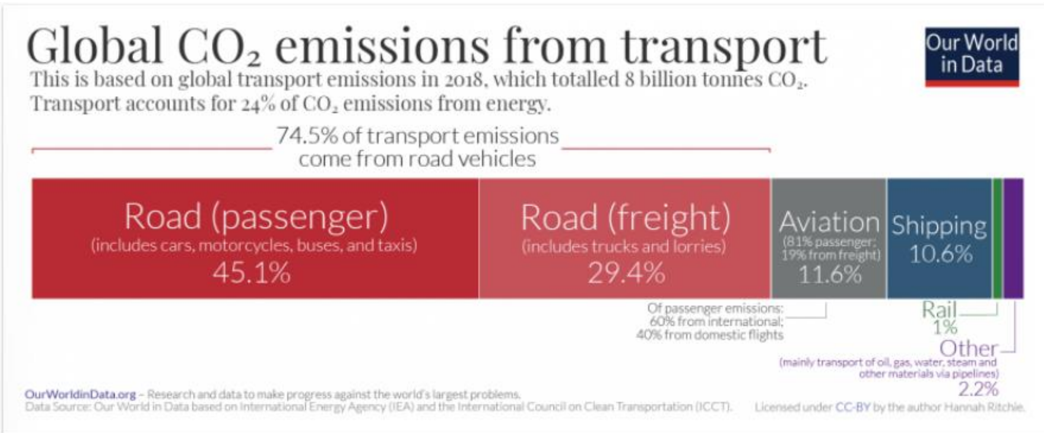

Figure 3.Global CO2 emissions from transport

In addition, modern life requires heating and cooling. This includes regulating the temperature in industrial processes as well as regulating comfort in homes and buildings. Additionally, it comprises the global cold chain that guarantees the safe transportation of food, medicine and vaccinations.

1.1.3 Energy sector

The CO_2 emissions by the energy sector are an issue of growing concern, as carbon dioxide is one of the leading contributors to climate change. The energy sector is responsible for a significant portion of global CO_2 emissions, and it is essential to understand the sources and trends of these emissions in order to address the problem. The energy sector is a significant contributor to global CO_2 emissions because it is primarily based on the use of fossil fuels such as coal, oil and natural gas. These fuels release CO_2 into the atmosphere when burned for energy production, leading to significant greenhouse gas emissions. The burning of fossil fuels for energy production accounts for approximately 70% of total global CO_2 emissions. The electric power sector is the largest contributor to CO_2 emissions in the energy sector, accounting for approximately two-thirds of the sector's total emissions. The electric power sector is heavily reliant on coal-fired power plants, which are among the largest sources of CO_2 emissions globally. The use of natural gas-fired power plants is also significant, as natural gas releases CO_2 when burned. The trend towards the use of renewable energy sources, such as wind and solar, has the potential to significantly reduce CO_2 emissions from the electric power sector.

In addition to policy measures and investment in renewable energy, several other approaches can be taken to reduce CO_2 emissions from the energy sector. These include:

1. Energy efficiency: improving energy efficiency across all sectors of the economy can significantly reduce the amount of energy that is required to meet our needs, and thus, reduce CO_2 emissions. This can be achieved through measures such as improving the energy efficiency of buildings, vehicles, and industrial processes.
2. Carbon capture and storage (CCS): CCS is a technology that can capture CO_2 emissions from large industrial processes and store them underground, thus preventing them from entering the atmosphere. CCS has the potential to significantly reduce CO_2 emissions from the energy sector, particularly from the electric power sector.
3. Use of nuclear power: nuclear power is a low-carbon energy source that does not release CO_2 emissions when generating electricity. However, there are concerns about the safety and security of nuclear power, and the waste produced by nuclear power plants can be highly radioactive and pose environmental risks.
4. Bioenergy: bioenergy refers to the energy that is produced from biological materials, such as crops and waste materials. Bioenergy has the potential to reduce CO_2 emissions by replacing fossil fuels with low-carbon energy sources. However, it is important to ensure that the production of bioenergy do not compete with food production or lead to deforestation.

In addition to these measures, it is important to address the underlying drivers of energy consumption, such as population growth and economic development, to achieve sustained reductions in CO_2 emissions from the energy sector. This will require a multi-faceted approach that involves collaboration between governments, businesses and individuals to create a low-carbon future.
Another important aspect to consider in reducing CO_2 emissions from the energy sector is international cooperation. Climate change is a global problem that requires global solutions, and reducing CO_2 emissions from the energy sector will require the cooperation of countries across the world. This can be achieved through international agreements, such as the Paris Agreement, which aim to limit global warming to well below 2 degrees Celsius above pre-industrial levels. To achieve the goals of Paris Agreement, it will be necessary for countries to transition to low-carbon energy sources and to reduce the carbon intensity of their economies. This will require significant investment in renewable energy and energy efficiency, as well as policy measures that incentivize low-carbon practices. It is also important to recognize the role of the private sector in reducing CO_2 emissions from the energy sector. Businesses have a significant impact on energy consumption and CO_2 emissions, and they can play a key role in reducing these emissions through measures such as investing in renewable energy, improving energy efficiency and adopting low-carbon practices. Finally,

individuals can also play a role in reducing CO_2 emissions from the energy sector through their daily behaviours and choices. This includes reducing energy consumption at home by using energy-efficient appliances and light bulbs, choosing low-carbon transportation options, and supporting businesses and politicians that prioritize action on climate change [9][10].

Chapter 2

Electric vehicles and batteries

2.1 One possible solution: electric vehicles

Since more and more countries are setting net-zero emissions targets, electrification of many sectors is a step toward carbon neutrality. It consist of two main parts: renewable generation and energy storage. The first one use several renewable energy plants that handle with the advanced strategy of conversion of energy from nature into electricity. The latter concern the different type of energy storage that can convert electricity into another form, and back.

2.1.1 The growing demand for electric vehicles

The first electric car in the US, also if it seems incredible, hit the open road in 1890. But William Morrison's electric car only had a top speed of 14 miles per hour. Gas-powered and electric vehicles engaged in fierce market share competition for a period. But once Henry Ford unveiled the Model T in 1908, the trend shifted in favor of gas-powered vehicles, which become even more accessible. Since the Toyota Prius was introduced in 1997, electric car interest has increased significantly. With the introduction of the first hybrid electric vehicle for mass production, interest in the contemporary electric vehicle began to grow [11]. EV global sales have been growing steeply every year since 2010 as it is possible to see in Figure 4.

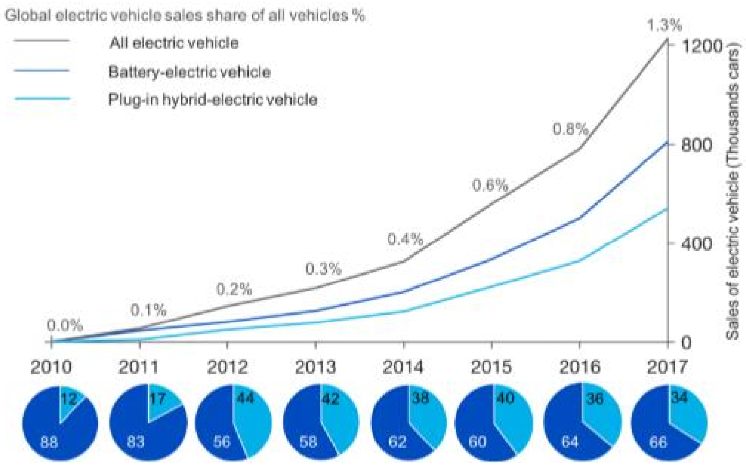

Figure 4. Electric vehicle trend in years

The trend continued to increase also after 2017 until these days. Around 4,3 million new battery-powered EVs (BEVs) and plug-in hybrid electric vehicles (PHEVs) were sold globally in the first half of 2022 with a rise of 75% for BEV and 37% for PHEVs [12].

For what concerns European Union, the trend follows the same behaviour. In particular, Nordic countries such as Norway and Sweden represent the leaders of the market as it is possible to see in Figure 5 [13].

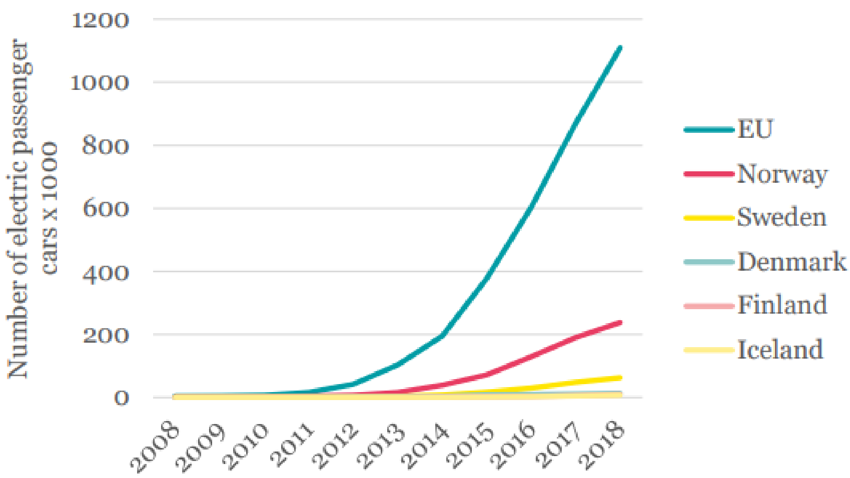

Figure 5.Number of electric passenger cars trend in some EU countries

Despite this good trend the transition to cleaner transport may not be happening fast enough to meet climate targets.
Like all new technologies, there are advantages and disadvantages. Some of the main pros include:

- Lower operating costs: electric vehicles are less expensive to operate than gasoline vehicles because electricity is cheaper than gasoline and electric vehicles have fewer moving parts, which means lower maintenance costs.
- Improved energy efficiency: electric vehicles are much more energy-efficient than gasoline vehicles. They convert about 59-62% of the energy stored in their batteries into power to the wheels, while internal combustion engines typically only convert about 17-21% of the energy stored in gasoline power at the wheels.
- Cleaner and greener: electric vehicles produce zero tailpipe emissions, which means they do not contribute to air pollution. Additionally, if the electricity used to power the vehicle comes from renewable sources, the overall carbon footprint of EVs can be significantly lower than that of gasoline vehicles.
- Quieter operation: electric vehicles are much quieter, which can be a major advantage in terms of noise pollution.
- Better performance: they offer instant torque, which provides better acceleration and performance than gasoline vehicles.
- Increased driving range: EV technology has improved dramatically in recent years, and many new models now have a driving range that is comparable to traditional ones.
- Government incentives: in many countries, governments offer incentives, such as tax credits and rebates, to encourage people to purchase electric vehicles.

- Reduced dependence on oil: they do not rely on oil, which can help to reduce dependence on foreign oil and improve energy security [14].

On the other hand, the main cons are:

- Higher initial purchase cost: also if the costs of operation are lower. The gap continues to decrease as technology matures.
- Driving range: depending on the type of the battery the range of electric cars varies. With the development of technology the driving range is increasing.
- Charging takes longer: related to the previous problem there is the charging. An EVs need time to be charged and at the same time the driving range is lower. Also in this case, as the technology matures a reduction of the charging time is expected. For example, a 60 kWh battery pack with a charging rate of 100 kW could be charged from empty to 80% capacity in around 30-40 minutes [14].
- Rare metals used in the batteries: the problem of lithium can be associated with the fact that is rare and it is possible to find it only in a few countries. Other metals used are copper, cobalt, aluminum, nickel and manganese. All these metals are rare, and used for other applications, some of them are toxic and deposits are in countries like Africa where the human-rights are not well respected [15].

2.1.2 Different kinds of batteries

There is a growing interest in the study and development of batteries used in electric and hybrid vehicles because of the rising demand for fossil fuels on the global markets and the worsening of environmental issues brought on by a growth in the number of internal combustion engine vehicles [16].

The most important characteristics of the batteries are:

- Capacity (Ah): refers to the amount of electrical energy that the battery can store and provide to a device. The actual capacity can depend on various factors, such as the temperature, the age of the battery, and the discharge rate.
- Voltage (V): it is a measure of the electrical potential difference between the positive and negative terminals of the battery. It represents the amount of energy that the battery can supply to an external circuit. In general, the voltage of a battery will decrease as it discharges and will eventually drop below the minimum voltage required by the device it is powering. Therefore, it is fundamental to choose a battery with a voltage rating that matches the requirements of the device.
- Energy content (Wh): it is the amount of energy that can be extracted from the battery through a chemical reaction between the battery's components. This energy can be used to power electronic devices or perform work. The energy content of the battery depends on its capacity and voltage, as well as its chemistry. Different battery chemistries have different energy densities, which can affect the amount of energy that can be stored in a given volume or weight of the battery. It is important to note that the energy content of a battery is not the same as its power output. Power is a

measure of how quickly energy is supplied, while energy content is a measure of the total amount of energy that can be supplied. The power output of a battery depends on its voltage and the load that is placed on it, while its energy content is determined by its capacity and chemistry.

- Polarization: refers to the buildup of a potential difference between the electrodes of the battery, which can impede the flow of current and reduce the battery’s efficiency. Two types of polarization that can occur in a battery: concentration and overpotential polarization. The first one occurs when the concentration of the reactants at the electrode surface is depleted due to the chemical reaction that occurs in the battery. As a result, a layer of depleted reactants forms at the electrode surface, which can impede the flow of current and cause the voltage of the battery to drop. The second one occurs when the voltage required to initiate the chemical reaction at the electrode surface is higher than the voltage supplied by the battery. As a result, the reaction does not occur, and a potential difference builds up between the electrodes, which can impede the flow of current and reduce the efficiency of the battery. To reduce polarization and maintain the efficiency of a battery, various techniques can be used, such as using additives to the electrolyte, optimizing the electrode surface area, or using high-quality materials in the construction of the battery.

The batteries in electric cars must be small, able to recharge quickly and frequently, and have enough power to move people where they need to go [17]. Electro-chemical energy storage systems have advanced significantly in the 160 years since the first rechargeable lead-acid battery was created. Finding the ideal balance between the battery’s weight, storage capacity, production costs, longevity, recharging capability and environmental impact, has been the focus of all scientific researches.

Lead-acid batteries are the oldest, cheapest and, the most common vehicle batteries available in the past. The basic principle of operation is that when the battery is charged, the sulfuric acid in the electrolyte dissociates into hydrogen ions (H+) and sulfate ions (SO4-2). The hydrogen ions react with the lead dioxide electrode to form water, while the sulfate ions react with the lead electrode to form lead sulfate. During discharge, the process is reversed, and the lead sulfate in the electrodes is converted back into lead and lead dioxide, while the sulfuric acid is regenerated (Figure 6).

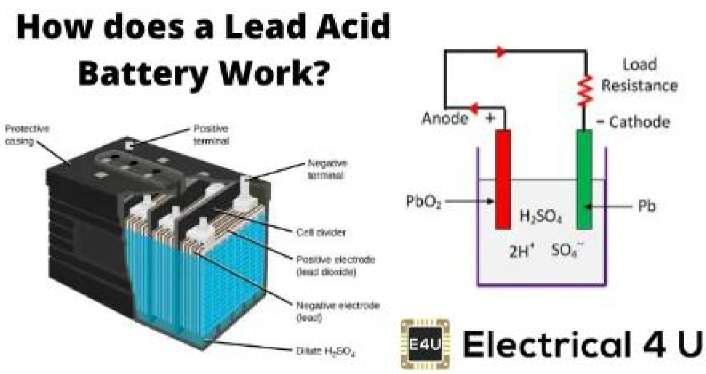

Figure 6. Representation of a Lead Acid battery

The two main types are automobile engine starter batteries and deep cycle batteries. The first ones are designed to utilize a tiny fraction of their capacity to give high charge rates to start the engine, whereas the second ones are intended to supply continuous electricity to run electric vehicles like forklifts or golf carts. These days, this type of batteries are no more used for traction but only to power electric circuit of accessories. The reason is linked to the fact that despite the lead-acid battery's substantial size and weight, it only delivers a limited capacity [18].

Nickel-metal hydride batteries (Figure 7) are considered an almost mature technology. The most important advantage is related to the specific energy, much higher than the one of lead-acid batteries (30-80 Wh/kg vs 30-50 Wh/kg) and the absence of heavy metals. The basic structure of a NiMH battery is similar to that of NiCd battery, with a positive electrode (nickel hydroxide), a negative electrode (a hydrogen absorbing alloy), and an alkaline electrolyte. When the battery is charged, nickel hydroxide is oxidized and hydrogen ions are absorbed into the negative electrode alloy. During discharge, the process is reversed, and the hydrogen ions are released from the alloy and react with the nickel hydroxide to produce water. They are mainly used in hybrid cars. The main limitations include their high price, robust self-rate and the fact that they generate a lot of heat at high temperatures [19].

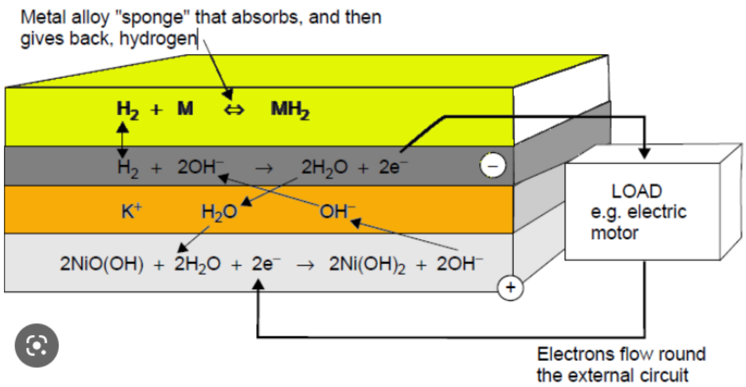

Figure 7. Design of a nickel-metal hydride battery

Another battery type for electric vehicles is the sodium nickel chloride or "Zebra" battery. It uses NaAlCl4 (molten sodium chloroaluminate salt) as the electrolyte. The specific energy is very high (120Wh/kg) and cold weather does not affect its operation a lot. The battery operates at a high temperature of around 270 to 350 degrees Celsius to keep the electrolyte in a molten state. The basic principle of operation for Na-NiCl2 batteries is that during charging, sodium ions are extracted from the negative electrode and travel through the molten salt electrolyte to the chloride. During discharge, the process is reversed, and the sodium ions migrate back to the negative electrode, releasing electrons that flow through an external circuit and producing electrical energy. A general electric model of sodium nickel chloride battery is reported in Figure 8.

Figure 2 Fiamm Sonick $NaNiCl_2$ ST523 module

Tab I Fiamm Sonick $NaNiCl_2$ ST523 module electrical characteristics

Rated discharge power	7.8 kW (3 h discharge time)
Rated voltage and cell connections	620 V in series connection of 240 cells
Regeneration rated Power	6 kW
Electrical stored energy	23.5 kWh
Initial discharge temperature	240 °C
Dimensions	862 (1016 with Battery Management System - BMS) L × 556 P × 389 A (mm)
Calendar life/ life cycles as a function of DoD	15 years / 4500 cycles DOD 80%
Weight	≅ 256 kg
Freeze-thaw	no limitations

Figure 8. Technical features of a general sodium nickel chloride battery

With energy storage capacities ranging from a few kilowatt-hours to several megawatt-hour installations, the single battery size spans from 4 to 25 kWh and it is suited for a wide range of applications [20].

Lithium-ion batteries are the most used for electric vehicles applications nowadays. A market pricing comparison of several EVs based on battery capacity are presented in Figure 9.

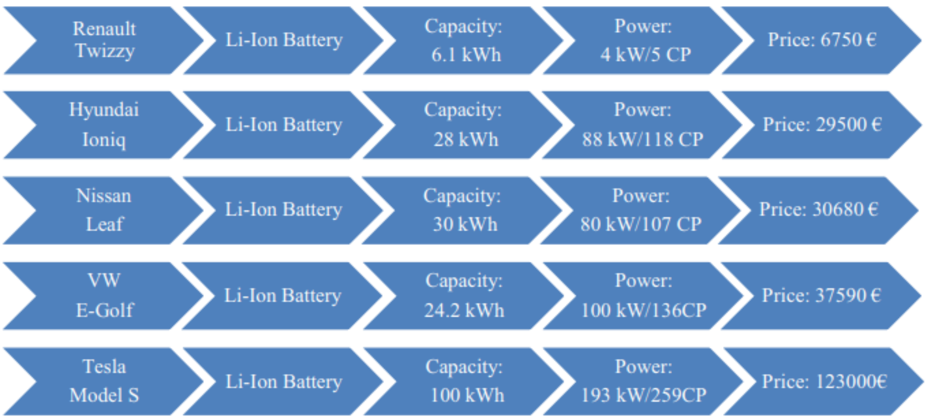

Figure 9. Market pricing comparison of different EVs based on battery capacity

This technology will be investigated in detail in chapter 2.3 since they are the ones studied for the development of the model in chapter 3.

2.2 Focus on Li-ion batteries: components and function

A lithium-ion battery is a class of rechargeable battery types in which lithium ions passes from the negative electrode to the positive electrode during discharge and back again during charging [21].

2.2.1 Basic principles

Like other batteries, lithium-ion ones are made up of a negative electrode and a positive electrode with different potentials separated by a separator (Figure 10). A conductive electrolyte is present between the poles that are oppositely charged, allowing the lithium ion to travel freely as the battery is being charged and discharged. The positive electrode (cathode) is commonly made of a lithium metal oxide, with a variety of chemical variations (ex. Lithium nickel manganese cobalt oxide or lithium cobalt aluminum oxide). The negative electrode (anode) is typically made of graphite [22]. During discharge, lithium ions (Li+) transport the current within the battery cell from the negative to the positive electrode through the separator diaphragm and non-aqueous electrolyte. During charging, an external electrical power source (the charging circuit) applies an over-voltage, and so a voltage that is higher than the battery produces and has the same polarity, forcing a charging current to flow within each cell from the positive to the negative electrode. At the end the lithium ions move from the positive to the negative electrode, where they undergo a process called intercalation in which they embed themselves in the porous electrode material [23].

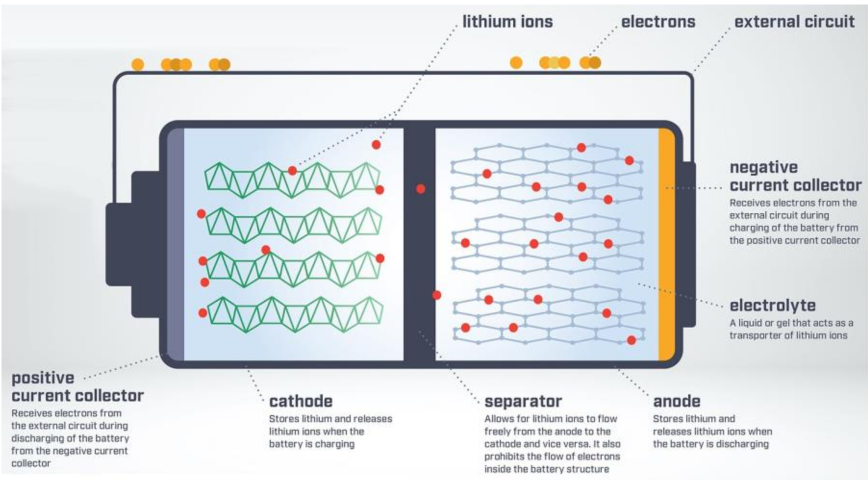

Figure 10. Main components of a Lithium-ion battery

The general formula for a lithium-ion battery is LiCoO2 for the positive electrode, graphite for the negative electrode and an electrolyte that is typically a lithium salt in an organic solvent, such as LiPF6 in a mixture of ethylene carbonate and dimethyl carbonate. LiCoO2 is a lithium-transition metal oxide, where lithium ions can move from the cathode to the anode during discharge and back during charging. The graphite anode has a layered structure that can intercalate lithium ions during charging, and release them during discharging. The overall chemical reaction during discharge can be represented by the following equation:

$$LiCoO2 + C6 \rightarrow Li_{1-x}CoO_2 + xLi_+ + xe^- \qquad (1)$$

Where C6 represents the graphite anode, $Li_{1-x}CoO_2$ is the lithium-intercalated cathode, and x is the number of lithium ions intercalated during charging.
The electrolyte is typically a non-aqueous solution that allows the movement of lithium ions between the electrodes, while preventing the mixing of the cathode and anode. The most common electrolyte is a solution of lithium hexafluorophosphate (LiPF6) in an organic solvent, such as ethylene carbonate and dimethyl carbonate.
The charging procedure for single Li-ion cells and complete Li-ion batteries are slightly different:

- A single Li-ion cell is charged in two stages: constant current (CC) and constant voltage (CV);
- A Li-ion battery is charged in three stages: constant current, balance (if cell groups are unbalanced during use) and constant voltage.

During the constant current phase, the charger maintains a constant current to the battery while gradually increasing the voltage. During the balance phase, the charger decreases the charging current while a balancing circuit balances the state of charge of each cell. During the constant voltage phase, the charger applies a voltage to the battery equal to the maximum cell voltage times the number of cells in series, as the current gradually decreases towards zero and eventually falls below a predetermined threshold of about 3% of the initial constant charge current [24].
In the specific case of an electric vehicle, while driving (discharge phase), lithium ions from the active material of the negative electrode flow through the separator to the positive electrode and are deposited there in the crystal lattice of the appropriate metal oxide. The required amount of electrical energy is sent to the electric motor, which serves as the battery's power consumption, at the same time that electrons travel outside the battery via an electrical cable connection from the collector (copper) of the negative electrode to the collector (aluminum) of the positive electrode. This process is reversed when charging an electric vehicle at a charging station: the lithium ions go back from the positive to the negative electrode using the same logic and are reincorporated into the graphite [22].

Many different lithium-ion cells must be coupled to reach the power characteristics, such as the necessary voltage (V) or energy (Wh) for entirely electric driving. The most basic level is the lithium-ion cell. By connecting different battery cells in series or in parallel, it is possible to store a much higher amount of energy. Usually the number of cells varies but generally it accounts for around 60 V per module. At the end battery modules are connected to form battery packs to meet the needed energy and power (Figure 11) [25].

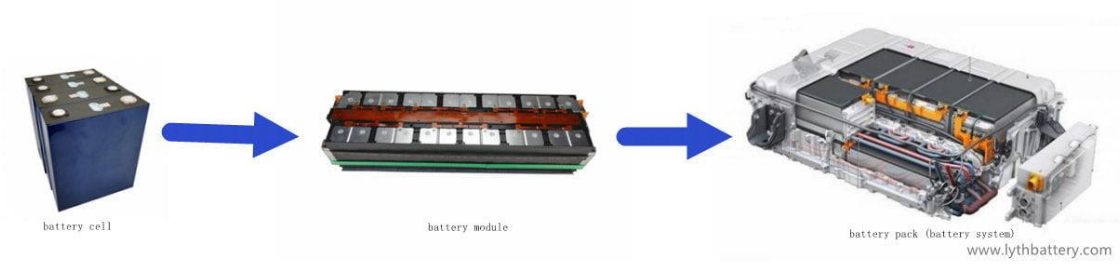

Figure 11. From battery cell to battery pack

2.2.2 Materials

A large number of possible materials for electrodes and separators of the lithium-ion batteries are studied to achieve the highest performance but only few are commercialized.

Starting from the anode materials, it is clear that the nature and properties of the anode material are cardinal to the overall battery performance. The capacity and performance of the battery not only depends largely on the intrinsic characteristics of the anode material but also on its morphology. Commercially, various kinds of carbon/graphite are most frequently used [26]. But it is well known that graphite anodes have a poor capacity issue and are linked to safety issues. Alloy anodes, such as those made of aluminum (Al), tin (Sn), magnesium (Mg), silver (Ag), antimony (Sb) and their alloys are employed to address these flaws [27].
On the other hand, for the cathode a wider range of materials are commercially available. Cobalt was the cathode's main active material at first. Nowadays since there are a lot of problems linked with this material, nickel is widely used in place of cobalt. Iron, vanadium and sulfur are three common undesirable metal contaminants that must be eliminated from cathode materials because cathode materials require extremely high purity levels [28].
Additionally, there are various kinds of commercial separators. The most used type is a polymer made from, for example, polyethylene (PE) or polypropylene (PP). The first one melts at a temperature of around 130°C, while the second melts at about 160°C. Sometimes, PE and PP are combined to create two layer PE-PP or tri-layer PP-PE-PP separators. These are called shutdown separators and they have a few safety benefits. To allow physical stability at higher temperatures (200 °C), the polymer separator can also be strengthened with ceramics [26].
The electrolyte conducts ions, not electrons, through the separator and between the anode and cathode. So, it needs the following characteristics:

- High ionic conductivity combined with high resistance to electrons;
- High cation-transfer capability to support high power levels;
- Wide electrochemical stability window;
- High thermal stability and high mechanical strength;
- Easy and low-cost to manufacture.

In general, the electrolyte is a mixture of a Li-salt, organic solvents and several additives. The exact composition used in commercial Li-ion batteries is never revealed. In addition they can be solid or liquid [29].
Also current collectors are always present. They are conductive plates or foils that connect the cathode and anode to the external circuit, allowing the flow of electrons during charge and discharge cycles.

The specific materials used in lithium-ion batteries can vary depending on the application and performance requirements of the battery [26].

2.2.3 Passenger Cars with Lithium-Ion Batteries

To achieve the needed power and energy, many battery cells are integrated into an electric vehicle. It is necessary to have a balance between the dimensions of the battery pack (bigger size means higher power) and the appropriate safety level. This component is usually added in a so called "safe zone" inside very stiff compartments such as the center of the chassis, between the wheelbase. There are three main configurations for the "safe zone", as reported in Figure 12.

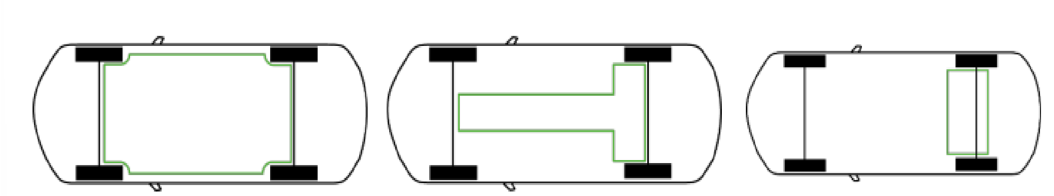

Figure 12.The "Floor" solution; the "T" solution and the "Rear" solution

The most common are the "Floor" and "T" designs, in which the battery is divided over a square or rectangle, or arranged in the shape of the letter "T". The "Rear" solution (the last represented), represents the third choice. Here, the battery pack is sometimes stacked higher in the back of the car.
A battery pack that is positioned below the vehicle's floor is referred to as having a floor type configuration in electric cars (EVs). Benefits of this layout include greater aerodynamics, increased internal room, improved safety, and improved driving dynamics. It optimizes interior space for passengers and freight while lowering the car's center of gravity to improve handling and stability. It also lessens wind resistance, boosts overall efficiency, and offers additional protection to the battery pack in the event of a collision. The Tesla Model S, Chevrolet Bolt, and Nissan Leaf are a few EVs that use the floor type battery layout (Figure 13) [30].

Figure 13. Detail of "Floor" solution for EVs

In the T-shaped battery design (Figure 14), the battery pack is divided into two portions with the shorter section forming a "T" shape and the larger section running perpendicular to it through the middle of the vehicle's floor. By fitting the battery pack into the gap between the front and rear wheels, the vehicle's center of gravity can be lowered improving handling. Many electric vehicles (EVs) use the T-shaped battery design, including Chevrolet Volt, Cadillac ELR, and BMW i3. These results to be less efficient than the "Floor" model [31].

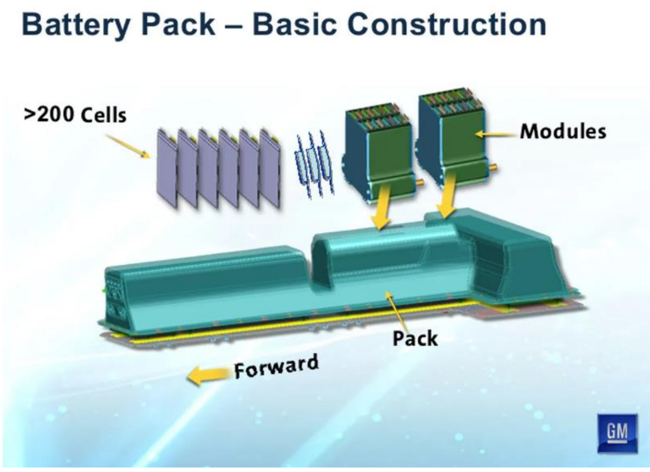

Figure 14. Detail of "T" solution for EVs

Utilizing the space between the vehicle's rear wheels is the "Rear" solution. As they need less storage space, this design is typically encountered in tiny cars or hybrids. Some EVs utilize the area above or behind the rear wheels to improve the amount of energy that is accessible [30].

2.2.4 Possible damaging

The risks with lithium-ion batteries are yet not fully studied nor understood. From experience it is possible to study the most common failure modalities to improve electric vehicles safety. Most of them can be classified into one of many homogenous classes that are described below based on their similarities.

Manufacturing defects

Despite the quality control procedures used by manufacturers, flaws can still appear during the manufacturing or assembly phases. These include a variety of potential causes:

- Contamination: the presence of impurities or foreign materials in the battery components, such as the electrodes, electrolyte, or separator, can lead to short circuits, reduced capacity, or other issues.
- Inconsistent electrode thickness: variations in the thickness of the electrode layers can lead to non-uniform current distribution, reduced performance, or even safety hazards.
- Electrolyte leakage: poor sealing or damage to the battery casing can cause the electrolyte to leak out of the battery, potentially leading to safety hazards or reduced performance.

- Internal shorts: these can occur when small metal particles or other debris are left in the battery during production, causing a short circuit between the cathode and anode.
- Poor cell matching: when assembling multi-cell batteries, it is important to ensure that each cell has similar characteristics and performance. Failure to match cells properly can lead to reduced performance, safety hazards, or even catastrophic failure.

Manufacturing defects can impact the safety, performance, and reliability of lithium-ion batteries.

Electrical abuse

The pursuit of fast charging and discharging combined with the high driving performance for EVs harm their fire risk. LIBs are designed to take in and store a specific quantity of energy in a predetermined amount of time. Overcharging or charging too quickly can result in exceeding these limits, which can reduce performance or cause early failure [31]. This can result in a variety of safety hazards and performance issues, including:

- Internal short-circuit: they result from contaminants, tiny metallic particles, dendrites on the active ingredients and separator degradation. Various kinds of internal shorts can happen and they are frequently the main cause of serious Li-ion cell accidents because they cause localized overheating and possibly thermal runaway.
- Overcharging: typically, it occurs when the cell is charged to a voltage that is too high (typically 4.2 V). Both electrodes may deteriorate: lithium plating on the anode may result in the creation of dendrites, which may then produce an internal short circuit (a micro short via the separator), followed by thermal runaway. The electronics in the battery pack typically have protective features built in, although malfunctions or improper charging cannot be completely ruled out. Thermal runaway will result from severe overcharging but also repeated little overcharges can potentially have negative long-term effects.
- Over-discharge: usually below 2 V, causes to the electrodes and current collectors only slight harm. However, the copper current collector may dissolve into the electrolyte near the anode. Along with the lithium plating that takes place during each recharge, copper ions also create new metallic copper layers on various cell components. These copper layers have the potential to cause micro-short circuits and, in the case of repeated recharges, even a thermal runaway. Larger battery packs with imbalanced or differentially aged modules are more likely to experience this failure, which further worsens the situation of current reversal.
- Excessive currents. Overheating may result from high currents (such as those brought on by external short-circuits), sometimes only locally at points with high impedance (such as tab connectors, electrodes etc..). During handling or shipping operations, it is especially crucial to prevent external short-circuiting [32].

To prevent electrical abuse, it is important to use the battery according to the manufacturer's specifications, avoid exposing the battery to extreme conditions, and handle the battery carefully to avoid physical damage.

Thermal abuse

Thermal abuse of lithium-ion batteries refers to exposing them to high temperatures that exceed their safe operating range, typically above 60-70°C. This can cause the battery to release its electrolyte, which can result in a thermal runaway reaction and lead to overheating, fire, or even explosion. It is important to store, handle and charge lithium-ion batteries according to the manufacturer guidelines to prevent thermal abuse.

Usually, rechargeable Li-ion cells are allowed to operate in a certain temperature range. They perform best at room temperature (20-30 °C) and extreme hot or cold temperatures are negative for the battery's performance and will shorten their lifespan (Figure 15).

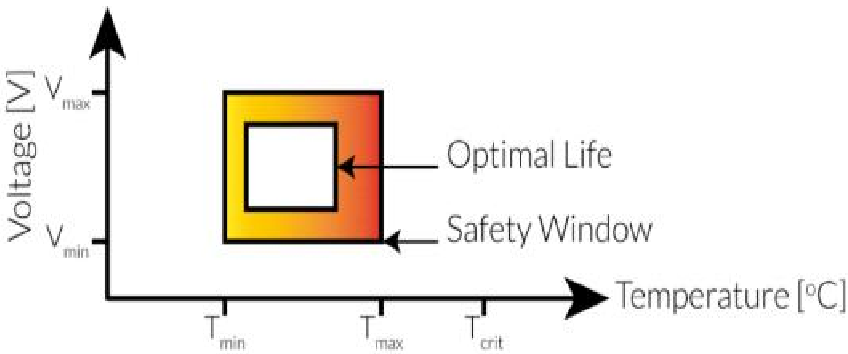

Figure 15. Working temperature window of Li-ion cells

High ambient temperatures or excessive heat created during operation that is not sufficiently dissipated by the cooling system, if present, can cause it or at least trigger it. Breakdown of the electrolyte begins at about 100°C, followed by the formation of gas and an increase in pressure inside the cell. Large systems are more susceptible to this event, with the middle of the module typically overheating. Battery degradation and thermal runaway will result from it.

Low temperatures can cause also problems. Due to altered electrode material properties and slowed reaction rates, it hinders the intercalation of lithium ions [32]. Typically, anode lithium plating and decreased battery capacity are seen.

For example, in Figure 16 is represented an external source of heat used to raise the temperature of the cell to the onset temperature (usually Tonset=0.2 °C/min).

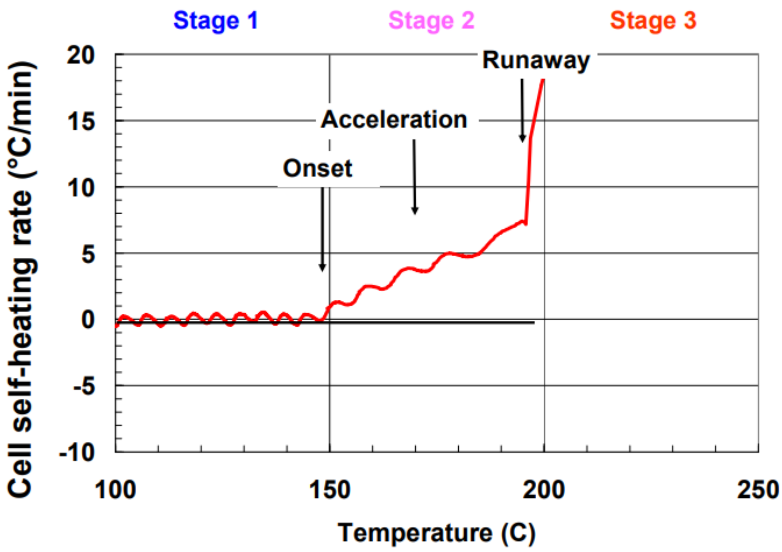

Figure 16. Evolution of temperature due to cell self-heating

If the heat is not expelled due to prolonged exothermic processes above the onset temperature, the cell reaches Stage 2 (Acceleration) which is characterized by faster and accelerating heat release. Further heating pushes the cell into Stage 3 (Runaway) where the high-rate anode and/or cathode reactions cause the temperature to rise quickly (thermal runaway) with flame or explosion potentially following.

Mechanical abuse

It entails any mechanical damage to the battery brought on by outside forces (impact, fall, penetration etc..); probable outcomes include case deformation, breach and collapse. The results can range from cell malfunctioning (lower efficiency, fewer cycles, etc..) to electrolyte leakage, internal short circuit, cell overheating and finally thermal runaway, depending on the extent of the damage. Especially after several cell cycles, more severe effects may still occur. The structural makeup of the cells is important from the perspective of mechanical abuse, with the pouch cells being the most susceptible to mechanical harm.

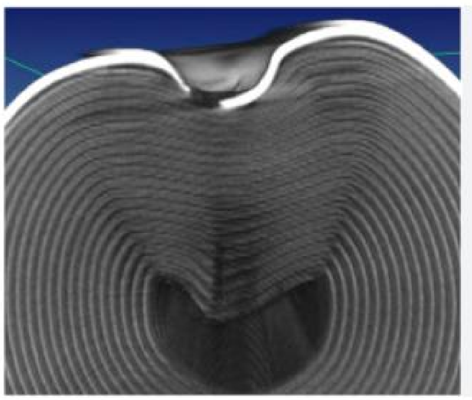

Figure 17. Mechanical abuse in Lithium-ion batteries

LIB packs are usually integrated into highly reinforced areas of the vehicles eliminating the risk of being penetrated during crash conditions. However, at high speeds, even the highest level of protection is not enough to prevent fire [30].

Ageing

The effect of age is still not well known, however, it is recognized that with the increase of internal impedance, the performance of the cell deteriorates. At the same time, the cell is more prone to overheating and so to a thermal runaway. The solid electrolyte interphase (SEI) layer can fail as a result of the cycle volume oscillations of the electrodes (fatigue), which are brought on by lithium ions intercalating during charge and discharge. This could result in overheating and thermal failure.

Lithium-ion batteries degrade over time due to several factors including:

- Charge cycles: each time a lithium-ion battery is charged and discharged, a small amount of capacity is lost. Over time, this loss accumulates, reducing the battery’s overall capacity.
- High temperatures: exposure to high temperatures accelerates the ageing process and reduces their lifespan.
- Depth of discharge: deeper discharges can cause additional stress on the battery, reducing its overall lifespan.
- Storage conditions: lithium-ion batteries degrade more quickly when stored at high temperatures, in high or low states of charge, or in a fully discharged state.

It is recommended to avoid fully discharging the battery and avoid leaving it unused for extended periods, as this can cause irreparable damage [30].

2.2.5 Environmental impact

Sustainability is a wide concept which concerns different aspects of the same topic. The increasing attention toward climate change and planet heath in the European Union, require technologies advancement with high energy efficiency and at the same time achieving a low environmental impact. The main critical elements in lithium-ion batteries are unevenly distributed around the world and sometimes scarce. These two factors could lead to geopolitical problems. Due to their geographical concentration, they also suffer from price volatility.

Considering the political availability of most used materials for batteries it can be stated that lithium accounts for 53 million tons of reserves worldwide with main concentration in South America, China and Australia. Some abundant materials that could be used as a replacement for lithium are sodium, zinc, magnesium and aluminium.

The geopolitical situation in the previously mentioned countries are all very different. For example in India and China, one of the main reason for economic growth is through increase of trade and exportation. The population of these two specific countries is also extremely large and therefore there is no problem finding labor to extract the materials. The problem lies more within the working situations for these people as well as the environment. These currently does not exist much legislation for the emission of greenhouse gases [33].

Also the extraction process of lithium could be a problem since it is very resource demanding and uses a lot of water in the extraction process. One metric ton of lithium is thought to require the usage of 500000 gallons of water in the mining process. Since Chile is the world's top producer of lithium, the lithium mines are located in rural areas with a remarkably diversified ecosystem. About 65% of the water in Chile's Salar de Atacama, one of the driest locations on earth, is used to mine lithium, forcing many of the area's farmers and community people to go for water elsewhere.
Additionally, the scarcity of lithium and cobalt creates concern about long-term sustainability because of the lower economic cost of 1 kg of lithium extracted versus the same quantity of recycled lithium. Another problem is related to the location of cobalt, the main part of which is located in the Democratic Republic of Congo, where human rights are not respected and it was already demonstrated that industrial mining and processing of metals has led to severe environmental pollution in that region. This explains why there are many efforts in investigating cobalt-free cathodes [34].

Chapter 3

Fire risk

Electric vehicles (EVs) are still in their infancy compared to internal combustion engine vehicles (ICEVs), which have undergone constant use and development over the past century. The reason is that linked with the perceived fire safety. This safety issue prevents the EV from taking over as the primary mode of transportation [35]. Road cars with electrified drive trains have a variety of ways and ways to store their energy. For this reason, there are many different forms of electric mobility. These range from mild hybrids, which enable electric motor support when starting up and increase the performance of internal combustion engines, to pure battery-powered vehicles, which can only be driven on electricity and require grid charging. Depending on the level of electrification, either mainly fossil fuels for internal combustion engine driving or rechargeable batteries for purely electric driving are used as energy sources. Hybrid driving is possible as soon as the vehicle drive is supported by at least two distinct energy storage systems (such as fuel and batteries) and two distinct energy converters (such as internal combustion engine and electric motor). The main types are classified in Table 1.

Vehicle Type	Electric Vehicle (EV)	Gasoline-Powered (Internal Combustion)	Plug-In Hybrid (PHEV)	Hybrid (HV)
Energy Source	Electric only	Gasoline only	Main: Electric Sub: Gasoline	Main: Gasoline Sub: Electric
Propulsion Mechanism	Motors	Engine	Combination of motor + engine	
CO2 Emissions	None	Yes	Yes	Yes
Fuel Facility Locations	Charging stations	Gas stations	Gas stations, chargers	Gas stations
Tax Liability	Low	High	Low	Low
Cruising Distance	Short	Long	Long	Long

Table 1. Classification of vehicle's types

These alternative kinds of propulsion, in contrast to internal combustion engines, typically rely on high-capacity batteries for their electrical energy, which pose fire concerns as well as other chemical or electrical problems because of their high energy content and highly reactive chemical components [36]. In the context of increasing urbanization and the increasing shift to underground infrastructures, the question of safety of these technologies is arising.

3.1 Chemistry and physics of fire

Combustion is defined as any chemical reaction in which a fuel, substance oxidizable, reacts with a comburent, oxidizing substance, releasing energy, generally in the form of heat. In this sense, the electrons pass from the fuel to the comburent. In the combustion reactions, reagents have more energy than products and this energy difference is equal to the heat emitted [37].
Related to this, there is the concept of fire triangle (Figure 18). The fire triangle, sometimes known as the combustion triangle, is a straightforward model for comprehending the elements required for most fires. Heat, fuel, and an oxidizing agent (usually oxygen) are the three components a fire needs to start, represented by the triangle. When the necessary materials are present and mixed together, a fire will automatically occur. By removing any one of the components in the fire triangle, a fire can be put out or preserved [38].

Figure 18. Fire triangle

The most common combustible substances are, to a large extent, composed of hydrogen and carbon and generally present in solid, liquid or gaseous form (wood, oil and natural gas derivatives). On the other hand, the comburent is almost always the oxygen present in the air. At the same time the concept of trigger energy must be considered. It is the quantity of energy needed to start or ignite a fire. This might change based on the fuel type and external factors like humidity and temperature. The rise in temperature is manifested by the emission of electromagnetic waves in the visible field. The reaction zone then appears bright and it is possible to call them flames. Therefore, after a combustion there is the production of heat, flames, gases and smoke. It is crucial to remember that even though trigger energy is required to start a fire, fuel, oxygen, and heat can all contribute to the fire's growth and spread.
The damages caused by the fire cannot be determined a priori, as its activation and propagation depends on many random variables such as the ignition phase and development, which in turn depend on the quantity and distribution of fuels, their geometric characteristics and ventilation conditions. It means that the only way to study a fire are assessment of the probability of risk, numerical simulations and experimental tests [37].

3.1.1 Factors of dependence of a fire

The severity of the fire depends on four main important factors: fire load, velocity of combustion, ventilation systems and geometry of the compartment.

The fire load is the amount of heat developed after a complete combustion of all the materials present in the compartment. It depends on the typology and quantity of combustion material. Higher amount of material means higher amount of heat developed and consequently higher fire load.

For what concern the velocity of combustion, it is possible to distinguish two different cases:

- If there is lack of oxygen, the velocity of combustion is proportional to the amount of air flowing through the apertures and it not depends so much on the quantity, porosity or dimension of the combustion fuel. It means that the combustion is governed by the ventilation;
- On the other hand, if the amount of oxygen is more than the necessary, the velocity is not dependent on the flowing air but it depends on the properties and on the quantity of the fuel. In this case, it is possible to say that the combustion is controlled by the layers of fuel [37].

The ventilation represents the amount of flowing air necessary for the complete combustion of the fuel. The volume flow rate entering (Q) follows the formula:

$$Q_a = kA_f\sqrt{H} \qquad (1)$$

Where Af and H are the area and height of the apertures respectively, k is a coefficient that depends on the difference in temperature between the inner and outer ambient and the ratio between the volume of the gas produced per unit mass and the volume of air required for the complete combustion of the unit mass of fuel. The use of natural or artificial ventilation is crucial in locations where there is the possibility of accumulation of flammable gases and vapors.
At the end, also the geometry of the ambient is one of the most important factor to take under consideration [37][39].

3.1.2 Fire propagation

Fire propagation is linked to convection, conduction and thermal radiation.

The main characters in fire propagation are the hot smoke currents leaving the combustion zone. They propagate thanks to the convection phenomenon. Some important aspects are:

- Thermal expansion of air caused by the increase of temperature: higher temperature means a proportional increase of the volume occupied by the gas. This phenomenon is responsible for the brokerage of windows and doors during a fire.
- Ventilation actions: the air currents permit the smoke movements and their main effect is the determination of horizontal movement not only of the smoke but also of the fire itself.
- Chimney effects: the main mechanism for the smoke movement is the draught. This depends on the presence of “chimneys” such as stairs, lift shafts and so on. It means that in the buildings all the plane crossing could be very dangerous if not adequately protected.
- Improper functioning of the mechanical ventilation: the ventilation systems, if not well projected, can cause fast transfers of smoke and heat

through air ducts. For this reason, fire dampers and automatic stop systems are necessary.

The second mechanism of fire propagation is thermal radiation. The heat of radiation is transmitted directly from the source in an electromagnetic way. The power of the radiation is inversely proportional to the square of the distance and this means that the radiation is more dangerous when the interested objects are nearer. Not all the external surface of a burn object has the same radiation power: in particular the apertures are very problematic, or in general, all the surfaces in which it is possible to see flames.
The last factor for fire propagation could be the conduction through the separation structures. Due to the continuity existing between the different parts of a structure, some parts may start to burn also if they are not directly in contact with the flames [37][39].

3.1.3 Fire dynamics

In the fire dynamic is fundamental to the location of the fire, so the behavior is different if it happens in an open or a confined environment. The main parameters are: peak thermal power developed, the total amount of energy released, thermal power growth rate, temperature values of air, smoke and surfaces in the nearby, quantity and speed formation of the combustion products.

Fire evolution is characterized by four phases (reported in Figure 19):

1. <u>Ignition phase</u>: it starts when the combustion material is in contact with hot source. In general, the available oxygen is overabundant because of the limited reactions in the initial phase. It means that this phase is rarely controlled by the available quantity of air. At the end of this stage, the rise of medium temperature is modest.
2. <u>Propagation phase</u>: in this stage other objects are involved and the fire dimension starts to increase and increase. The speed depends on the characteristics of the materials in particular conductivity and thermal capacity. If the heat is not sufficient to increase the temperature, a gradual extinction could be verified. Otherwise, if the balance is positive, the combustion will continue at a faster rate and the temperature will rise. The progress of the fire is not regular.
3. <u>Generalized fire (flash-over):</u> it is characterized by a rapid increase in temperature and a strong rise in gas emissions which expand and are transported horizontally and mainly in the upward direction. Fire propagates, and temperature rapidly increases but is not sufficient for the autoignition of all the combustion substances. Auto extinction is improbable at this stage. High quantities of smoke are developed.
4. <u>Extinction and cooling:</u> when all the combustion material is finished, the reduction temperature phase starts. It is due to the progressive decrease of residual heat input and heat dissipation through smoke. Fresh air gradually reduces the average temperature [39].

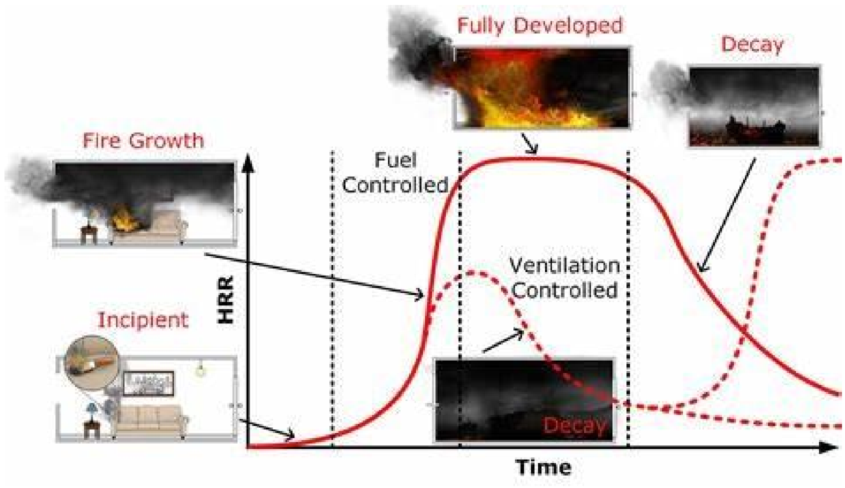

Figure 19. Phases of fire evolution

3.2 Potential fire hazards of EVs

Focusing the attention on lithium-ion batteries, EV fires are mostly related to their utilization. The amount of heat that could be released from an EV in the event of a fire also increases as EV manufacturers strive for longer electric driving ranges and add more LIBs. This rise in fire risk is correlated with the battery's (or fuel's) increasing mass and capacity. The production of toxic fumes and flammable/explosive gases during the burning of LIBs, including hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and hydrogen fluoride (HF), can endanger individuals who are involved. The fire-safety issues about EVs are intricate and complex, necessitating careful consideration [38]. However, a greater understanding of these important fire factors aids in the methodical assessment of EV fire. Some common Li-ions batteries include Lithium Iron Phosphate ($LiFePO_4$), Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NMC), Lithium Cobalt Oxide ($LiCoO_2$), Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) and Lithium-titanate ($Li_4Ti_5O_{12}$). The names of the different batteries come from the materials for cathodes except for $Li_4Ti_5O_{12}$ which is the anode material. A power-optimized Li-ion battery cell has a mass percentage of the flammable liquid of roughly 12%, graphite of about 12% and polymers around the cell of about 5%. The typical heat of combustion for the solvent from the battery cell can be found in Figure 20 with an average value of 16 MJ/kg used for typical solvents [41].

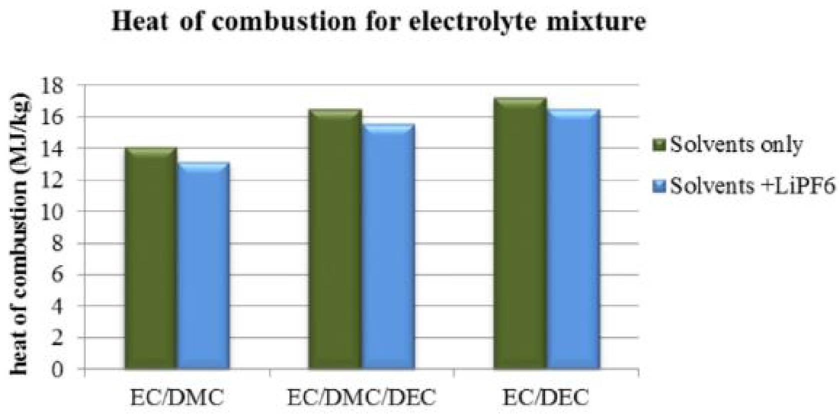

Figure 20. Heat of combustion for different electrolyte mixtures

In the following sections some key fire parameters are reported for a better understanding and to provide a systematic evaluation of EV fire.

3.2.1 Thermal runaway

The most dangerous event following a cell failure is the thermal runaway. A common occurrence in chemical and combative processes, thermal runaway refers to an overheating incident in which exothermic chain reactions take place and outperform cooling. The rate of heat generation, temperature and pressure gradually increase during thermal runaway reactions [31]. Due to the vaporization of some reaction mixture constituents and the breakdown of some gaseous products at high temperatures, the system pressure may rise. In batch operations, the rate of reaction and production are controlled by maintaining the amounts of the reactants, solvents, catalysts and non-reacting chemicals charged to a reactor. Chemical reactions conducted in batch reactors may get out of control due to other reasons including a change in operating conditions and the usage of inappropriate materials [42]. For an electric vehicle, after a thermal runaway, the gases vent out in the form of a jet. This behaviour is particularly noticeable during the initial stage of venting of a cell or a module. At this point, electrolyte makes up the majority of the venting gases. However, it is not anticipated that the flame will be as lengthy as a jet fire from a pressurized gas tank. If a fire does not originate from the battery, the fire hazard may be similar to an internal combustion engine car. An electric battery vehicle may also experience a vapour cloud explosion [25].

Under typical working conditions, the sum of the reversible heat produced by the electrochemical processes and the irreversible heat produced by the charging/discharging process is the total heat emitted in the LIB. The formulation is the following:

$$Q_{tot} = Q_{rev} + Q_{rxn} \qquad (2)$$

Where Qreve and Qrxn are described respectively by:

$$Q_{rev} = -I * T * \left(\frac{\partial E_{OC}}{\partial T}\right) = -a_s * J * F * T * \left(\frac{\partial E_{oc}}{\partial T}\right) \qquad (3)$$

$$Q_{rxn} = I * (E_{oc} - E) = a_S * J * F * (E_{oc} - E) \qquad (4)$$

In which I is current, T is the absolute temperature, Eoc is the open circuit potential, E is the potential of the cell, (Eoc – E) is the overpotential accounting for irreversibilities such as ohmic losses, charge-transfer overpotential and mass-transfer limitation, as is a specific interfacial area of the electrode, J is the transfer current that resulted from the intercalation/deintercalation of lithium and F is the Faraday constant [43].
The causes of the cell temperature increase are numerous. Figure 21 illustrates various forms of abuse that could result in a thermal runaway in a single cell, which could then spread to nearby cells and finally the entire battery system. The point of no return for the TR is typically about 150-200°C but it differs for different time scales, cells, battery pack layouts, abuse type and methods [25].

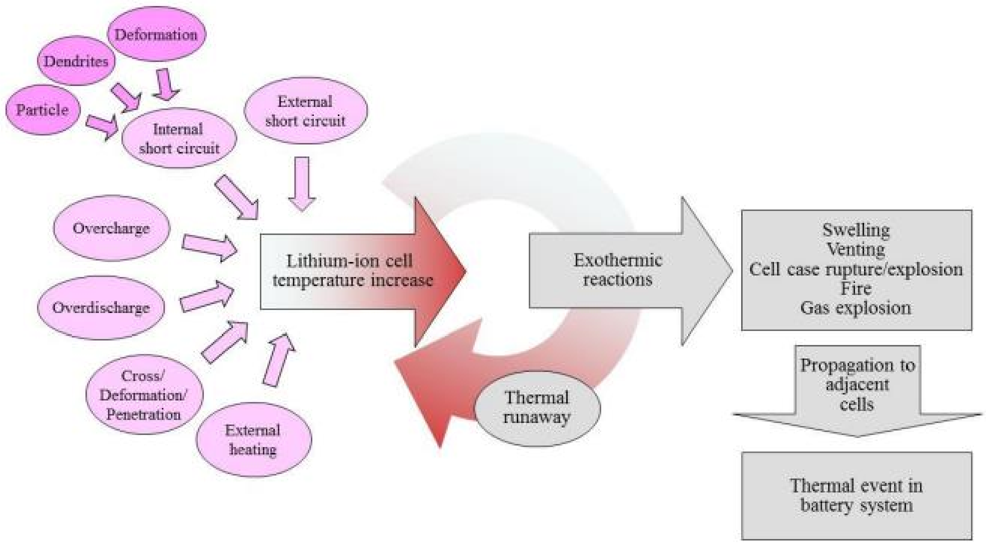

Figure 21. Schematization of thermal runaway causes and effects

As said before, an electric vehicle after a thermal runaway generates gases in the form of a jet. It can occur if the battery pack is compromised or burst after an accident or other catastrophic event, triggering the release of flammable electrolyte chemicals. These substances have the potential to ignite quickly and produce a jet fire if they come into touch with an ignition source, like a spark or flame. A jet fire varies from a typical fire as its initial momentum has a significant influence on the flame characteristics. Jet fires normally correspond to longer flame lengths and higher heat fluxes compared to traditional vehicle fires. The mass flow rate (kg/s) can be calculated by:

$$\dot{m} = C_d * \left(\pi * \frac{d^2}{4}\right) * \rho u \qquad (5)$$

Jet fires are especially dangerous because they send out a high-velocity stream of heat and flame that can quickly and significantly destroy nearby thins, such as other cars and structures. Also, they produce a great deal of heat, which can make it challenging for firemen to approach and put out a fire.
Some of the key parameters that can be calculated or measured in a jet fire include:

- Jet flame length;
- Flame temperature;
- Heat flux (the rate of heat transfer per unit area);
- Velocity of the flame front;
- Radiation intensity;
- Pressure and gas flow rate

The flame length can be estimated using different models, for example Heskestad model, Delichatsios model and Lowesmith et al.'s model [41].

These parameters can be used not only to assess the risk of a jet fire, but also to design safety measures.

3.2.2 Energy release from EV battery fire

A large quantity of flammable materials are contained in electric vehicles. They are mainly the power system (battery) and plastic components. The mass of polymers used in current automobiles ranges from 100 to 200 kg, which is larger than gasoline (less than 50 kg).
For what concerns the battery in particular, since LIB contains a variety of flammable materials, its heat of combustion is influenced by chemistry, packing, capacity and state of charge (SOC). In general, the heat of combustion of this kind of batteries is around one order of magnitude smaller than gasoline. For example, for a 2,9 Ah (11 Wh) commercial pouch-type LIB, the heat of combustion is found to be about 4 MJ/kg, while it is about 2 MJ/kg for a 18650 cylindrical battery. The thermal energy released from the battery fire, which includes both the thermal runaway heat inside the battery (also known as the internal heat) and flame sustained by the flammable gases injected from the battery (also known as the flame heat), is much higher than the electrical energy stored in the battery. As it is visible in Figure 22, the battery fire can release 5-10 times more energy of the stored electrical energy [30].

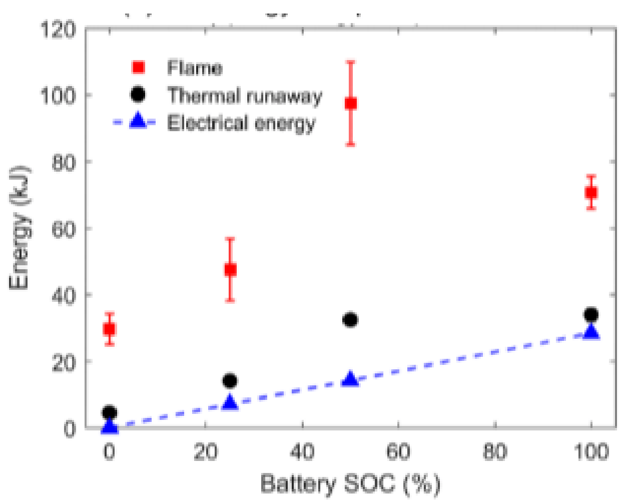

Figure 22. LIB energy comparison vs SOC

So, assuming the heat of flaming combustion is seven times its stored electrical energy, the total heat release from burning an EV battery pack of 90 kWh is [42]:

$$Q_{LIB} = 90\ kWh * 7 = 2{,}3\ GJ \qquad (6)$$

3.2.3 Heat Release Rate (HRR)

The HHR (or the power of fire) is the most important parameter to characterize a fire but also the most critical. Compared to the heat of combustion or the total heat release from fire, HRR is a better indicator of fire intensity and hazard. It can be expressed with the following formulation [47]:

$$HRR\ [MW] = \dot{m}\Delta H_e = A_f \dot{m}''\eta\Delta H_c \qquad (7)$$

Where $\dot{m}$ is the burning rate [kg/s]; $\Delta H_e$is the effective heat of combustion [MJ/kg]; Af is the floor/surface area of fuel [m2]; $m''$is the burning flux [kg/m2-s]; η is the combustion efficiency and ΔH_c is the heat of combustion.

It is defined as the variation of thermal power in a combustion reaction, expressed in kW, calculated compared to the fuel, to the ventilation conditions and depending on the geometric characteristics of the material. It can be also defined as the combustion speed since one kW is equivalent to one MJ/s. Higher is the maximum value of the curve, the higher will be the burning rate.

In the curve, three phases are distinguished: the starting phase represents the fire propagation in a quadratic form, the intermediate phase refers to the stationary stage and it is constant and the final phase is related to the extinction of the fire in a linear form [45][46]. The ideal curve is reported in Figure 23.

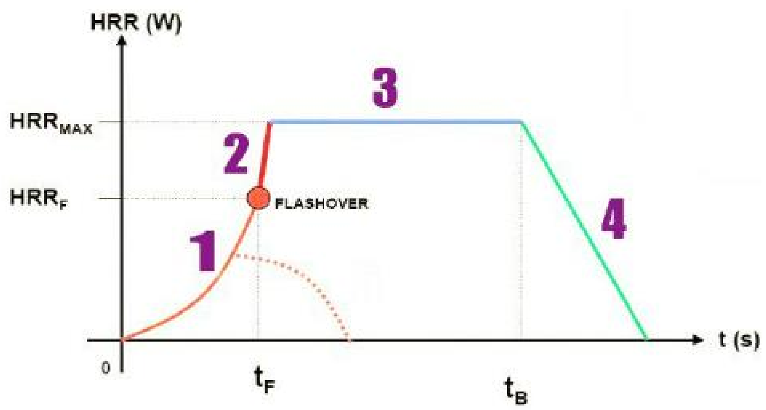

Figure 23. Ideal heat release rate curve

The reference HRR curve for the vehicles combustion is a curve developed taking into account experimental results and reported in Figure 24 [47].

Figure 24. General curve of an internal combustion engine vehicle (ICEV)

The curve increases until a peak of slightly more than 8000 kW is reached at around 1500 seconds. This curve will be taken as a comparison for the validation of the results in this paper.
In particular, focusing the attention on LIBs, based on the test data in the literature, the PHRRs (peak heat release rate) of different LIBs are summarized in Figure 25 [48]. They approximately follow the rule:

$$PHRR = 2E_B^{0,6} \qquad (8)$$

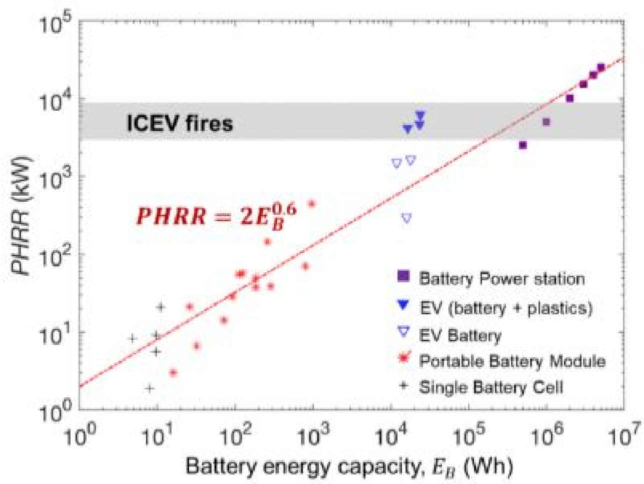

Figure 25. Peak heat release rate based on test results

3.2.4 Smoke and Toxicity

Lithium-ion battery fires can release toxic smoke when they burn. The smoke produced by these fires can contain a range of harmful chemicals, including carbon monoxide (CO), hydrogen fluoride (HF), hydrogen cyanide (HCN) and various metal oxides. Inhaling the smoke from a lithium-battery fire can cause serious health problems, including lung damage, eye irritation, and chemical burns to the skin and eyes. In addition to the smoke, the heat generated by this

type of technology can also cause toxic fumes to be released from the materials used in the battery. For example, burning lithium metal can release highly toxic lithium hydroxide fumes, while burning the electrolyte used in the battery can release hydrogen fluoride fumes [49].
The decomposition of LiPF6 is promoted by the presence of water/humidity according to the following reactions:

$$LiPF_6 \rightarrow LiF + PF_5 \quad (9)$$
$$PF_5 + H_2O \rightarrow POF_3 + 2HF \quad (10)$$
$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \quad (11)$$

The toxicity of HF and its derivative hydrofluoric acid is well known, however, there are no data on the toxicity of POF3, a reactive intermediate that would eventually react with water or other organic molecules to produce HF. These gas emissions vary between EV makes and types, with the size and chemistry of the LIB having an impact on any potential gas emissions [50].
In addition, it’s important to remember that lithium-ion batteries can catch fire if they are damaged, overcharged, or subjected to high temperatures. To minimize the risk of a battery fire, it’s recommended the use of only certified batteries to meet safety standards, and that follow manufacturer guidelines for charging and storing the batteries. In the event of a lithium-battery fire, it is also important to consider the potential environmental impact of the fire. They contain several toxic and flammable chemicals that can pose a hazard to the environment if released. For example, the electrolyte used can contaminate soil and water, while the burning of battery components can release harmful pollutants into the air [49][50].
Figure 26 shows the total amount of HF, HCl and HBr measured during an experimental test by FTIR compared with the one captured by the gas-washing bottles. The second type is very sensitive, and for this reasons the amount of the same gases are much higher.

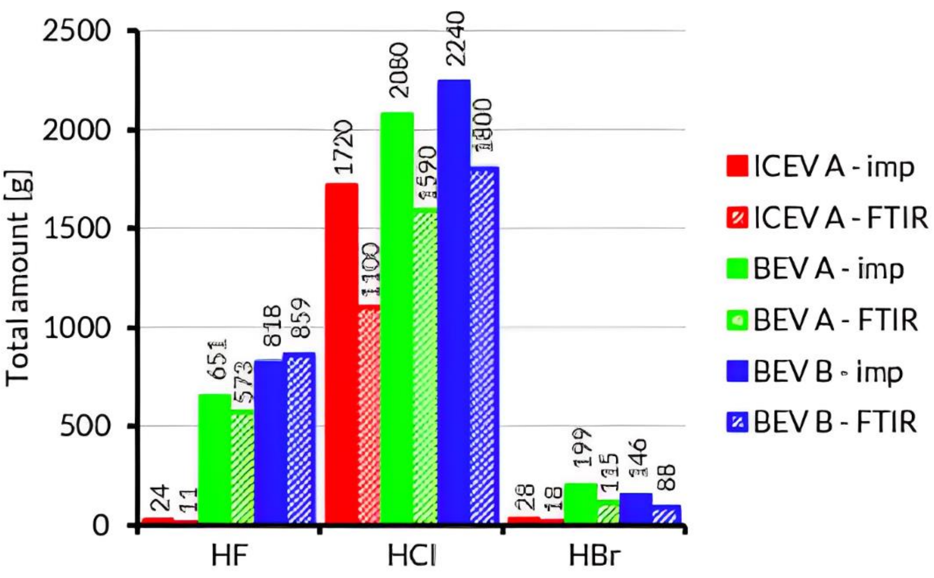

Figure 26. HF, HCl and HBr measuring test for ICEVs and BEVs

As it is possible to see, for all the three (fluoride, chloride and bromide) the amounts are higher in case of BEV with respect to the internal combustion engine cars.

3.3 Criticality of gallery fires

Galleries are a place where events like fires are very rare and even more the repercussions on structures, plants and people are rare. Nevertheless, if not studied in advance can cause serious disasters.

3.3.1 Security elements of the road tunnel

Measures directly connected with the security of the vehicles in a gallery can be of different: planning, plant engineering, of adjustment etc..

The ventilation system is particularly important to remove smoke and other harmful gases from the tunnel, ensuring that drivers and passengers can breathe easily. There are different kinds of ventilation systems: longitudinal with jet fans or with Saccardo nozzle injections; semi-transverse ventilation; transverse ventilation with uniform supply and extract of air or with remotely controlled dampers; massive point extraction systems or combined ventilation systems. The most used is the longitudinal ventilation and it is also the one used for the development of the project.

Linked to the ventilation system there is the backlayering phenomenon. It refers to the accumulation of smoke or other harmful gases behind a fire as it burns in a confined space, such as a tunnel. This can occur when the ventilation in the tunnel is not sufficient to remove the smoke and gases produced by the fire. The term “backlayering” refers to the way that the smoke and gases can build up in layers, with the most dangerous gases being closest to the fire and the least dangerous gases being furthest away. This can create a hazardous environment for anyone trapped in the tunnel, including firefighters who are trying to extinguish the fire. The backlayering phenomenon is defined as the return length of the smoke in the top layer of fire when the longitudinal ventilation speed is less compared to the critical value [51].

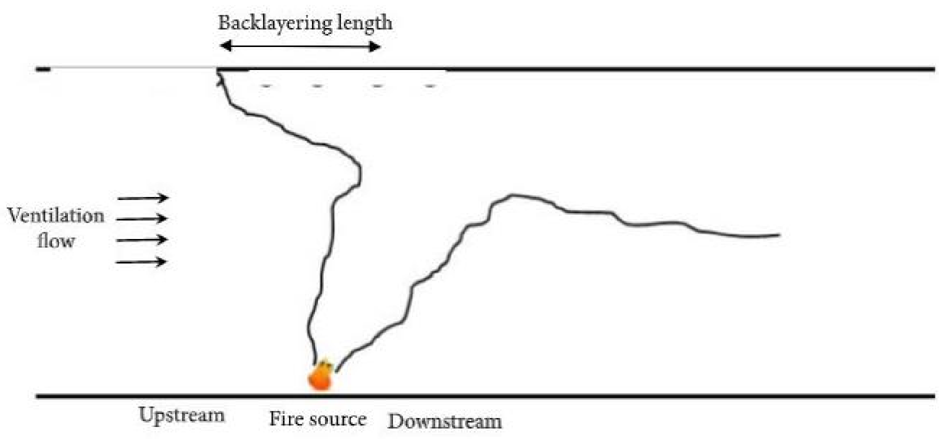

Figure 27. Backlayering effect

The speed limit can be calculated with Thomas formulation (2005):

$$u_{CR} = k * \left(\frac{g\dot{Q}H_t}{C_p T \rho_0 A}\right)^{1/3} \qquad (12)$$

The most difficult part in the resolution of this equation is the calculation of the temperature of the hot layer. A simpler formulation is given by de Ris:

$$u_{CR} = \frac{\Delta\rho g H}{\rho_0 u^2} \qquad (13)$$

The phenomenon can be eliminated if the result of this expression is lower than 1. To mitigate the risk of backlayering in a tunnel, it is important to have effective ventilation systems in place that can quickly remove the smoke and gases produced by the fire. This may involve the use of fans, vents, or other equipment to move the air and prevent the build-up of harmful gases. Additionally, it is important to have emergency response plans in place and to train personnel on how to safely evacuate a tunnel in the event of a fire or other emergency [52].
Other safety devices are: escape routes and emergency pitches, signs, safety devices, passive interventions and sanitation operations.
Starting with escape routes and emergency pitches, they are realized in a design phase. Except for the shortest tunnels, all others must have emergency exits that allow people to leave the traffic tube on foot and head to safety in the event of an emergency. The following factors determine the ideal distance between emergency exits [53]:

- The types of vehicles using the tunnel, which determine the nature of the events that could occur;
- The volume of traffic and the number of tunnel users who may need to use the exits;
- The ability of the tunnel ventilation system to maintain sustainable conditions for tunnel evacuation;
- Incident detection and alarm systems;
- The nature of protected paths outside emergency exits (including their dimensions and the presence of significant gradients or stairs);
- Human behaviour.

For what concerns signs, inside the tunnel they are reduced to the minimum. This allows do not create contrast with the ventilation system and replaces the footprint of the signals with appropriate design criteria for the road system. Light signs shall be today, the most widely used and most effective system.
Safety gadgets serve as instruments for both preventing risk situations and educating users about them when they may occur inside the tunnel. Most road tunnels have emergency stations positioned at intervals along their length, usually equipped with emergency telephones and portable fire extinguishers (and sometimes hoses) which can be used by tunnel users in the event of failures. Of course, when the alarm is triggered all the safety systems are activated, which concern:

- Stopping the traffic flow entering the tunnel;
- The exit of vehicles into the tunnel;

- Adaptation of ventilation and emergency lighting;
- Diversification of sources of electricity (for major galleries) [53].

In addition, it is possible to apply some passive interventions related to the materials of the tunnel, their utilization and disposition.
Overall, the security elements of road tunnels are designed to detect and mitigate any risks or emergencies and to ensure the safe and efficient flow of traffic through the tunnel.

3.3.2 Performance thresholds for tunnel users

Lifesaving is addressed in performance design by considering behavioural and environmental aspects, or taking into account the effects of the fire on users of the gallery. The viability of tunnel users depends on the quantification of the effects on the exposed population and the zoning of the hazard flow within the structure, defined as the evolution of physical and chemical phenomena that determine critical states resulting from the occurrence of critical incidental events.

The consequences for the exposed population are determined by the characteristics of the critical event considered and measured in terms of absorbed incapacitating doses; the doses disability depends on the temperature and concentration fields of toxic substances and harmful inside the structure.
The reference performance thresholds are reported in the "Codice di prevenzione incendi" and they are reported in Table 2.

PERFORMANCE	THRESHOLD VALUE
Min visibility (height of 1.80m)	10 m
Temperature (max exposition temperature)	60°C
Max radiation	2.5 kW/m^2
FED (max amount of toxic gases)	0.1

Table 2. Reference performance thresholds

Therefore, in the evaluation of the results, these indicators will be taken into consideration.

3.3.3 Some examples from the literature

Despite statistics show that accidents that occur in the road sections in the tunnel are in fewer number than those that occur in road logs to the open sky, they involve greater concerns as they feature an amplification of the damages to the borne by both people and structures. In Italy, the number of accidents in tunnels is around 1.5% of the total accidents in the roads. Incidental situations which, as a result, are the greatest concern are those which results in the phenomenon of fire. The reason for this is that developed toxic fumes and gases can create considerable problems to people present in the tunnel and on the rescuers who must intervene [47].

In particular, the electric vehicle the situation is slightly different since they are still not so common. Although though EVs have been around for a while, their market share is still quite modest because of a variety of issues, including their high price, their short driving range, the lack of a charging infrastructure, and the desire of consumers for conventional vehicles.

A summary of some electric battery vehicle incidents is given in Table 3 and Figure 28 shows some photos of the incidents.

Year	Country	City	Vehicle	Fire location	Ignition	Consequence
2011[9]	China	Hangzhou	Zotye M300 EV	road		no one injured
2012[10]	USA	California	Karma	parking lot	overheating of fan	no one injured
2012[11]	China	Shenzheng	BYD	road	crashed by a car and then run into a tree	3 persons killed
2013 [12]	USA	Washington	Tesla	road	fire after running over large metal objects	fire
2013 [13]	Mexico	Merida	Tesla	road	fire after hitting a tree	fire
2014 [14]	Canada	Toronto	Tesla	Garage		fire
2013[15]	USA	California	Tesla	Road	Fire after running over large metal objects	fire
2016[16]	Norway	Gjerstad	Tesla	Charge station	Might be a short circuit	burnt

Table 3. Summary of some electric vehicle incident

As said in the previous sections, similar to how gasoline or diesel is the main fuel to feed ICEV fires, the battery is not only the fuel to power the EV but also the main fuel to feed the EV fire.

The market for electric vehicles is growing and EV ownership is rising along with it. This trend is driven by elements like a rise in environmental consciousness, financial incentives from the government, improvements in battery technology, and the creation of new charging infrastructure.

Meanwhile, the energy density of LIBs continues to rise, despite unresolved fire-safety difficulties. As a result, there will be more chances of EV fire accidents.

Figure 28. Electric vehicle incident with fire evolution

Chapter 4

Case study: methane car and electric vehicles in confined areas

4.1 Description of the project

Starting from different possible critical events in galleries, some different scenarios are identified. The chosen critical events are the following:

- fire ignition of a methane car;
- fire ignition of an electric vehicle.

The results are taken for two different positions of the vehicles in the gallery. In the first case, the car is positioned in the middle of the gallery while in the second case the vehicle is near the entrance.
A detailed discussion of the hypothesis made for the development of the model is reported in sections 4.2 and 4.3.

4.2 Fire Safety Engineering-Performance approach

Fire Engineering relays on suitable models based on system physics and it makes a dynamic prediction evolutionary of the fire. This method has as its strong point its extreme flexibility. By assigning several input data (domain geometry calculation, ventilation condition, fuel type and amount, HRR curve vs time), it is possible to create even very complex field models.

There is a wide variety of models that can be used to predict the evolutionary dynamics of fire, depending on the parameters and equations that are used to solve the problem. A first distinction can be made at the parametric level:

- Models with concentrated parameters (or zones that precisely solve one or more approximate equations in which operational parameters appear);
- Distributed parameter (or field-solving models which solve a set of exact equations).

A second distinction can be made based on mathematical and physical principles and according to their complexity:

- Empirical and semi-empirical parametric models;
- Eulerian and Lagrangian numerical models.

For what concerns the simulation, there are two models: "zone" and "field" reported in Figure 29.

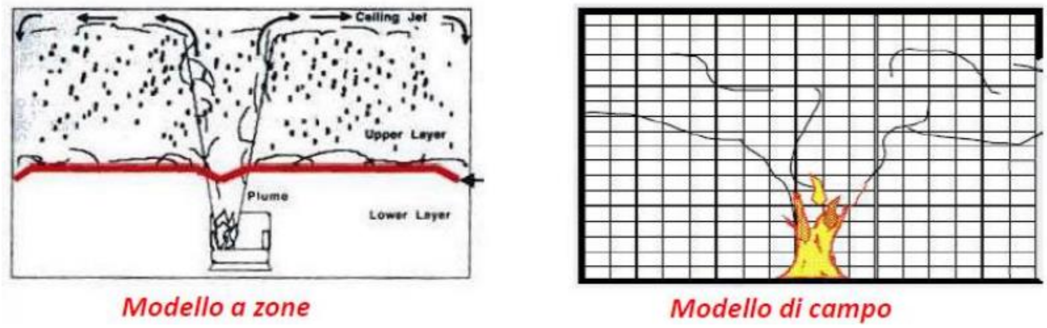

Figure 29. “Zone” and “Field” model in FDS simulations

All FDS models that include combustion must define a gas phase reaction: the combusted fuel to combustion products. The simple chemistry approach is investigated. The fuel consists in carbon, hydrogen, oxygen and nitrogen that react with oxygen to form water, carbon dioxide, carbon monoxide and nitrogen.

Two other parameters must be specified: the heat of combustion and the radiative fraction. The first one can be specified by seeing the SFPE Handbook of Fire Protection Engineering.

Pyrosim is an FDS precompiler. The software is specifically indicated for input data processed by FDS. The presence of graphics during the pre-processing phase facilitates very much the decision and evaluation of the data that it is possible to introduce into the software. Therefore it is relatively easy to modify data instantaneously and check the changes made to the elements that make up the geometry of the structure under examination (such as changes to the mesh or conditions to the outline). For these reasons, Pyrosm is perfect to fit the results of this thesis. In addition, using the same equations as FDS for processing data and the same post-processor (Smokeview), is particularly suitable for the simulation of medium/slow evolution fires and for the study of smoke propagation.
PyroSim provides four editors for the fire model developed: the 3D View, 2D View, Navigation View, and the Record View. If an object is added, removed, or selected in one view, the other views will simultaneously reflect the change. The navigation view is a tree-like view on the left side of the PyroSim main window (reported in Figure 30).

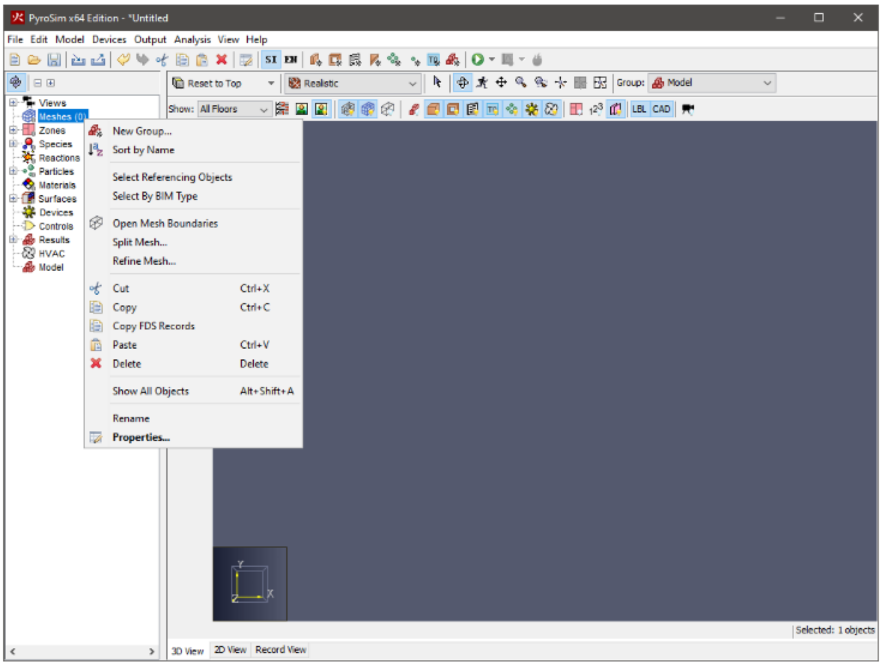

Figure 30. Pyrosim main window

The 3D view gives a representation of the current model and the 2D view is useful for sketching geometry such as walls and furniture in the fastest and more precise way.

4.3 Fire modelling

4.3.1 Mesh

In Pyrosim it is possible to create a mesh to define a certain control volume in which the simulations will be performed. The mesh length is around 250 m, chosen to avoid excessive long simulations but at the same time obtain correct results. In this particular case the mesh is divided in three parts as it is possible to see in Figure 31.

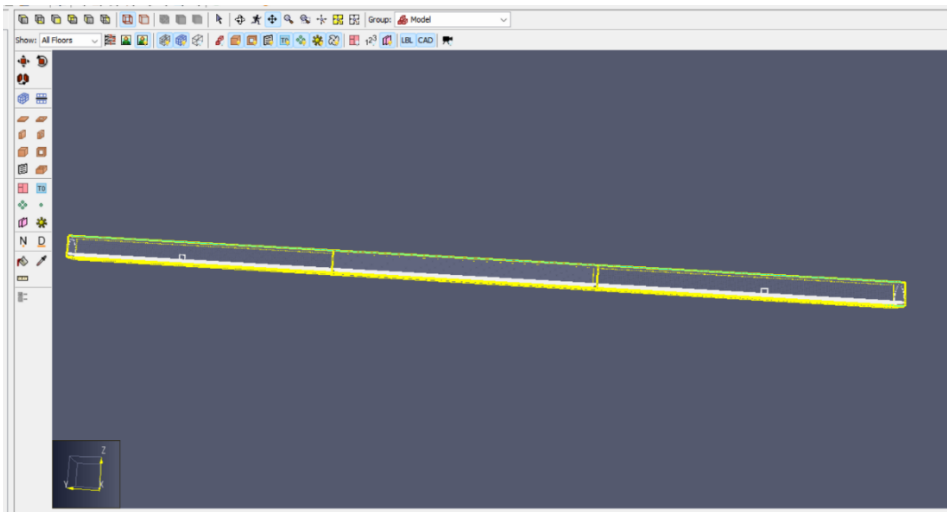

Figure 31. Mesh division

It is composed of 399616 cells. One part is thicker and it contains 324352 cells with a cell size of 0,25 x 0,2490 x 0,25 m and the other two parts are less dense each with 37632 cells and with a cell size of 0,5 x 0,5 x 0,5. The fire and all the most important elements will be positioned in the thicker part. The difference in the meshes is visible in Figure 32.

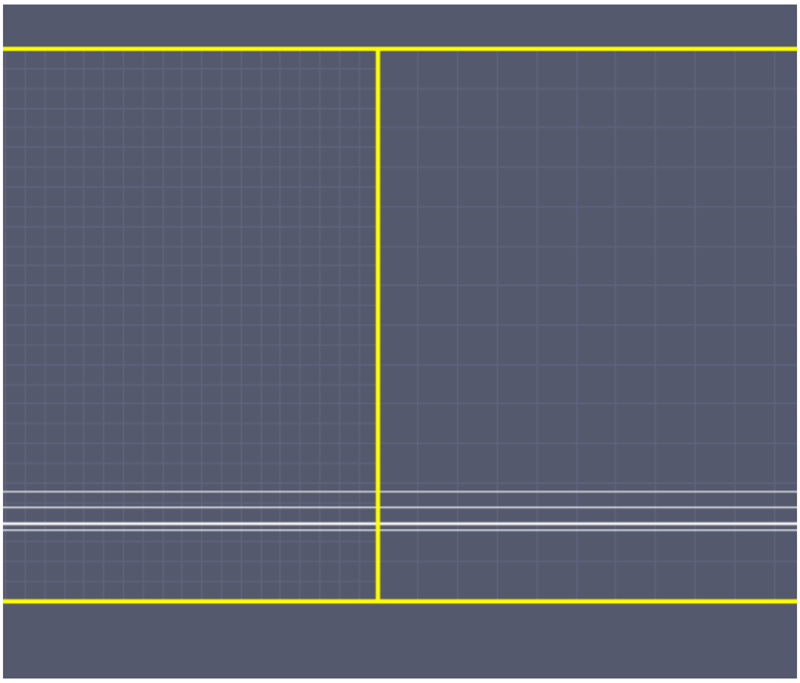

Figure 32. Different meshes of the model

To arrive to this mesh choice, a trial and error method was used. This to reduce as much as possible the complexity of the simulation but at the same time to have appreciable results.
Different simulations will be performed with different positions of the burnt car, so the meshes will be moved depending on the simulation. Once the correct geometry was found, all the other elements were inserted in their positions.

4.3.2 Gallery

The gallery taken under consideration is a unidirectional highway tunnel with two roadways as the one reported in Figure 33. The figure of the tunnel was imported from an online website (free3D.com) from which a .fbx file was discharged.

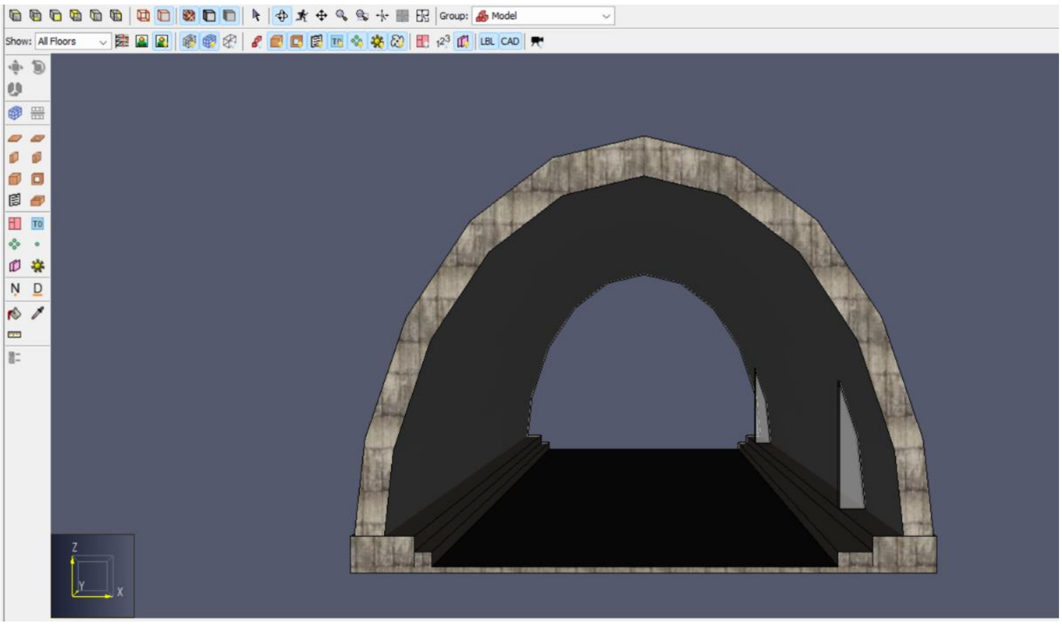

Figure 33. Tunnel used for simulations

The main characteristics of the tunnel are the following:

- two lanes, one for normal transit and the other for overtaking, with the same direction each of 3,9 m in line with the international guidelines;
- following the directives, the height must be more than 4,5 m. In this specific case is set as 5,7 m;
- a gallery of 256 m length is considered to avoid very long simulations and at the same time obtain correct results;

To ensure the security of the structure two emergency exit are represented. The optimal distance between them is usually estimated from 100 up to 500 m [52]. In this case, it was chosen a distance of 180 m to remain in the control volume of the gallery.

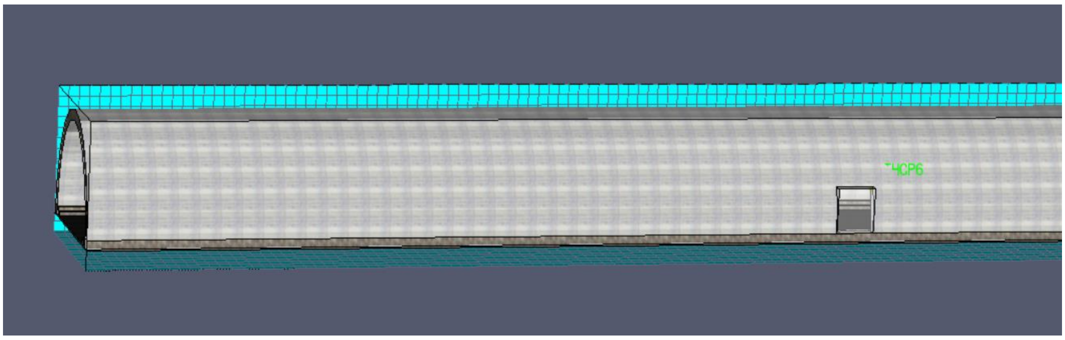

Figure 34. Emergency exit of the gallery

The material considered for the structure of the gallery is concrete.

4.3.3 Ventilation system

The recent EU directive (EU 2004/54/CE) on the minimum safety criteria for tunnels in the trans-European road network acknowledges the significance of ventilation and ventilation control. This Directive addresses the requirement for systems to control the pollutants emitted by road vehicles during routine and congested operation as well as the management of heat and smoke in the event of a fire [48].
Tunnel ventilation is based on the application of one of two principles:

1. Dilution of polluted air/smoke or
2. Removal of polluted air/smoke

The normal operation typically benefits from dilution, in which case the goal is to keep the vision and air quality above the limit threshold. In an emergency condition, air renewal techniques, such as smoke and air extraction, are appropriate for managing smoke. Dilution can, however, improve tenability, for instance, by lowering harmful gas concentrations. As a result, dirty or smoke-free air is substituted for contaminated air and is either mechanically supplied or brought in through the portals [48].
Since the gallery considered is unidirectional, longitudinal ventilation with jet fans is adopted. It ensures a longitudinal flow (Figure 35) along the axis of the tunnel. Two jet fans are positioned in the tunnel composed by an impeller, started using an electric motor, with blades that by rotating push the air flow. Differently from classic fans these are not channelled.

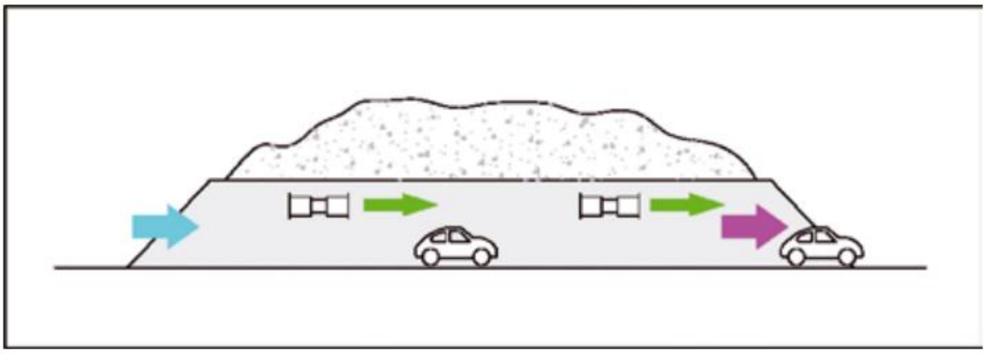

Figure 35. Longitudinal ventilation with jet fans in a road tunnel

To correctly identify the type of fan to use in the gallery, the following points must be taken into account:

1. Type of fan chosen with specified characteristics of flowrate, pressure, number of revolutions, supply voltage, and frequency;
2. Orientation;
3. Construction;
4. Engine position;
5. Accessories.

The FDS model requires the flowrate of the fan as input. The flowrate of the fan can be calculated with the following formulation:

$$Q_V = V * R \qquad (14)$$

Where Qv is the volumetric flowrate of the fan (m^3/s), V is the ambient volume (m^3) and R is the hourly turnover.
It is assumed to have couples of jet fans divided in two groups with a distance of 80 m. They switch on after three minutes with a rump-up time of 30 seconds. The length of each jet fan is 2.25 m and the diameter is 0.30 m. In addition, the volumetric flowrate is 24 m^3/s and they are installed attached to the upper part of the gallery.

Figure 36 and 37 report the 2D and 3D view of the jet fans as they appear in Pyrosim.

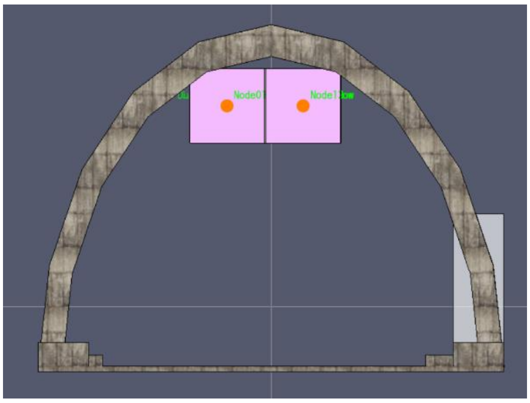

Figure 36. 2D view of modelled jet fans

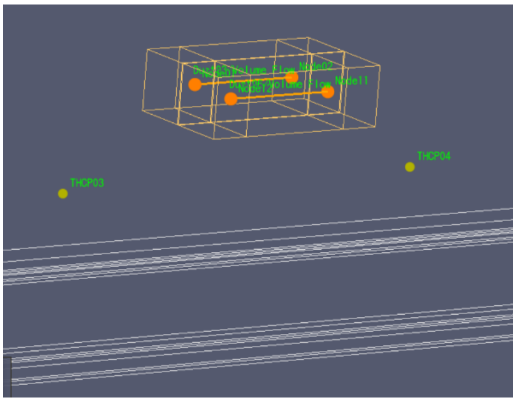

Figure 37. 3D view of modelled jet fans

Due to buoyancy forces, hot smoke from a fire in a tunnel rises. Smoke will spread along the ceiling on both sides of the fire if the air is not moving or is flowing extremely slowly. If the tunnel slopes, buoyancy effects might be enough to force the tunnel's bulk flow to migrate higher following the gradient of the tunnel. Additionally, smoke will be carried in this direction. Fresh air is sucked in behind these layers of smoke, or towards the fire. Stratification describes this division between the warmer lower layers and the hotter higher layers.
As it will be demonstrated in the simulations, where the incident part of the tunnel is ventilated, a longitudinal airflow drives the smoke downstream from the fire through the tunnel while slowing its movement on the upstream side.

Backlayering is the term for the situation where the smoke layer moves counterclockwise to the direction of the wind [48].

4.3.4 Materials

The study was subdivided in two parts. In the first part a common methane car is studied while in the second part the results for an EV are shown. For both scenarios, fires are constituted by vehicles designed as blocks in a rectangular form with certain dimensions (reported in Table 4).

Typology	Length [m]	Width [m]	Height [m]
Methane car	5	2	2
Electric vehicle	5	2	2

Table 4. Dimensions of the modelled vehicles

In addition, it is assumed that only one side of the parallelepiped burns, the upper one.

4.3.3.1 Methane car composition

In the case of a methane car burning it is necessary to take into account all the main materials as it will be done also for the electric vehicle. It is not easy to find the accurate percentage of the materials used in a vehicle but, generally speaking, an example of a typical breakdown of the material used in a modern car is reported:

1. Steel accounts for approximately 60% of the vehicle's weight;
2. Aluminum is from 5 up to 10%;
3. Different types of plastics such as polyurethane (PU), polypropylene (PP) and polyethylene (PE) which account for around 15% of the total weight;
4. Glass is around 4%;
5. Tyres (rubber) represent around 4%;
6. Lead composing the battery accounts for around 5%
7. Carbon fiber, magnesium, zinc and titanium: these materials may account for less than 1% of the vehicle's weight, as they are only used in certain high-performance or specialized components.

These percentage are approximate and can vary depending on the specific model of the vehicle [55]. Fluids are excluded. For the simulations in this paper, the value used are reported in Table 5.

	Mass Fraction	Material
1	0,6	STEEL
2	0,06	Aluminum
3	0,04	Glass
4	0,05	Paint
5	0,16	Plastics
6	0,04	Tyres
7	0,05	Battery (lead)
*		

Table 5. Materials used for the characterization of the methane car

Pyrosim permits to use the parameters for the combustion products of only one material without giving the possibility to make the weighted sum of all the components. Only one material must be chosen to represent in the best way possible the consequences of the entire vehicle. In Table 6, all the combustion products with the respective materials are reported [54].

Materiale	Quantità per autovettura [kg]	ΔH_T [kJ/g]	y_{CO} [g/g]	y_S [g/g]
Gomma	58,8	28	0,08	0,08
Vernici	31,5	-	0,114	0,166
Polyester-polyamide (Tessili)	9,45	-	0,008	0
Olio motore	5	46	-	-
Liquido freni	1	41,5	0,041	0,097
Liquido del servosterzo	0,5	41,5	0,041	0,097
Carburante	50	44,5	0,01	0,034
Olio del cambio	2,4	41,5	0,041	0,097
PU	19	-	0,2	-
PP	15	43,4	0,024	0,059
PE	11	43,6	0,024	0,06
Poliestere	11	32,5	0,08	0,089
PVC	8	16,4	0,063	0,172
Altre plastiche	26	34,06	0,08	0,09

Table 6. Materials and respective combustion products

From the table is evident that the main material, both for weight in the vehicle and combustion products is rubber, underlined in Table 7.

Material	ΔH_T [kJ/g]	y_{CO}[g/g]	y_S[g/g]
Rubber	28	0,08	0,08

Table 7. Rubber characteristics

These values are added in the model as byproducts of the reaction.
For what concerns the HRR curve, two input parameters are requested: the HRRPUA and the ramp-up time.
The HRRPUA of a vehicle is the heat release rate per unit area and it is typically measured in kilowatts per square meter (kW/m^2). It depends on various factors, such as the typo of fuel, the size and shape of the vehicles, and the ventilation conditions. The HRRPUA of a methane car can be lower than that of a gasoline or diesel-powered vehicle because natural gas is less combustible than liquid fuels. According to a study by the National Fire Protection Association (NFPA), this value for CNG-fueled vehicle is around 200 kW/m^2 [55]. This value is added in the model.
Regard the ramp-up time, it is difficult to provide a specific numerical value for it. However, it is worth noting that methane fires generally have a fast burn rate, due to the high flammability of the fuel. For this reason, a 30 s rump-up time is set.

4.3.3.2 Electric vehicles material

The 72% of batteries used in EVs in 2020 are NMC batteries and so, they are the most frequently used in the automotive sector. The cathode is composed of nickel, manganese and cobalt along with lithium. A very high specific energy of up to

220-240 Wh/kg can be achieved with this chemical. This is unquestionably a significant competitive advantage for a car because it enables the installation of more energy in the vehicle than other lithium-based technologies by enabling enormous amounts of energy to be stored with little weight and volume [56]. There are different types of NMC cathode composition:

- NMC 111 with Nickel 33.3%, Manganese 33.3% and Cobalt 33.3%;
- NMC 622 with Nickel 60%, Manganese 20% and Cobalt 20%;
- NMC 811 with Nickel 80%, Manganese 10% and Cobalt 10%.

The most common are the NMC 622 cells.
The typical battery which has a 60 kWh capacity has about 185 kg of minerals in each of its cell. The electrolyte, binder, separator and battery pack casing are not included in this calculation. The detailed percentage is reported in Table 8.

Mineral	Cell Part	Amount Contained in the Avg. 2020 Battery (kg)	% of Total
Graphite	Anode	52kg	28.1%
Aluminum	Cathode, Casing, Current collectors	35kg	18.9%
Nickel	Cathode	29kg	15.7%
Copper	Current collectors	20kg	10.8%
Steel	Casing	20kg	10.8%
Manganese	Cathode	10kg	5.4%
Cobalt	Cathode	8kg	4.3%
Lithium	Cathode	6kg	3.2%
Iron	Cathode	5kg	2.7%
Total	**N/A**	**185kg**	**100%**

Table 8. Weight and percentage of different materials in a lithium-ion battery

The cathode, which is likely the most significant and expensive part of the battery, contains the greatest diversity of minerals.
The battery composition assumed in the model is reported in Table 9.

	Mass Fraction	Material
1	0,282	Graphite
2	0,157	NICKEL
3	0,108	Copper
4	0,054	Manganese
5	0,043	Cobalt
6	0,032	Lithium
7	0,027	Iron
8	0,189	Aluminum
9	0,108	STEEL
*		

Table 9. Material composition of the lithium-ion battery assumed in the model

As said in the previous section usually the battery pack is positioned in the bottom part of the car and this general rule is used for the development of this model. Since the weight of an electric vehicle depends almost on the battery, its composition is crucial and it became the most relevant component of the entire car. For example, an electric Fiat 500 weighs exactly 385 kg more than the petrol Fiat 500 [57]. This of course represents also an issue to solve in to reach lighter electric vehicles.
The chosen battery has the characteristics reported in Table 10. It takes into account a passenger car with medium dimensions [58].

Characteristics	Value
Energy	42 kWh
Autonomy	320 km
Power	87 kW
Width	1.69 m
Length	3.61 m

Table 10. Battery characteristics of the new Fiat 500 electric

All this data are inserted in the model.
The weight percentage of the battery in an EV can vary depending on the specific make and model of the vehicle. According to Fiat, the lithium-ion battery pack in the Fiat 500e weights approximately 272 kg, which is around 20% of the vehicle's total weight (1352 kg) [59]. The other materials in the car are listed below:

1. Steel: used in the construction of the vehicle's body and frame to provide strength and durability accounts for around 55%;
2. Aluminum: used in some parts of the vehicle, such as wheels and suspensions components, to reduce weight and improve fuel efficiency is almost 10%;
3. Plastics: used for interior trim and exterior panels, due to their lightweight and durability is 8%;
4. Glass: used for vehicle's windows and windshield is about 4%;
5. Rubber is around 2%
6. Others: 1%

All the components are inserted in the model as reported in Table 11. It summarizes all the considerations of the section.

	Mass Fraction	Material
1	0,0564	Graphite
2	0,0314	NICKEL
3	0,0216	Copper
4	0,00108	Manganese
5	0,0086	Cobalt
6	0,0064	Lithium
7	0,0054	Iron
8	0,57912	STEEL
9	0,14	Aluminum
10	0,08	Plastics
11	0,05	Glass
12	0,02	Tyres
*		

Table 11. Material composition of the electric vehicle considered in the model

In addition, as for methane car, rubber is set as the main material producing combustion products. Values of Table 8 are used also in this case.

For what concern the HRR, in case of an electric vehicle the heat release rate per unit area (HRRPUA) can vary widely depending on the battery chemistry and the state of charge. A general number is around 100 kW/m2 in a fully developed fire [60]. At the same time, electric vehicle fires have a relatively slower ramp-up time compared to gasoline or diesel vehicle fires due to the design of the battery systems, which typically have safety features to prevent thermal runaway and overheating. For this reason, a ramp-up time of 150 seconds is considered.

4.3.5 Combustion

The combustion reaction depends on the type of phenomenon under investigation. The burning of a methane car can be a dangerous event, as methane is a highly flammable gas. A methane vehicle on fire can produce a huge fireball and extremely hot temperatures. If the fuel tanks rupture or explode, the fire can be hard to put out and there is a chance of an explosion.
A simple combustion reaction is given for methane. Chemically, this combustion process consists of a reaction between methane and oxygen in the air. When this reaction takes place, the result is carbon dioxide (CO_2), water (H_2O) and a great deal of energy.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (15)$$

On the other hand, the complicated chemical reactions that take place during lithium-ion battery combustion can be influenced by several variables, including the material used in the battery, temperature, and the presence of reactive gases like oxygen. The thermal breakdown of the electrolyte during burning is one potential reaction that could take place and result in the production of flammable gases like ethylene and propylene:

$$2LiPF_6 \rightarrow 2LiF + 3PF_5 + C_2F_4 \qquad (16)$$

The released gases can ignite and contribute to the spread of the fire.
Meanwhile, the anode material can go through a procedure known as reduction, in which it sheds electrons and interacts with the electrolyte to release lithium ions. For instance, the lithium ions can interact with the graphite in a graphite anode to generate lithium graphite:

$$C_6 + Li \rightarrow LiC_6 \qquad (17)$$

This can also contribute to the generation of heat and further exacerbate the thermal runaway.
Additionally, the cathode material is capable of oxidation, a chemical reaction that releases heat and energy when it comes into contact with oxygen. Cobalt oxide, for instance, can combine with oxygen to generate cobalt oxide in a lithium cobalt oxide cathode:

$$CoO_2 + heat \rightarrow Co_3O_4 \qquad (18)$$

This can further contribute to the heating and thermal runaway of the battery.
From a study made by S. Shahid and M. Angelin-Chaab, as the temperature of the battery increases, multiphase fumes are released, which include gases, liquids and

particles. Therefore, it is crucial to study the fumes that are released during thermal runaway [61]. The summary of the gases vented during the thermal runaway of these battery chemistries is shown in Table 12.

Type	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)	C_2H_2 (%)	C_2H_4 (%)	C_2H_6 (%)
LFP	23.34	4.50	25.39	5.90	0.08	3.26	1.29
LTO	8.41	5.30	37.60	1.23	0.0008	1.38	0.40
NMC 1	12.39	30.30	13.22	10.50	0.0026	0.10	0.16
NMC 2	12.54	28.06	19.91	12.90	0.0027	0.16	0.21

Table 12. Summary of vented gas characterization

As said in section 4.3.3.2, the most common Li-ion battery used in automotive applications are NMC. From the table, it is evident that the biggest impact is given by carbon monoxide (around 30% of the total). CO is also an important fuel because it releases a considerable amount of heat when it burns in the air, depending on the reaction:

$$2CO + O_2 \rightarrow 2CO_2 \qquad (22)$$

Since in the model is not possible to set more than one active combustion reaction, the reaction related with CO combustion is set as input in the model.

4.3.6 Devices and controls

To better understand the evolution of the fire in the tunnel some devices and controls are added in the simulations.

Devices are appliances that permit the punctual measurement of the chosen parameters.
Thermocouples are sensors that are used to measure temperature in a variety of settings. They consist of two dissimilar metal wires joined at one end, and the other ends are connected to a measuring device. When the junction of the two wires is exposed to a temperature difference, an electromotive force (EMF) is generated, which is proportional to the temperature difference. They are popular due to low cost, durability, wide temperature range and fast response time. They can measure temperatures from as low as -200 °C to as high as 2500 °C depending on the materials used for the thermocouple wires. However, their accuracy can be affected by factors such as ageing, contamination, and electromagnetic interference, which must be taken into account during the calibration and use of the sensors [62].
Thermocouples are positioned in strategic points to know the temperature evolution along the tunnel in time. Nine thermocouples are considered: five near to the car (therefore near to the fire), two near to the two couple of jet fans and two near to the emergency exits. It is possible to see their position in Figure 38 and 39.

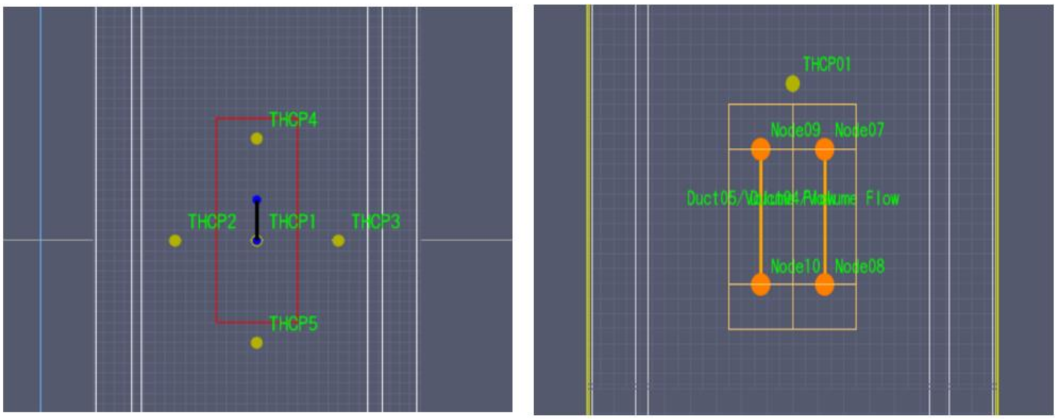

Figure 38. Position of thermocouples 1-2-3-4-5-01

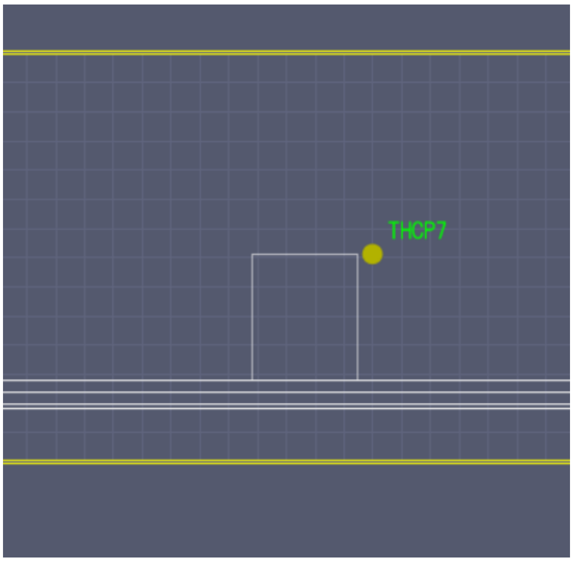

Figure 39. Position of thermocouple 7

The characteristic of all the thermocouples are the same and they are reported in Table 13.

Bead Diameter:	1,0 mm
Emissivity:	0,85
Bead Density:	8908,0 kg/m³
Bead Specific Heat:	0,44 kJ/(kg·K)

Table 13. Parameters chosen for the thermocouples in the model

Another important device is the calorimeter. A calorimeter is a device used to measure the amount of heat released or absorbed in a chemical or physical process. It works by measuring the temperature change that occurs when a reaction takes place or a substance is heated or cooled. There are different types of calorimeters, but the most common type is the constant pressure calorimeter, also known as a bomb calorimeter. This type of calorimeter typically consists of a sealed container, usually made of stainless steel, which is filled with a sample of the substance to be analyzed and a known amount of oxygen. The bomb is then placed in a water bath, and the temperature of the water is measured before and after the reaction (Figure 40). When the sample is ignited, it reacts with oxygen, producing heat, which raises the temperature of the water [63].

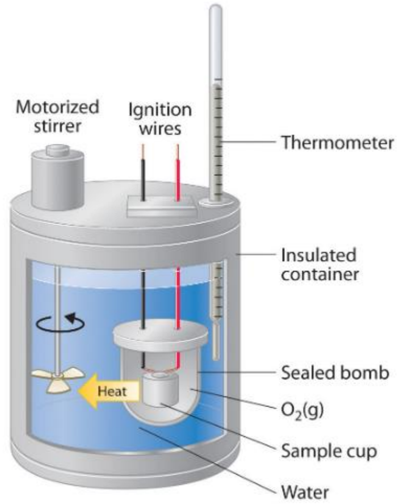

Figure 40. Calorimeter representation

By measuring the temperature change and knowing the heat capacity of the calorimeter, the amount of heat produced by the reaction can be calculated using the formula:

$$\Delta H = -mC\Delta T \qquad (20)$$

Where ΔH is the heat released (J), m is the mass of water in calorimeter (kg), C is the specific heat capacity of water (4,18x103 J/kgK), ΔT is the rise in temperature of water in calorimeter (K) [63].
In the model, one calorimeter is used to calculate the heat release rate of the fire and it is positioned near to the combustion place.

A flow measuring device is also used. It is a tool used to measure the rate at which a fluid, such as a gas or a liquid, is flowing through a pipe or channel. There are several types of flow measuring devices, each with their own advantages and limitations. In this case, thermal flow meters is taken into account to measure heat flow. These devices use the principle of thermal dispersion to measure the flow rate of a fluid. Thermal flow meters have two temperature sensors, one that is heated and one that is not. As the fluid flows over the heated sensor, it conducts heat away from the sensor, which causes a temperature difference between the two sensors (Figure 41). The heat loss from the sensor is proportional to the flow rate of the fluid [64].

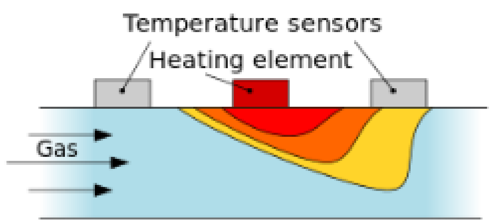

Figure 41. Flow measuring device

By measuring the temperature difference and the power required to maintain the sensor at a constant temperature, the flow rate of the fluid can be calculated. Also in this case the position chosen in the application is near to the fire.
All the numeric results will be reported in the section 4.4.

An apparatus for fire protection known as a sprinkler sprays water or other extinguishing materials to contain or put out a fire. Typically, sprinkler systems consist of a network of pipes that are joined to a water source and managed by a valve. The sprinkler heads on the pipes discharge water when a fire is detected (Figure 42). Sprinkler are intended to turn on at a certain temperature, typically between 68 °C and 165 °C [65] [66].

Figure 42. Sprinklers in a real gallery

The heat from the flames enables the sprinkler heads to turn on and release water when a fire starts. Water cools the fire and stops it from spreading, decreasing property damage and lowering the possibility of injury or fatality.
Two sprinklers are added in the model with the characteristics reported in Figure 43.

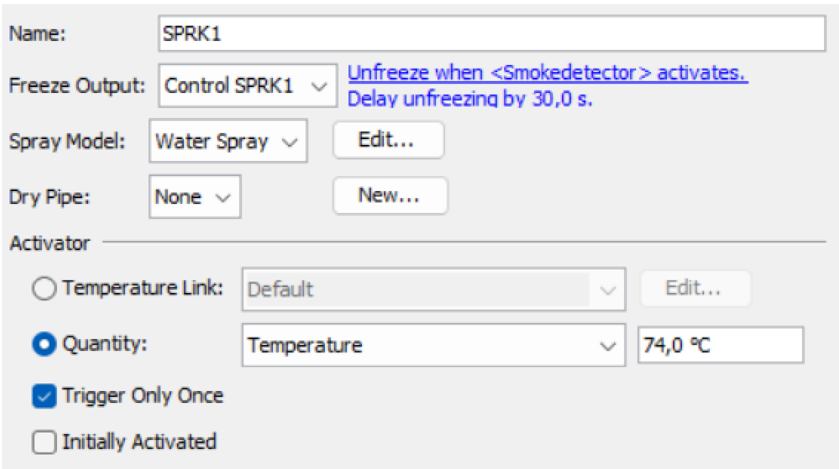

Figure 43. Sprinkler characteristics

An additional device is the smoke detector. A smoke detector is a gadget that recognizes smoke and warns users that a fire is present. In houses and commercial buildings, smoke detectors are normally high on a wall or installed on the ceiling. The same happens in the road galleries.

Figure 44. General smoke detector

Most smoke detectors function by ionizing the air using a tiny radioactive source, like americium-241. The detector sounds an alarm when smoke particles get inside and stop the ionization process. Other kinds of smoke detectors detect smoke using optical or heat sensors. In the event of a fire, smoke detectors are a crucial safety tool that can help save lives and shield property from harm [67].
In the model, the two smoke detectors are positioned near a couple of jet fans attached to the ceiling of the tunnel. The type selected is the clear ionization I1. It is because it has a faster response concerning the others.

On the other hand, for what concern the control devices, they are used for the activation/deactivation of the elements in the model.
A control device is used to activate jet fans. In particular, they are activated after 180 seconds from the beginning of the simulation (and from the beginning of the fire). The main characteristics are reported in Figure 45:

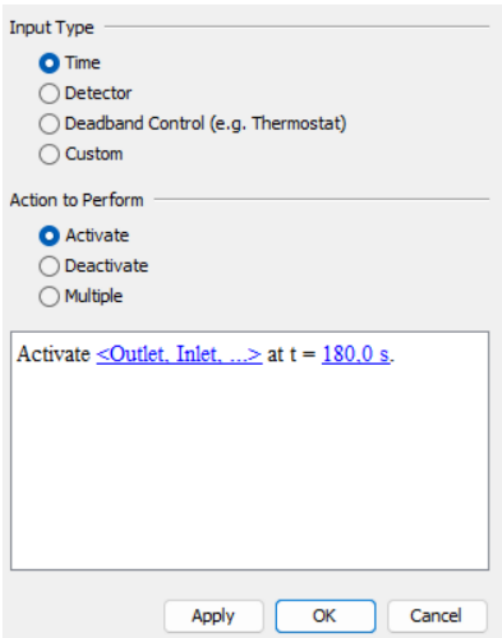

Figure 45. Characteristics of smoke detectors

Control devices are also added for the sprinklers. In particular, they are considered to activate when smoke detectors activate with a delay of 30 seconds as reported in Figure 46.

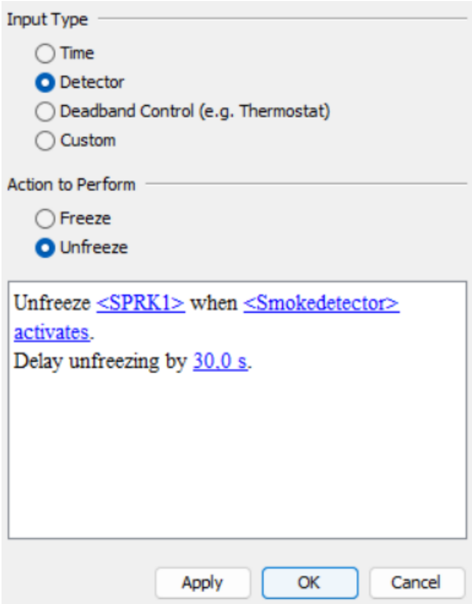

Figure 46. Control system for sprinkler activation

Control devices are not visible in the model.

4.4 Results

4.4.1 Methane car: first case

In this first case, the car is positioned exactly in the mean of the tunnel as it is possible to see in Figure 47. It is represented with the upper part in red (the one is burning) and the other in yellow.

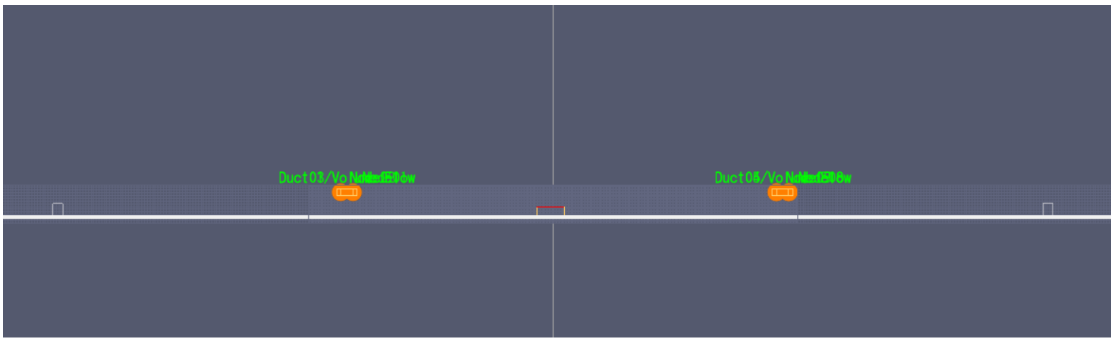

Figure 47. Car position

The simulation is performed for 300 seconds (5 minutes) and the results are showed in the following figures. Despite the different meshes to reduce the computational time, the simulations are very long (around 30 hours).

The heat release rate curve is reported in Figure 48.

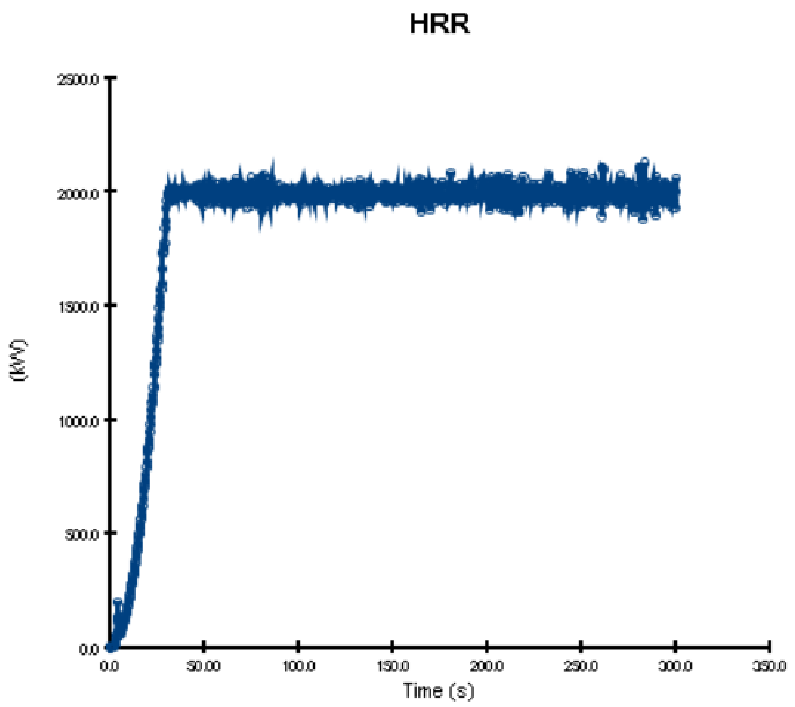

Figure 48. HRR curve

A fast increase of the heat released is shown in the first 50 seconds. This is due to the fire spread in the compartment. Then, it remains stable at around 2000 kW. According to the National Fire Protection Association (NFPA), the heat release rate of a fully-involved car fire can range from 1 to 5 MW. Therefore, this result, follows our expectations [68].
During the stable phase, the thermal power release starts smoothly and continues until the fire is over. A reduction is expected with combustible consumption until zero.
By following the findings of different researchers, the extinction of the fire and therefore the decrease of the curve is expected after 20 minutes from the beginning of the fire [69].

Thermocouples are used to better understand the behaviour of the temperature in different sections of the gallery. Thermocouples from 1 to 5 are positioned near to the burning machine.
The first thermocouple is the one positioned in the center of the car at the ceiling altitude. The temperature has a steep increase in the first part. Then, as it is visible in Figure 49, it reaches the highest temperatures from 180 °C to 210 °C, without a real peak. The curve oscillates until 200 seconds. After that, the temperature starts to dramatically reduce until around 30 °C after 230 seconds. In the end, it continues to slightly decrease until the ambient temperature is reached.

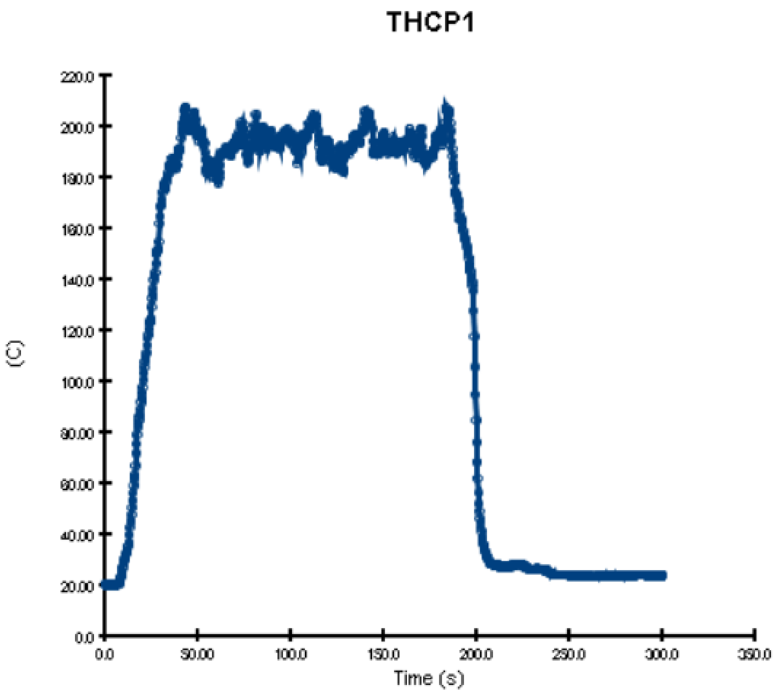

Figure 49. Temperature of thermocouple 1

Thermocouple 2 and 3 are positioned on the left and right part of the car respectively. The results (Figure 50) are similar with a peak of around 31 °C for thermocouple 3. They are not interested in the fire evolution.

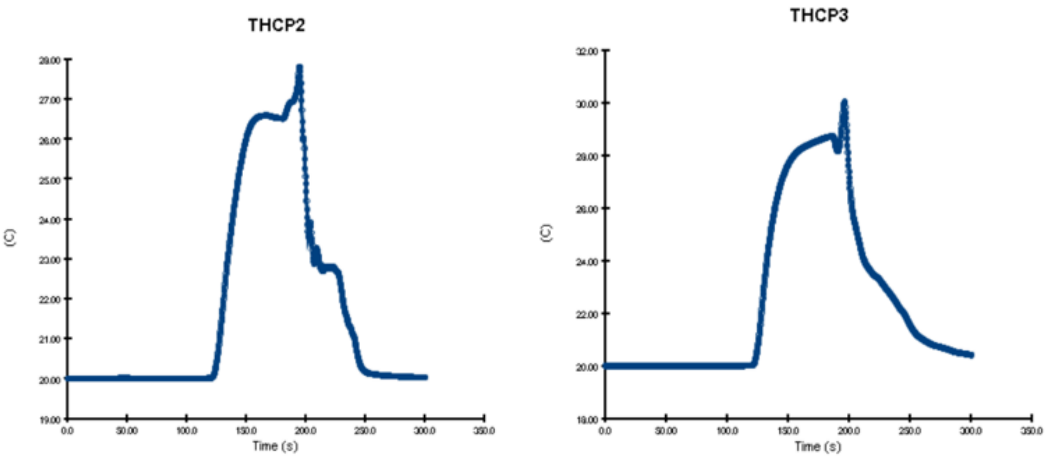

Figure 50. Temperature of thermocouples 2 and 3

For what concerns, thermocouples 4 and 5, their behavior is reported in Figure 51. The forth is positioned in front of the car, the other behind. Since the ventilation system operates in the same direction of the car, thermocouples 4 shows the most relevant results. In the first part, the temperature remains almost stable around 80 °C. The most visible increase happens after 200 seconds in which the highest temperature is reached (around 300 °C). In the last part, the temperature reduces in the range of 80 °C-100 °C.

Instead, the temperature of thermocouple 5 arrives to almost 60 °C after 50 seconds and then stays almost steady until 200 seconds when it quickly decreases arriving to the ambient temperature.

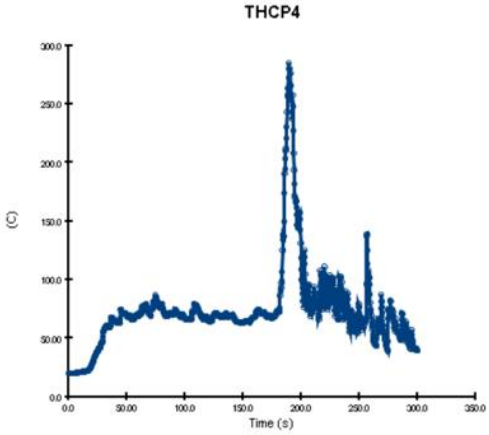

Figure 51. Temperature of thermocouple 4 and 5

For what concerns thermocouples 6 and 7, they are positioned near to the two emergency exits. They are not particularly involved in the accident. Their behaviour is almost the same in the first part, with a temperature increase up to 20 °C-25 °C and then, thermocouple 7 reaches a constant temperature around 21 °C. Thermocouple 6 returns to the original value (the variation is completely negligible) . The results are visible in Figure 52.

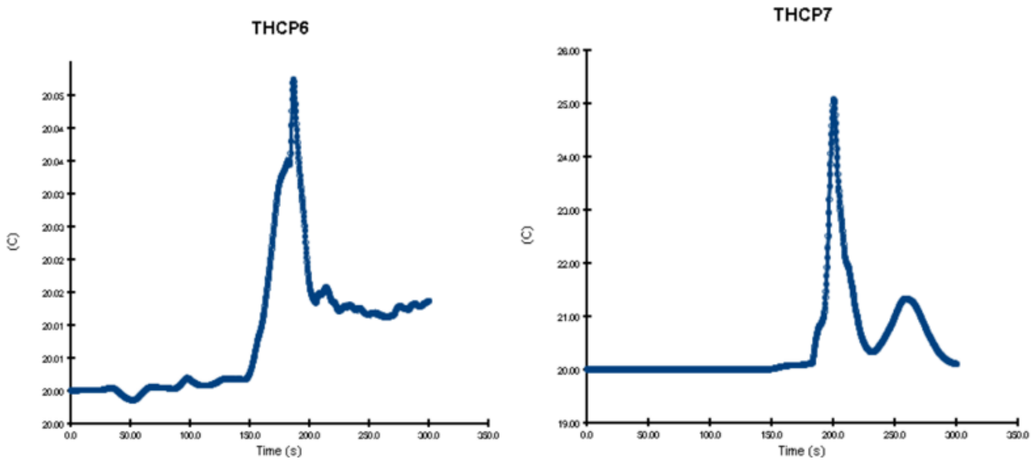

Figure 52. Temperature of thermocouples 6 and 7

Thermocouples 01 and 02 are positioned near to the two couples of jet fans. As expected, after the first phase in which both increases their temperature until around 70/80 °C, the temperature of 01 returns to 20 °C.
On the other hand, the temperature of 02 decreases but it remains higher than the ambient one (30-50 °C) as it is possible to see in Figure 53.

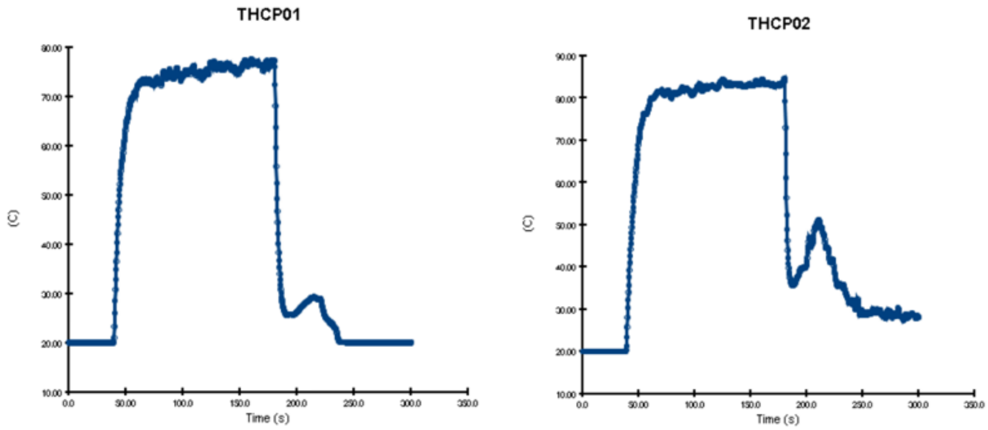

Figure 53. Temperature of thermocouples 01 and 02

Therefore, watching the results of all the thermocouples it is possible to say that the maximum temperature is reached by thermocouple 4. The value is 290 °C.

Now the smoke detector outputs are investigated (Figure 54). As expected, they are activated after 30 seconds and they reveal a 85 %/m presence of smoke. The smoke detector 1 is positioned in the direction of the flow. After 200 seconds it continues to detect a high presence of smoke also if the value is reduced (50 %/m). Then a peak of 70 %/m appears after 210 seconds and after that the presence of smoke reduces until 20 %/m at the end of the simulation.
The smoke detector 2 shows a different output since the flow goes towards the opposite direction. The first part is similar but in this case at 200 seconds the presence of smoke is reduced a lot (20 %/m). Then, after another peak around 30%/m, the smoke is no more detected (0 %/m).

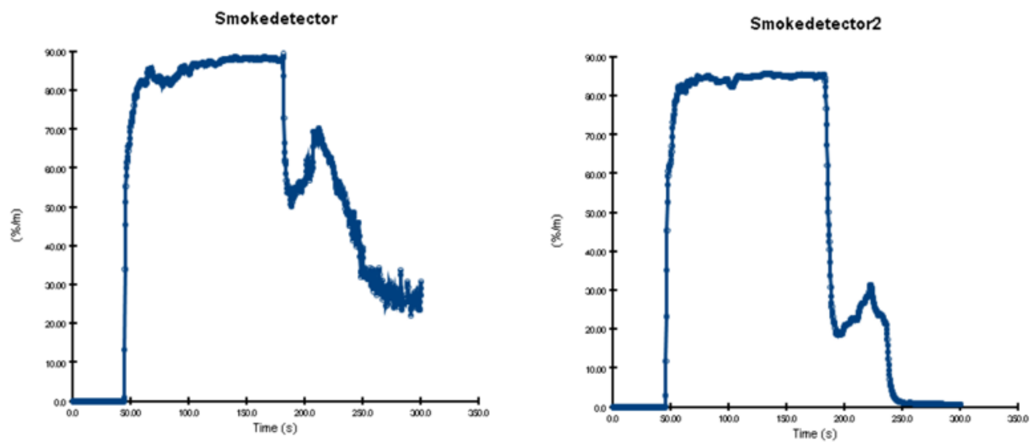

Figure 54. Smoke detector 1 and 2 results

As said in section 3.1.2, the fire propagation is due to convection, conduction and thermal radiation. For the sign convention, the heat reported in the following figures is negative since it is heat released.
The heat due to the conduction phenomenon (Figure 55) seems to be relevant between 100 and 200 seconds when the fire is going to be stable, with a peak of around 1200 kW. On the other hand, for what concerns the convection, it arrives to the peak (1900 kW) after 200 seconds and then it is rapidly decreases to 1000 kW.

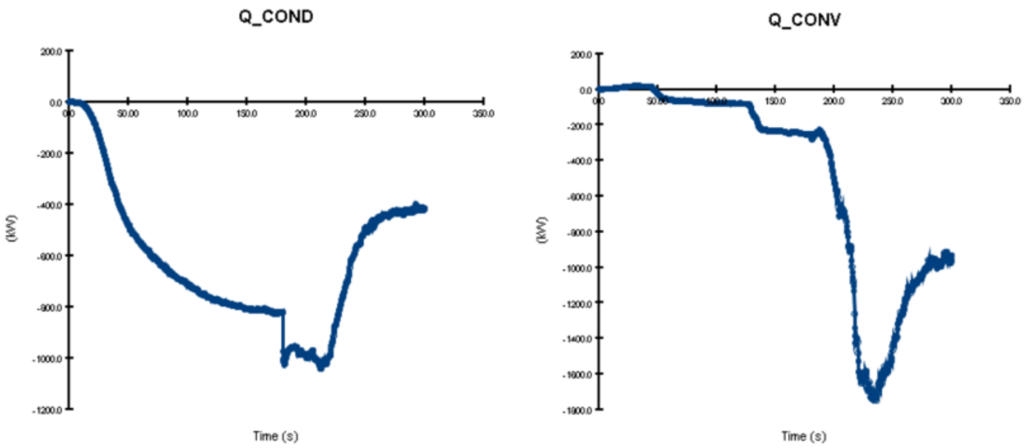

Figure 55. Heat released due to conduction and convection phenomena

In Figure 56, the diffusion and radiation are shown respectively. In general, the diffusion is not considered a relevant phenomenon. Indeed, the value detected are constant around 160 kW as expected. The radiation is more relevant in the first part reaching a peak of 800 kW, then there is a huge reduction till 300 kW at 200 seconds and at the end, it slightly increases to a range between 600 kW and 700 kW until the end of the simulation time.

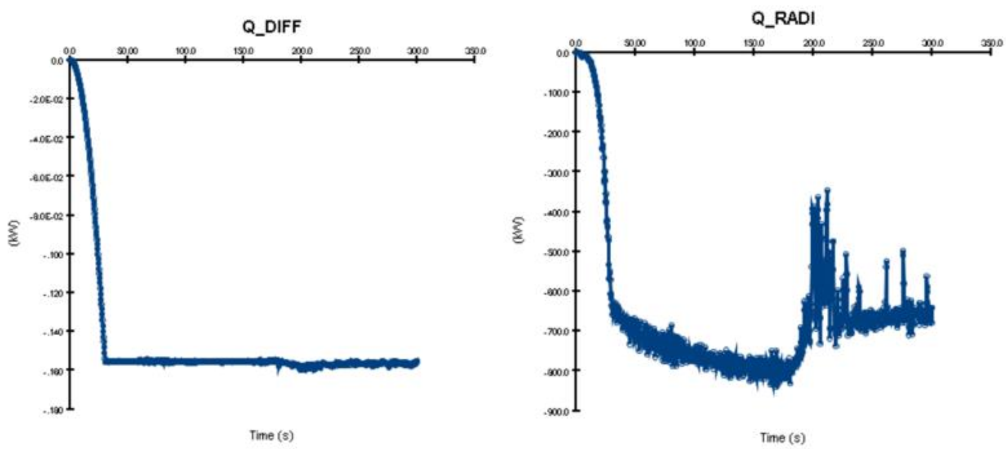

Figure 56. Heat released due to diffusion and radiation phenomena

The type of fuel, quantity of fuel, and combustion conditions are only a few of the variables that affect how much heat is produced overall throughout a combustion event. Enthalpy of combustion, defined as the amount of heat released when one mole of substance is entirely burned in abundant oxygen, can be used to calculate the heat released during a combustion reaction. By multiplying the enthalpy of combustion by the quantity of fuel consumed and the length of the combustion reaction, one may get the overall amount of heat emitted under the assumption that the rate of combustion is constant. This can be written mathematically as:

$$Q_{TOT} = H_{comb} * moles\ of\ fuel\ burnt * t_{comb} \quad (21)$$

Results for the case under investigation are reported in Figure 57.

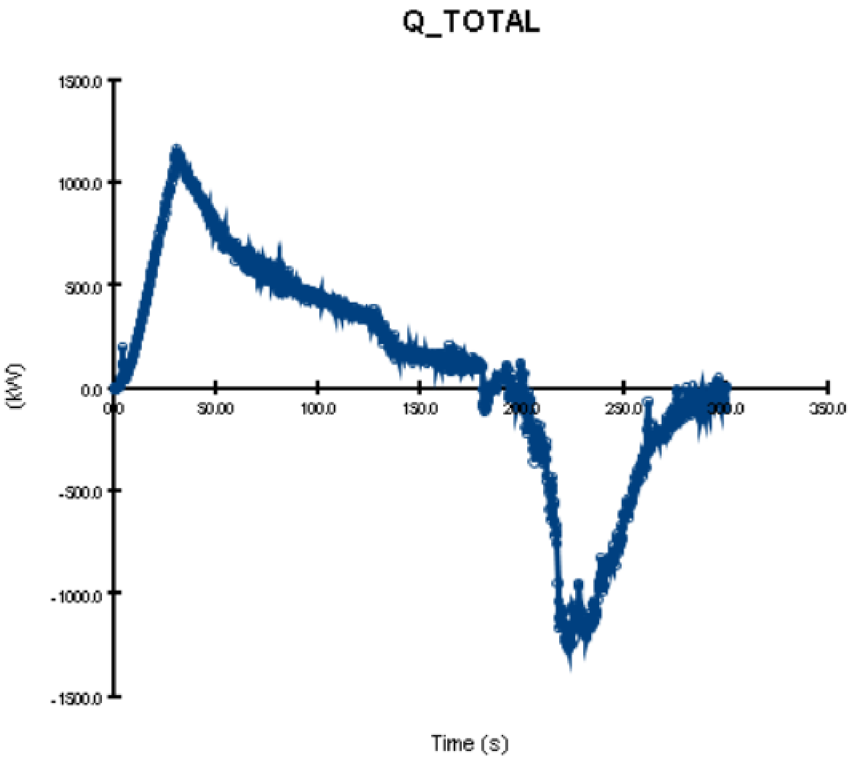

Figure 57. Total heat

In the first part, the heat is absorbed. The fuel starts to burn and the fire starts to grow. At 200 s, when all the fuel is burnt and the peak temperatures are reached, heat starts to be released. The curve at this point assumes negative values and at the end arrives to low values.

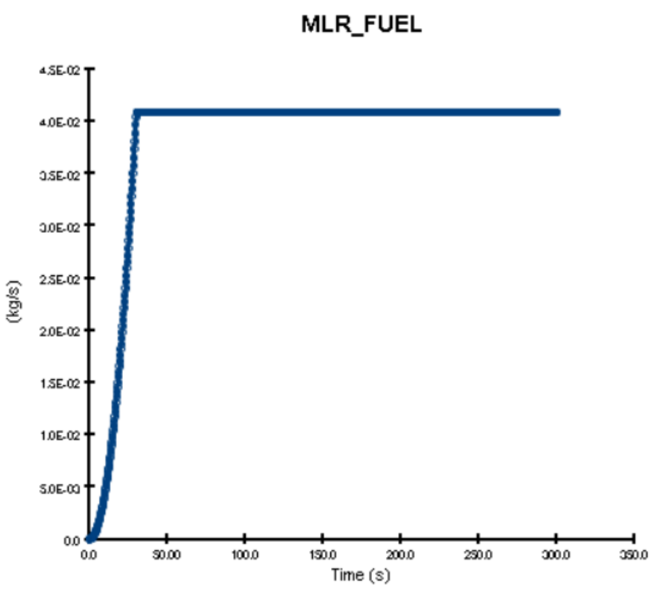

Figure 58. Mlr fuel

4.4.2 Methane car: second case

In this second case, the methane vehicle is positioned near to the first couple of jet fans instead to be in the middle as reported in Figure 59. This is still the part of the mesh that is thiner. The tunnel is hidden in order to have a better view on the simulation inside it.

Figure 59. Car position: second case

The simulation is performed with the same duration of the first case (300 s). At the beginning of the simulation, the combustion products are free to move in both directions. In addition, in the first minutes, the smoke touching the ceiling tends to fall along the walls (Figure 60) because initially the surface is cold, so the gas gives heat to the structure and cooling becomes denser.

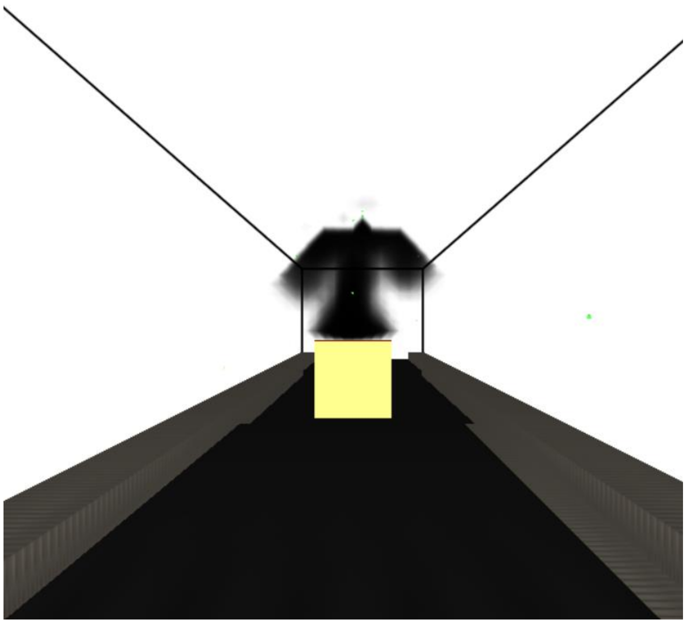

Figure 60. Smoke diffusion in the gallery after 15 seconds

As it is possible to see in Figure 61 and Figure 62, the smoke tends to stratify and to accumulate in the upper part of the gallery. In this way, the walls become hotter and hotter.

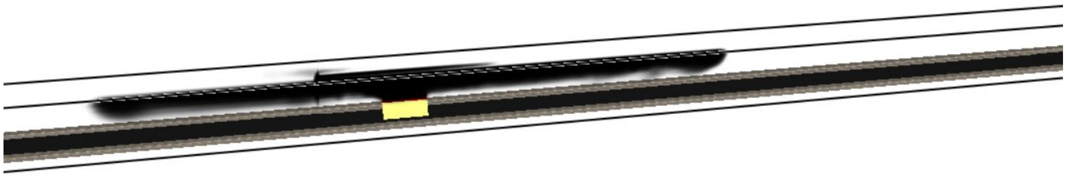

Figure 61. Stratification of the smoke in the first part of the simulation

Figure 62. Stratification of the smoke in the first part of the simulation (second view)

After that, smoke tends to go towards the inner/outer parts of the gallery as is visible in Figure 63. It represents the situation after 200 seconds when the jet fans are switched on from almost 20 seconds.

Figure 63. Simulation after 200 seconds

After 250 seconds, it is possible to see that the motion of the fumes changes and they have already retreated some tens of meters. The fact that the smoke is pushed in a predetermined direction causes it to spread throughout the section and not only on the vault, where it is no longer able to accumulate due to lack of space. Due to the "backlayering" effect, for some meters the smoke can move in the opposite direction concerning the thrust direction

Figure 64. Simulation after 250 seconds

After 5 minutes (end of the simulation), the fluid dynamic condition of the gallery is almost stationary because the fire is completely developed and jet fans are in function from some minutes.

Figure 65. Simulation after 300 seconds

In the following figures 66,67,68, the data related to HRR, heat and temperature are reported.

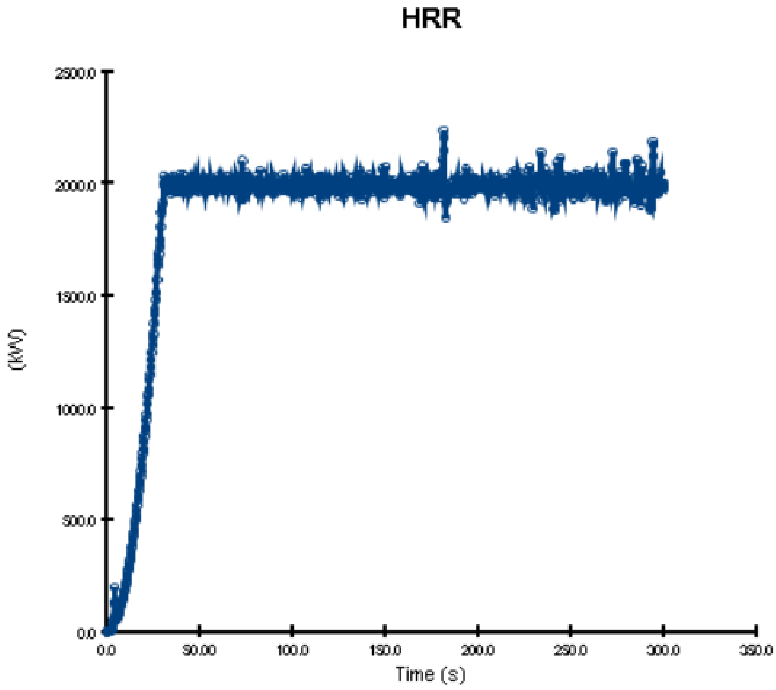

Figure 66. HRR curve for methane vehicle (second case)

The curve looks very similar to the previous case.

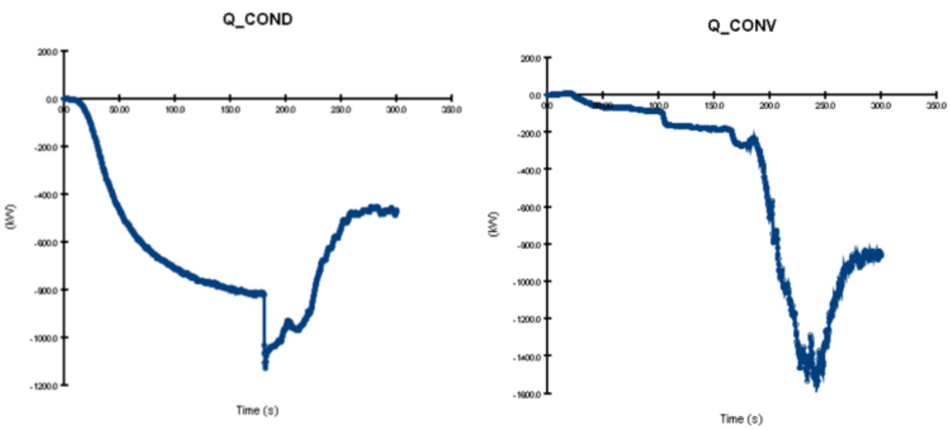

Figure 67. Heat released due to conduction and convection phenomena

At 200 seconds the curves in Figure 68, representing the heat for diffusion and radiation, seem to have a strange behavior. This peak could represent an outlier in the data. Other outliers are visible at the end of the curve of heat radiation. These data can be eliminated with a process called data mining. This includes two stages: exploration and modeling. The objective of these techniques is to reduce the complexity of the database to try to explain the phenomenon under study.

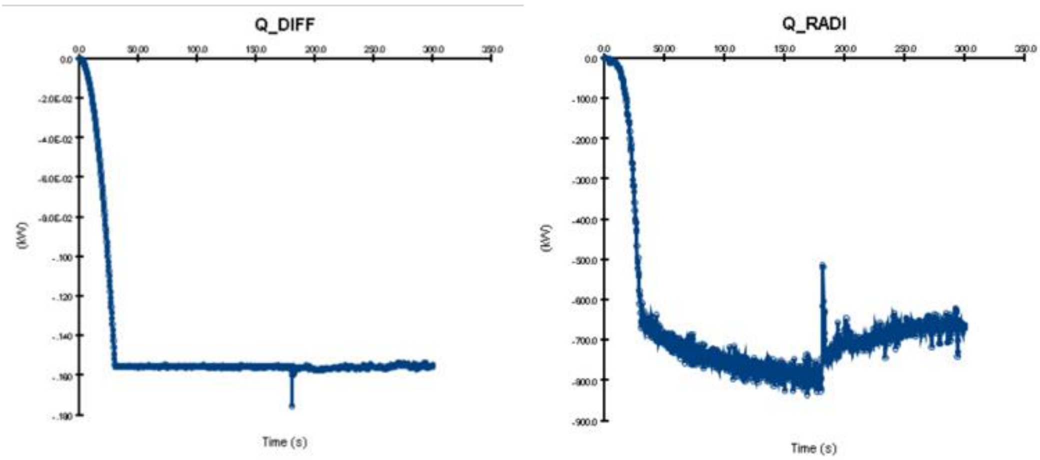

Figure 68. Heat released due to diffusion and radiation

As said for the previous case, the predominant component in fire propagation in the first part are conduction and thermal radiation, while in the second part convection is more important. Diffusion and radiation are quite negligible.

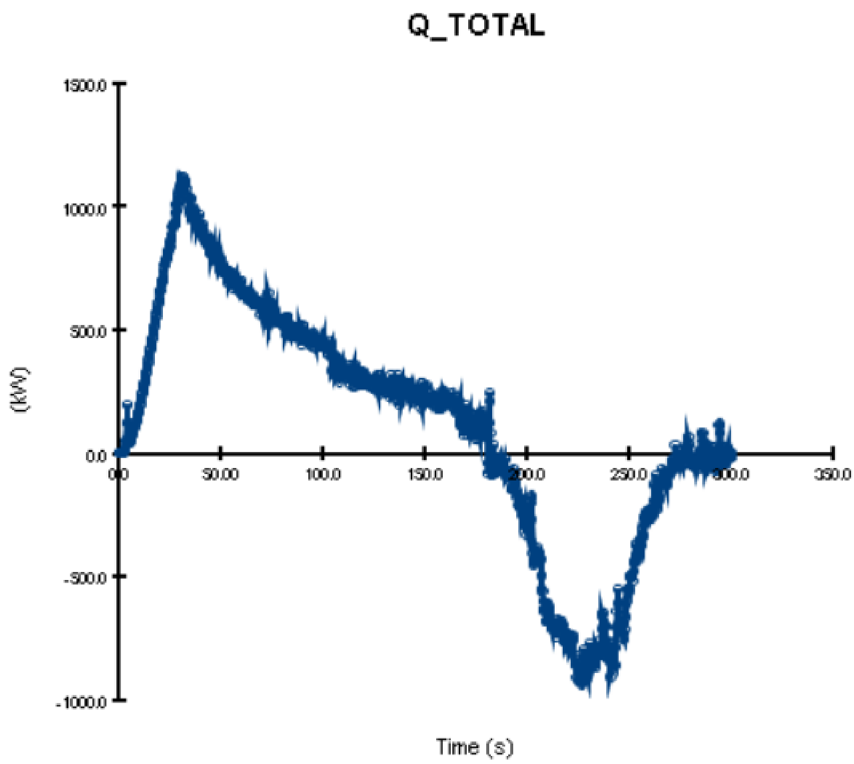

Figure 69. Total heat curve of a methane car (second case)

Temperature results are reported in Figures 70 and 71. Thermocouples 1, 2 and 3 are affected by the fire propagation. They show almost the same trend with an fast temperature increase in the first part, a stable phase in with thermocouple 1 reaches the highest values (200 °C) and a dramatic reduction in the last part.

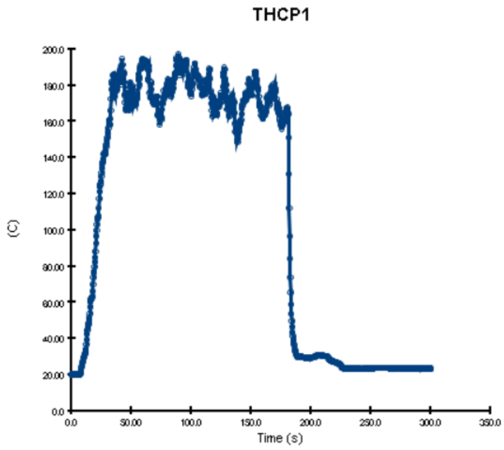

Figure 70. Thermocouple 1 results (second case)

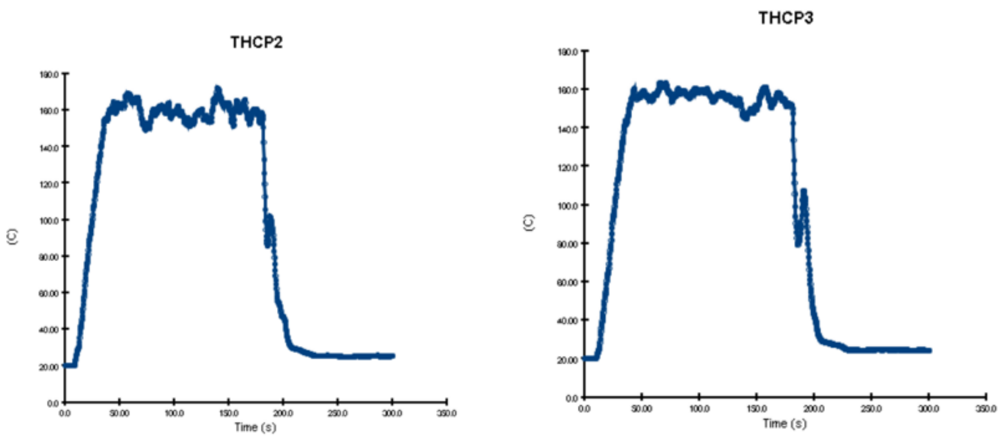

Figure 71. Thermocouple 2 and 3 results (second case)

Thermocouple 4 is the most involved in temperature evaluation since it is in the direction of fire propagation. After 200 seconds, the oscillation are very big and temperatures continuously pass from 200 °C to 50 °C. Also thermocouple 5 shows an high peak (around 110 °C).

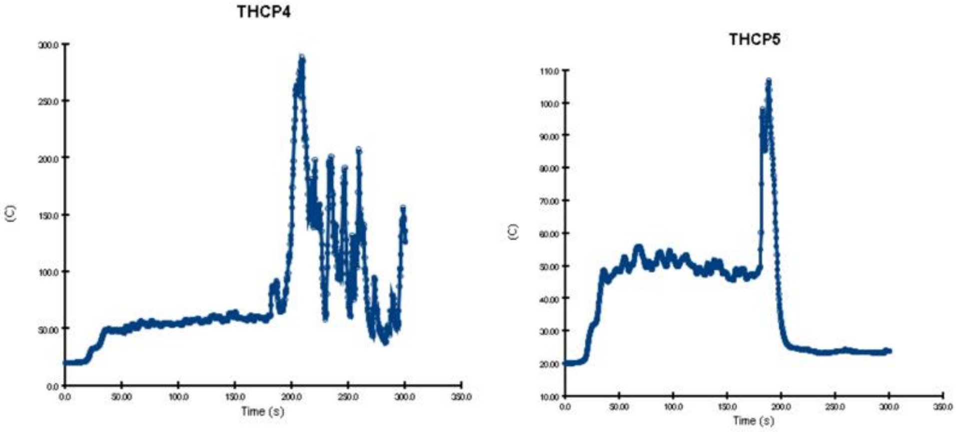

Figure 72. Thermocouple 4 and 5 results (second case)

On the other hand, thermocouples 6 and 7, near to the emergency exits are not involved in the fire evolution. Their temperatures remain almost stable at ambient conditions (Figure 73).

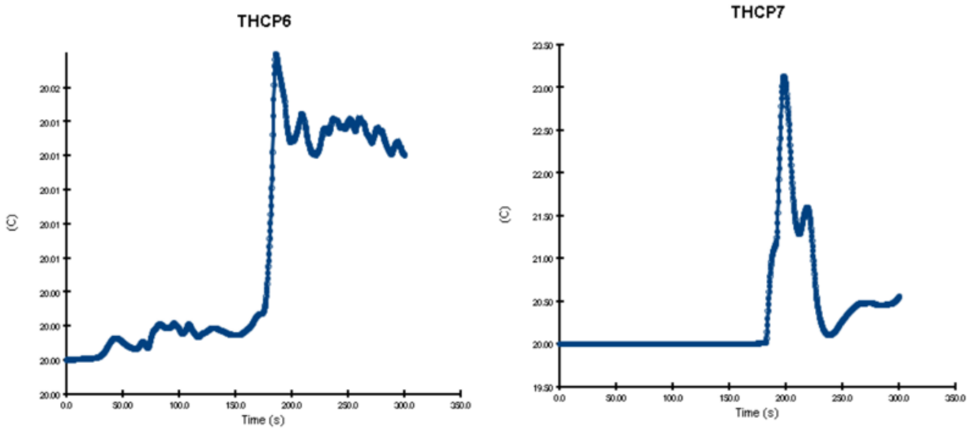

Figure 73. Thermocouple 6 and 7 results (second case)

For what concerns, thermocouple 01 and 02 (Figure 74), near to the jet fans they behave differently. Thermocouple 01 is participating more since the fire is developing in nearby. It reaches temperatures of 150 °C. At same time, thermocouple 02 is positioned in farer jet fans and it arrives to 60 °C.

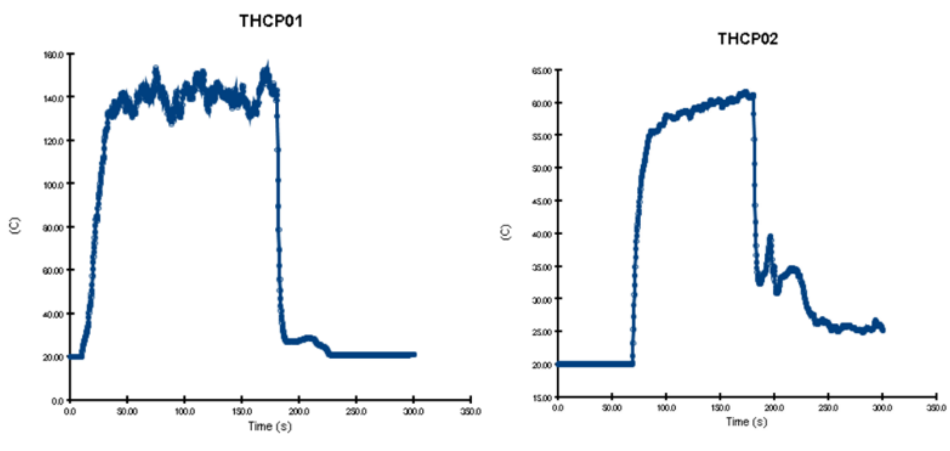

Figure 74. Thermocouples 01 and 02 results (second case)

The smoke detectors surveys are reported in Figure 75.

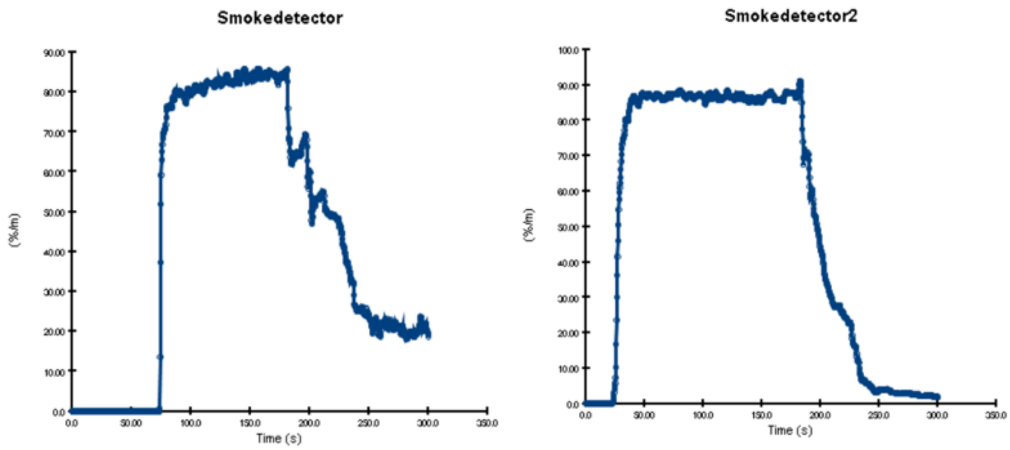

Figure 75. Smoke detectors results (second case)

Since the two cases show only a few differences, for the electric vehicle it was chosen to simulate only the case in which the vehicle is in the middle of the tunnel and then compare the results with the one obtained for the methane car.

4.4.3 Electric vehicle: first case

For what concerns the electric vehicle, it was chosen to simulate for a shorter time. The simulation starts after 100 s and stops after 400 s. This is because the reaction of combustion in an EV is expected to start slowly and the situation after 400 seconds should be evolved and almost completely developed.

The heat release curve is reported in Figure 76. After the ignition, once the fire has started, it quickly grows in intensity. The heat release rate continues to increase as the fire spreads to other parts of the vehicle, such as the tires, interior, and other flammable materials. At 250 s, the fire reaches the fully developed stage and it means the maximum intensity, and the heat release rate is at its highest.

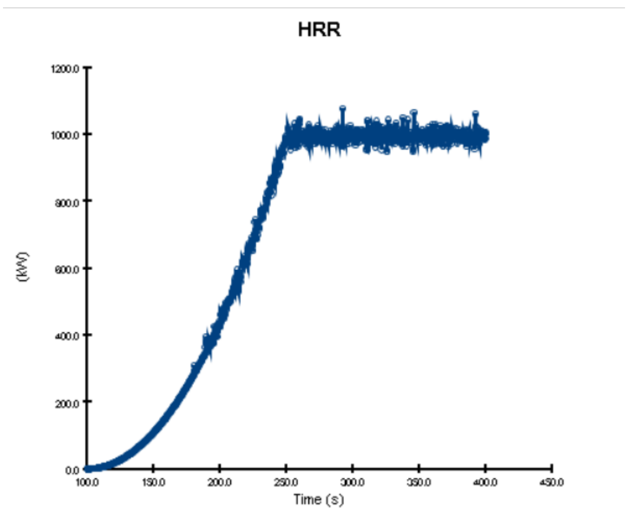

Figure 76. HRR curve EV

After many minutes, fire decay is expected but not simulated since a computer with higher performance is necessary.
In this simulation, the velocity of gases in underlined. In the gallery, it was considered an empty air bottom velocity, therefore at the beginning of the simulation, the only gas in motion is the smoke generated by the flames that first rises upwards and then expands towards the two portals. Jet fans starts to switch on after 3 minutes.

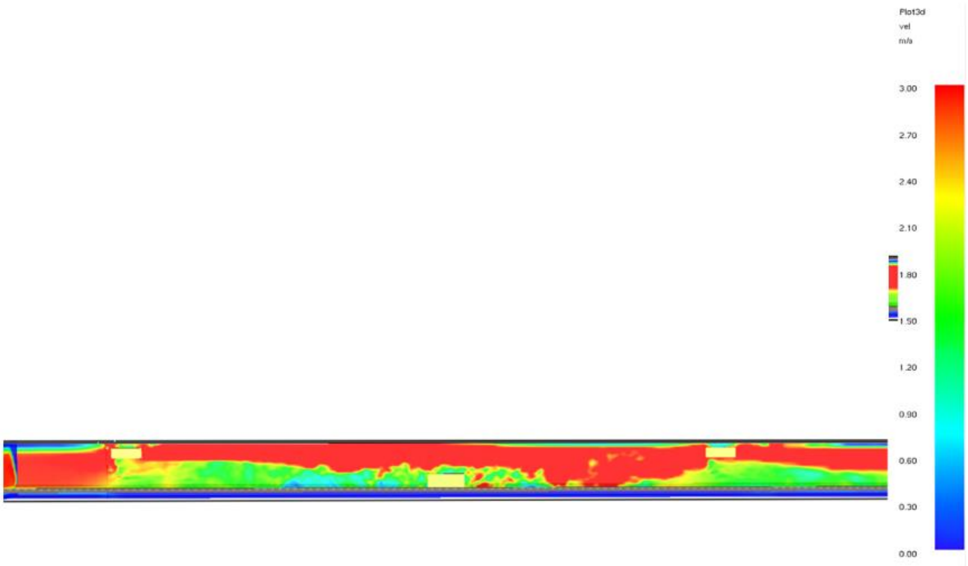

Figure 77. Gas velocity in the tunnel after 100 seconds

Figure 78. Gas velocity in the tunnel after 200s and 300s

Next to the figures 77 and 78 is shown the gas speed scale in m/s. In Figure 77, the gas speed scale has a maximum of 3 m/s. Instead, for Figures 78, the maximum is 5.5 m/s. When the smoke, accumulated at the top of the tunnel, begins to expand towards the portals the air begins to flow towards the point of fire, moving the bottom of the tunnel. As it is possible to see in Figure 77, a non-zero velocity area is generated due to the collision between the layer of smoke moving away from the fire and the air layer that goes in the opposite direction. After jet fans are switched on, smoke is progressively pushed towards the right of the figure. The maximum velocity is around 5.5 m/s.

For what concerns temperatures, thermocouples results are investigated.
Thermocouple 1 is positioned in the ceiling of the tunnel in the direction of the center of the vehicle. It shows an increasing temperature with a peak of around 63 °C after 180 seconds. Then, jet fans are activated and the temperature dramatically decreases until the ambient temperature is restored.

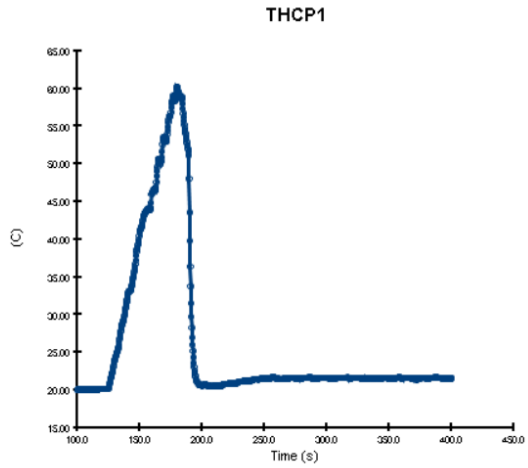

Figure 79. Thermocouple 1 results (EV case)

On the other hand, thermocouples 2, 3 and 5 are not affected by the increase of temperature as it is possible to see in Figure 81. Also thermocouples 01 and 02 show the same behaviour.

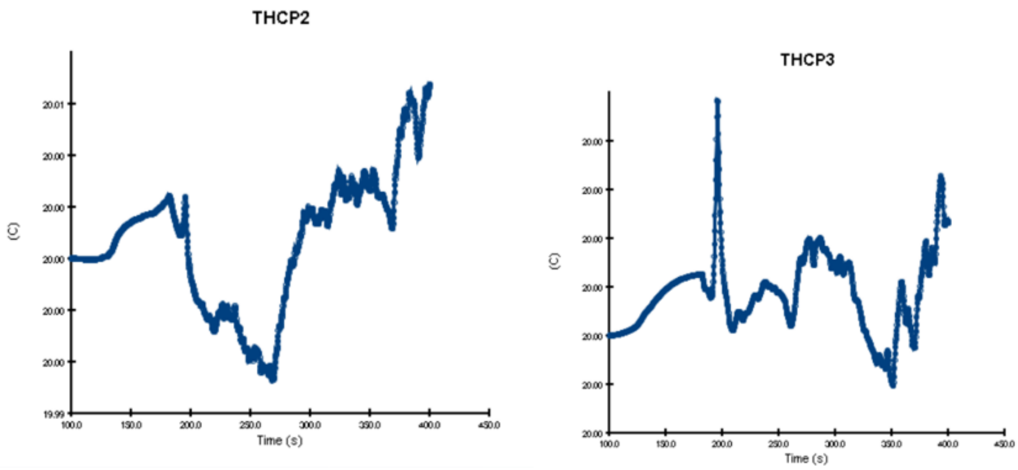

Figure 80. Thermocouple 2 and 3 results (EV case)

Thermocouple 4 (Figure 82) reaches a peak of around 70 °C when the fire is developing. After that, the temperature reduces and continues to oscillate till the end of the simulation between 25 °C and 45 °C.

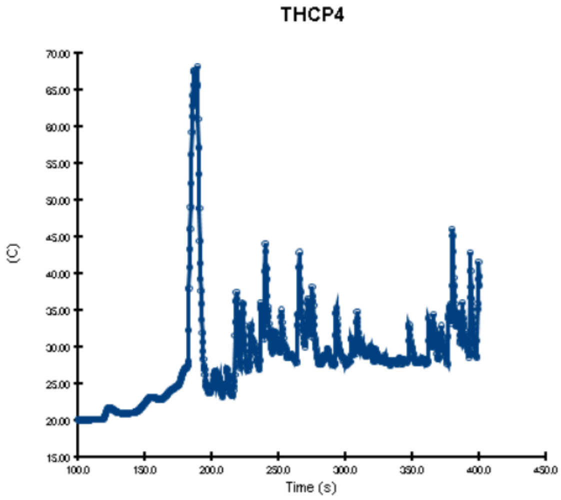

Figure 81. Thermocouple 4 results (EV case)

Thermocouples 6 and 7 do not register a high-temperature variation as visible in Figure 83. The same can be verified for thermocouple 01 and 02. This is because they are too far concerning to the fire.

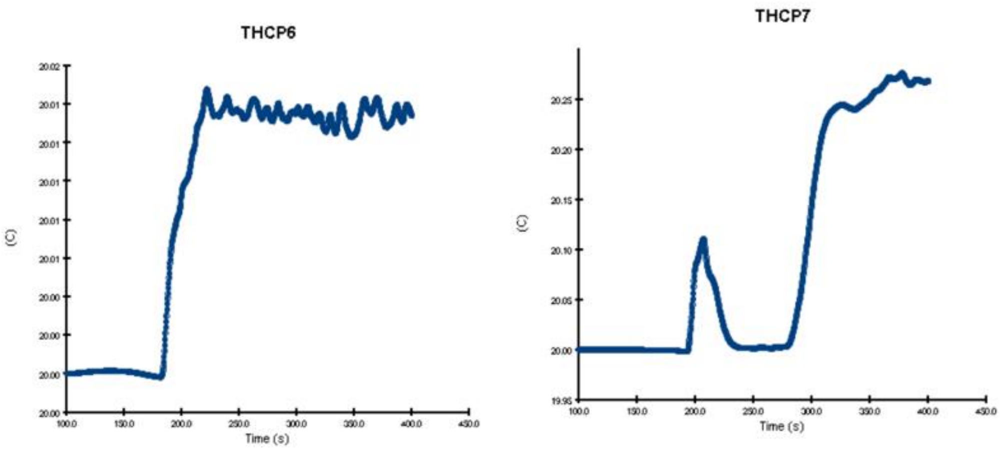

Figure 82. Thermocouple 6 and 7 results (EV case)

The results for the smoke detectors are reported in Figure 84. In this case, they have completely different behaviors. Smoke detector 1 starts to reveal the presence of smoke after 180 s. The percentage arrives immediately to 90 %/m and then decreases a bit remaining in a range between 50 %/m and 80 %/m until the end of the simulation.

On contrary, smoke detector 2 is not able to detect the presence of smoke until 240 seconds. Then only a very small fraction (0.300 %/m) is found.

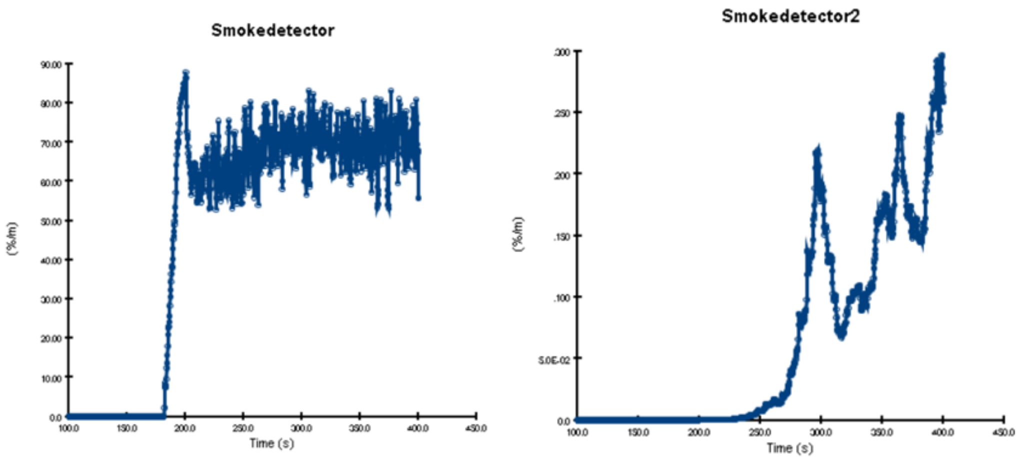

Figure 83. Smoke detectors results (EV case)

At the end, the curve of total heat is reported in Figure 85.

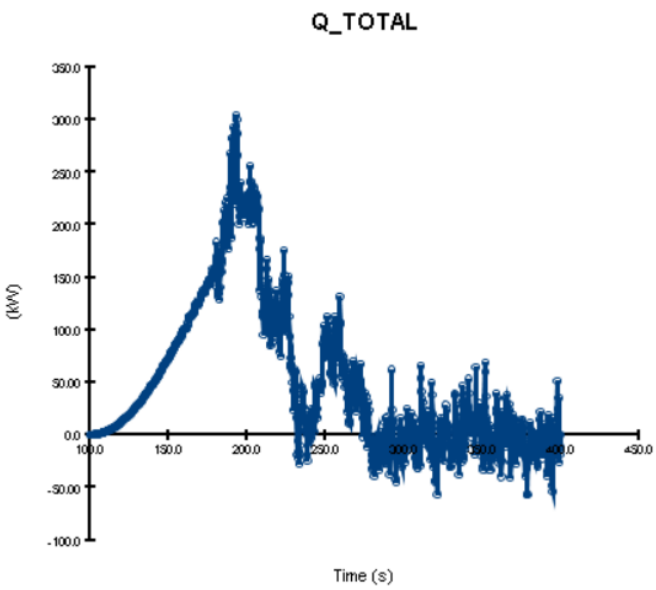

Figure 84. Total heat curve (EV case)

Chapter 5

Comparisons and conclusions

There are several significant distinctions to take into account when comparing methane automobile fires and electric vehicle (EV) fires:

- Cause of fire: thermal runaway, a chain reaction that takes place inside the vehicle's battery pack, is a common cause of EV fires. On the other hand, methane automobile fires are often brought on by a fuel system leak, such as a ruptured gas tank.
- Fire intensity: compared to methane vehicle fires, EV fires often burn at a lower intensity. This is so that the fire can't spread quickly because an EV's battery pack is built to control the heat and flames. On the other hand, because methane is such a highly combustible fuel, car fires are expected to be more violent and spread more rapidly.
- Fire suppression: the techniques utilized to put out EV flames and methane car fires may differ due to the variances in fire intensity and origin. For instance, water can be used to put out a methane vehicle fire, but due to the risk of electrocution, it is not advised to use it on an EV fire. An EV fire may instead call for specialist extinguisher materials or methods.
- Environmental impact: methane vehicle fires can release greenhouse gases into the atmosphere, which exacerbates global warming. EV fires, on the other hand, have the potential to discharge hazardous chemicals and metals into the environment, endangering both the ecology and human health [70][71].

The heat release curves of the two car types are reported in Figure 86. As expected the HRR curve of the methane rises much more rapidly than the one of the electric vehicle. In addition, after the fire development phase, the stable phase arrives at 2000 kW, almost double concerning the other curve (around 1000 kW).

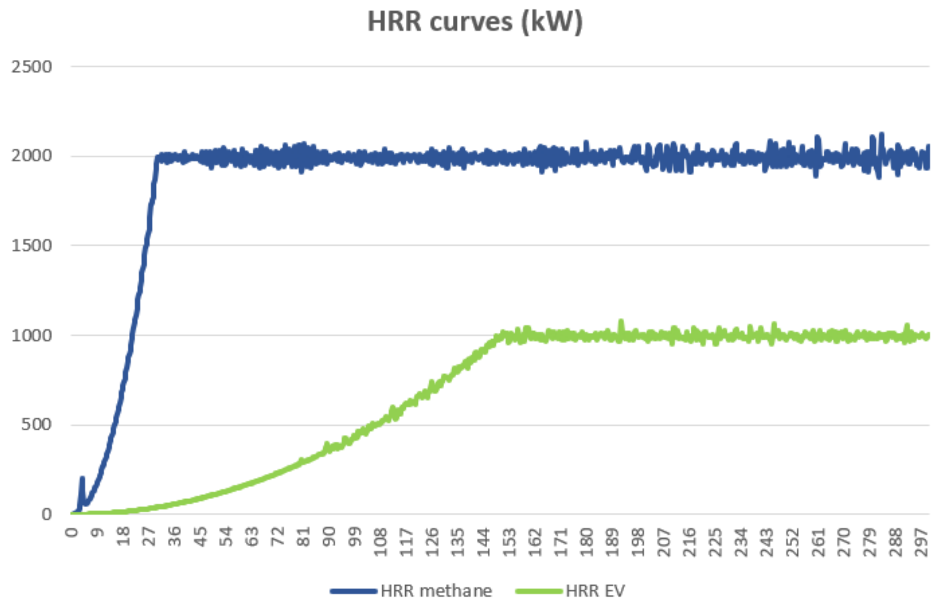

Figure 85. HRR curves comparison

For what concern temperatures, the most interesting thermocouple for comparison is thermocouple 1. As it is visible in Figure 87, as expected, temperatures reached by methane car fire are much higher. Values oscillate between 180 °C - 200 °C, very different from the EV in which temperature arrives to a peak of 60 °C. These temperatures are not the temperature developed in the center of the fire that could be much higher.

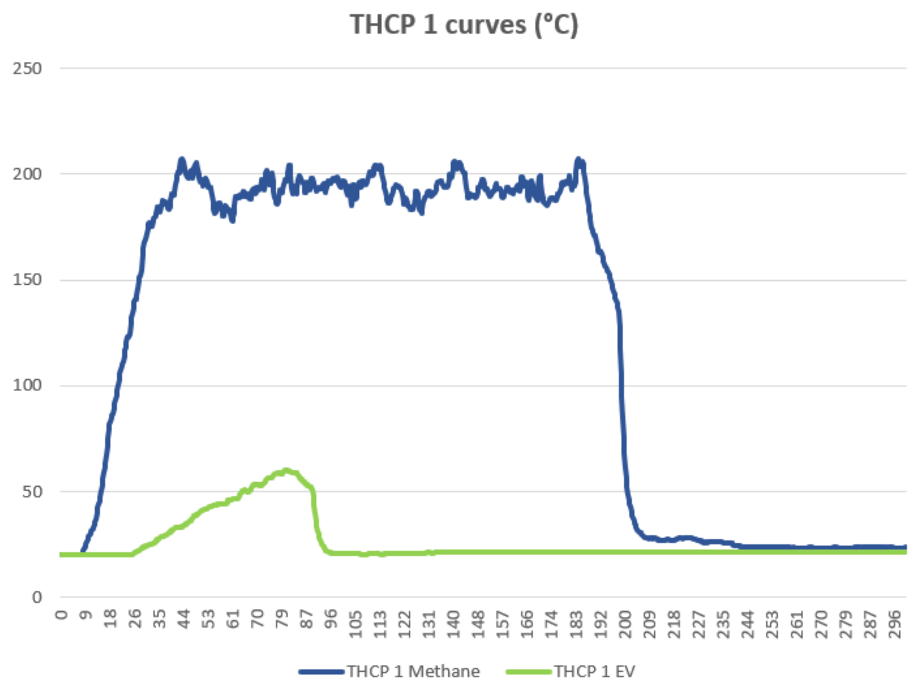

Figure 86. Thermocouple 1 curves comparison

A comparison between the heat total curves is reported in Figure 88.

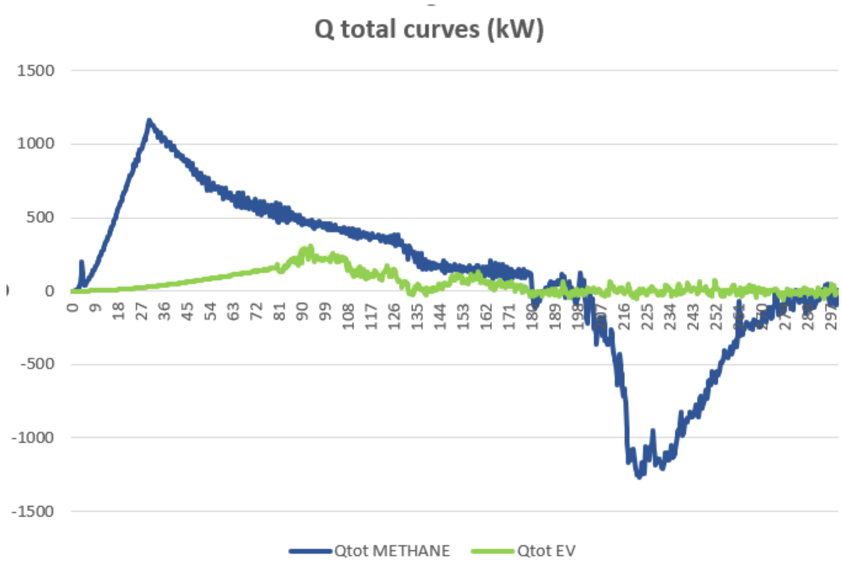

Figure 87. Total heat curves comparison

Overall, because both EV and methane car fires can be dangerous, appropriate safety precautions must be taken to reduce and prevent the risk of fire. Yet, when assessing the safety of each technology, it is necessary to take into account the significant distinctions between the two types of fires.

At the same time, compared to conventional methane-powered vehicles, electric vehicles (EVs) have been demonstrated to have a decreased risk of catching fire and in general lower risk after the fire development. This is because batteries have a lower danger of starting a fire when used to power EVs and the fire itself reaches the lowest temperatures and heat released.
To reduce fire risk, EV manufacturers have put a safety precautions, including battery cooling systems, firewalls, and battery management systems to monitor and regulate the battery's temperature and state of charge. Emergency personnel are also receiving training on how to react to EV accidents safely. Some precautions for EVs fire are reported in the following list:

1. Battery management system: a battery management system (BMS) is a feature found on electric vehicles (EVs) that continuously tracks the battery's temperature, charge level, and other factors. The BMS is made to stop the battery from being overcharged, over-discharged, or overheated, all of which can start fires.
2. Thermal management system: another feature of EVs that helps control battery temperature is a thermal management system. To maintain the battery at a secure temperature and stop thermal runaway reactions that can result in fires, this system uses cooling and heating.
3. Firewalls: EVs are equipped with firewalls to stop flames from spreading to other interior compartments. Usually constructed of heat-resistant materials, firewalls can endure extreme temperatures.
4. Fuses and circuit breakers: the electrical system in EVs is protected from overloading and short circuits, which can result in fires, by fuses and circuit breakers.

5. Emergency shut-off: in the event of an emergency, EVs include a shut-off system that can be engaged. To stop future damage or fires, this mechanism turns off the electrical system and disconnects the battery [72][73].

Taking into account all these variables and knowing that in a real road tunnel there are safety instruments not considered in the model, it is possible to say that the simulations in this work of thesis are developed "in favour of safety", underlying the most dangerous situations.
At the end, it is important to underline that both electric vehicle (EV) fires and methane (gasoline-powered) car fires can release harmful substances into the air. However, the type and amount of pollutants released varies. The primary source of emissions from EV fires is typically the battery. Li-ion batteries have the potential to produce gases including hydrogen fluoride (HF) which is a very toxic gas with a peak of 0.0009 kg/s. This value is much higher than the one resulting from an ICEV fires (0.00002 kg/s). The same consideration is valid for HCN [74]. On the other hand, methane car fires can also release a range of volatile organic compounds (VOCs), which can be hazardous to human health and the environment.

EV-related incidents continue to receive a lot of attention, which can make people more cautions when responding to them. There is no doubting that EVs come with additional dangers, but there is no proof that EVs are less safe than traditional vehicles. However, as the number of EVs grows, failures will occur more frequently. The best way is to take on this problem and implementing safety measures and procedures that reduce hazards to manageable levels. Only then society will achieve the same comfort level of conventional vehicles.

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