Politecnico di Torino

Master’s degree in Automotive Engineering
A.y. 2022/2023
October 2023

Modelling and Simulation of an Electric Truck for public lighting maintenance

Supervisors:
Prof. Andrea Tonoli
Prof. Enrique Alcalà Fazio

Student:
Luca Preite
s286069

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
CHG	Compressed Hydrogen Gas
DC	Direct Current
DOE	Design of Experiments
ECU	Electronic Control Unit
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FMEA	Failure Modes and Effective Analysis
GHG	Green House Gas
GRPE	Group of Rapporteous on Pollution and Energy
GTR	Global Technical Regulations
HD	Heavy Duty
HEV	Hybrid Electric Vehicle
HV	High Voltage
ICE	Internal Combusiton Engine
ICEV	Internal Combustion Engine Vehicle
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Machine
IMU	Inertial Measuerement Unit
LD	Light Duty
LH	Liquid Hydrogen
LV	Low Voltage
MD	Medium Duty
MH	Metal Hydrogen
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NaN	Not a Number
OBD	On Board Diagnostic Device
OCV	Open Circuit Voltage
OPD	One Pedal Drive
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional-Integral
PM	Permanent Magnets
SoC	State of Charge
SoH	State of Health
UDELAR	University of Republic (Montevideo)
UNECE	United Nations Economic Commision for Europe
UPM	Universidad Politécnica de Madrid
UTAP	Technical Unity for Public Lighting

Abstract

The thesis project has been developed in collaboration with the INSIA, Instituto Universitario de Investigacion de Automovil, which belongs to the Universidad Politécnica de Madrid (UPM), through an agreement established with an Erasmus+ program for thesis preparation. The study refers to the European project SOLUTIONSplus, which brings together highly committed cities, industry, research, implementing organizations, and finance partners and establishes a global platform for shared, public, and commercial e-mobility solutions to kick start the transition towards low-carbon urban mobility. The project aims to boost the electrification of urban mobility in Europe, Asia, Africa, and Latin America. This paper is part of a technical consultancy for a case study of the conversion of a Diesel Truck to an electric version, for the technical team of the Faculty of Engineering of the University of Republic (UDELAR, Montevideo). The vehicle is an Iveco Daily 70C17 HD equipped with a crane with a basket to carry out lighting maintenance tasks and it belongs to the Public Lighting Technical Unit of the Municipality of Montevideo (UTAP). Two models of the same electric vehicle will be developed using AVL Cruise M and MATLAB/Simulink, in the second case, adapting the models of the GRPE of the United Nations. In such a manner, it will be possible to compare and validate the performances through the simulations of the two models of the electric version of the vehicle to have a possible range of values as an outcome and, consequently, a proper design of the electric part (battery, motor, aerial platform). An electrified version of the truck could be particularly useful to reduce the impact both in terms of noise and pollutant emissions in the urban area since it follows a standard operation cycle that does not require covering long distances during the working day. It is also interesting to have the possibility to compare the two versions of the same vehicle in terms of costs and energy consumption.

Outline of the Paper

The remainder of this paper is organized as follows:

1. Chapter 1: Introduction and general description of the project. The second part of the Introduction aims at highlighting the contribution of this thesis to the main project.
2. Chapter 2: the first part of the thesis regards an overview of the current technologies and state of art of the electric vehicle. In the next chapter, there will be a brief explanation of all the components and technologies that characterize a vehicle with electric traction. To assess all the technical characteristics, a selection of electric vehicles is investigated that belong to the same category of the Iveco Daily to be modified.
3. Chapter 3: the second part of the paper will focus on the methodology used for the analysis and the simulation of the vehicle. It will start with an analysis of the reference vehicle, from the collecting of the technical data and driving cycle to the implementation of them into the software. The second part of this chapter is about the analysis of longitudinal dynamics. This analysis will be the starting point for the choice of the real components. Through the study of the longitudinal dynamics of the vehicle it will be possible to understand which are the limits of the truck and define the basic performance factors that the vehicle must fulfil. Successively, it will be done a first definition of the requirements of the real components to be installed such as the type of battery, electric motor, inverter, and connection of the aerial platform that best suit the parameters of the current vehicle and its performance. Furhtermore, it will be discussed how the algorithm of the driving strategy works and how it is implemented in the software. Eventually, it will be done an overview of the virtual models, explaining all the components and blocks that build the complete model, thereby having a proper understanding and visualization of the final model.
4. Chapter 4: in this chapter, the attention will be on the results of the simulations. It will explain the simulation run and which are the main factors to be considered for the sizing of the new components that will have to be installed on the current vehicle. Eventually, it will be made a comparison of the results between the two models.
5. Chapter 5: this section is about the discussion and conclusions of the project. Some comments will be added regarding the highlights of the project and how the development of the overall will be continued in the future.

6. Chapter 6: Acknowledgements.
7. Chapter 7: Appendix. In this part of the paper, the codes used in MATLAB/Simulink and AVL Cruise M are available for the implementation of the driving strategy.
8. Chapter 8: References.

1 Introduction

SOLUTIONSplus is a European project that aims at the boost of vehicle electrification, integrating urban electric mobility solutions in the context of the Paris Agreement. This project in Uruguay is focusing on building a strong collaboration among local and other European companies, consolidating the needs and the ecosystem for the scale-up of electric mobility in the country. Moreover, discussions with local stakeholders have been an important part of the set-up of a national capacity-building program for all education levels. [1]. Uruguay has a well-developed renewable energy infrastructure, and the government is promoting increased electric vehicle use. The country is giving high priority to renewable sources and 98% of the electricity is produced from renewable energy. Furthermore, it has been noticed an excess of electric energy production during the non-demanding hours. For this reason, the government created incentive policies to promote electric transportation and make it more feasible [2]. The study focuses on the development of an electrification of an existing Diesel truck for public light maintenance. The vehicle is equipped with a crane with a basket to carry out lighting maintenance tasks and it belongs to the Public Lighting Technical Unit of the Municipality of Montevideo (UTAP), and it is mostly used in an urban environment. This is a pilot project from which a deep understanding of the technology will be achieved by UTAP. The goal is to reach an electrification of part of the transportation used by the Municipality of Montevideo, to increase the efficiency of part of the fleet, cut costs, and contribute to environmental sustainability. Besides that, the project also presents important advantages for the workers and occupational health since they would no longer be exposed to the emission of tailpipes near the working area. If the electrification of the vehicle will be successful and replicable this conversion will be applied also to other vehicles used for similar tasks. [3]

1.1 Project Overview

The project is an agreement recently signed between the Julio Ricaldoni Foundation (FJR), which belongs to the Faculty of Engineering, and the Municipality of Montevideo. The contribution of the Universidad Politécenica de Madrid (UPM) is related to advisory tasks and simulation model for the electrification of this vehicle, to assist the Faculty of Engineering of Montevideo in a series of specific and technical issues that require the use of specific tools and know-how. The activities of the main project are listed below:

- Analysis of the result obtained from the instrumented vehicle: the data about the vehicle and driving cycles are provided by the technical team of the Faculty of Engineering of the University of the Republic (UDELAR). The first part of this technical consultancy will be a data analysis of the instrumented vehicle. The necessary guidelines will be given to carry out a correct analysis of the data obtained from the powertrain during the operation cycle. These data will work as input to the simulation models that will be developed in the later phases.
- Development of two longitudinal dynamic models: two software are used to simulate the model: AVL CRUISE^{TM} M and MATLAB/Simulink, trying to recreate the architecture of the real vehicle. These two models will be developed in parallel, and their performance and simulation, and results will be compared. The final goal is to obtain reliable outcomes and define possible operating ranges.
- Assist in the Selection of components: these components will be part of the future powertrain and auxiliary systems of the vehicle. The goal is to study the best sizing method for them through the performance data of the real operation cycle provided to the UPM.
- Sizing of the traction motor: the main three criteria taken into consideration through the results of the tests and different regulations applicable to this type of vehicle are the following ones:
    a. Acceleration
    b. Climbing performance
    c. Maximum speed
- Sizing of the aerial work platform motor: by analysing the results of the tests it will be possible to match the requirements for the platform motor, to understand if it is possible to keep the current system or if it is necessary to replace it by coupling an electric motor.

- Battery sizing: considering the information obtained in the previous tasks together with the vehicle characteristics, the goal is to develop a virtual model of the High Voltage Battery to compute the necessary energy and power to be shipped. This information will be the input data for the selection of the most suitable battery pack, according to the available products in the market.
- Simulation with the selected components: once all the parts and components of the electrified vehicle are defined, these will be introduced in the virtual model, to validate the performance through the simulation.
- Structural and stress analysis of the electric vehicle: with Inventor Autodesk, a 3D model of the new truck will be developed, to analyse the structural stress, vibrations, and structural behaviour of the new parts. Through this final simulation, it will be possible to have a solid design for the truck.

Figure 1 Iveco Daily 70C17HD - UTAP

1.2 Thesis Aim and contribution to the project

This thesis aims to complete the first part of the virtual modelling and simulation of the electric version of the vehicle. First, all the data regarding the vehicle and the driving cycle will be collected and analysed, then it will be possible to set up the simulation on the two software and perform it to validate the performance of the battery electric vehicle. The goal is to obtain a vehicle which performance that can be comparable to the original vehicle equipped with the internal combustion engine and that can complete the task requested from the real driving cycle. Once defined the technical requirements of the new electric vehicle it will be possible to search for real components that have to be installed on the truck. This thesis project has been developed with the contribution of the INSIA, in the "Alternative propulsion systems and environmental impact of motor vehicles", with the collaboration of a technical team of researchers. The main contribution to this part of the project are the activities listed below:

- Analysis of the results obtained from the instrumented vehicle.
- Development of two simulation models on AVL Cruise M and MATLAB/Simulink.
- Definition and implementation of the driving strategy algorithm to be adopted over the cycle.
- Longitudinal dynamic analysis of the vehicle
- Sizing of the traction motor considering acceleration, climbing performance and maximum speed
- Sizing of the high-voltage battery.
- Simulation with the selected components.
- Validation Metric for response histories: Sprague and Geers metric for data similarity.

The part of the project regarding the purchase of the components and their installation on the vehicle will be not discussed in this paper, as well as the structural analysis, Failure Modes and Effects Analysis and circular economy of the final product. This part will be developed in the future by the technical team of the UDELAR, once the virtual model is completed and validated.

2 Electric Vehicles Overview

Electric mobility (e-Mobility) is the general term used for the development of electric-powered drivetrains, designed to shift vehicle design away from the use of fossil fuels and carbon gas emissions. Nowadays, vehicle manufacturers, researchers, and policymakers are boosting their attention to electric vehicles, to help reach environmental, societal, and health objectives. EV fleets are expanding in several types of vehicle markets, including two/three-wheelers, light-duty vehicles, shared vehicles, buses, and heavy-duty vehicles with short-range requirements. The success of EV development is driven by multiple factors, but the main factor is a sustained policy support. Public spending on subsidies and incentives for EVs allows a growing number of countries to have ambitious vehicle electrification targets for the coming decades. On the other hand, EV sales are still lagging behind other emerging and developing economies where the few available models are unaffordable for the majority of consumers [4] , [5]. The advantages of using a BEV in traffic are the high torque of the electric motor that is transmitted to the wheels and the smoother acceleration compared to vehicles equipped with an internal combustion engine. Furthermore, BEVs operate without emitting noise and they do not produce pollutant emissions. These aspects make this type of vehicle ideal to be used in urban environments. However, electric vehicles still have many challenges to face, such as high-cost production, limited autonomy, top speed, large recharging times, and weight payloads [6]. One of the most interesting features of the all-electric vehicles is the regenerative braking. It is a system found in EVs that recharges the battery by capturing the kinetic energy of braking and it converts it to electrical energy that charges the vehicle's high-voltage battery. The electric machines can be controlled to work as a motor and as a generator, allowing in this way the energy conversion. This technology also slows the car down, which works as an assistant to the traditional brakes. Regenerative braking systems allow electric and hybrid vehicles to recover part of the kinetic energy usually dissipated in heat when using traditional friction braking systems, saving up to 25% of the total used energy in a driving cycle. It is important to realize a proper design of the regenerative braking system, in terms of efficiency and safety of the driver. The braking power that can be generated from traditional brakes is much way higher than the regenerative braking power that can be provided by the electric machine. For this reason, the presence of traditional brakes is still essential, despite there are control strategies that allow the driver to use only the accelerator pedal in normal driving conditions. Moreover, there are some cases in which regenerative braking cannot be used, e.g. when the state of charge is too high, or the battery reaches exceedingly elevated temperatures [7]. The main benefit of this system is a higher efficiency, greater range in terms of km, and reduced stress and heat dissipation for the used components. It is usually desirable to use regenerative braking both to recoup energy and as a convenient form of frictionless braking [8]. There are three main types of electric vehicles available on the market that, in turn, can contain many other subcategories:

- ***Battery electric vehicle (BEV):*** It is a type of electric vehicle in which energy is provided only from a battery pack. BEVs do not use internal combustion engines to operate, so they do not produce tailpipe emissions when driven. However, the electricity they use may produce heat-trapping gases and pollution at the source of its generation depending on the producing energy method. This is particularly true in the case of the extraction of fossil fuels. The concept of BEVs is simple, and the vehicle consists of a chassis, an electric battery for storage, an electric motor, and a controller. The battery is normally charged via a plug; indeed, electric vehicles are equipped with a dedicated socket for charging. The controller is responsible for controlling the power supplied to the motor, and hence the vehicle speed. Furthermore, electric vehicles do not need a multiple-gear transmission. One reduction gear at the final drive level is usually enough because electric motors produce a consistent amount of torque at any given rpm within a specific range. Thus, the torque required by the wheels is already reduced by the motor shaft.
- ***Hybrid Electric Vehicle (HEVs):*** a hybrid electric vehicle is defined as a vehicle that includes an internal combustion engine (ICE) and at least one electrical machine fed from a battery using power electronics. In this type of vehicle, the battery can be charged directly from the ICE through a control strategy or by the grid through a dedicated socket for charging in the case of plug-in hybrid vehicles (PHEVs). In turn, hybrid electric vehicles can be classified according to several factors:
    a. *Drive train structure:* the linkage between ICE and electric motor and the overall layout of the drivetrain can define the typology of a hybrid vehicle. The structure can be differentiated into series, parallel, combined, or complex hybrid vehicles.
    b. *Traction power contributed by electric motor:* The vehicle can be categorized as a mild or micro hybrid, medium or power assist hybrid, full hybrid, and plug-in hybrid depending on the share of traction power given by the electric

motor. The basic methodology behind the hybrid vehicle design is to operate the electric motor first. Then, the internal combustion engine is added to the drivetrain only when it is needed and to operate at a minimal state to optimize fuel consumption. Plug-in hybrids, among the other types of hybrid vehicles, can cover moderate distances by only using the electric motor (in many vehicles this is called EV mode) thanks to larger batteries. The category is developed using the degree of hybridization, which can be expressed with a factor known as the hybridization factor or ratio HF. It is defined as the ratio between the maximum power of the electric motor (P_{eM}) and the ICE ($P_{ICE.}$) [9].

$$Hybdridization\ Factor\ (HF) = \frac{P_{eM}}{P_{eM} + P_{ICE}} \tag{1.1}$$

- ***Fuel Cell Electric Vehicles (FCEVs):*** in contrast to the other electric vehicles, the electricity is produced by using a fuel cell powered by hydrogen instead of drawing it from only the battery pack. FCEVs offer the same advantages as the BEVs such as zero roadside emissions. In addition, they can offer a driving range comparable to that of the ICEVs and the time required for a complete refuelling of the hydrogen tank is less compared to the time required to fully charge a battery. The amount of energy stored onboard is determined by the size of the hydrogen fuel tank. The main challenge is the high initial cost, because of the use of expensive fuel cells. Hydrogen refuelling represents another big problem related to this type of vehicle because the infrastructures are absent. The practical ways to store hydrogen are compressed hydrogen gas (CHG), liquid hydrogen (LH), and metal hydrogen (MH). When adopting the first method, the pressure reaches levels of about 350-700 bar. Thus, the infrastructure is like that of compressed natural gas for some alternative fuel vehicles. Using the LH method, the infrastructure is very demanding since the hydrogen needs to be cooled to about -253 °C while still pressurized. When adopting the MH method, the infrastructure is like the one used for battery swapping to mechanically replace the discharged MH with the fully charged MH. In the coming future, the commercialization of the FCEV depends on whether there will be a breakthrough in fuel-cell technology in terms of cost per kilowatt and whether there will be a mandate or energy policy to establish the hydrogen refuelling infrastructure [10].

2.1 Key components of a battery electric vehicle

The BEV architecture is the simplest one in terms of electrical and mechanical components among the other electric vehicles mentioned before. The technologies for e-mobility include elements such as electrical machines, power electronics, electrical drives, and battery packs. Breaking down the key parts that make up an electric vehicle is fundamental to having a proper understanding of each component.

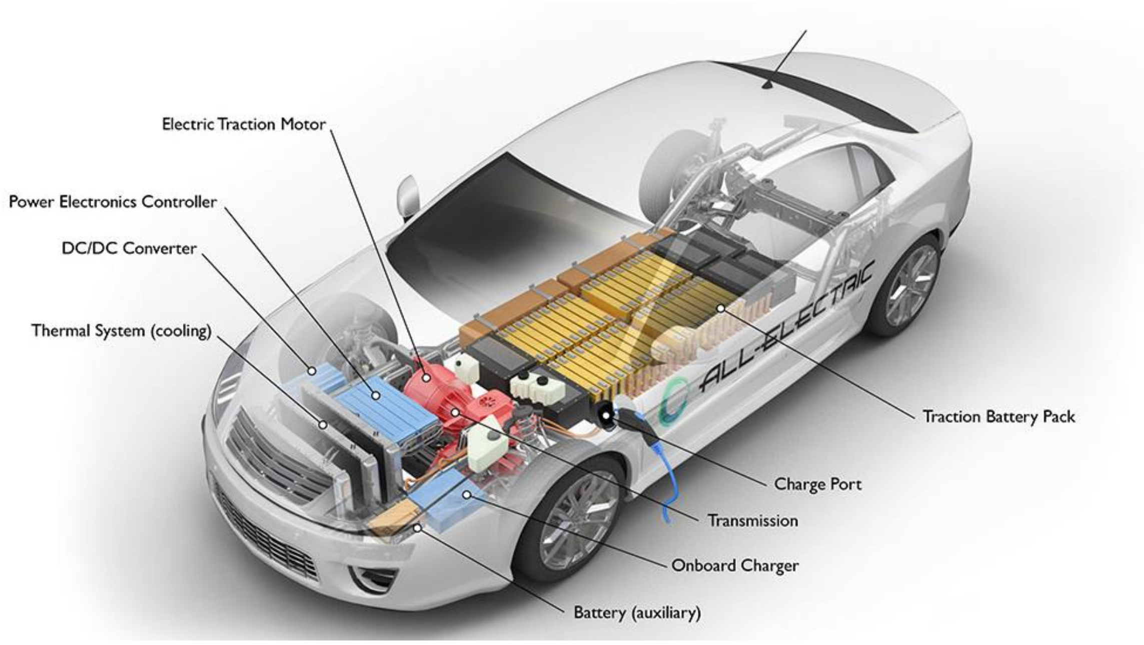

Figure 2 Battery Electric Vehicle general scheme [11]

2.1.1 Battery

In the most basic terms, a battery is an electrochemical cell in which an electric voltage is generated at the battery terminal by a difference in potential between the positive and negative electrodes In EVs, it is an element representing a bidirectional energy source. A battery cell is made up of five major components:

1. Electrodes-anodes and cathode.
2. Separators.
3. Terminals
4. Electrolyte.
5. Case or enclosure.

Battery cells are grouped into a single mechanical and electrical unit which is called a battery module. Then, these modules are electrically connected to form a battery pack, which is the source of power for the electronic drive systems. The electrolyte can be a liquid, gel, or solid material. Many battery manufacturing technologies are suitable to equip an electric vehicle, technologies that today, are widely accepted by the companies in the manufacturing industry:

- ***Lead Acid battery (Pb-acid):*** this type of battery is the oldest one used worldwide. They have the main disadvantages related to handling acid substances, the presence of lead in their construction, low stored energy/weight, and energy/volume ratios. For these reasons, this type of battery has an inexpensive manufacturing technology, being a cheap solution for equipping electric vehicles.
- ***Nickel-Cadmium battery (NiCd):*** it has the highest lifespan expressed in terms of the number of cycles of charge and discharge (about 1500). The main drawback is the use of Cadmium, a heavy metal that has harmful effects on the environment. Nowadays, the EU has limited the use of this typology of batteries.
- ***Lithium-ion battery (Li-ion):*** it is characterized by a large power storage capacity with an exceptionally good energy/density weight ratio. Nowadays, it is the most popular technology used for electric vehicles. This type of battery has a higher cell voltage compared to other technologies. For this reason, it is possible to have fewer cells connected in series to obtain high voltage. On the other hand, the main limitations of Li-ion batteries are due to their excessive costs, the potential of overheating, and a limited life cycle.
- ***Sodium Nickel Chloride battery (NaNiCl):*** it is also known as the "Zebra battery". This type of battery uses a molten salt electrolyte with an operating temperature range of 270-350°C. The Sodium Nickel Chloride battery offers a high stored energy density, but it can present problems related to its operational safety and its storage for longer periods [6].

When an electrical load, such as a motor is connected to the battery terminals, an electric circuit is completed. The battery provides power to the electric motor through the traction inverter, and current is passed through the motor generating torque. Outside of the battery, the current flows from the positive terminal, through the motor, and returns to the negative terminal. In this way, the battery delivers its stored energy from a charged to a discharged state. If the electrical load is replaced by an external power source that reverses the flow of the current through the battery, the battery can be charged [12]. Two types of batteries are installed on the vehicle:

1. High Voltage (HV) Battery ($V_{DC} \geq 48\ V$)
    - Provides power to the motor through the traction inverter.
    - Charging systems.
2. Low Voltage (LV) Battery
    - 12 V for auxiliary systems.
    - Bidirectional DC-DC converter between LV and HV battery.

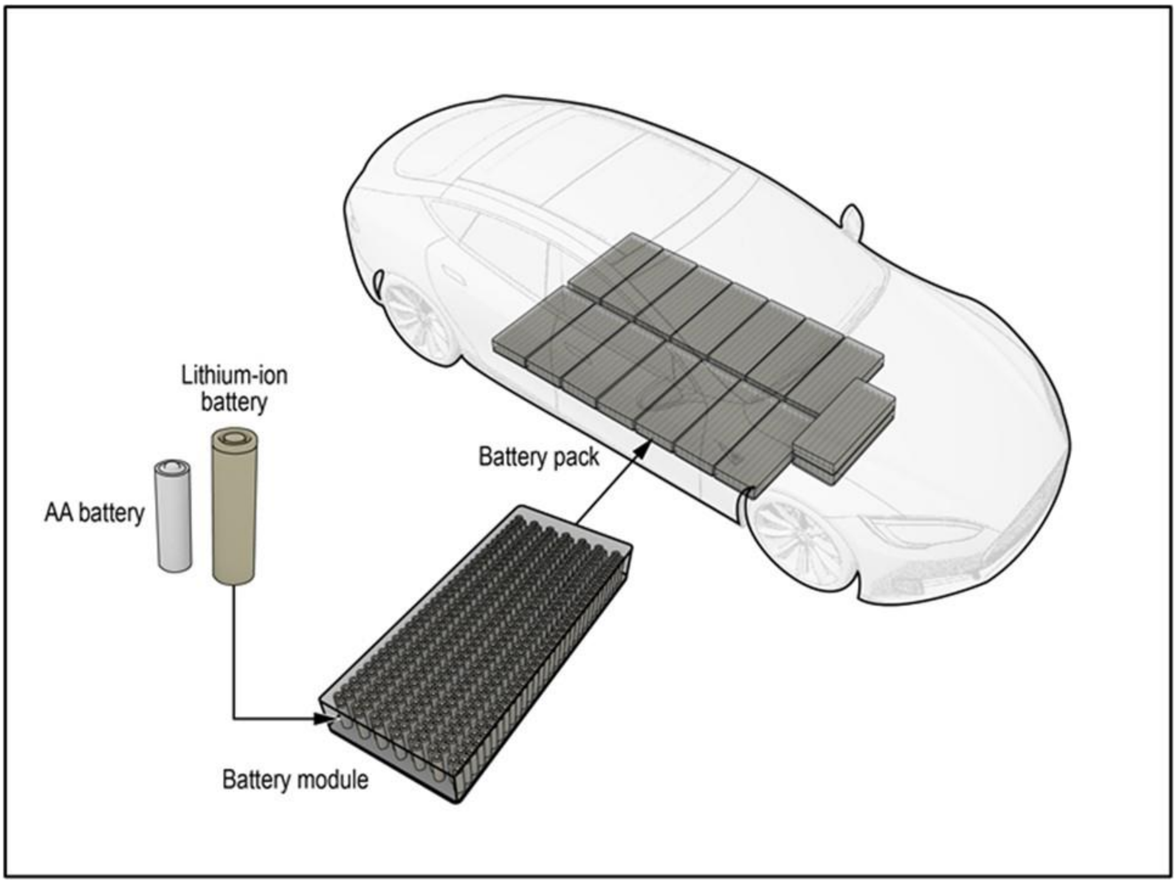

Figure 3 Automotive Battery Pack scheme [13]

2.1.2 Battery Management System

Battery Management Systems are electronic control circuits that monitor and regulate the charging and discharging phases of batteries. This system controls and optimizes the battery pack, and it prevents damaging the battery from a surplus of current/voltage or temperature due to variations in the demand and driving conditions. It is a complex system and the main characteristics of the BMS are the following:

- Monitoring of the battery temperature, voltage, and state of charge (SOC).
- Control of the power availability for the e-powertrain.
- Protection from overcharging and over discharging.
- Communication interface.
- State of Health of the battery (SOH).

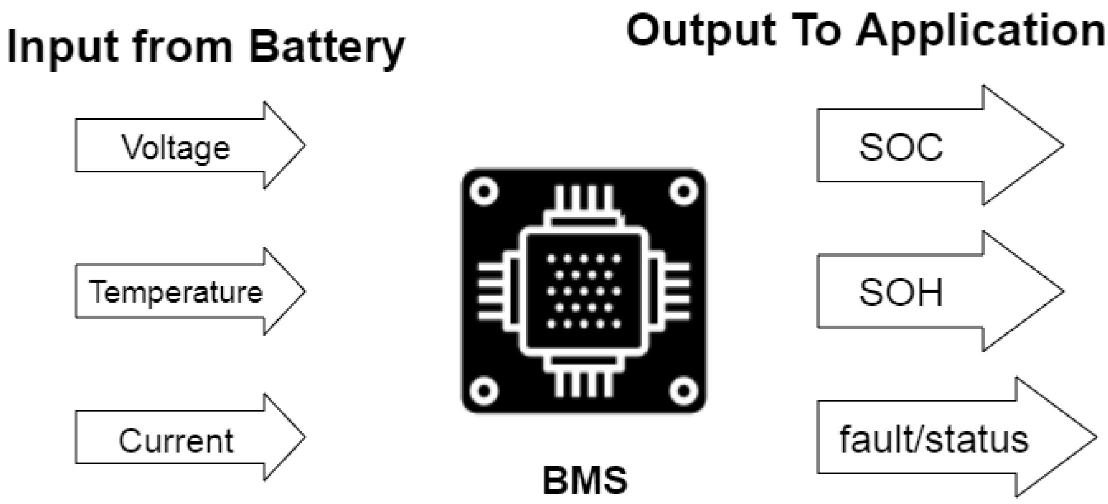

Figure 4 Battery Management System block diagram [14]

2.1.3 Electronic Control Unit

In an electric vehicle, it is particularly important to know how to manage the energy flow among all its components. Electronic Control Units (ECU) are the devices that control the amount of power/energy delivered to/consumed by the motor to drive the vehicle. To do so, they can vary the voltage, current, and even frequency delivered to the electric motor, ensuring that the vehicle responds to the driver's input depending on the pedal's command. Today, ECUs activate power supplies in BEVs using digital commands, which provide infinitely faster response and smooth operating conditions. It is possible to electronically manipulate both direct current and alternating current into the exact signal required to meet driver requirements. This increase in operational control allows more flexibility in the design phase of modern EVs. [15]

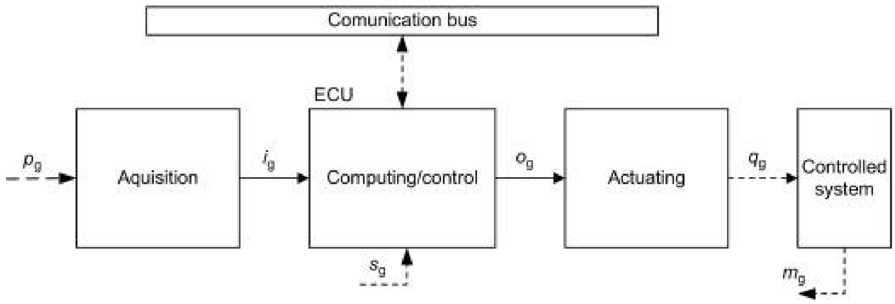

Figure 5 ECU Control Loop: Automotive Application. [16]

2.1.4 Power Electronics and Converters

A power converter is defined as an interfacing element between an electrical energy source and an electrical load. It allows the adaptation of the parameters of the electrical power to the load according to its characteristics or to regulate the provided power. Power electronics are facilitating the technologies to impel the shift from conventional vehicles to EVs. The extremely proficient circuits built with high-power electric switches and analog-digital control circuitry are known as power converters in the automotive industry. The classification of power electronic converters is decided by the source and load characteristics. The main types are listed below:

- ***AC/DC converters (rectifiers):*** from AC sources to DC loads. These components are used as components of DC power supplies and high-voltage direct power transmission systems.
- ***DC/DC converters:*** from DC sources to DC loads having different voltage levels. To operate at its optimum operating point, this type of converter is a variable voltage converter.
- ***DC/AC converters (inverters):*** from DC sources to AC loads. It is mainly used in electrical power applications where complex circuits and high voltages are present. It allows the connection of the power flow from the battery to the AC motor. The output sinewave of the AC current is constructed by switching alternatively ON/OFF a system of multiple

transistors at a certain frequency using Power Width Modulation techniques. At each switch, a part of the energy is lost during the commutation through conduction losses in the inner resistance and capacitance of each component.

- ***AC/AC converters:*** from AC sources to AC loads. It allows control of voltage, frequency, and phase of the way from applied to a load from a supplied AC system.

Generally, a power converter is always designed for overload conditions (max output current) and therefore its rated power is higher than the load-rated power. Compared to electromechanical converters, the power electronic ones have higher efficiency, lower cost, less bulky, and less maintenance due to no moving parts. On the other hand, the main drawback is that there is less overload capability compared to their electromechanical counterparts. The most used converters in automotive applications are the DC/DC and DC/AC ones [17]. Their combination enhances the system's performance and affords more flexibility. The converters also allow recharge in the battery pack during regenerative braking [9].

The key part of the electronic converters are the switches, whose main rated parameters are voltage, current, switching time, and the ON state resistance. The main three types used in the Automotive Industry are:

- ***Power Diode:*** is the simplest power electronic device and it is characterized by two terminals: Anode (A) and Cathode (K). It is classified as a unidirectional device because it allows the current flow only from A to K. If the power diode is conducting, it works as a closed switch, if not it works as an open switch. The power diode uses an additional internal layer with a low doping level that defines the breakdown voltage of the device, in other words, is the minimum voltage to experience an electrical breakdown of an electronic device. If the negative voltage exceeds the breakdown voltage, the inverse current will cause irreversible damage to the power diode.
- ***Metal Oxide Semiconductor Field Effect Transistor (MOSFET):*** a MOSFET is an electronic device made of semiconductor materials that is used to amplify or commute electronic signals. It is made of three main terminals; in such a manner it can be connected to the external circuit. A voltage applied on two terminals allows for control of the current flux in the device.

- ***Insulated Gate Bipolar Transistor (IGBT):*** it works as a controlled switch in power electronics circuit. An IGBT can commute high values of current and voltages. It is made of two power terminals (Collector and Emitter) and one command terminal (Gate).

As a rule, the more switches are needed, the higher are the inverter losses.

2.1.5 Electric Motor

Electric machines are defined as machines that use electromagnetic forces and they work electromechanical converters. In the automotive field, an electric machine is used as a motor or generator. A motor converts electricity to mechanical power, while the generator does the opposite. Electric machines are the key element for motor drive technology, which is to convert the onboard electrical energy to a mechanical output. Thanks to the ECU's ability to manipulate the characteristics of the DC power that flows from a battery to an electric motor nowadays it is possible to do away with the brush/commutator connection used in conventional DC motors. The lack of physical contact between components improves the overall efficiency of the motor and its reliability. While the scientific principle behind modern electric motors remains unaltered, there is now a vast choice of electric machines that are involved in the automotive industry.

Concerning automotive applications, electric motors must meet some basic specifications for passenger cars and light-duty vehicles:

- Power ratings around 100 kW.
- Torque ratings around 200 Nm.
- Good regenerative braking.
- 10-year lifespan.

Nowadays, modern EV development finds its best application in three main electric motor families that best suit the above-mentioned basic requirements.

1. ***AC induction motors:*** it is a type of AC electric motor in which the current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field or of the stator winding. The Induction Machine (IM) is composed of a magnetic excitation winding on the stator and armatures on the rotor. IMs can

eliminate brushes and commutators to achieve a brushless drive [18]. Torque is produced only if there is no synchronism between the frequency of the electric stator quantities (current and voltages) and the rotor angular speed. For this reason, this type of motor is also called asynchronous e-motor. It has been the most widely deployed in a diverse range of applications and is thus the most mature and proven technology, also because it is not expensive and extremely reliable. However, its efficiency deteriorates at low load levels, and it has a narrow constant power range. IMs have been widely applied to commercial EVs, such as the Tesla Model 3 and Model S, BMW i3, Mercedes-Benz B Class Electric, Toyota RAV-4, and Nissan Leaf.

2. ***AC switched reluctance motors*:** it is an electric motor that runs by reluctance torque. If the rotor is anisotropic (the inductance is not constant along the airgap) the rotor reacts to the stator magnetic field and tends to follow the wave of currents [17]. They are also proving to be inexpensive and reliable, due to their simple construction. Moreover, they present a good torque/speed characteristic with a wider constant power range. However, switched reluctance motors face difficulty in power control. However, due to its torque density limitation, practical applications for passenger BEV propulsion systems can be hardly found. Despite this, the switched reluctance motor is still suitable for small-size electric vehicles, such as golf buggies, scooters, or food delivery vehicles [18].
3. ***Permanent magnet motors*:** this type of electric motor uses permanent magnets in addition to windings on its field. They provide the highest efficiency levels among EM rivals. Moreover, they provide remarkably high flux density without consuming any energy and the high energy density allows for a very compact motor design. The main drawback is the high cost, due to the rare-earth metals required for their construction. Furthermore, they suffer from a narrow constant power range [15]. Due to the rapid development of PM materials, this type of motor is increasingly preferred in electric drive systems for EVs and HEVs. Permanent magnet machines find applications in many vehicles nowadays available on the market, such as Chevrolet Bolt, Ford Focus Electric, Hyundai Ioniq, and Jaguar I-Pace

2.1.6 Control of the Electric Drive

Control is one of the most important technical areas of electrical power conversion and electric drives. From an electric drive perspective, there are two main feedback control loops on a vehicle. The outer loop is the vehicle speed loop. This loop is slow, and it is generally closed in the brain of the human driver. The second main loop is the torque command, which is fed into the vehicle powertrain by the command given on the accelerator or brake pedal. This loop is significantly faster than the former, and the vehicle can give a fast response and regulate the machine's torque. This inner torque loop is essential in the electric vehicle. In this way, the current is easily regulated and is proportional to the machine’s torque. A PI controller can be used for controlling both torque and speed loops [19].

2.2 Electric commercial vehicles comparison: market analysis

Heavy-duty vehicles are defined as a category of vehicles that weigh more than 3.5 tonnes for trucks, or more than eight seats for passenger transport vehicles, like coaches and buses. These vehicles find applications in many sectors, from local delivery to construction and maintenance. Cutting greenhouse gas emissions (GHG) is becoming essential to reach climate neutrality by 2050 and mitigate climate change. Today, heavy-duty vehicles contribute about 8% of the total European Union (EU) [20] GHG emissions. The needed strategy from the EU is moving to a competitive low-carbon economy in 2050, which means that the transport sector should reduce the emissions of CO_2 by about 60% compared to its 1990 level [21]. To solve the issues of increasing pollution, global warming, decreasing natural resources, etc., an electric vehicle is considered a potential substitute for the current generation of vehicles. Nowadays, research focuses its attention on low-emission and fuel-efficient vehicles due to environmental issues and strict emission rules. Electrical commercial vehicles are becoming increasingly popular because of their low carbon emissions, cheap maintenance requirements, smooth ride, and reduced engine noise. [22]. However, the limited distance range, long charging time, and payload penalties are the biggest disadvantages of this type of electric vehicle if compared to traditional ICEVs. Since the IVECO Daily 70C17 HD to be analysed in this paper is equipped with a crane, its weight exceeds the limit of 3.5 tonnes and thus is considered a Heavy-Duty vehicle. In this part of the chapter, the focus will be a comparison among electric medium and high-duty commercial vehicles like the Iveco which are nowadays available on the market. This analysis will be useful to understand the currently used technologies, technical specs of the vehicles, and range of power, torque, battery energy, and maximum distance in km of the real vehicles. In this way, it is possible to have whether a comparison of the performances of the simulated model with real references at the end and or to have reliable data to choose properly the new components (such as battery and traction motor) of the Iveco Daily 70C17 HD to modify. Normally, the electric vehicles in this category are used in optimal duty cycles such as local delivery, food distribution, and maintenance operations. Several manufacturers produce electric trucks/vans for food and beverage, parcel delivery, utility, and maintenance work [23]. The results of the comparison done among these real vehicles are summarized in the table below.

	Gross weight [kg]	Battery Energy [kWh]	Max Power [kW]	Max Torque [Nm]	Range [km]
IVECO eDaily 72C	7200	111	140	400	120-180
FUSO eCanter 7.5t	7500	82.6-123.9	129	430	140-200
VMC 1200	5443	150	150	1085	241
MULLEN Three	4990	89	120	319	210
FORD e-Transit cabina	4250	68	198	430	237
CENNTRO Logistar 400	6531	80.6	85	[-]	135
JAC MOTORS iJac 7.5t	7490	106.95	91-171	550-1050	230

Table 1 Comparison of electric commercial vehicles [24], [25], [26], [27], [28], [29], [30]

Besides the FORD e-Transit Cabina, which is the lightest one among this list of vehicles, all the other vehicles have battery energy values between 80 and 150 kWh. For what concerns the range all vehicles have a declared range of at least 120 km, and generally the trend is between 120 and 240 km. Eventually, although all the vehicles have more or less a similar range of power, some of them, like the VMC 1200 and the iJac 7.5, can have some versions with a level of torque that is practically double compared to the other commercial vehicles. This could depend on the application because important levels of torque are required with a lower level of transmission ratio at the final drive or a higher request of maximum slope. To sum up, it is convenient to make a list of the possible range of values regarding the characteristics mentioned before, to have some values as a reference for the vehicle to simulate. The target ranges are:

- Battery energy: 80-150 kWh
- Power: 85-170 kW
- Torque: 320-1100 Nm
- Maximum range: 120-240 km

Compared to light-duty BEVs, there are few medium-duty and high-duty electric vehicles on the road to date. This is in part because not all light-duty BEV technologies cannot be transferred directly to medium-duty and high-duty applications, due to the requirements for higher power and durability in different and harsh working conditions, especially for very high-weight vehicles. Due to differences in duty cycles, one truck electrification model cannot be considered representative of all other truck applications. As a result, there is still limited commercial availability for electrified versions of medium-duty and high-duty vehicles. The electrification technology of these categories of vehicles is still in the initial stages of development, despite grand expectations for their future market. The main challenges to face to reach an important level of availability in the current market are:

1. Feasibility studies of the battery electric vehicle and priority across types and duties of MD/HD vehicles.
2. Cost-effectiveness of electrifications.
3. Alignment of stakeholder needs and policy.
4. Energy consumption analysis
5. Charging infrastructure for the fleets and charging time of the vehicles [23]

2.3 Future of electric vehicles

Electric motors deliver more performance and efficiency compared to an internal combustion engine. These vehicles have the potential to contribute to the reduction of GHG emissions. They can contribute to the reduction of air pollution and noise in urban areas. Restrictions imposed by governments are creating interest in electric vehicles. However, EVs have currently higher costs than conventional vehicles and some less favourable characteristics such as shorter driving ranges and long charging times. For a more rapid market penetration of EVs, the introduction of supporting policy measures is important as well as non-monetary measures, such as free parking spaces, availability of fast charging, and the possibility to use EVs in public transportation. Currently, the most popular electrified vehicles are the HEVs, because of similar costs and operating ranges as conventional ICE vehicles [31]. Generally, the literature increasingly confirms the technical feasibility of heavy-duty vehicles, due to improved technology. Several studies imply a great potential for urban and regional delivery with a daily mileage of less than 400 km [20], as also confirmed by the comparison of real vehicles done in the previous sec,ion.

3 Methodology

In this chapter it will be discussed the methodology and more in details the tools used for the development of the project. The chapter is organized as follows:

1. The first part regards the data collection about the vehicle and the driving cycle. Thanks to continuous collaboration with the technical team of the Julio Ricardoni Foundation, it has been possible to obtain and collect data directly from the original instrumented vehicle, by using an On-Board Diagnostic (OBD) device.
2. The focus of the second part is on the implementation of the driving control strategy, which in this case is the "One Pedal Drive." The basic concept of this strategy is that the accelerator pedal can be used to perform regenerative braking. It is a method widely adopted by many car manufacturers.
3. The third part is about the analysis of the longitudinal dynamics of the vehicle, which equations will lead to a preliminary design of the electric parts to be installed in the vehicle, such as electric motor, high-voltage battery, and inverter.
4. This part focuses on the description of some real components that can be installed in the future on the real vehicle, based on the considerations of step 3. Taking into account these components, it will be possible to run the simulation and observe the performance of the new electric vehicle.
5. The last part focuses on the simulation models. Breaking down all the block that compose the model is essential to better explain their working flow.

The study is based on the development and simulation of the same virtual vehicle model on two different software: AVL Cruise™ M and MATLAB/SIMULINK. The idea of using the two models is to have reasonable outcomes in terms of results, to obtain similar values or, at least, a range of possible values to operate and choose the best components for the real sizing of the single parts, such as the battery, the electric motor, and the aerial work platform. Many design issues will be discussed, such as the idea of keeping the gearbox or to install a new final drive with another transmission ratio. The output values that will be considered for the comparison of the two versions of the model are all the parameters related to the main parts that compose the electric vehicle. In particular, it will be used a validation metric method to study the correlation between the two models, describing the agreement between the results. To reach this goal, the first step of the study is the analysis of the received data. In collaboration with the technical team of the Faculty of Engineering of the University of the

Republic, all the necessary data about the vehicle and the operating cycle are provided to the research team of the INSIA. In particular, the data regarding the mechanical parts like wheels, brakes, chassis, gearbox, and engine are provided from the technical specs and the official manual of the use of the Iveco Daily 70C17 HD, while an Excel file containing all the information about the driving cycle, altitude, time, and engine load percentage, is provided through real road test done by the team of Montevideo. The cycle defines a representative use of the vehicle during an ordinary operation cycle. The idea of substituting the internal combustion diesel engine with an electric one starts from modelling a new electric motor having similar performances, in terms of maximum power and torque, to the original ICE. In this way, it is possible to size properly a battery that matches the performance of the new electric motor. For what concerns the transmission part, the idea of eliminating the gearbox will be considered. A first attempt is to keep the original gearbox with a fixed gear ratio of the first gear, and the transmission will be realized through a final drive that connects the differential to the electric motor. Then, depending on the results obtained through the original gear ratio, the idea of having another final drive with a different transmission ratio will be considered. If all the requirements are satisfied by keeping the transmission ratio of the first gear, the original gearbox will not be eliminated. Once defined all the parameters through the simulations, it will be possible to search for real components available on the market and choose the best solution in terms of cost and performance to provide to the technical team of Montevideo for completing the consultancy. Eventually, it will be possible to test the vehicle model with the real selected components. Once defined all the parts and components of the electrified vehicle, and the used driving strategy, these will be introduced in the virtual model, to validate the performance through the simulations.

3.1 Data Analysis

The first step of the study is the collection and analysis of the data. All the useful information such as the operating cycle and technical specs of the original vehicle are provided by the Faculty of Engineering of the University of the Republic, through a collaboration with the municipality of Montevideo. The data that are not provided by the other technical team which is requested to develop the simulations are calculated, found on official documents, or supposed based on the characteristics of the vehicle.

3.1.1 Reference vehicle general specs

The vehicle to be modified is an IVECO Daily 70C17 HD, propelled by a diesel engine. In particular, the vehicle is the chassis version, with a double cabin and equipped with a crane for public light maintenance. In this chapter, it will be done an overview of all the technical specs of the vehicle and how this data will be analysed for the simulation. The technical specifications of the truck can be found in the official vehicle user manual. The mechanical data regarding the chassis, transmission, and electrical system of the vehicle to be converted are listed below in Table 2, Table 3 and Table 4. Figure 6 is a representative image of the original vehicle, while Figure 7 shows the architecture scheme of the Diesel vehicle on AVL Cruise M.

Figure 6 Iveco Daily 70C17 HD Chassis Cabina Doble [32]

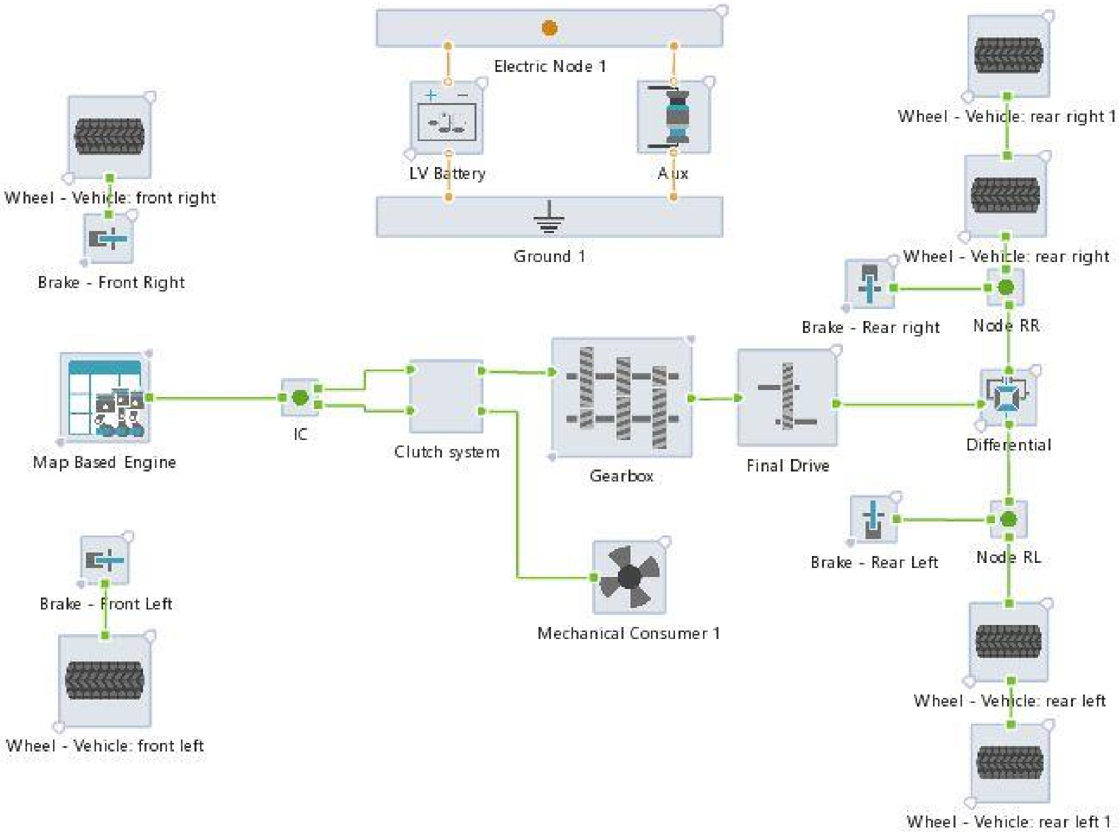

Figure 7 AVL Cruise M Iveco Daily 70C17HD virtual model

CHASSIS	
Brand	IVECO
Model	70C17HD
Version	2018 (Latin America)
Class	Heavy-Duty Vehicle
Weight (vehicle + aerial platform)	5820 kg
Wheels dimensions	215/75 R17
Wheelbase	4350 mm
Layout	Front engine – Rear wheel drive – 6 wheels
Drag coefficient	0.335
Frontal Area	4.48 m^2
Front Brakes	Disk brakes
Rear Brakes	Drum brakes

Table 2 Chassis mechanical data

TRANSMISSION	
Type	6-speed gears + R, Manual Transmission
1st	5.070
2nd	2.614
3rd	1.524
4th	1.000
5th	0.770
6th	0.657
Reverse	4.823
Rear axle ratio	5.86

Table 3 Transmission Data

ELECTRICAL SYSTEM	
Battery voltage	12 V
Battery capacity	110 Ah
Starting Motor power	2.5 kW
Alternator	14 V / 140 Ah

Table 4 Electrical system data

3.1.2 Internal combustion engine

The internal combustion engine of the vehicle is a 4-line cylinder, 16 valves DOHC engine, with chain distribution. It is a 4-stroke diesel engine with direct injection, turbo, intercooler, and electric management of the injection, common rail type. The cooling system is sealed and equipped with an electromagnetic fan. The motor block is made of steel, while the cover is made of aluminium. The escape system has a silencer, located in the middle of the chassis. It has a maximum power of 125 kW (170 CV) @3500 rpm, with a maximum torque of 400 Nm @1250-3000 rpm. This engine model is intended for the Latin American market. In the table and image that follow are expressed the character of the engine. [33]

INTERNAL COMBUSTION ENGINE	
Number of cylinders/valves	4L/4
Injection system	ECR
Turbocompressor	2st
Total displacement	3.0 L
Maximum power	125 kW (170 cv) @ 3500 rpm
Maximum torque	450 Nm @ 1400 rpm
Certification	Euro V
Aftertreatment system	Pre Cat – DOC – Cdpf
Dimensions	803x720x754 mm
Weight	262 kg

Table 5 Internal Combustion Engine Technical Specs

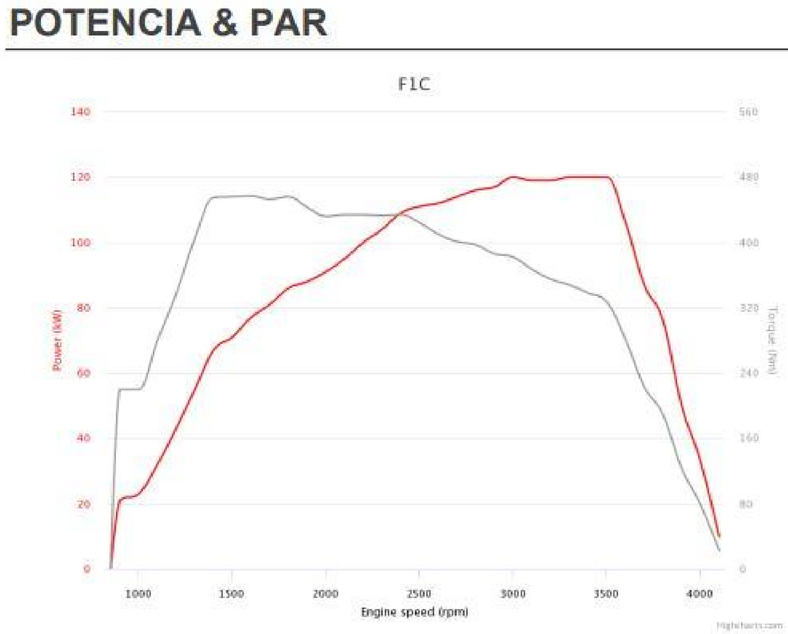

Figure 8 ICE Power and Torque characteristics [33]

3.1.3 Driving Cycle and Environment

The driving cycle is not standardized, but a real operating cycle done by the truck during a light maintenance operation in the city of Montevideo. To design modelling and validate a reliable model of the conventional and the electric truck, it is essential to test the vehicle with a real road test, to obtain information about its capability and functionality. To have precise and reliable data, a first measurement has been done using the Inertial Measurement Unit (IMU). This is an electronic device that can provide data about acceleration, orientation of the vehicle, angular speeds, and other important data of the vehicle. The use of an IMU during the driving cycles allows obtaining precise data and details about the key variables that define the behaviour of the vehicle in different situations. The device is made up of three accelerometers, three gyroscopes, and three magnetometers. These sensors work together to provide information about the state and the efficiency of the vehicle in each instant of time. To implement the IMU it is needed a laptop and the installation of the sensors and the correspondent antenna. Due to the operational complexity of the IMU, for a second attempt of measurement, it was chosen to use a set of mobile applications with complementary tools, which include GPS Logger and Torque, together with On-Board Diagnostic (OBD) II device. The application Torque can capture instantaneous data of the vehicle, such as the speed of the engine and of the vehicle. This combination of tools and applications turned out to be a practical and simpler solution for the study, compared to the use of the IMU. Furthermore, it has been proven that the obtained results of the two methods show a difference in the measurement of the overall distance that is less than the 0.5%, as shown in the image below.

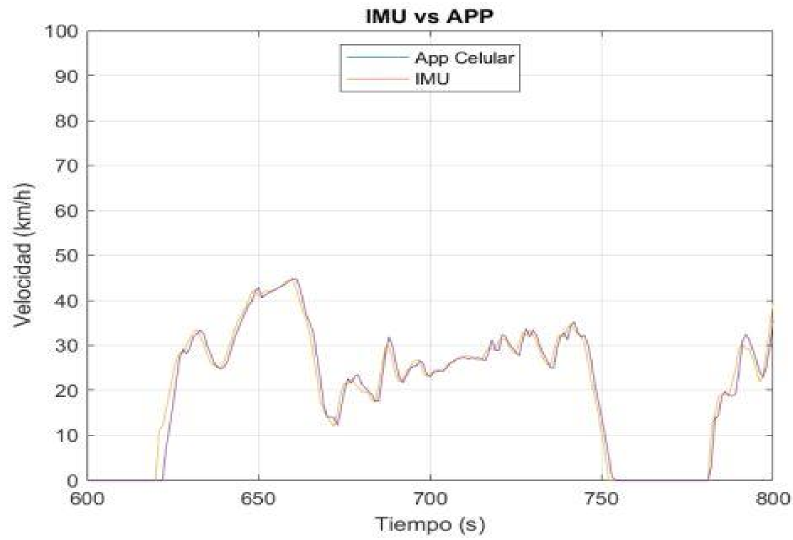

Figure 9 IMU vs APP zoom on driving cycle data comparison.

Consequently, the set of tools and applications has been used for the study because it is sufficiently precise and comparable to the IMU device. It was possible to collect data about the cycle and the vehicle's behaviour through a real driving test.

- Reference Time
- GPS speed
- Longitude
- Latitude
- Altitude
- Accelerator pedal position
- Engine Load
- Trip Distance

The cycle represents a trip to the Montevideo hill, which it is includes an operation with the crane to analyse its functioning and effect on the truck. This path also allowed to analyse the behaviour of the vehicle in terms of gradeability and high-speed routes, such as the roads that consent the access to the city. The cycle has a duration of 3863 seconds and a length of 24.331 km, and it is divided into 3 parts. The first and third ones consider an urban and extra-urban path, with frequent stops and a maximum speed of about 73 km/h in the former, and about 85 km/h in the latter. The part of the cycle in the middle represents a stop of the vehicle in which there is the effective operation of the aerial platform for public light maintenance. Once obtained all the data needed in the simulations must be corrected because they contain errors such as duplicated or incorrect trends of data during the cycle. Eventually, it is possible to reorganize the data in the way needed by the software and implement them in the simulation. In the end, it will be analysed the behaviour of the vehicle and the validation of its performance. The corrected cycle implemented in the software is shown in the following picture. This driving cycle is intended to be representative of the general drive that this type of vehicle must perform because it contains the following images represent the velocity profile depending on time and the route covered on the map.

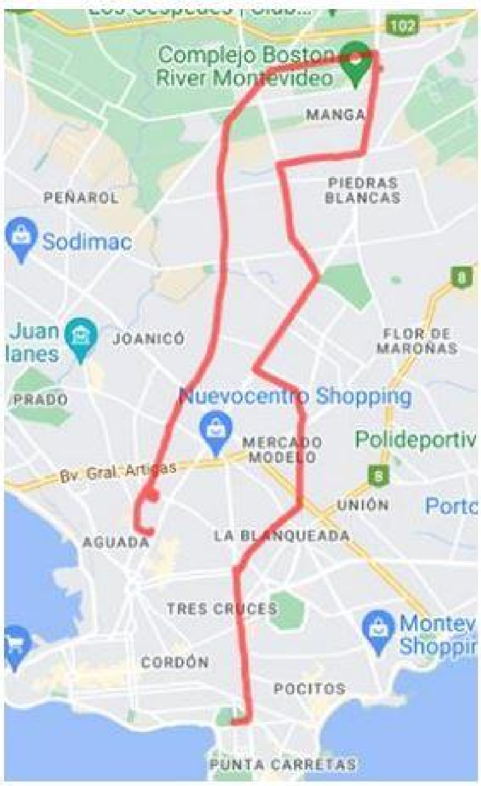

Figure 10 Montevideo driving cycle – route map.

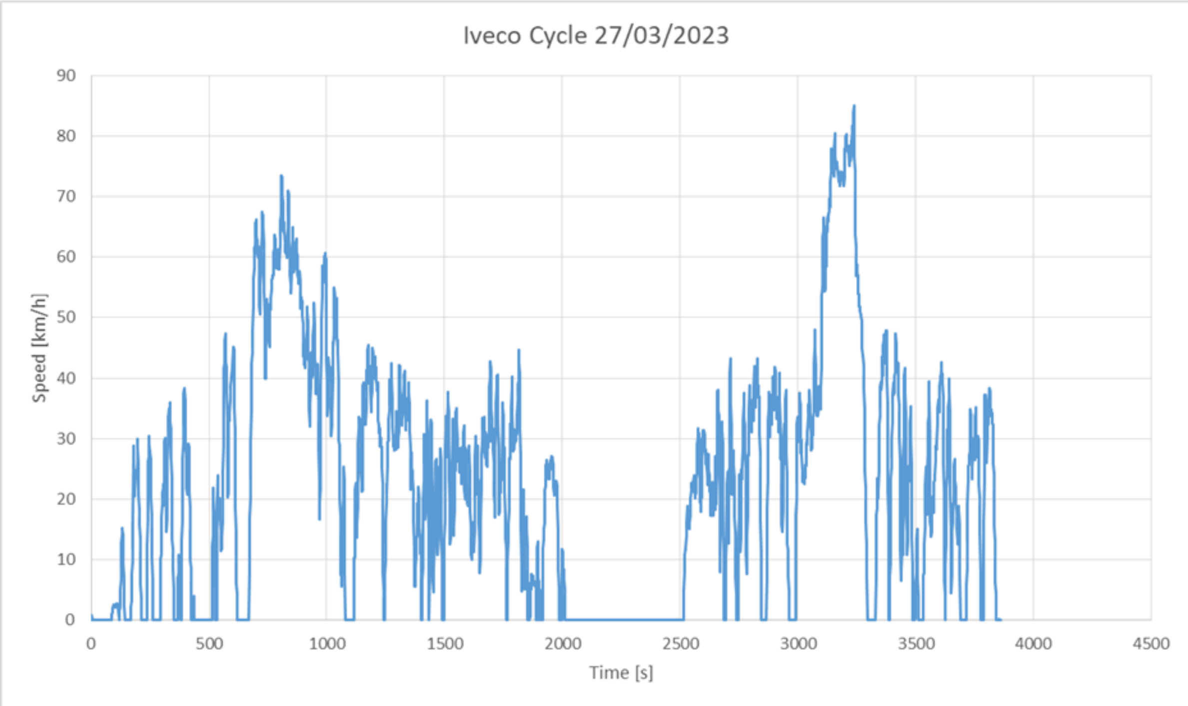

Figure 11 Montevideo driving cycle – Speed vs Time Profile

Besides the driving cycle characteristics, the instantaneous atmospheric pressure and density as well as the temperature play a significant role to perform a reliable simulation. The parameters considered are listed below.

ENVIRONMENT			
DESCRIPTION	*Symbol*	*Value*	*Unit*
Ambient Temperature	T_{amb}	20	[°C]
Ambient Pressure	p_{amb}	1.013	[bar]
Air Density	ρ_{air}	1.19	[kg/m^3]

Table 6 Environment Data

This driving cycle is also representative of the slope capability of the vehicle since the stop for the maintenance point is located at the top of a hill. In this way it is possible to have an idea of the maximum gradeability that the new vehicle needs to perform. The provided data about altitude needs to be filtered because otherwise the data obtained by the sensors collection generates an altitude profile with inclinations that are not realistic. For this reason, the altitude data have been filtered through the MATLAB function "smooth," to have a more realistic performance of the vehicle. Although the smoothed data are still not 100% reliable, the simulation will provide a more realistic situation with the altitude profile instead of a test in a plane road, also because by implementing the road altitude it will be possible to have a better look at the regenerative braking effect depending on the slope. The figure below shows the altitude profile over time, in which the highest part of the cycle corresponds to the point in which the truck stops for the maintenance operation.

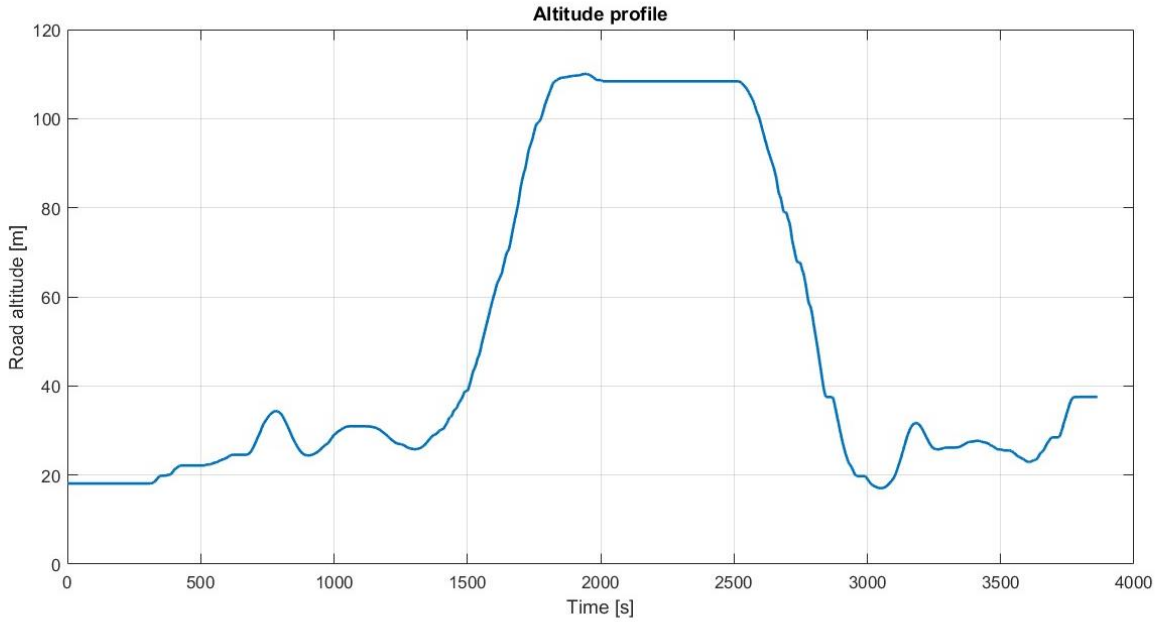

Figure 12 Altitude profile over cycle.

Further information about the driving cycle is summarized in Table 7.

OPERATING CYCLE INFORMATION	
Average distance per month	900 km/month
Registered power / torque / speed	122 CV / 460 Nm / 2600 rpm
Average fuel consumption	5 km/L
Aerial platform power	5 hp

Table 7 Operating cycle information

3.2 One Pedal Driving strategy

One of the main advantages of driving an electric vehicle compared to a conventional ICE car, is that an important part of the deceleration could be achieved without applying any pressure on the brake pedal. This feature allows to recover significant amounts of braking energy and EVs, HEVs and FCEVs can generally be controlled to convert the kinetic energy or potential energy of the mass into vehicle electric energy, which can be stored and reused as braking input. This control can be developed through dedicated driving strategies, which can manage the energy flow from the generator to the brakes. One of the most used strategies, is the so called "One Pedal Drive," where the accelerator pedal can also be used to perform regenerative braking. This control strategy is nowadays applied in several electric vehicles, such as the new Iveco e-Daily electric. This method allows to have a bigger energy recover, a reduction of the maintenance costs and a better comfort in driving. Other examples of vehicles that use this technology are the Tesla Model S, the BMW i3, Renault Zoe, Mitsubishi Outlander PHEV, and Volkswagen e-Up!. In a vehicle with an electric motor and fixed reduction like the Iveco Daily to be modified, very high and consistent levels of deceleration can be achieved, and the driver needs to use the brake pedal only in emergency cases or if the regenerative braking torque is not enough to stop the vehicle in time. For this reason, this observation has led to this type of strategy to be adopted in the future electric vehicle. The control logic is divided into three main parts: coasting, regenerative braking, and traction, which will be better explained in the next sub-chapters. The implemented algorithm has been inspired by a design of a One Pedal Strategy for the TU/e Lupo EL developed by the technical team of the Eindhoven University of Technology [34]. One Pedal Driving is defined by applying a negative or positive torque to the wheels considering the position of the accelerator pedal position. The pedal position will be expressed by the variable p, which represent a percentage of the maximum accelerator pedal stroke. The variable τ instead, represents the demanded motor torque, where:

- $\tau = 1$ means maximum acceleration.
- $\tau = -1$ means maximum regenerative braking.
- $\tau = 0$ no torque is applied.

Then, it will be considered:

- $\tau_{traction} = \tau \qquad if\ \tau > 0$
- $\tau_{regenerative} = |\tau| \quad if\ \tau < 0.$

Two important conditions to define in the implementation of the algorithm to avoid superimposition of driving modes, are the following ones:

$$if\ \tau_{traction} > 0 \rightarrow \tau_{regenerative} = 0 \tag{3.1}$$

$$if\ \tau_{regenerative} > 0 \rightarrow \tau_{traction} = 0 \tag{3.2}$$

Finally, the demanded torque signal is sent to the electric motor, and it is defined as:

$$T_{dem} = \tau_{traction} \cdot T_{trc} + \tau_{regenerative} \cdot T_{reg} \tag{3.3}$$

Where T_{trc} and T_{reg} represent respectively the characteristic torque curve of the electric machine in accleration and regenerative braking mode.

Another crucial factor to be considered is to define the torque limits of the electric motor, to analyse the working points of the motor. In the case of traction, the curve corresponds to the original torque curve available from the machine constructor, while for the regenerative curve there are some limits to be considered. The most important limit to take into account is the maximum charging current of the High Voltage Battery pack. The maximum charging power limits the battery in terms of quantity of energy that could be regenerated from the electric machine in each second. This limit is variable and depends on the state of charge and temperature of the battery. Starting from this point, a torque limit value has been computed to be applied to the electric motor to never overcome the current limit. In this way, a limit of electric power of the battery during regeneration can be defined, considering the worst case: maximum charge current and minimum voltage.

$$P_{lim,el}^{batt} = V_{min}^{batt} \cdot I_{max,ch}^{batt}\ [W] \tag{3.4}$$

The value of the voltage is not constant. For this reason, it could be measured over time to proportion a variable limit of electric power. However, this method could lead to regenerative braking that could be experienced as uncomfortable and too aggressive from the driver point of view. The power flow goes from the battery to the electric motor, also considering the efficiencies that characterize electric machine and inverters. In such manner, it will be obtained a limit power from the battery that should be greater than the limit power of the electric motor divided by the efficiencies.

$$P_{lim,el}^{batt} = \frac{P_{lim,el}^{eM}}{\eta_{inv} \cdot \eta_{eM}} \; [W] \tag{3.5}$$

At this point, it is possible to create a torque curve limit, depending on the angular velocity of the electric motor. This limit defines the maximum regenerative braking used in the driving control strategy. Hence, the electric motor can supply this value of power while keeping the charging current below the maximum limit defined from the high voltage battery.

As an example, let us consider the case of a battery pack composed of three modules in parallel. Each battery module has a limit charging current of 108 A, thus 324 A in total. The lowest voltage of the battery pack is equal to 540 V, while the efficiencies has been considered equal to 1, to consider a stricter limit in regeneration mode. The electric motor instead has a maximum torque of 500 Nm and a maximum speed of 12000 rpm. Once defined the limit power level, it is possible to obtain the values of torque for each point of speed that define the torque curve.

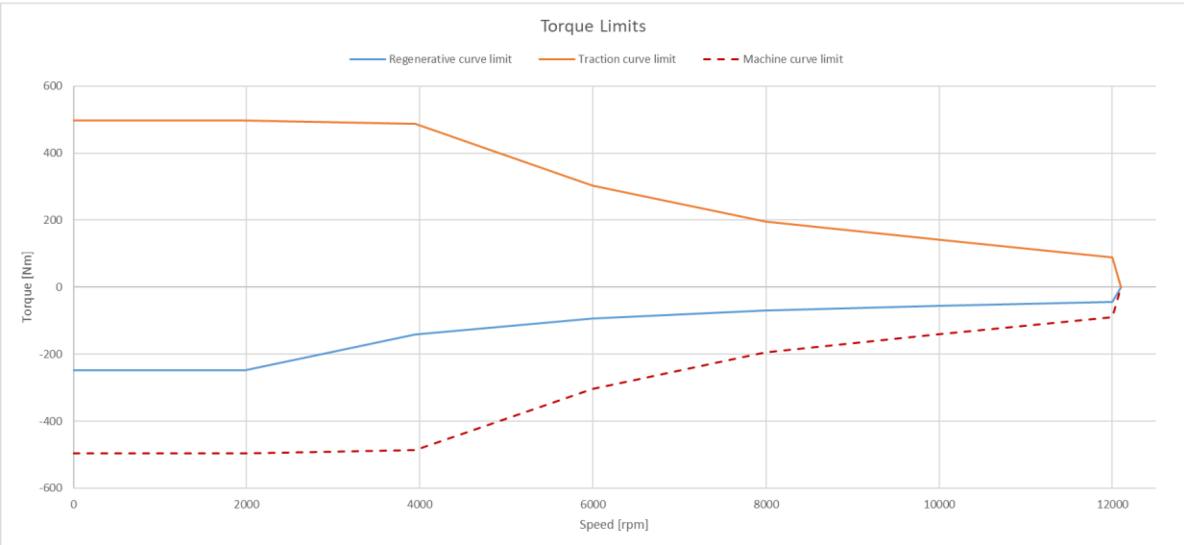

Figure 13 Traction and regenerative torque curve limits

Since the value of the regenerative torque would be too high in absolute values, it has been considered a correction factor equal to 0.5, to keep the regenerative braking below a reasonable value. This because the high values of regenerative braking could affect:

- Vehicle stability

- Comfort of the driver and the passengers
- Damage to electric motor, battery, and inverter (temperature, excessive demand of power, etc.)
- Driving cycle

3.2.1 Coasting

Since the kinetic energy cannot be totally recovered, in specific driving conditions the best thing to do is to let the car roll freely, without any command of demanded torque to the motor. This condition is known as coasting, and it is represented in the case in which $\tau = 0$. In the algorithm, two velocity dependent coasting limits will be defined, considering an upper and lower limit, which work as a boundary of the pedal position.

To do that, it is important to introduce some factors that are essential for computing the two boundaries.

- ϕ represents the pedal stroke at top speed when a driving torque is applied.
- c_h defines the size of the coasting range at top speed.
- m this variable can be use as a shape factor.
- n represents the motor speed.
- n_{max} represents the maximum motor speed.

Once defined these parameters, it is possible to compute the upper and lower limit of coasting mode.

Upper limit:

$$p_{cu} = \phi \left(\frac{n}{n_{max}}\right)^{\frac{1}{m}} \tag{3.6}$$

Lower limit:

$$p_{cl} = \phi \left(\frac{n}{n_{max}}\right)^{\frac{1}{m}} - c_h \left(\frac{n}{n_{max}}\right) \tag{3.7}$$

In this way, when the accelerator pedal travel is between these limits, the driving mode is set in coasting, which means that there is no demanded torque.

3.2.2 Regenerative braking

A too high level of deceleration could be experienced as too harsh and aggressive for the driver. For this reason, it is convenient to define a maximum value of regenerative braking torque, to avoid discomfort for the driver which is defined as τ_{rm}. Moreover, the driver must be able to control the amount of the regenerative braking. To do that, the following equation is used to describe this control:

$$\tau_r = a_r p^{\psi} + b_r p + c_r \tag{3.8}$$

Where:

- τ_r defines the actual amount of regenerative braking.
- ψ is an exponent that gives a control over the degree of non-linearity.
- a_r, b_r, c_r are three coefficients that are computed considering the following conditions:
  - $\tau_r = \tau_{rm}$ when $p = 0$
  - $\tau_r = 0$ when $p = p_{cl}$
  - $\frac{d\tau_r}{dp} = 0$ when $p = p_{cl}$

By solving the equations considering the related conditions it is possible to obtain the values of the three coefficients:

$$a_r = \frac{c_r}{{p_{cl}}^{\psi}(\psi - 1)} \tag{3.9}$$

$$b_r = \frac{\psi\, p_{cl}\, c_r}{1 - \psi} \tag{3.10}$$

$$c_r = 1 \tag{3.11}$$

In doing so, it is possible to ensure a smooth application of the braking torque. In this case, the regenerative braking is applied to both models only to the rear wheels, considering the rear-wheel-drive layout of the truck.

3.2.3 Traction

As done for the regenerative braking part, a function is used to define the requested driving torque as a function of the accelerator pedal travel. The function is expressed as:

$$\tau_a = \left(\frac{p - p_{cu}}{1 - p_{cu}}\right)^{\gamma} \tag{3.12}$$

Where γ is an exponent that can be used as a shape factor, to make the characteristics smoother and more progressive and to give feedback to the driver.

3.3 Longitudinal dynamics analysis

The study of the longitudinal dynamics considers the fundamental equations that describe the motion of the vehicle, taking into account rolling resistance, aerodynamic resistance and slope resistance and the original transmission ratio of the vehicle. Considering only one fixed transmission ratio, which is the most probable hypothesis for the final vehicle, it has been possible to obtain values of torque and speed of the ideal electric motor starting from the desired speed and gradeability of the truck. To compute all the needed data of the vehicle to develop the simulation a study of the longitudinal dynamic of the vehicle is needed, in which it will be possible to compute the resistance forces that affect the motion of the vehicle. The performance of the electric version of the vehicle will be validated through the simulation of two longitudinal models of the same vehicle that will be created using two different software: AVL Cruise M and MATLAB/Simulink, whose methodology will be discussed in paragraph 3.5. This will be also useful to have a proper selection of the real components that will be installed on the vehicle. The main factors to be considered are the following ones:

- v_{max}: Max vehicle speed (empty vehicle)
- $T_{v_{max}}$: Engine torque @ max speed
- a_{max}: Max vehicle acceleration
- α_{max}: Max slope

3.3.1 General Equations

These performance factors must match the provided driving cycle to complete the mission. The values can be found through a study of the longitudinal dynamics of the vehicle, considering the main resistance that affects the truck during the motion, such as the aerodynamic resistance R_a, the rolling resistance R_r, and the slope resistance R_s. After that, it is possible to evaluate the overall resistance to motion of the vehicle. To do that, the data listed in the table below are needed:

PRE-SIMULATION DATA			
DESCRIPTION	*Symbol*	*Value*	*Unit*
Vehicle mass	M	5820	[kg]
Rolling Radius	R_c	0.366	[m]
Transmission ratio	i_t	1.524 (3rd gear)	[-]
Differential ratio	i_d	5.86	[-]
Transmission efficiency	η_t	0.9	[-]
Frontal Area	A_f	4.48	[m^2]
Air density	ρ_{air}	1.19	[kg/m^3]
Max motor speed	n_{max}		[rpm]
Max motor torque	T_{max}		[Nm]
Aerodynamic drag coefficient	C_x	0.335	[-]
Rolling resistance factor	fr(v)	1.40 @ max speed	[m]

Table 8 Input pre-simulation data.

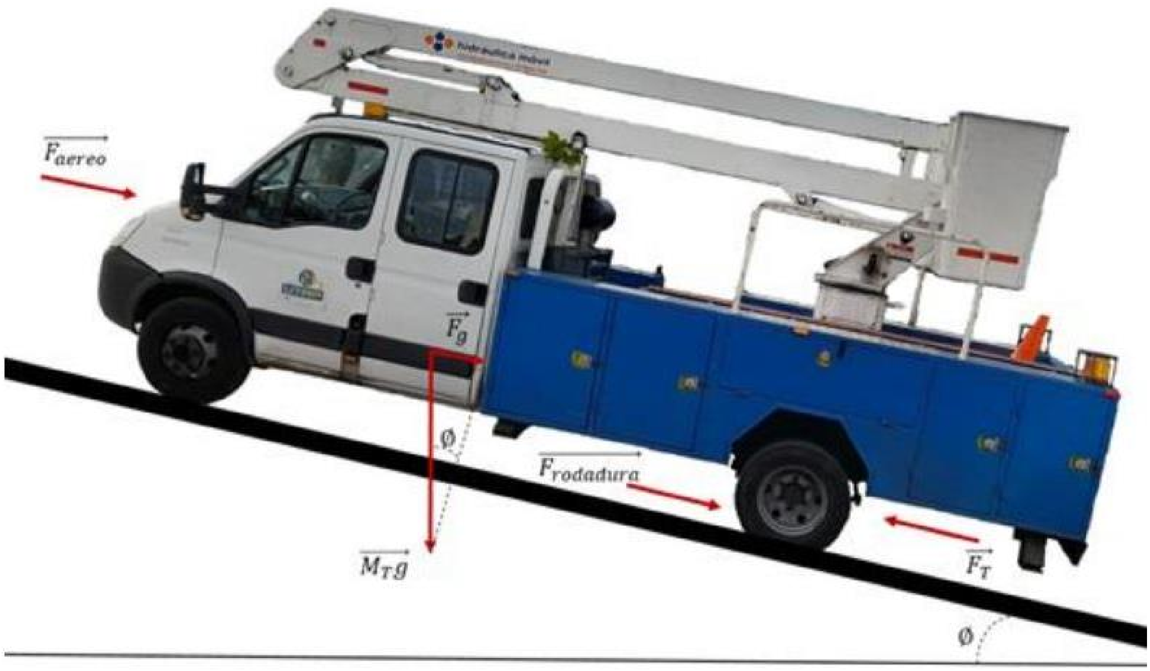

Figure 14 Iveco Daily forces diagram.

After defining these values, it is possible to compute the needed input data, it is possible to analyse the forces diagram and calculate all the values of the forces needed to find the simulation parameters. The general equations used in this analysis are listed below:

$$R_a = \frac{1}{2}\rho_{air} C_x A_f v^2 \ [N] \tag{3.13}$$

$$R_r = M \cdot g \cdot fr(v) \ [N] \tag{3.14}$$

$$R_s = M \cdot gsin(\alpha) \ [N] \tag{3.15}$$

$$F_{tot} = R_a + R_r + R_s \ [N] \tag{3.16}$$

Once these values are calculated, it is possible to evaluate the estimated performance of the vehicle in terms of max speed, max torque, max acceleration and max gradeability.

$$v_{max} = \frac{n_{max} \cdot R_C}{i_d \cdot i_t} \left[\frac{km}{h}\right] \tag{3.17}$$

$$T_{vmax} = \frac{F_{tot} \cdot R_C}{i_d \cdot i_t \cdot \eta_t} \ [Nm] \tag{3.18}$$

$$a_{max} = \left(T_{max} - T_{V_{max}}\right)\frac{i_d \cdot i_t \cdot \eta_t}{M \cdot R_C} \ [m/s^2] \tag{3.19}$$

$$\alpha_{max} = \arcsin(a_{max} \cdot g) \ \ [rad] \tag{3.20}$$

$$a_{max,\%} = \tan\{(\arcsin(a_{max} \cdot g)\} \ [\%] \tag{3.21}$$

The real components will be chosen based on these factors and must have equal or similar technical specifications. Eventually, the development of a simulation with the selected components will be performed to validate the performance of the electrified version of the truck.

3.3.2 Technical Requirements Definition

To define the technical requirements, a representative table indicating the needed values of torque and speed to guarantee the desired maximum speed and maximum gradeability, considering the chosen transmission ratio among the one available of the original gearbox. Two different cases have been considered. The former milder, the latter stricter:

CASE	DESIRED MAXIMUM VEHICLE SPEED	DESIRED GRADEABILITY
CASE 1	90 [km/h]	20%
CASE 2	100 [km/h]	30%

Table 9 Desired maximum vehicle speed and gradeability.

Those cases refer to a vehicle mass of 5820 kg, which is the mass of the original vehicle in working conditions. In this way it has been possible to find, for each value of the available transmission ratios, the related values of maximum torque and maximum speed of the ideal electric motor to guarantee the requirements listed in Table 9. The computation of these values starts from the equations already mentioned in the paragraph 3.3.1. More in detail, the inverse formulas that have been used will be discussed.

$$n_{max}^{obj} = \left(\frac{i_d i_t v_{max}^{des}}{R_c}\right)\ [rpm] \tag{3.22}$$

Where n_{max}^{obj} is the maximum target speed of the electric motor, while v_{max}^{des} is the desired speed of the vehicle, defined at the beginning of the design, considering the two cases and the characteristics of the driving mission. The target maximum torque, instead, is defined as follows:

$$T_{max}^{obj} = \frac{\left[M \cdot R_c \cdot \left(a_{max} + T_{vmax} \cdot \frac{i_d \cdot i_t \cdot \eta_t}{M \cdot R_c}\right)\right]}{i_d \cdot i_t \cdot \eta_t}\ [Nm] \tag{3.23}$$

Where T_{max}^{obj} is the target torque value of the electric motor and T_{vmax} is the maximum torque available at maximum speed, which equation has already been discussed in the previous paragraph. All the data regarding the vehicle refer to Table 8. Eventually, starting from the value of the maximum desired gradeability (starting from standstill) the value of the maximum acceleration has been computed. This calculation has been done for each value of transmission ratio related to each gear. Also considering the ratio of the differential, the values of speed and torque can be defined for each gear, considering that eventually the vehicle will have one final drive with a fixed ratio in the most probable of the hypothesis. The results of the performance evaluation are summarized in Table 10 and Table 11.

CASE 1			
Maximum Speed	v_{max}^{des}	**90 km/h**	
Maximum Gradeability	α_{max}^{des}	**20 %**	
Gear [-]	**Transmission ratio [-]**	**Maximum e-Motor speed n_{max}^{obj} [rpm]**	**Maximum Torque T_{max}^{obj} [Nm]**
1st	5.07	19067	175
2nd	2.614	9831	339
3rd	1.524	5731	581
4th	1	3761	886
5th	0.77	2896	1150
6th	0.657	2471	1348

Table 10 Definition of electric motor performance - Case 1

CASE 2			
Maximum Speed	v_{max}^{des}	**100 km/h**	
Maximum Gradeability	α_{max}^{des}	**30 %**	
Gear [-]	**Transmission ratio [-]**	**Maximum e-Motor speed n_{max}^{obj} [rpm]**	**Maximum Torque T_{max}^{obj} [Nm]**
1st	5.07	21185	249
2nd	2.614	10923	483
3rd	1.524	6368	828
4th	1	4179	1262
5th	0.77	3218	1639
6th	0.657	2745	1921

Table 11 Definition of electric motor performance - Case 1

Following these considerations, it is possible to start a preliminary purchase of the real components. It is especially important to consider the desired fixed transmission ratio to obtain reasonable values of speed and gradeability. Moreover, another key factor to take into account, is the maximum acceleration and deceleration of the vehicle with the new electric motor, to avoid discomfort and motion sickness for the passengers. Since the value of the transmission ratio of the 4th gear is equal to one, the best solution would be to find an electric motor that have the characteristic already computed for this gear. In this way, it would be possible to eliminate the gearbox, which is one of the options considered at the beginning of the project. However, since this is a step that will be developed later, currently it was not found a motor which match these technical specs, since it would be an electric motor with a remarkably high torque for the type of power and considered application. Based on the characteristics of the electric motor, it will be possible to choose the high voltage battery and the inverter that match those requirements. More details about the real components will be discussed in the next paragraph.

3.4 Components

The longitudinal dynamics analysis of the vehicle is extremely important to have an idea of the limits of the vehicle and the resistance forces that the truck must overcome during the driving cycle. Considering the results of this analysis and the desired transmission ratio to be fixed in the gearbox, it has been possible to do a preliminary purchase of the components of the electric part of the vehicle. The choice has a first focus on the electric motor, and, consequently on high voltage battery and inverter.

3.4.1 Electric Motor

The selection of the electric motor for a certain application should be done depending on the maximum efficiency. However, many factors can affect the choice of this component, such as weight, cost, maintenance, easiness of control and low level of noise. Some guidelines to follow to have a desirable choice of the electric machine are listed below:

- Efficiency on the electric motors depends on their size.
- Electric motors that can reach high angular speeds have a better efficiency compared to motors that have lower speed limit. This is because the main losses depend on the torque. This means that at low-speed electric motors have higher torque at the same power, and this means more losses.
- Electric motors that are equipped with a liquid cooling system can work at lower temperatures, reducing the resistance of the windings. This affects the performance of increasing the efficiency of around 1%.
- The real efficiency could differ from the value specified in the datasheet if the electric motor is not working in the optimum operational points.

Since the values mentioned in the paragraph 3.3.1 are ideal, the idea is to find and electric motor which technical specs are similar to the ones listed in Table 10 and Table 11. The range of power for the new electric vehicle lies between 85 and 200 kW, as discussed in the market analysis in the paragraph 2.2. However, the original vehicle equipped with the internal combustion engine, has already a maximum power of 125 kW. For this reason, it would be convenient to set the lower limit of power at this level, searching for electric motors in the range of power between 125 and 200 kW. In Table 12, are listed a some of the electric motors found during the preliminary purchase. Along with the values of power and torque, it is also indicated the value of the maximum gradeability from standstill, the maximum velocity, the maximum voltage under operating conditions and the gear to fix considering that type of motor.

MOTOR	n_{max} [rpm]	T_{max} [Nm]	P_{max} [kW]	Voltage [V]	Gear [-]	α_{max} [%]	v_{max} [km/h]
EM1	8200	470	155	700	3rd	14	129
EM2	12000	500	210	700	2nd	31	110
EM3	7350	580	174	600	3rd	19	115
EM4	3250	1590	162	750	5th	29	101
EM5	6000	640	200	650	3rd	22	94

Table 12 Electric motors options

The values regarding the maximum gradeability and the maximum vehicle speed have been computed using the equations already discussed in the paragraph 3.3.1. Generally, an electric motor should be as light and small as possible. Eventually, further considerations on the efficiency are the following:

1. Higher power leads to higher efficiencies, and consequently higher specific power.
2. Higher speed values lead to higher density power. An electric machine with high speed and low torque, is smaller. It would be convenient to connect the electric machine directly to the axle. However, it is quite common that an electric machine with high speed is connected to the axle through a gearbox with a ratio 10:1 (generally).
3. Electric machines with high efficiency such as permanent magnet and reluctance motor, have higher power density compared to the induction motors.

3.4.2 High Voltage Battery Pack

The choice of the high voltage battery pack must be done depending on the type of motor, to match the voltage, current and power requirements, whether in charge or discharge mode. Moreover, the power of the battery should be at least equal or greater than the power of the electric motor divided by its efficiency.

$$P_{bat} \geq \frac{P_{eM}}{\eta_{eM}} \tag{3.24}$$

If it is not possible to find a battery pack with the appropriate limits in terms of voltage, current and energy an alternative solution it is to operate oppositely: to fix the voltage range and to find an electric motor that can work below this operating voltage. If the voltage requirements are not matched between electric motor and battery, a DC/DC converter is needed to adapt the voltage level. The high voltage option batteries are listed below.

BATTERY	Nominal Voltage [V]	Nominal Capacity [Ah]	Energy [kWh]
OPTION 1	355	104	35
OPTION 2	648	107	69
OPTION 3	657	60	39
OPTION 4	355	96	34
OPTION 5	614	100	61

Table 13 High-Voltage Battery pack options

The two usual values of voltage considered in the battery packs for most of the vehicle applications are around 400 and 700 V. The main difference between the two main options is the value of the current that flows in the battery and the electric machine. This is a crucial factor to consider when there is the need to limit the current for safety reasons and inverter matching. Using a higher voltage battery allows to work at the same power with a lower current and, consequently, the use of thinner wires and easy installation. Another important factor to be considered on the installation phase is the complexity level of the system. It is possible to buy single cells and to build the battery pack in situ, or to buy complete systems, also considering a Battery Management System (BMS), depending on the available providers and the quotes.

The required range in terms of distance, considering the daily missions that the vehicle needs to complete is about 100 and 140 km. A single block of battery could not be enough to guarantee a fulfilment of the daily mission and the desired performances in terms of acceleration, maximum speed and gradeability. For this reason, it could be possible to implement 2 or 3 modules of chosen battery in parallel to complete the high voltage pack. This is a solution widely adopted by different manufacturers, also confirmed by the market analysis of existing commercial vehicles discussed in the paragraph 2.2. In such manner the battery pack can reach an energy value comparable to the electric vehicles of the same category (80 ÷ 150 kWh).

3.5 Simulation set-up

Modelling is a way to represent a virtual model of an existing system. In this way, it is possible to simulate the virtual model by varying the different conditions to observe its performance and behaviour. For example, this methodology is used in the very first part of a project, in which the hardware is still not available. [35]. Modelling and Simulations are especially useful to verify conditions that are difficult to test with only hardware prototypes. System Simulations for development allow the achievement of the set vehicle targets. A vehicle has many variants and many combinations of components, as well as their interaction. The concept based on a virtual model avoids late and costly changes from the outside. In this case, the vehicle model is a battery electric vehicle, in which the main questions are about the sizing of the battery pack, the requirements of the electric motor, the coordination with the transmission, and the operating strategy. The design of a smart strategy allows the optimal use of the vehicle, considering range, performance, costs, and safety. The main benefits of this method are real-time capability since it is possible to obtain reliable results about the behaviour of the virtual components in milliseconds, and time and cost savings at the beginning of the development phase [36].

3.5.1 AVL/Cruise M Virtual Model

AVL Cruise™ M is a multidisciplinary system that allows the development of model-based simulation using high-quality real-time models from different domains, such as engine, flow, after-treatment, driveline, electric components, and hydraulics. It includes state-of-art tools for:

- Pre-processing and Post-processing
- Simulation and process control
- Parametrization and scenario management

- Design of Experiments (DOE) and optimization
- Common model compiler for a quick and easy generation of plant models

It is possible to develop any kind of electrified powertrain through an electric solver. The electric components can interact with mechanical components and can be connected through linkages to cooling networks. The general workflow that is recommended by the software and guides the final user through all the phases that lead to a reliable simulation are listed below in order:

1. Setup project
2. Simulation model setup
   a. Insert components.
   b. Connect components.
   c. Input data in components
   d. Setup Simulation task
3. Run Simulation
4. View & evaluate results.

The first model of the IVECO Daily 70C17 HD is developed by using this software, considering the standard vehicle and the one equipped with the aerial platform motor. All the blocks that build the model of the vehicle are connected through a data bus that allows the communication of needed signals. For a better understanding of how the model setup is made and how it works, it could be useful to have a closer look at every single component that composes the model. [37] The version used in this project is the R2022.2.

3.5.1.1 High Voltage Battery Pack

The battery model which is present in the software is based on the theory of the equivalent electrical circuit. It predicts the voltage response based on a certain level of State of Charge (SoC) and temperature of the battery. The model is made up of a voltage source and a Ohmic resistance, which describes the voltage output related to a particular current. Depending on the case, one or more RC networks can be added to the circuit. Furthermore, it is possible to build an electrical network that acts as a battery module or battery pack. Besides the electric model, there is also a thermal model able to compute the transient heating behaviour of the battery. The battery model that is present inside the simulation model is made up with two battery modules, to guarantee the performance requested by the driving cycle.

3.5.1.2 Electric Motor with Inverter

The electric motor model is defined as an electric machine component. It can work as a motor or generator, by using a simple map-based approach. With this method, it is possible to select the quadrant in which the useful motor/generation information can be inserted. The table below summarizes the four available maps.

ELECTRIC MACHINE QUADRANTS	
Q1 Motor	Motor information for positive speed
Q2 Generator	Generator information for negative speed
Q3 Motor	Motor information for negative speed
Q4 Generator	Generator information for positive speed

Table 14 AVL Cruise M Electric Machine Quadrant Selection

If desired, the inverter model can be included in the same block of the electric motor, and in this way, it is possible to also evaluate the inverter's power losses. The modelling approach is simple: the machine tries to deliver the requested torque based on the selected control mode, which can be based on:

- **Mechanical load:** a signal that is between 0 and 1.
- **Torque:** depending on an input of demanded torque given via the data bus, which is be the method used in the simulation.

3.5.1.3 Transmission

The basic idea of the transmission that will be present in the real vehicle is to keep the gearbox with a fixed ratio that depends on the performance requested from the operating cycle. As mentioned before, through a study of the longitudinal dynamics of the vehicle it is possible to estimate the values of the performance of the truck in terms of maximum speed, maximum acceleration, and climbing performance (gradeability). In this sense, the final drive transmission will be composed of a single ratio transmission and the rear axle with the differential. In terms of the software model, the Single Ratio Transmission element represents a gear step with a fixed ratio under constant efficiency. A driving torque will be transferred to a power take-off torque of the transmission step by considering transmission, efficiencies, and moments of inertia. The differential unit compensates for discrepancies in the respective rotation rates of the drive wheels. Since is not possible to put the rear axle ratio inside the model of the differential, the final vehicle model will have a gearbox element with only the selected gear, a single transmission ratio, and a differential that is finally connected to the wheels.

3.5.1.4 Clutch system

The model is equipped with two different clutches. The former is connected to the gearbox, the latter is connected to the mechanical consumer, which is intended to be representative of the aerial platform. This system is necessary to allow the change of the operation mode. Since the aerial platform is connected directly to the electric machine through a clutch, when the vehicle stops for the maintenance operation, the main electric motor must be disconnected from the rest of the transmission, to not transfer torque to the wheels and move the truck. A logic control of the clutch is made with the function block in a C code, which controls the status of the two clutches.

3.5.1.5 Power Consumer

The power consumer represents an electrical resistor, but this model is used to take into account the losses due to the auxiliary electric block. It is not possible to apply a negative power, indeed this element is just a consumer, and it cannot be used as a power source in the electrical circuit of the virtual model. The power loss is not constant, but it is modelled with a map that can define a characteristic chosen by the user. In this case, the map is modelled such as the lowest possible loss is equal to 1000 W and constant when the vehicle is stationary, and it can increase up to about 2000 W when the vehicle is in motion.

3.5.1.6 Brakes

The brake component is used to perform the braking characteristics of each wheel of the vehicle. It is possible to insert all the data and dimensions of the dedicated block and to define drum and disk brakes. The mechanical connection of the element block can be made with the wheel or differential component. The brake component can have two different control variables:

- **Braking pressure:** by using this method, the instantaneous braking torque will be:

$$M_B = 2 \cdot p_B \cdot A_B \cdot \eta_B \cdot \mu_B \cdot r_B \cdot c_B \tag{3.25}$$

  where:
  - M_B = Braking torque
  - p_B = Braking pressure
  - A_B = Brake Piston Surface
  - η_B = Efficiency
  - μ_B = Friction Coefficient
  - r_B = Effective Friction Radius
  - c_B = Specific Brake Factor

- **Braking Torque:** in this case, which is the method chosen in the model, the brake pressure is not considered, and the braking command is defined by using a function that will be explained in the "Strategy" section. The braking torque is zero when the rotational speed is equal to zero.

3.5.1.7 Wheels

This block represents the wheels and tires of the vehicle. This element considers many variables that can influence the behaviour of the vehicle and the effect of the wheel rolling state. In the settings block it is possible to define:

- Moment of inertia of the wheel
- Friction coefficient of the tire: it depends on the material.
- Reference wheel load: represents the calculation of the longitudinal force
- Wheel load correction coefficient: since the real wheel load is never equal to the reference one, a correction factor is needed.

Once defined these settings of the wheel block, it is possible to define the values of the rolling radius (static and dynamic) and the characteristic of the rolling resistance. The former can be developed with an array of data that maps input values to output values through an interpolation function. In this way, it is possible to approximate a mathematical function to define the rolling resistance factor depending on the vehicle speed.

3.5.1.8 Driver

This block represents the behaviour of the driver, through the action of the accelerator and brake pedal. The data needed to complete the driver block are the following:

- Data regarding the driving behaviour
- Data regarding the launching behaviour
- Data regarding the shifting behaviour

The variations of the throttle and brake pedal position are defined by the following equation:

$$\dot{\alpha} = (I \cdot dv + P \cdot da) \cdot [1 - D \cdot (1 - C)] \tag{3.26}$$

Where:

- $dv = v_t - v_a$ with v_t that is the target velocity and v_a the actual velocity
- $da = a_t - a_a$ with v_t that is the target acceleration and v_a the actual acceleration
- $[1 - D \cdot (1 - C)]$ = this factor represents a function that is used to weaken velocity when the clutch is open

The driver works through a PI controller, by defining feedback through integral and proportional actions. The control variable is the velocity, and each parameter can be defined as a constant or data-bus signal.

3.5.1.9 Strategy

As mentioned in the paragraph 3.2, the used driving strategy for this model is the One Pedal Drive. The algorithm can be implemented into the software using a component named "Function." The Function block can be used for calculating with user-defined functions. The language programming is C and inputs and outputs are transferred through the Data Bus Channels. Since the demanded torque will be computed through a map curve, in AVL CRUISE^{TM} M, two curves have been defined: the former for the traction and the latter for the regeneration part. In the first part of the regeneration curve, there is a linear part between 0 rpm and 200 rpm that avoids the computation of a non-realistic braking torque at very low speed. Furthermore, in the C code, there is a control over the motor speed at below 5 rpm, to avoid NaN values and errors during simulations. Note that the regenerative braking torque command is connected through the data bus only to the rear wheels. The C code of the strategy control function is available in the Appendix.

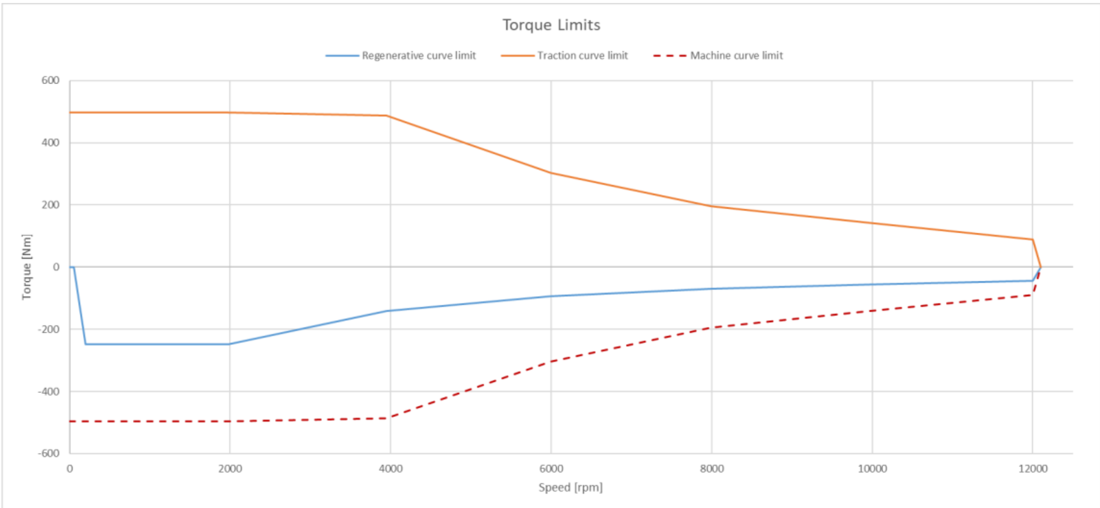

Figure 15 Traction and Regeneration torque limits (corrected)

3.5.1.10 *Complete Vehicle Model Overview*

Once explained all the component blocks that build the electric version of the Iveco Daily, they can be put together to build the entire vehicle model as shown in Figure 16.

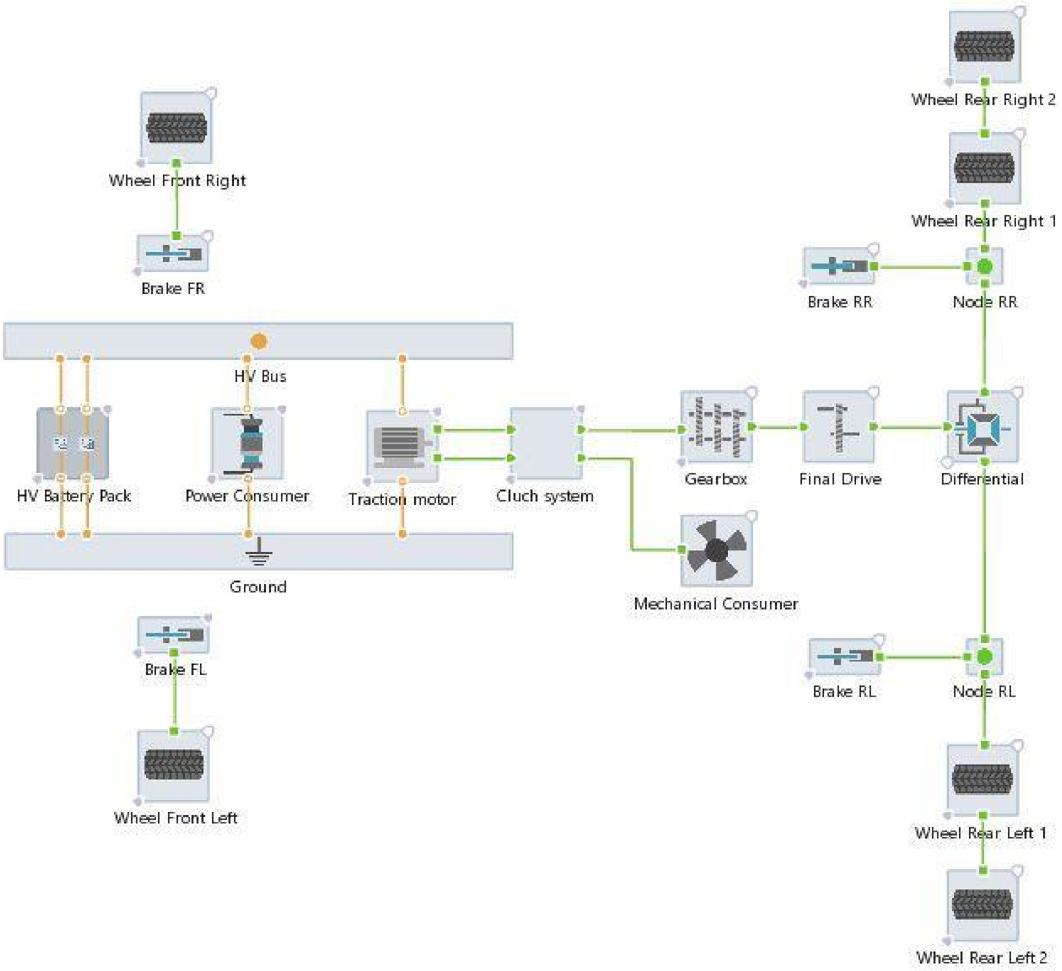

Figure 16 AVL Cruise M - Complete vehicle model overview

3.5.2 MATLAB/Simulink Virtual Model

The MATLAB/Simulink model is developed starting from an open-source model that can be found on the UNECE public website, adapting the models of the GRPE of United Nations. The UNECE Sustainable Transport Division provides the secretariat service to the World Forum that includes regulatory framework technological innovation of vehicles to improve global safety and the entering of these technologies into the market. In particular, the UN GTRs (Global Technical Regulations) contain globally harmonized performance-related requirements and they provide a predictable regulatory framework for the global automotive industry. The original model can be found in the section "HDH General Files" and it represents a model of a series-hybrid heavy-duty vehicle for Hardware in the loop simulation, for GTR certification, established by the technical teams of Chalmers University of Technology, Vienna University of Technology and Graz University of Technology [38], [39]. The model has been downloaded and modified to obtain a battery-electric vehicle, which will work with a similar logic to the AVL Cruise M model. Among the files that are available online, there is a Simulink library that contains the basic blocks for modelling an electrified vehicle. The toolbox contains:

- Auxiliary systems
- Chassis
- Driver
- Electrical powertrain components
- Energy converters
- Mechanical powertrain components
- Rechargeable energy storage systems

The electric vehicle Simulink model has been created starting from this library, by modelling all the connections that a battery-electric vehicle must have. Furthermore, every single block has been modified according to the needs of the simulation. As done before, it is useful to break down all the parts that compose the general model of the vehicle to have a better understanding of how every component works. In the next sub-chapters, the focus will be on the main changes and modifications that have been made to the original blocks taken from the library. The adopted modelling philosophy is known as forwarding, which is used to describe models using differential equations and allows the use of feedback control. Moreover, it is possible to consider dynamic effects such as engine speed-up and vehicle inertia. Every single block transfer bus signal to the other elements containing all the necessary information as input and/or feedback. The used MATLAB version is the R2020a.

3.5.2.1 Vehicle model interface

The top-level model interface is made up of three main blocks. It includes the ECU block, the driver block, and the vehicle model. The driver works with a PI controller, which uses the desired and actual velocity of the vehicle to command the vehicle through the throttle and braking pedals. The driver command is then sent to the vehicle model which work as input for all the blocks that compose the truck model. The virtual vehicle model gives as output sensor's command that are put inside the ECU block, which converts the signals into the proposed signal interface needed from the vehicle block, creating a loop. The control strategy algorithm is contained inside the ECU block.

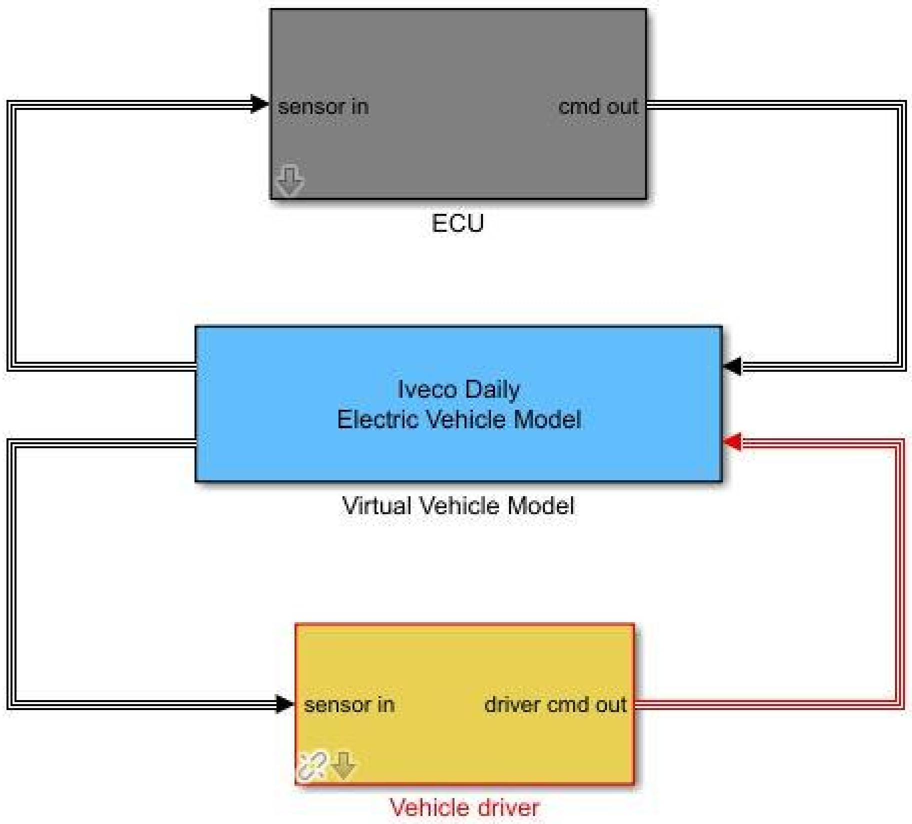

Figure 17 MATLAB/Simulink - Vehicle Model Interface

3.5.2.2 High Voltage Battery

The battery block is modelled in a way that all the parameters depend on the level of the State of Charge. The main block is made up of three sub-blocks. A local controller, which collects the desired signals, the battery model in which is also developed the single cell model and the block in which is computed the calculation of the total input and output energy over cycle of a single module of battery.

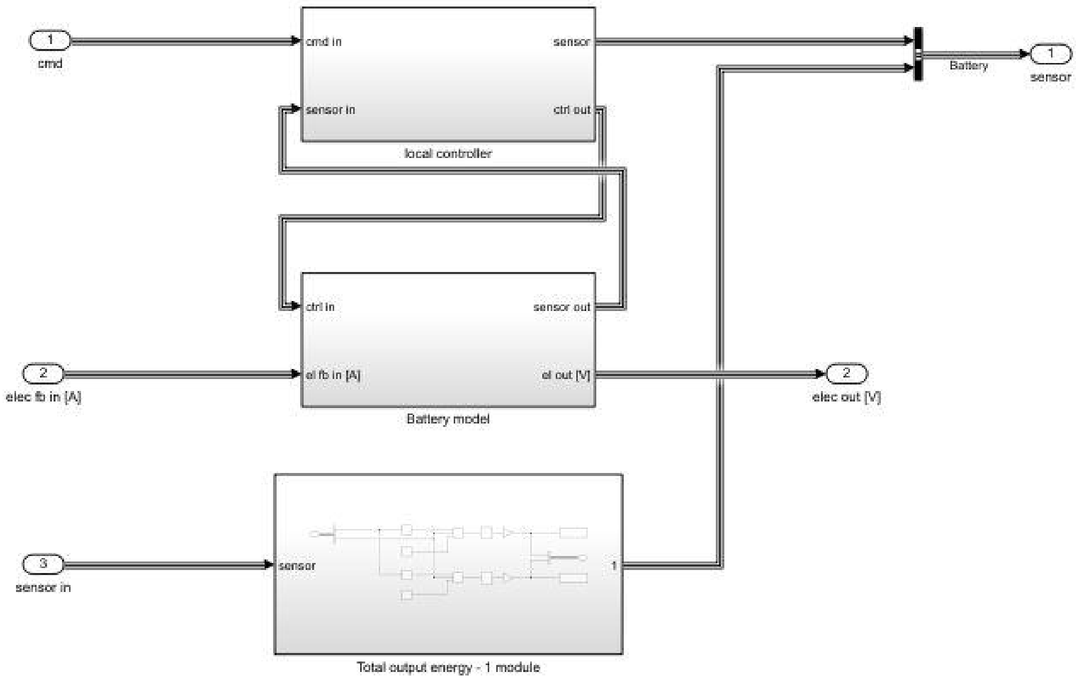

Figure 18 MATLAB/Simulink - Battery Pack interface

The system has an open circuit voltage (OCV) in series with an ohmic resistance R_0 and the overall power loss is due to this resistance. The single cell model block receives as input the cell current, which is considered positive in discharging phase and negative during charging phase and gives as output the State of Charge, the physical voltage, and the power loss. The SoC is computed using a gain that considers the capacity of the battery, and then this value is saturated between 100 and 0. Since the value of the resistance is different in charge and discharge, it is necessary the use of a flag, which in Simulink is represented by a “Compare to Constant” block, which considers:

- 1 = discharge.
- 0 = charge.

In this way, it is possible to compute properly the losses due to the resistance. The OCV instead, is calculated by means of a 1-D lookup table which contains as table data the values of voltage and uses as breakpoints the values of state of charge. Then, the voltage in output by the single cell block is computed as:

$$V_{cell} = OCV - i_{cell} \cdot R_0 \ [V] \tag{3.27}$$

At the exit of the single cell block, a gain multiplies the voltage per the number of cells connected in series.

The power loss, instead, is calculated as follows:

$$P_{loss} = R_0 \cdot {i_{cell}}^2 \ [W] \tag{3.28}$$

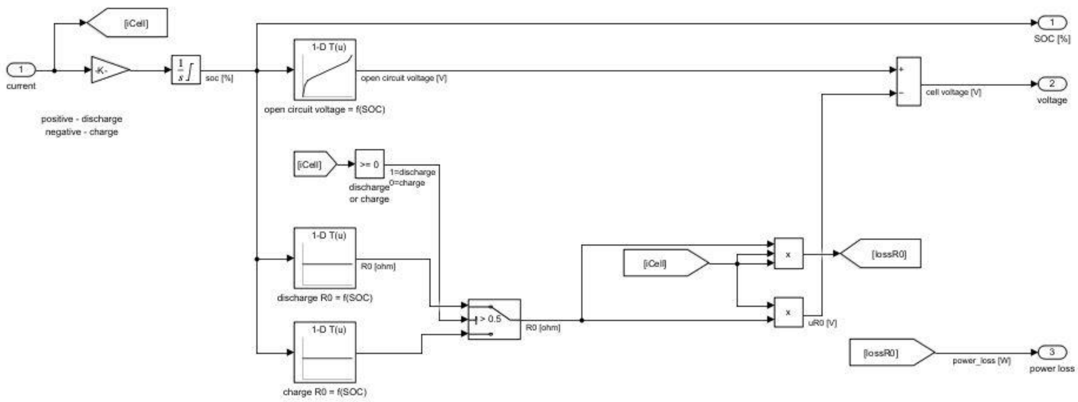

Figure 19 MATLAB/Simulink - Single Cell model

In transportation, energy is measured in kWh, while to estimate the energy consumption of a vehicle the unity of measure is indicated as kWh/km. Considering a plane road in dry conditions with a high level of adherence, the total energy consumption of the vehicle is expressed as:

$$E_{trac} = \int_{a \geq 0} P_{trac}\,(t) \cdot dt \tag{3.28}$$

$$E_{reg} = \int_{a<0} P_{trac}\,(t) \cdot dt \tag{3.29}$$

Where E_{trac} is the total output energy of the battery, while E_{reg} is the total input energy of the battery due to the regenerative braking. The term a is a parameter that defines the sign of the considered power of the electric machine. Eventually, the net traction energy can be computed as follows:

$$E_{trac}^{net} = E_{trac} - \eta_d \cdot \eta_t \cdot \eta_{gen} \cdot \eta_{batt} \cdot \eta_{eM} \cdot E_{reg} \; [kWh] \qquad (3.30)$$

In the Simulink model, the sub-block receives as input the speed and the actual torque of the electric motor during the simulation, considering a simulation time of 0.1 s. The definition of sign of the power is defined by a saturation block on the torque control, which is set as a positive filter in the case of the computation of the total output energy and as a negative filter in the case of the total input energy. The torque is then multiplied by the actual speed of the electric machine, obtaining the value of the power for each simulation step. The value of the power goes to a Discrete-Time Integrator which computes the value of the energy. Eventually, through a gain, it is possible to convert the value of the energy from Joule to kWh.

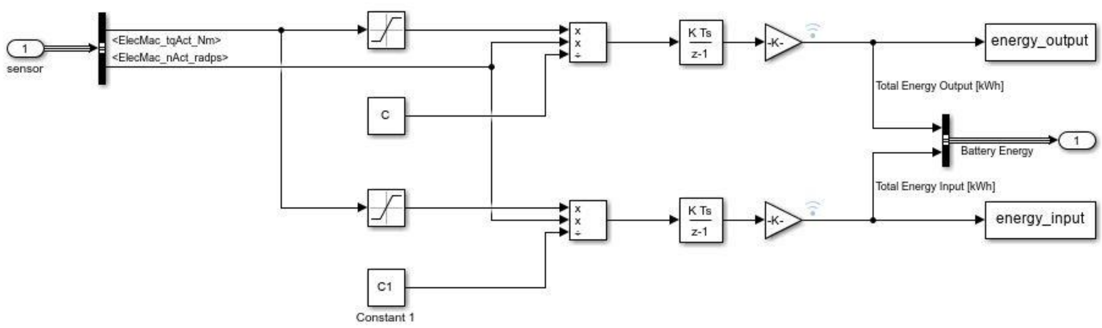

Figure 20 MATLAB/Simulink - Battery energy block

3.5.2.3 Electric Motor with inverter

The electric machine block is modelled in a way that the requested torque delivers an actual value of torque depending on the rotational speed of the motor. A local controller receives the signals from the data bus, which are provided by the ECU block. The controller receives the requested motor speed and torque, and it is statically limited by the maximum (full motor demand) and minimum (full generator mode). This torque command is then sent to the actual electric machine block which is used as an input to determine motor or generator mode, while the data regarding speed and current are sent out from the controller block through a sensor signal. This signal, before arriving at the motor block, is filtered through a Rate Limiter Dynamic block that limits its rising and falling rates.

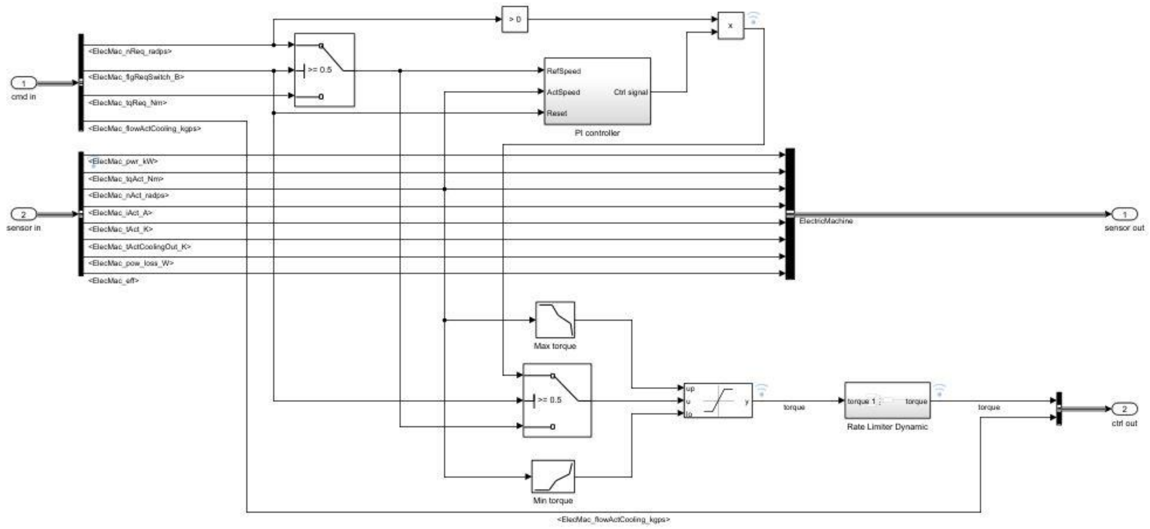

Figure 21 MATLAB/Simulink - Electric Machine local controller

In the main block, 3-D lookup tables are used to compute the values of the current power of the motor and generator, machine losses, and inverter losses, through specific power maps. There is no specific block for the inverter but is modelled through lookup tables to also consider the losses due to this component. These lookup tables take into account torque, voltage, and speed. Eventually, the efficiencies of the machine and the inverter are computed as follows:

$$\eta_{eM} = \frac{P_{loss,m}^{eM} + P_{loss,g}^{eM}}{|P_{tot}|} \tag{3.31}$$

$$\eta_{inv} = \frac{P_{loss,m}^{inv} + P_{loss,g}^{inv}}{|P_{tot}|} \tag{3.32}$$

Where:

- $P_{loss,m}^{eM}$ represents the power losses of the electric machine in motor mode.
- $P_{loss,g}^{eM}$ represents the power losses of the electric machine in generator mode.
- $P_{loss,m}^{inv}$ represents the power losses of the inverter in motor mode.
- $P_{loss,g}^{inv}$ represents the power losses of the inverter in generator mode.
- P_{tot} indicates the total power delivered from the electric machine.

These values are then filtered by a MATLAB function to avoid NaN values and have a clearer view of the results.

The total loss of the machine is given by:

$$P_{loss}^{tot} = P_{loss,m}^{eM} + P_{loss,g}^{eM} + P_{loss,m}^{inv} + P_{loss,g}^{inv} + P_{aux} \tag{3.33}$$

Where P_{aux} are the losses due to the electrical auxiliary system.

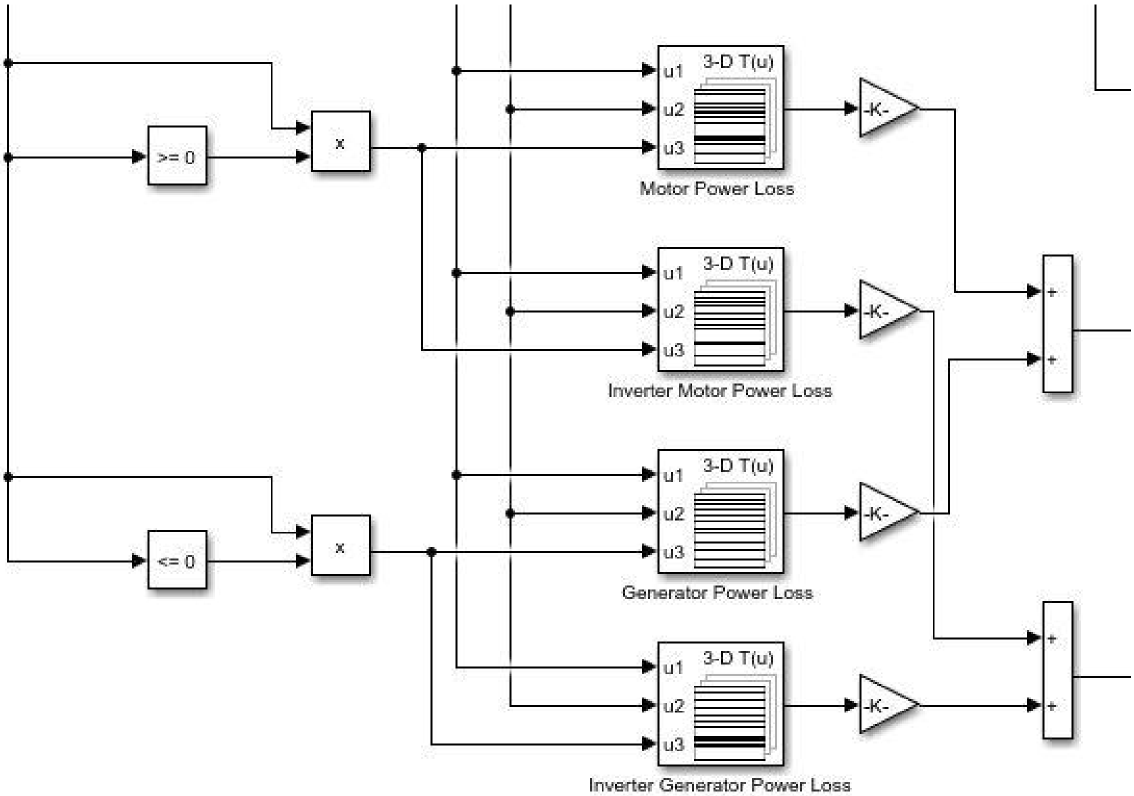

Figure 22 MATLAB/Simulink - Zoom on electric machine main block.

To summarize, the electric machine receives the following information as input:

- Speed feedback from the Chassis
- Voltage from the Battery Block
- Command from ECU

And gives as output:

- Sensor's data bus
- Torque
- Current
- Power consumer losses
- Electric motor power
- Electric machine total efficiency

3.5.2.4 Transmission

The transmission block receives as input the feedback of the mechanical signal given by the electric machine and the speed that is out of the chassis block, which is representative of the actual speed of the vehicle. The output signals of the transmission blocks are a torque command that goes to the chassis block as input and speed feedback to the electric machine block. Inside the block, the speed received from the chassis block is multiplied by a gain that has inside the values of the fixed gear transmission ratio and the differential ratio. The mechanical signal instead contains information about torque and inertia, which are useful to compute the actual torque given to the chassis block, considering the gear ratio and the transmission efficiency.

3.5.2.5 Chassis

The chassis block is representative of all the mechanical data of the vehicle, such as mass, inertia, brakes, and wheels. In this block are all the main resistance forces, like the rolling resistance, the road slope, and the aerodynamic drag. In this way, it is possible to compute the actual resistance torque and subtract it from the available torque that arrives as input from the data bus of the transmission block. Moreover, this block takes into account also the torque requested by the brake to stop the vehicle. The chassis block gives as output a data bus signals with essential information for the ECU block, such as the actual speed of the vehicle and the wheels, and the torque at the wheels.

3.5.2.6 Electrical auxiliary system

The electrical auxiliary system block receives the information about the power loss from the electrical machine block. The power loss values are computed utilizing a 1-D lookup table in the function of the actual power of the electrical motor. The logic is simple, the power consumer loss has a minimum value of 1000 W that can reach about 2000 W when high power is demanded from the electric motor. The electrical auxiliary system block gives current feedback to the battery, taking into account the voltage signal received from the electric motor. The requested current from the battery becomes the sum of the current requested from the electric machine and the one requested from the auxiliaries.

3.5.2.7 Driver

The driver model aims to perform all the required tasks of the driving cycle. It includes the accelerator and brake pedal commands, and the driver is intended to be as simple as possible to adapt it at several models. The driver model receives as input the difference between the desired vehicle speed and the actual vehicle speed. It is modelled with a PID controller with an anti-windup method, which keeps integrating the tracking error even if the input is saturating. In other words, the internal signals in the block can be unbounded even if the output appears bounded by saturation limits. This method is needed because otherwise, the controller performance can suffer. If there is no anti-windup control, two scenarios are possible:

1. If the sign of the input signal never changes, the integrator continues to integrate until it overflows.
2. If the sign of the input signal changes once the weighted sum has grown beyond the output limits, it can take a long time to unwind the integrator and return the weighted sum within the limits.

There are several methods to perform anti-windup, in this case, the chosen one is the clamping method. Clamping can be useful for plants with small times, which is the case of this type of simulation. By using this logic, integration stops when the sum of the block components exceeds the output limits and the integrator output and block input have the same sign. Integrator resumes when the sum of the block components exceeds the output limits and the integrator output and block input have opposite signs. The driving strategy is implemented inside the driver block, through a MATLAB function, which uses the same logic described in paragraph 3.2. This block sends to the ECU all the information regarding brake torque demand, electric machine torque requests, and accelerator, and brake pedal positions.

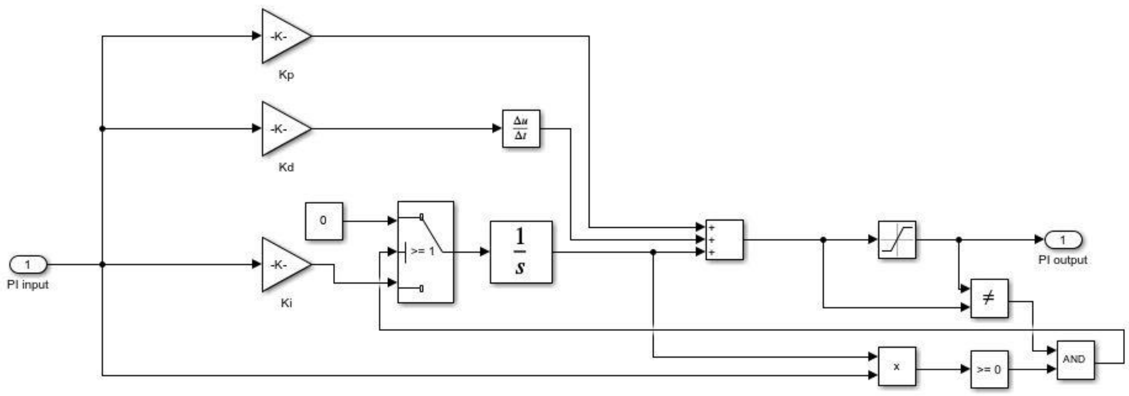

Figure 23 MATLAB/Simulink - Driver PI controller - clamping method

3.5.2.8 ECU

The Electronic Control Unit receives signals from the driver and the main vehicle block. Through the information received the ECU sends back the requested information to the vehicle block such as requested traction and braking torque and requested motor speed. Inside the ECU block, there is the MATLAB function block representative of the driving control strategy, which code is available in the Appendix. The main information sent back to the vehicle block is as follows:

- Requested torque signal: This information flows from the output of the control strategy block and goes directly to the electric machine block, which is then saturated considering the powertrain limits.
- Requested braking torque signal: This signal goes to the chassis block. It takes into account the value of braking torque due to the regenerative braking and of the front mechanical brake. For what concerns the mechanical brakes, a sub-block called the “Front brakes regulator” controls the mechanical braking torque to not exceed the adherence limits of the vehicle.
- Cooling system information to the battery pack
- Information about the One Pedal Drive strategy: Along with the torque requests, the block gives as output the lower and upper coasting limits.

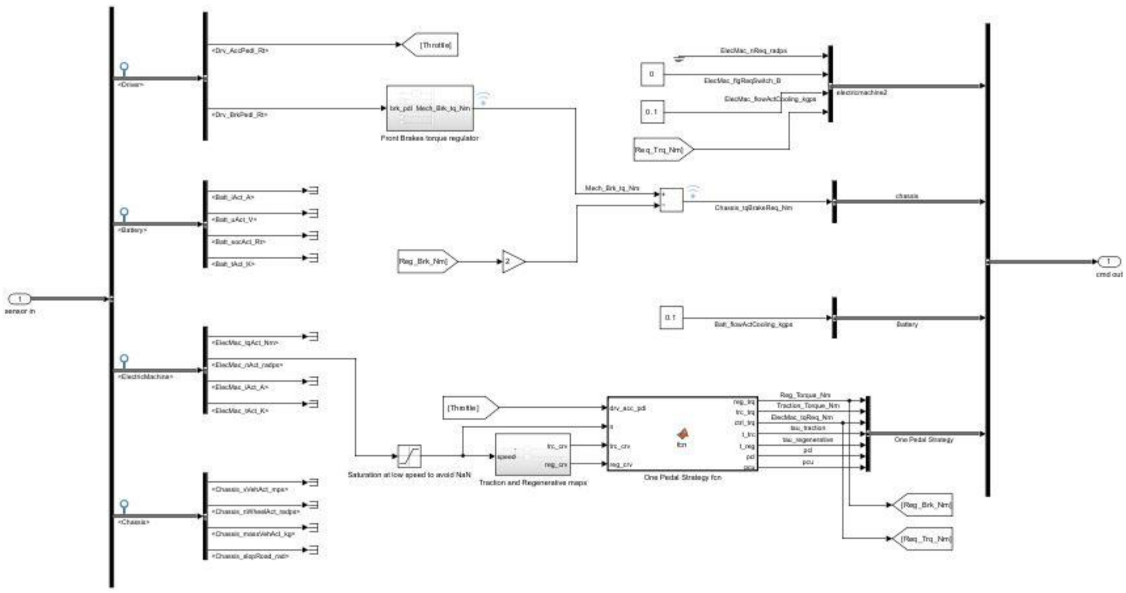

Figure 24 MATLAB/Simulink - Electric Control Unit block

The computation of the torque signals for traction and regeneration uses the same maps already discussed for AVL Cruise M. In this case, the two maps are implemented in Simulink using a 1-D look-up table, which receives as input the angular velocity of the electric motor.

3.5.2.9 *Post-Processing Analysis*

For the verification of the simulation model, some characteristic signals need to be recorded to describe the power and energy flow in the battery electric vehicle. In the main Simulink block, there is a part dedicated to the data collection for the post-processing. Along with the collection of signals useful for the analysis, these signals are also sent back to the ECU and the driver, creating a loop.

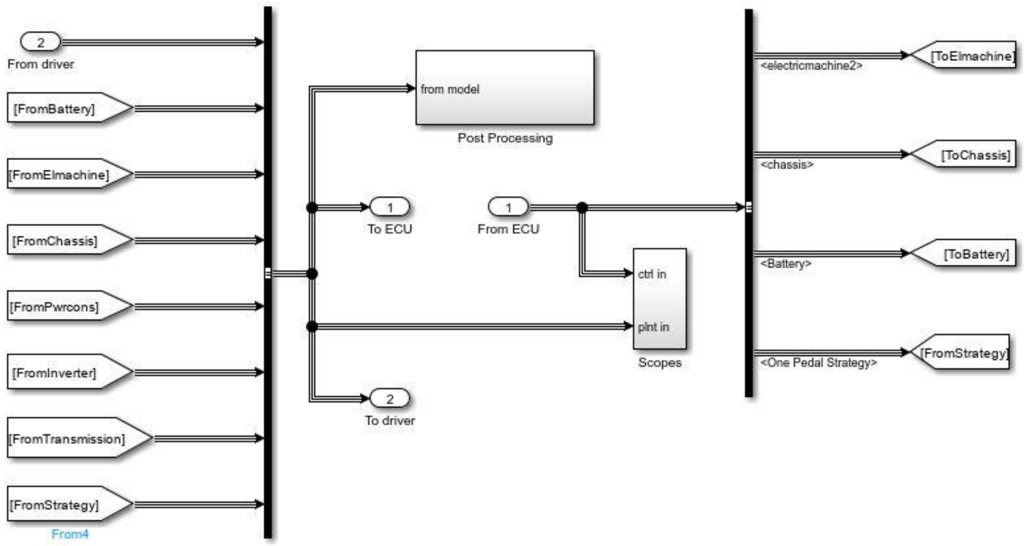

Figure 25 MATLAB/Simulink - Post Processing signals scheme

In this way, it is possible to collect all the needed data from each block of the simulation, for a total of 35 signals. These signals are then sent to the MATLAB workspace, and through a .m file for the post-processing analysis are re-organized in a struct for each category. In doing so, all the collected signals are easy to read and to create plots for the needed data. The most important plots that can be created out of this analysis file are listed below:

- Driving cycle and pedals positions
- Battery data
- Electric Machine data
- Driving strategy
- Operating points map

These data will be compared with the results obtained in the simulation of AVL Cruise M software.

3.5.2.10 *Complete vehicle block overview*

To summarize, the complete vehicle block is made up of:

- Electrical Auxiliary system - purple
- HV battery pack - green
- Electrical machine with inverter - red
- Transmission – orange
- Chassis – light blue

These block use data bus creators/selectors to create and send all the needed signal to the other blocks, driver, and ECU. The part above the coloured blocks represents the post processing analysis block, already discussed in the paragraph 3.5.2.9. Figure 26 shows an overview of the complete vehicle Simulink model.

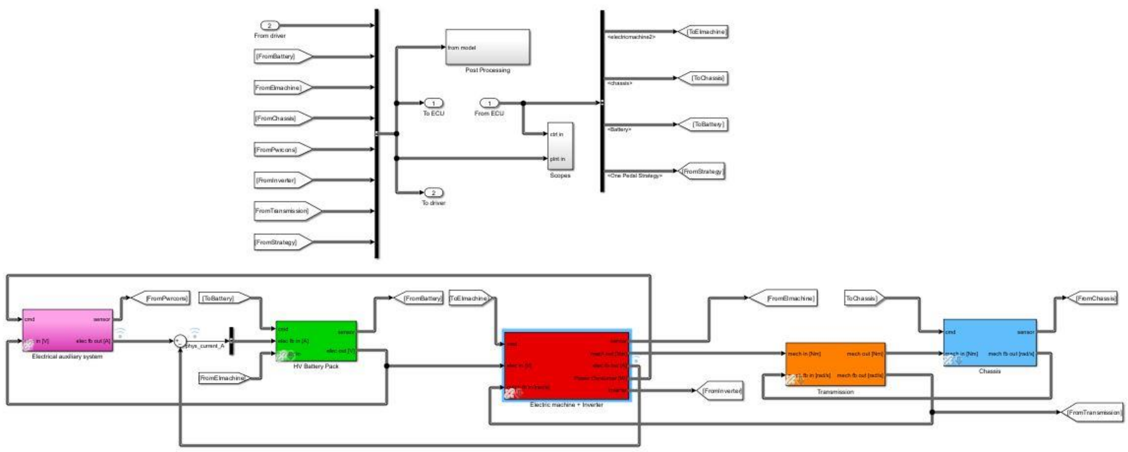

Figure 26 MATLAB/Simulink - Complete vehicle block overview

4 Results

In this part of the paper, the results about the simulations on the two different software will be discussed, commenting on the similarities between the two models. The first part of the chapter is about the choice of the component to be tested on the simulation. The second part regards the results obtained from the simulations of the two models, while the last part will focus on the validation of the results. For this part, the validation metric has been done using the Sprague & Geers method, which will be better discussed in the dedicated paragraph.

4.1 Choice of the components

The choice of the components of the new electric part is essential for a successful and reliable simulation of the model. The requirements about the characteristics of electric machines and battery have already been discussed in the Chapter 3. Based on previous considerations, and, starting from the electric machine, the choice fell on the Option 1 listed in Table 12, which specs are described in Figure 27 and Table 15.

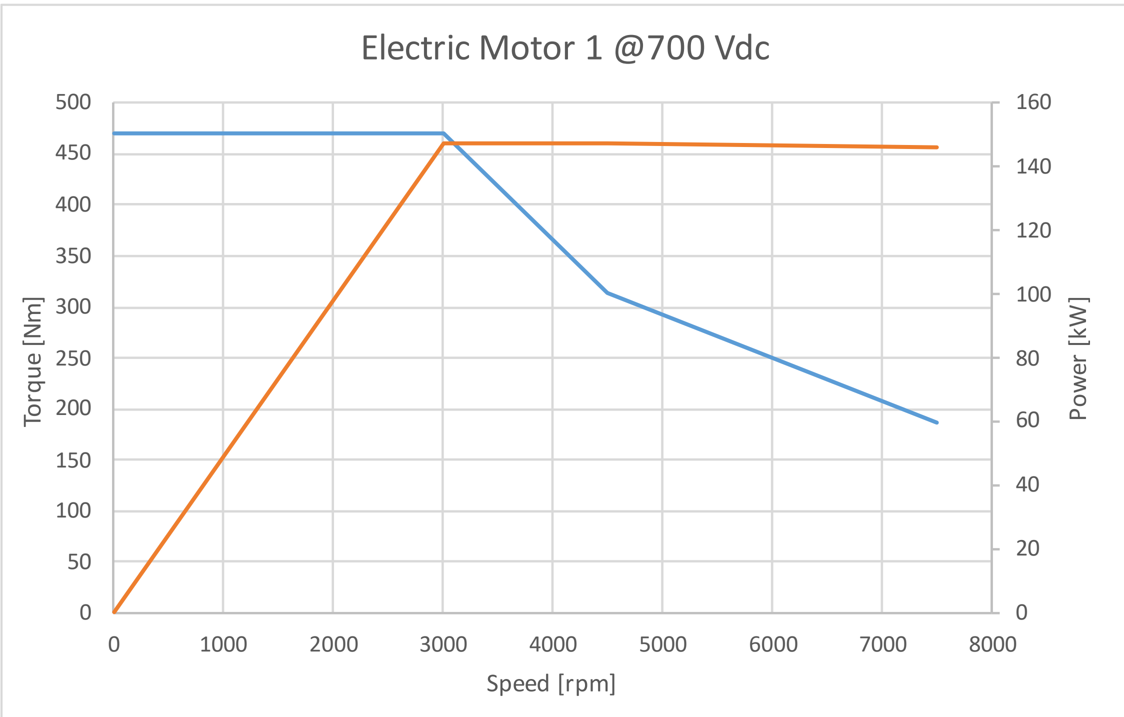

Figure 27 Characteristic curve of Electric Motor 1

EM1 – TECHNICAL SPECS		
Peak Power	155	kW
Peak Torque	470	Nm
Maximum Speed	8200	rpm
Maximum efficiency	93	%
Voltage	700	V
Moment of inertia	0.04	$kg \cdot m^2$

Table 15 Electric Motor 1 - Technical Specs

The battery pack must match the specifications indicated from the electrical machine. It has been opted for a high voltage battery pack in the range of 700 V. More specifications about the single module of the battery are listed below.

BATTERY PACK – TECHNICAL SPECS		
Nominal Voltage	657	V
Min/Max Voltage	540 V / 756 V	V
Capacity	60	Ah
Charging Power	118	kW
Discharging Power	39	kW
Nominal Energy	39.5	kWh
Weight	372	kg
Modules	2	[-]

Table 16 Battery Pack - Technical Specs

Since a single block of battery could not be enough to guarantee a fulfilment of the daily mission and the desired performances in terms of acceleration, maximum speed and gradeability, it has been opted for a battery pack with 2 modules in parallel for the simulation.

4.2 Simulation Results

The simulations have been performed on the two software, showing a good correlation between them. In this part of the paper, the focus is on the comparison of the two models' output. The data about the vehicle, driving cycle, and PI controller settings are implemented in the same way in both models. However, there are still some unavoidable differences, due to the different logic behind the two software. However, the models can be improved and updated in the future. Both models have led to comparable results, showing a satisfactory level of reliability in the simulations.

4.2.1 AVL Cruise M

The reference model has been considered the one developed on AVL Cruise M. The results of the driving cycle are shown in Figure 28. In this graph, it is possible to see the comparison between the desired and actual velocity of the vehicle, the altitude profile, and the State of Charge of the battery over the cycle.

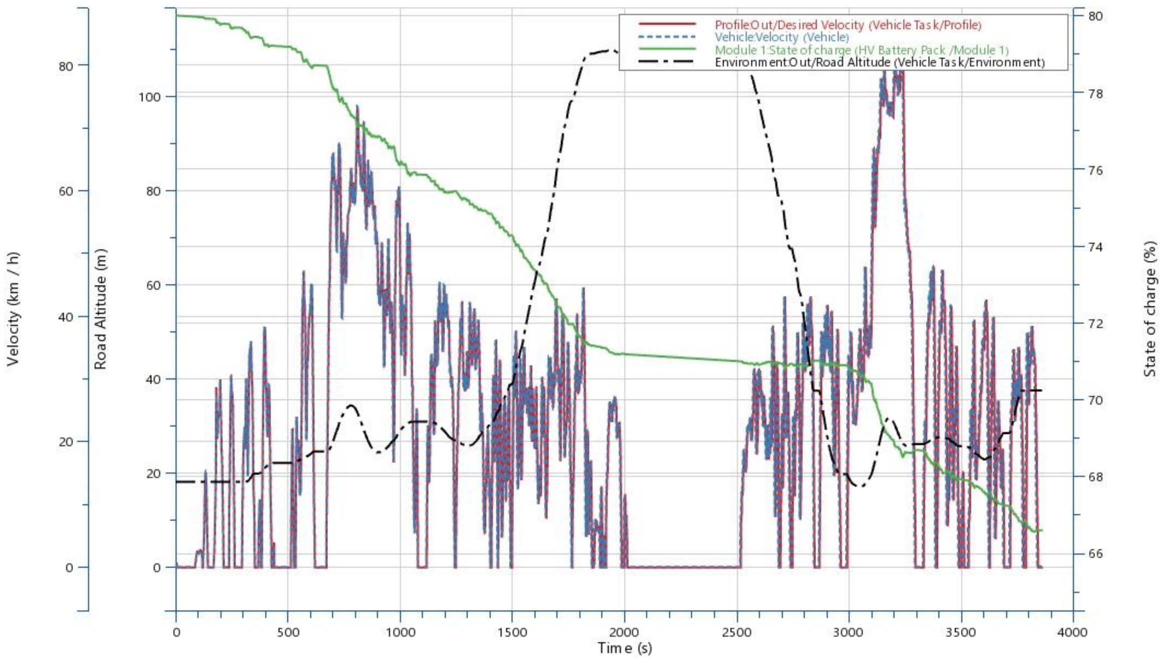

Figure 28 AVL Cruise M - Driving Simulation Results

The controller works properly, and the vehicle can follow the desired velocity profile. An interesting point to notice is the State of Charge curve. Between 2000 and 2500 s the vehicle stops for the maintenance operation. As is possible to see from the altitude profile, this stop is done on the highest part of the cycle, which is in correspondence of a hill. After the stop, there is a driving downhill part, in which the state of charge of the vehicle does not have a decrescent part but is generally constant. This shows a good functioning of the regeneration braking and of the control driving strategy. The final value of the SoC is 66,6 %, considering an initial SoC of 80%. In such a manner, taking into account this driving cycle, it is possible to estimate the autonomy in km of the electric vehicle. The state of charge decreases by 13,4 % every 24.6 km. Considering a discharging window of 85 – 15 % it has been possible to estimate a distance range that is around 130 km with this driving cycle. This value is in line with the distance ranges shown in Table 1.

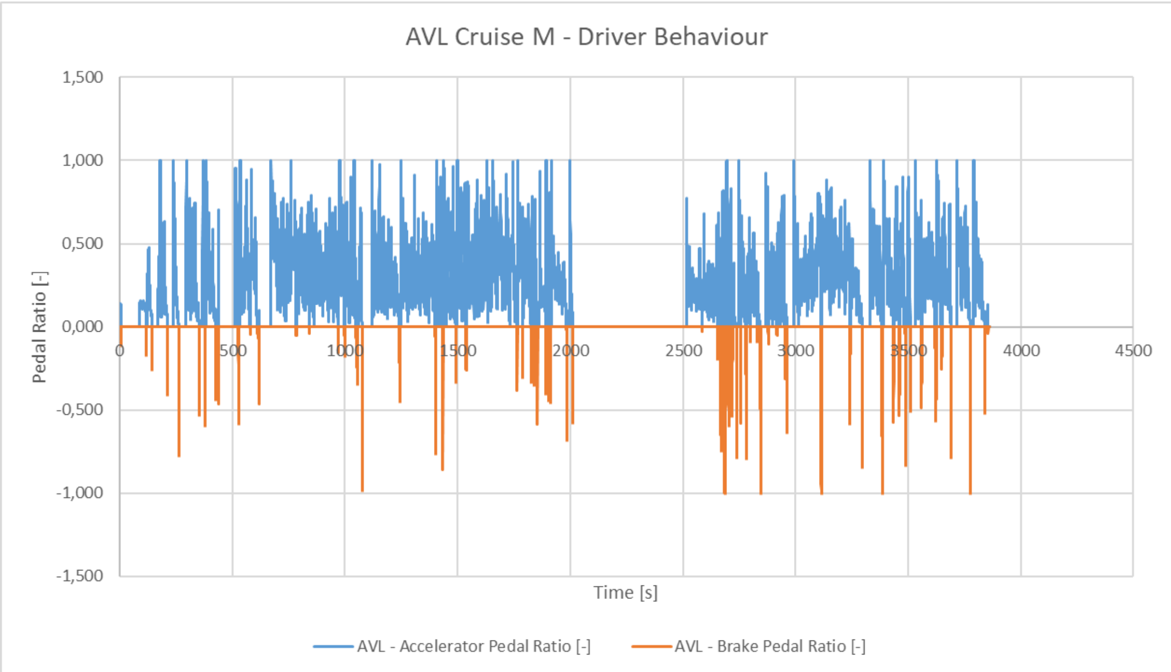

Figure 29 AVL Cruise M - Driver Behaviour

In Figure 29, it is interesting to notice the driver behaviour over the cycle through the pedal pressure. The One Pedal Drive strategy is working properly because the driver uses much more the accelerator pedal than the brake pedal. The latter is mainly used in emergency cases or when the cycle demands a high braking performance. This happens, for example, in the time between 2500 s and 3000 s, when the truck is driven downhill, and the regenerative braking is not enough to keep the desired speed.

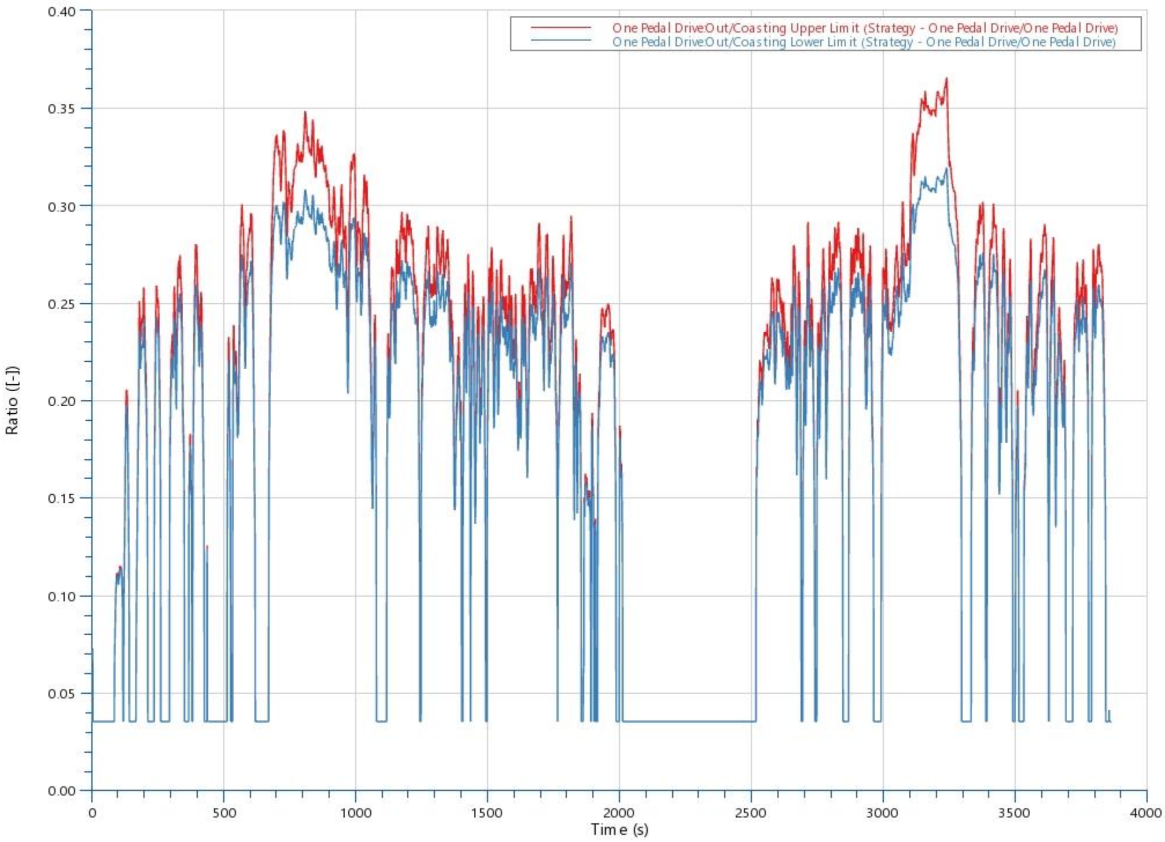

Figure 30 AVL Cruise M - One Pedal Drive strategy: Coasting Limits

As mentioned before, the driving strategy is made up of three phases: traction, coasting, and regeneration. Since kinetic energy cannot be recuperated with 100% efficiency, in some parts of the cycle the best thing to do let the truck roll freely, without any pressure on the brake and throttle pedals. This technique is known as coasting. To monitor the development of the One Pedal Drive control strategy over the driving cycle, a representation of the coasting limits is useful for a better understanding of driving behaviour. In paragraph 3.2.1 it has already been discussed how to compute the limits of this region for the strategy, which results over the cycle are represented in Figure 30. On the y-axis, it is the accelerator pedal ratio, while on the x-axis there is the simulation time. The blue line is representative of the lower coasting limit, while the red one defines the upper coasting limit. If the accelerator pedal ratio value is above the red line, the vehicle is in traction mode, if it is under the blue curve the vehicle is in the regeneration phase, while the area between the two lines defines the coasting zone.

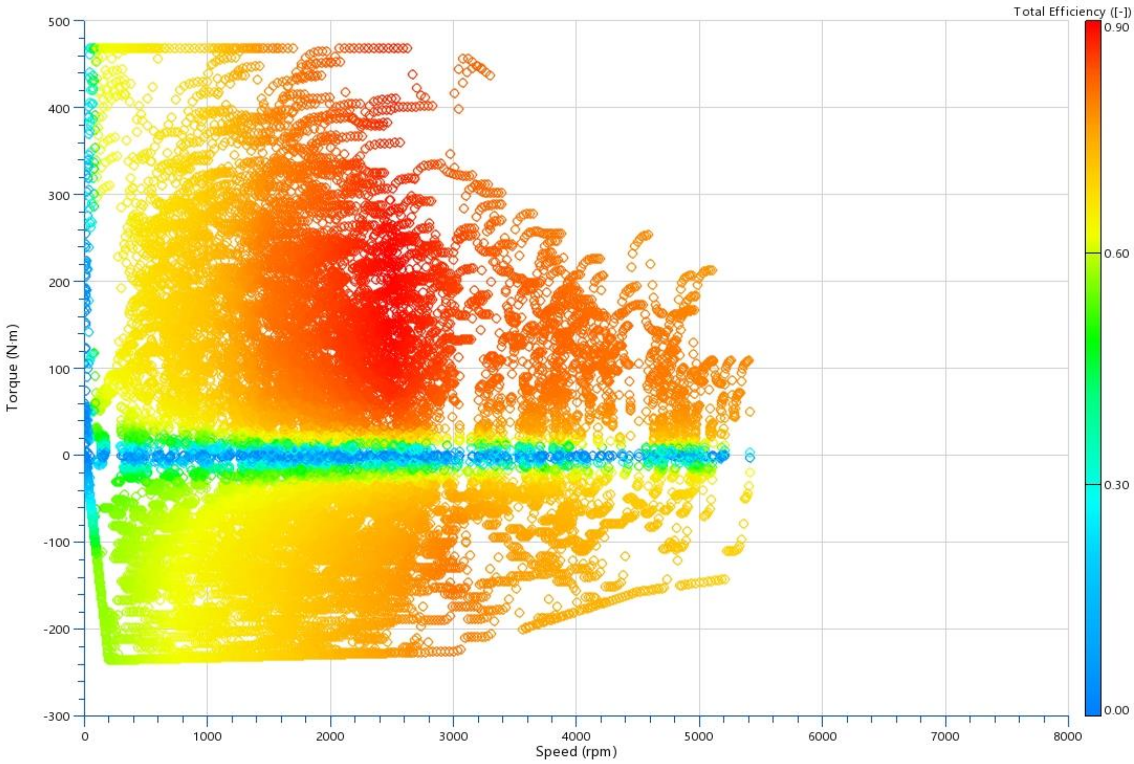

Figure 31 AVL Cruise M - Operating Working Points Map

Figure 31 shows the operating points of the electric motor over the driving cycle. It consists of a scatter plot in which the values of two variables, in this case, torque and total efficiency (also considering the inverter), are plotted along the two axes. Each point on the graph reveals the correlation between these two variables, considering the electric motor speed on the x-axis. This type of graph is extremely useful for understanding the relationship among efficiency, torque, speed, and the trend of the electric machine over the cycle, which would be difficult to see in other forms. Through this graph, it was easy to understand and correct some problems in the model, because it easily shows the correlation among three important variables for an electric machine. It is interesting to notice that the electric machine keeps a high efficiency, reaching peaks that are higher than 90% in some traction points. The efficiency in the regeneration part is a bit lower than the traction one, but this is due to the limits already discussed in paragraph 3.2.2.

To widen the operation of an e-motor, it is necessary to provide more power by increasing the maximum speed and to provide more torque over the speed range. Unfortunately, many factors play a vital role in the value of efficiency. The increase in torque and speed introduces many side effects regarding the components, such as the inverter and the electric machine itself. Copper losses are predominant at lower speeds and high torque. To get more torque, it is necessary to send more current in the copper coil, to strengthen the magnetic field. In such a manner, the resistive losses increase reducing the overall efficiency. Therefore, also the heat dissipation increases, causing potential damage to the machine. Iron losses, instead, are predominant at high speed and low torque, and are caused by currents inducted in the iron by the copper coils (Eddy currents) [40]. It is possible to define an optimal region between the two areas, in which the overall efficiency reaches its peak. This is also confirmed by Figure 31, where the red area is the zone in which there is the maximum efficiency, which in this case lies between approximately 1500 rpm and 3000 rpm.

4.2.2 MATLAB/Simulink

The MATLAB/Simulink model has led to equivalent results, obtaining similar values and trends of the graphs discussed in paragraph 4.2.1.

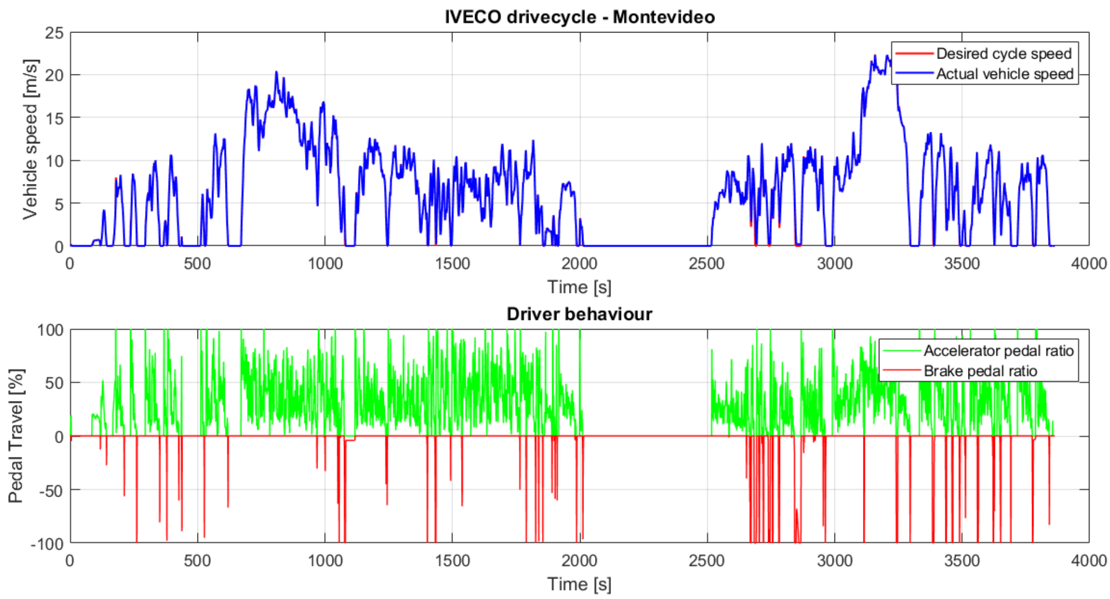

Figure 32 MATLAB/Simulink - Driver behaviour

Even in the MATLAB/Simulink model, the controller works properly, allowing the vehicle to follow the desired speed with a good reaction time. The driver behaviour follows a similar trend as the one seen for the AVL Cruise M simulation. The driver indeed, mainly uses the accelerator pedal over the driving cycle, using the braking pedal only for high braking torque demand, as in the case of the downhill.

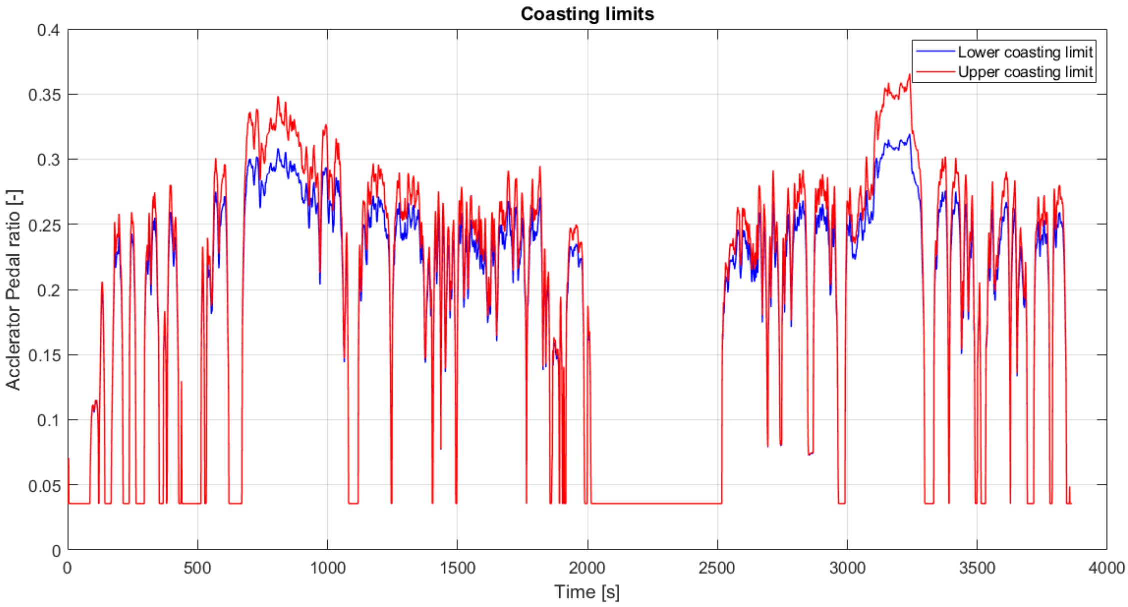

Figure 33 MATLAB/Simulink - Coasting Limits

The same considerations already discussed in Figure 30 can be done also for the coasting limits computed in the MATLAB/Simulink model, confirming a proper working of the driving strategy.

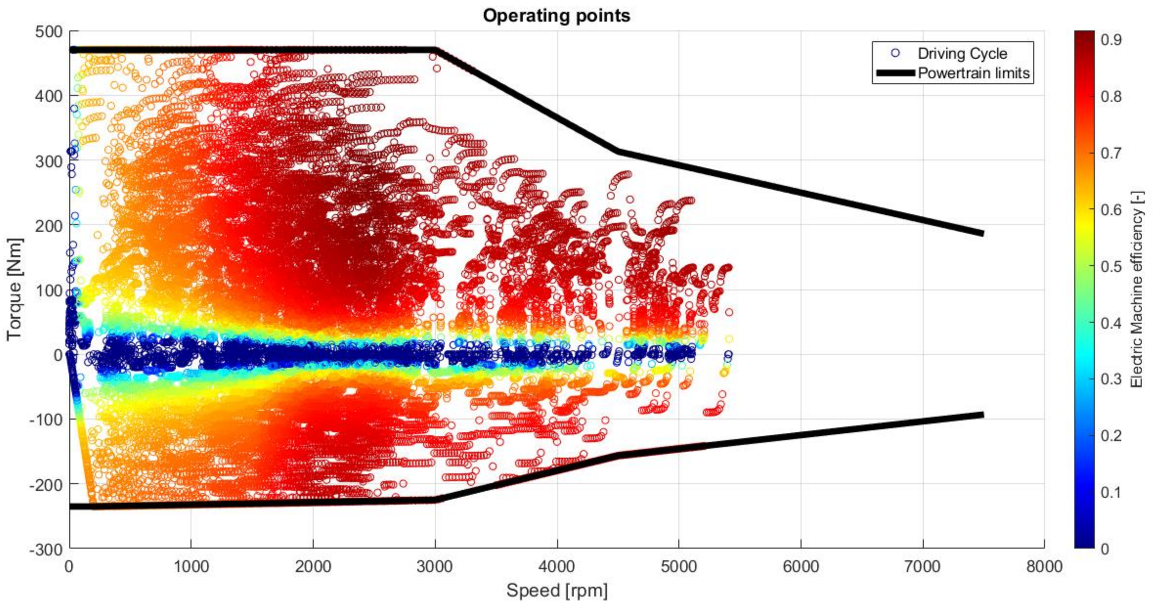

Figure 34 MATLAB/Simulink – Electric Machine Operating Points Map

This scatter plot confirms what was discussed before in Figure 31. It is possible to notice a reduction of efficiency at high torque and low speed and high speed and low torque, with the optimal working area in between due to copper and iron losses. In Figure 34, it is interesting to have a look at the powertrain limits and how the operating points are spread among them.

4.3 Validation Metrics

To evaluate and improve numerical models, it is interesting to make a comparison between the transient response results of the two models. Quantifying such comparisons, it is useful to minimize subjectivity, while maintaining a correlation between the two different models. The most common method used for the comparison is the relative error between the measurement and the simulation results, typically expressed as a percent difference. In the present study, it has been used the Sprague and Geers metric to some of the waveforms given as output from the simulation. This validation metric for comparing measured and stimulated response histories is an integral comparison of the waveforms combined in the metric. [41] In this case, the measured value has been considered the one obtained from the AVL Cruise M simulation and the stimulated value from the MATLAB simulation. The time integrals are defined as follows:

$$\vartheta_{mm} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m^2(t)dt \tag{4.1}$$

$$\vartheta_{cc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} c^2(t)dt \tag{4.2}$$

$$\vartheta_{mc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} m(t)c(t)dt \tag{4.3}$$

Where $m(t)$ is the measured history and $c(t)$ is the corresponding computed history. $t_2 < t < t_1$ instead, is the time interval of interest. Then, the error in magnitude is defined as:

$$M_{SG} = \sqrt{\frac{\vartheta_{cc}}{\vartheta_{mm}}} - 1 \tag{4.4}$$

The phase error is given by:

$$P = \frac{1}{\pi} cos^{-1}\left(\frac{\vartheta_{mc}}{\sqrt{\vartheta_{mm}\vartheta_{cc}}}\right) \tag{4.5}$$

The idea is to obtain a comprehensive error which represents the combination of magnitude and phase differences. In such a manner, it is possible to combine the two metrics by obtaining a number that is representative of the differences between the two models. The comprehensive error can be computed as follows:

$$C_{SG} = \sqrt{{M_{SG}}^2 + P^2} \tag{4.6}$$

All the data about the simulation, considering each step of the simulation time, have been implemented in a spreadsheet. Consequently, it is possible to facilitate the comparison and validation metrics of the two models, by calculating the time integrals using the trapezoidal rule for integration, which evaluates the area under the curves by dividing the total area into smaller trapezoids rather than using rectangles.

The simulation results have been exported into spreadsheets to facilitate the calculation of the time integral. The three main parameters that have been considered for this analysis regard the high-voltage battery pack, and are listed below:

- State of charge [%]
- Total Input Energy [kWh]
- Total Output Energy [kWh]

More details about the comparison between these parameters will be discussed in the next paragraphs.

4.3.1 State of Charge

The analysis of the state of charge over a driving cycle gives valuable information about the vehicle, considering the energy consumption and the distance range. Both simulation models have led to a similar final value, but in this case, a further study will be done to focus on the differences along the whole simulation.

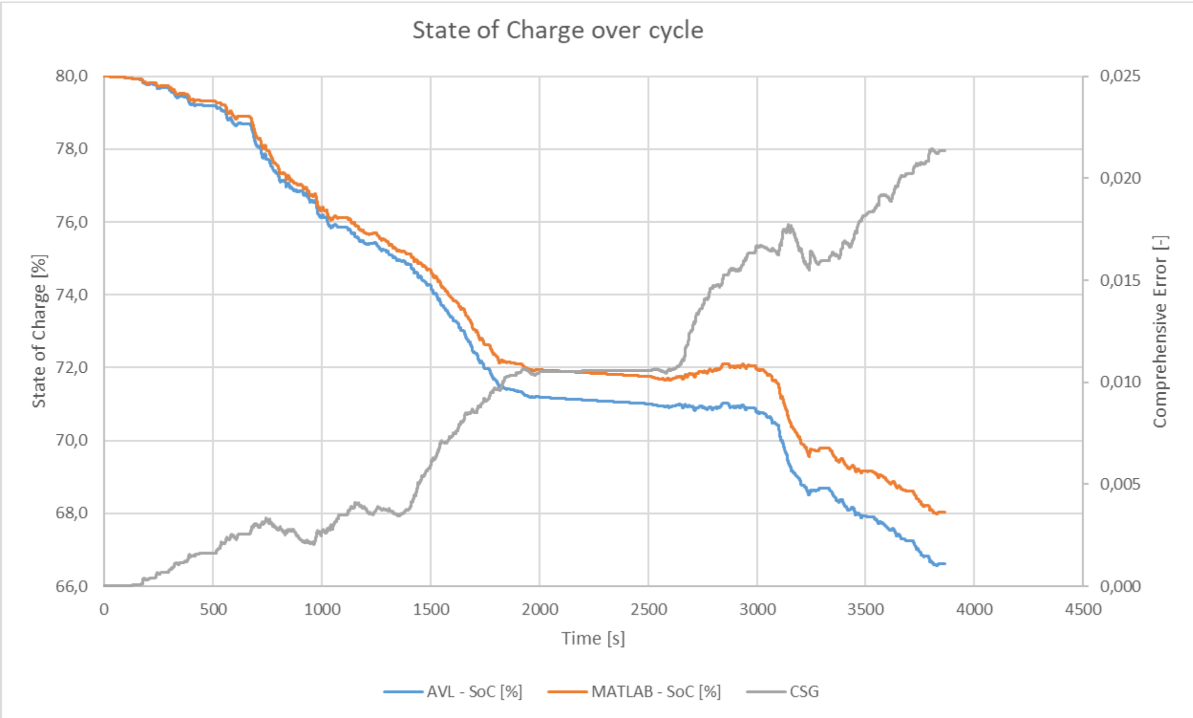

Figure 35 S&G Validation Metrics - State of Charge

The two models show a similar trend in terms of State of Charge, with a final value of 66.6 % for the AVL Cruise M (blue line) model and 68 % for MATLAB/Simulink model (orange line) at the end of the driving cycle, starting from an initial SoC of 80%. The grey line is representative of the comprehensive error C_{SG}, considering the measured value obtained from AVL Cruise M, while the stimulated from MATLAB/Simulink. The final value of the comprehensive error is of 2.13%, with a mean value of 0.91 %, which confirms a good correlation between the two models. The interesting thing to notice is the trend of the curve in the time window between 2500 s and 3500 s. In this window, both models show an increasing trend, during to the regeneration part. This part of the cycle is interesting because the vehicle is driving downhill, getting the best advantage possible for the regeneration part in this cycle. This is a further confirmation of the good functioning of the driving strategy. However, some differences are still unavoidable due to the different working of the two PI controllers, and still some points of the model that can be improved.

For the sake of simplicity, since the battery pack is made up of two modules, the overall state of charge has been considered the mean of the two modules, starting from the same initial state of charge.

4.3.2 Total Input Energy

The Total Input Energy is defined as the electrical energy that is used to charge the battery. In the case of a Li-ion battery, which is a rechargeable battery, it is used the reduction of lithium ions to store energy. By convention, the input energy is considered as positive.

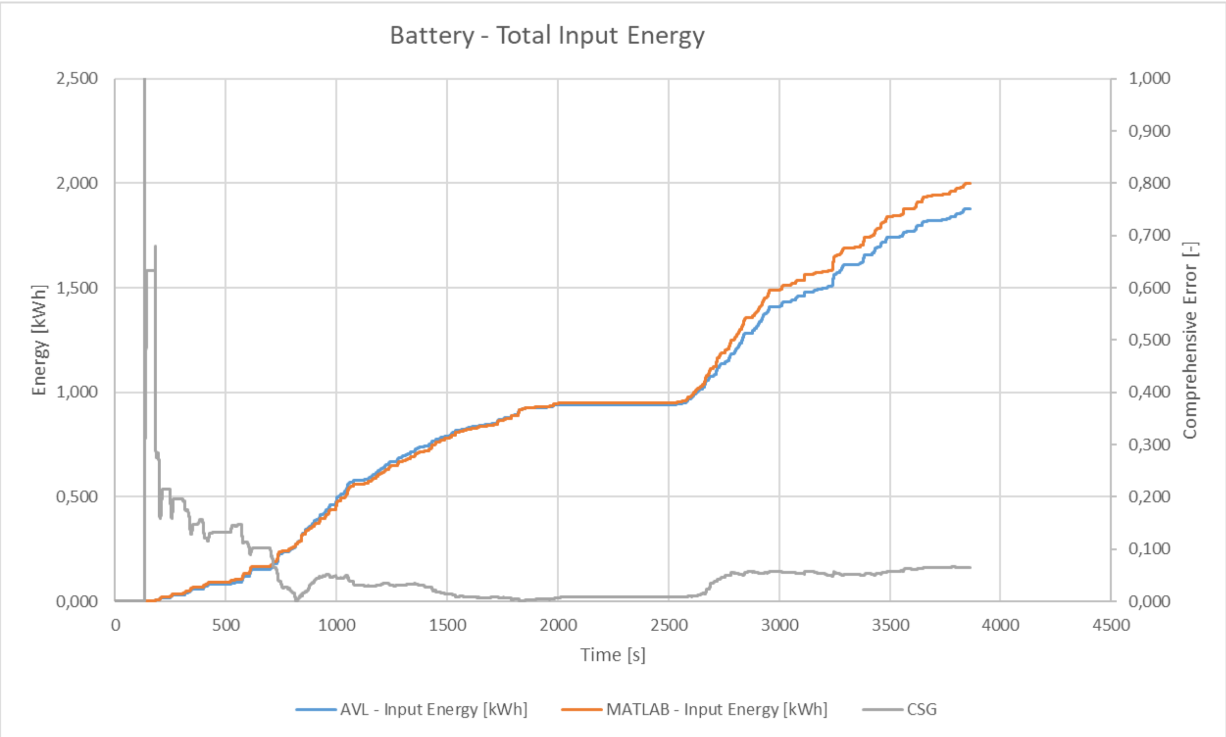

Figure 36 S&G Validation Metrics – Battery Total Input Energy

The two lines show an almost complete matching until the point of the downhill, in which the MATLAB/Simulink model has a better regeneration part compared to the AVL Cruise M model. When the vehicle is driving downhill there is a greater increase of the input energy in the MATLAB/Simulink model, and therefore, a higher value of the State of Charge already discussed in the previous paragraph. The value of the comprehensive error shows extremely high values at the beginning of the simulations, which is not representative of reality. This is due not to extreme differences in the values but to the division by small numbers in the error calculation. Indeed, where there is a superimposition of the two curves, the value of C_{SG} is clearly near to zero. The value of the error at the end of the simulation reaches a value of 6.49 %, while the mean value is 5.50 %, also considering the error at the beginning. The final value of the input energy over the cycle is of 1.876 kWh for AVL Cruise M and 1.998 kWh for MATLAB/Simulink.

4.3.3 Total Output Energy

The Total Output Energy represents the energy dissipated from the battery during the discharging phase over the cycle. AVL Cruise M has an inner function that computes this value of the energy automatically after the simulation, while in MATLAB/Simulink a dedicated block for this calculation has been created, which logic has already been discussed in the paragraph 3.5.2.2. By convention, the output energy is considered as negative.

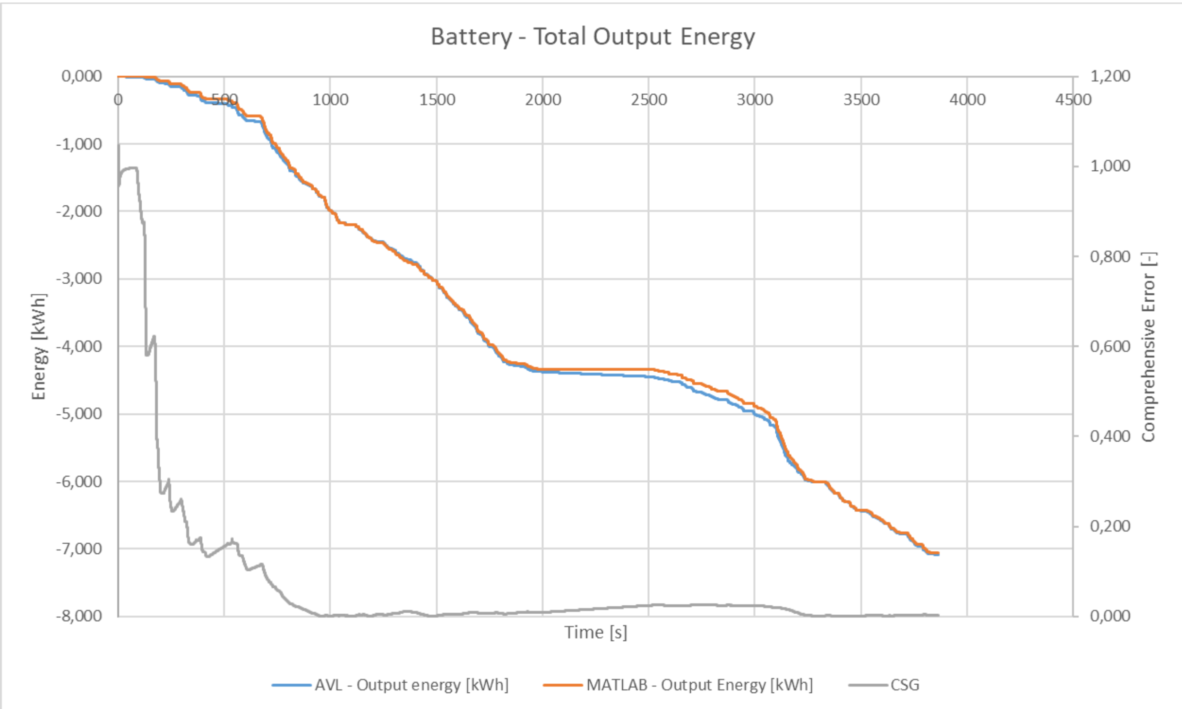

Figure 37 S&G Validation Metrics – Battery Total Output Energy

The final values of the two models are almost identical with an absolute value of 7.080 kWh for the AVL Cruise M model and 7.055 kWh for the MATLAB/Simulink one. As per the input energy calculation, even here there is the same problem at the beginning, but the trend shows realistic results after a certain time of the simulation, getting closer to zero. The final value of the error, indeed, is 0.35 % showing a particularly good correlation between the two models.

5 Conclusions and future perspectives

The work carried out during these 5 months represents the beginning of this project for the conversion of the truck from a Diesel propulsion to an electric one. The goal of this paper was to develop the first part of the main project that involves the design and realization of the electric version of the truck. The two simulation models, although the different logic behind them, have shown a good correlation among the results, then confirmed by the validation metrics explained in paragraph 4.3. However, the main project is still not completed and there are still some aspects that can be improved compared to what has been achieved so far. The two models still show some unavoidable differences due to a different logic of the controllers that cannot be modified and to some improvements that can be done in the future. The price of the components and the available budget for the overall project can represent a strong limitation for what regards the final product. This is also a key point to consider during the purchase of the real components, because along with the technical requirements, it is essential to consider the availability, physical constrains and price of the single parts. Moreover, once the model is validated with the selected components, the goal is to carry out a deep analysis on the stresses on the chassis with the new powertrain. To carry out this design, a 3D model will be developed from a private company with the aim of a solid design of the new version of the truck. The unnecessary elements of the truck, such as the internal combustion engine and the fuel tank will be removed from the design in order to start the mechanical design from the electric version, with proper adaptions. Then, a Failure Modes and Effective Analysis (FMEA) will be carried out. This is a systematic and proactive process for identifying where and how failures can happen. This method consists of two phases:

1. Failure Modes analysis: in this phase, it is determined which parts or components are likely to fail and possible causes of those failures are investigated.
2. Effective Analysis: in the second phase, it is studies which is the impact that these failures would have on the performance of the system and its safety.

For this reason, a more advanced design of the electric truck under development is needed. It is essential to have a detailed understanding of each part of each new component to analyse their potential for failure. With this information, preventive measures can be taken to develop more effective diagnostic strategies.

Eventually, it is important to consider a circular economy of the electric vehicle. Generally, when talking about Circular Economy, three phases of a vehicle's life are considered: manufacturing, operation and final disposal. This method seeks to minimise waste generation and maximize reuse, repair and recycling of the product to create a more sustainable system. In the case of the automotive industry, circular economy focuses on reducing the environmental impact starting from the design phase, considering a recycling, and recovering of materials and components reuse. Based on the aforementioned concepts, it is useful to apply these methods to vehicles that have already some engine problems or near the end of their useful life, but with the body and chassis in good conditions. Since this is a pilot project, if this concept will work in a proper way, the same method will be applied also to other trucks of the fleet. There is trust in the future because scientific literature and development of battery electric vehicles in the current years confirm the technical feasibility of heavy-duty vehicles. Several studies imply a great potential for urban and regional delivery with a daily mileage of less than 400 km, which is the case of this type of vehicles adopted in urban mobility.

6 Acknowledgements

I would like to take the opportunity to thank the supervisor of this thesis, Professor Andrea Tonoli, who provided me with constant support in the revision and writing of this thesis project. In addition, the knowledge I learnt during his Master's degree courses has been essential in the realisation of this thesis project.

I would like to thank Professor Francisco Javier Páez Ayuso, for welcoming me into the INSIA family and giving me the opportunity to carry out this project. My most sincere thanks go to my co-supervisor Enrique Alcalà Fazio, head of the Alternative Propulsion Systems and Environmental Impact of Motor Vehicles Unit, for his patience, transparency, and supervision throughout the months I worked on the project. I had the opportunity to test myself with my first work experience and to expand my knowledge of electric vehicles. I will treasure everything that Prof. Enrique Alcalà has taught to me. I sincerely thank all the team members, Gabriele Segale, Jaime Álvarez, Juan Pastor and Nuria Flores. Your contribution was fundamental, and I learnt a lot from each of you, especially from your experience and availability.

Important thanks go to the technical team from the University of Montevideo, for all the information provided, the discussion of ideas and the extraordinary collaboration during the project.

Special thanks go to my parents and family, who have constantly supported me both morally and financially during these years of study. Thank you for always believing in me, in my plans and for always giving me the time and opportunity to choose what was right for me. All this would not have been possible without you.

My thanks go to all the friends and colleagues I have met during these years of study, among Turin, Leiria and Madrid. Each of you has contributed to my personal and professional growth.

7 Appendix

7.1 One Pedal Drive code - MATLAB

```
function [reg_trq,trc_trq,ctrl_trq,t_trc,t_reg,pcl,pcu] =
fcn(drv_acc_pdl,n,trc_crv,reg_crv)
%% ONE PEDAL STRATEGY

% CONSTANTS DEFINITION

m = 3;
gamma = 1;
cr = 1;
phi = 0.42;
psi = 6;
ch = 0.07;
n_max = 8200*pi()/30;

% COMPUTATION OF UPPER AND LOWER COASTING LIMITS

pcu = phi*(n/n_max)^(1/m);
pcl = phi*(n/n_max)^(1/m)-ch*(n/n_max);

% COMPUTATION OF THE TRACTION AND REGENERATIVE SIGNALS

if (drv_acc_pdl < pcl)
    ar = cr/((pcl^psi)*(psi-1));
    br = (cr*psi)/(pcl*(1-psi));
    t_trc = 0;
    t_reg = ar*(drv_acc_pdl^psi) + br*drv_acc_pdl + cr;

    else if(drv_acc_pdl > pcu)
            t_trc = ((drv_acc_pdl - pcu)/(1-pcu))^gamma;
            t_reg = 0;
        else
            t_trc = 0;
            t_reg = 0;
        end
end

% SATURATION OF TAU LIMITS

if (t_trc > 1)
    t_trc = 1;
else if (t_trc < 0)
        t_trc = 0;
    else
        t_trc = t_trc;
    end
end

if (t_reg > 1)
    t_reg = 1;

else if (t_reg < 0)
        t_reg = 0;
    else
```

```
        t_reg = t_reg;
    end
end

reg_trq = t_reg*reg_crv;
trc_trq = t_trc*trc_crv;
ctrl_trq = reg_trq+trc_trq;
```

7.2 One Pedal Drive code – C code

```
/*double realTime;*/



// ONE PEDAL DRIVE STRATEGY



#define m a[0]

#define gamma a[1]

#define cr a[2]

#define phi a[3]

#define psi a[4]

#define ch a[5]

#define n_rpm a[6]

#define drv_acc_pdl a[7]

#define reg_crv a[8]

#define trc_crv a[9]

#define n_max a[10]



#define pcu y[0]

#define pcl y[1]

#define ar y[2]
```

```
#define br y[3]

#define t_reg y[4]

#define t_trc y[5]

#define reg_trq y[6]

#define trc_trq y[7]

#define ctrl_trq y[8]

#define n y[9]



// CONTROL AT LOW SPEED TO AVOID NaN


if (n_rpm <= 5){


    n=5;

}

else{


    n=n_rpm;

}



pcu = phi*pow((n/n_max),(1/m));

pcl = phi*pow((n/n_max),(1/m)) - ch*(n/n_max);
```

```
//COMPUTATION OF THE TRACTION AND REGENERATIVE SIGNALS

if (drv_acc_pdl < pcl){

  ar = cr/(pow(pcl,psi)*(psi-1));
  br = (cr*psi)/(pcl*(1-psi));
  t_trc = 0;
  t_reg = ar*(pow(drv_acc_pdl,psi)) + br*drv_acc_pdl + cr;
  }

  else if(drv_acc_pdl > pcu){

      t_trc = pow(((drv_acc_pdl - pcu)/(1-pcu)),gamma);
      t_reg = 0;
      }

    else{
      t_trc = 0;
      t_reg = 0;
      }

//SATURATION OF TAU LIMITS

if (t_trc > 1){
```

```
    t_trc = 1;
    }

else if (t_trc < 0){
        t_trc = 0;
        }

    else{
        t_trc = t_trc;
        }

if (t_reg > 1){
    t_reg = 1;
    }

else if (t_reg < 0){
        t_reg = 0;
        }

    else{
        t_reg = t_reg;
        }

//TORQUE COMMANDS
```

```
reg_trq = t_reg*reg_crv;

trc_trq = t_trc*trc_crv;

ctrl_trq = reg_trq+trc_trq;
```

8 References

[1] SOLUTIONSplus, “Montevideo | Solutionsplus,” 2023. [Online]. Available: https://www.solutionsplus.eu/montevideo. [Accessed 2023].

[2] “Uruguay Electric Vehicles,” 19 02 2021. [Online]. Available: https://www.trade.gov/market-intelligence/uruguay-electric-vehicles. [Accessed 08 May 2023].

[3] I. d. M. |. F. J. Ricaldoni, “INFORME Proyecto Retyrofitting,” in *Convenio IM-FI-UdelaR* , Montevideo , 27 May 2023.

[4] “Global EV Outlook 2021,” [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2021/introduction#overview. [Accessed 28 April 2023].

[5] “Global EV Outlook 2022,” May 2022. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022/executive-summary. [Accessed 28 April 2023].

[6] F. M. Sergio Manzetti, “Electric vehicle battery technologies: From present state to future systems,” *Renewable and Sustainable Energy reveiws,* pp. 1004-1012, 2015.

[7] J. M. L. Martinez, “Vehículos híbridos y eléctricos. Diseño del tren propulsor.,” ETSII | UPM sección de publicaciones, Madrid, 2016.

[8] J. L. J. Lowry, Electric Vehicle Technology Explained, Chichester, West Sussex, U.K: Wiley, 2012.

[9] S. C. Krithika V., “A comprehensive review on choice of hybrid vehicles and power converters, control strategies for hybrid electric vehicles,” *International journal of energy research,* pp. Vol. 42 (5), p. 1789-1812, 2018.

[10] K. T. Chau, Electric Vehicle Machines and Drives: Design, Analysis and Application, Newark Wiley, 2015.

[11] U. D. o. Energy, “Alternative Fuels Data Center: How Do All-Electric Cars Work?,” [Online]. Available: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

[12] S. Dhameja, Electric Vehicle Battery Systems, Oxford: Elsevier, 2001.

[13] N. T. S. Board, “Risks to Emergency Responders from High-Voltage, Lithium-Ion Battery Fires Addressed in Safety Report,” [Online]. Available: https://www.ntsb.gov/news/press-releases/Pages/NR20210113.aspx. [Accessed August 2023].

[14] E. Garage, “Understanding battery management systems,” August 2023. [Online]. Available: https://www.engineersgarage.com/understanding-battery-management-systems/.

[15] J. V. F. Serra, Electric vehicles: technology, policiy and commercial development, London: Sterling, Va. : Earthscan, 2012.

[16] A. Vega, B. Pradip and B. Alper , “Chapter 8 - Rugged autonomous vehicles,” in *Rugged Embedded Systems | Computing in Harsh Environments*, Elsevier Inc., 2017, pp. 237-266.

[17] I. R. Bojoi, “Teaching material, Electrical drives for eMobility,” Torino, 2020.

[18] C. K. C. H. T. L. Z. S. Chunhua Liu, “A Critical Review of Advanced Electric Machines and Control Strategies for Electric Vehicles,” *IEEE,* pp. Vol. 109 (6), p. 1004-1028, 2021.

[19] J. G. Hayes and G. A. Goodarzi, Electric Powertrain: Energy Systems, Power Electronics, and Drives for Hybrid, Electric and Fuel Cell Vehicles, Newark: John Wiley & Sons, Incorporated, 2018.

[20] P. P. Steffen Link, “Technical Feasibilty of Heavy-Duty Battery-Electric Trucks for Urban and Regional Delivery in Germany - A Real-World Case Study,” *World Electric Vehicle Journal,* vol. 13 , no. 9, p. 161, 2022.

[21] E. Commission, "Question and Answers on the Commission strategy for reducing Heavy-Duty Vehicles (HDVs) fuel consumption and CO2 emissions," 21 May 2014.

[Online]. Available: ec.europa.eu/commission/presscorner/detail/de/MEMO_14_366. [Accessed 2023 May 12].

[22] “Electric Commercial Vehicle Market Size | Growth Forecast 2030,” August 2022. [Online]. Available: https://www.strategicmarketresearch.com/market-report/electric-commercial-vehicle-market. [Accessed 03 May 2023].

[23] Z. L. S. C. D. A. K. B. Zhiming Gao, “Quantitative Evaluation of MD/HD Vehicle Electrification Using Statistical Data,” *OSTI.GOV,* pp. p. 2-5, 2018.

[24] "e-Daily viewer paper," IVECO, March 2023. [Online]. Available: https://viewer.ipaper.io/iveco-hq/master/edaily/?page=1. [Accessed 2023 April 13].

[25] "Fuso eCanter 6,0 toneladas," FUSO Trucks Espana, 2023. [Online]. Available: https://www.fuso-trucks.es/productos/ecanter/6-0-toneladas-e/#749t-confort. [Accessed 2023 April 13].

[26] "Vicinity Motors releases specs for new medium-duty electric truck," Green Car Congress, 25 June 2021. [Online]. Available: https://www.greencarcongress.com/2021/06/20210625-vmc.html. [Accessed 2023 April 13].

[27] "2023 Ford E-Transit Chassis Cab All-Electric Van | Model Details & Specs," Ford Motor Company, 2023. [Online]. Available: https://www.ford.com/commercial-trucks/e-transit/models/chassis-cab/?gnav=vhpnav-specs. [Accessed 2023 April 13].

[28] "Logistar-400 All Electric Urban Delivery Vehicle," Centro ElectrIc Group Limited, 2023. [Online]. Available: https://cenntroauto.com/vehicles/logistar-400/. [Accessed 2023 April 13].

[29] "La revolucion de los camiones éléctricos para el reparto de ultima milla," Jac Motors Iberia, 2023. [Online]. Available: https://www.jacmotorsiberia.com/. [Accessed 2023 April 13].

[30] "Mullen Commercial: Class 1-6 Electric Vehicles," Mullen Commercial, 2023. [Online]. Available: https://mullencommercial.com/. [Accessed 2023 May 18].

[31] A. Ajanovic, “The future of electric vehicles: prospects and impediments: The future of electric vehicles,” *Wiley interdisciplinary reviews. Energy and environment,* pp. Vol. 4 (6), p. 521-536, 2015.

[32] “Camiones y buses,” 09 December 2016. [Online]. Available: https://www.camionesybuses.com.ar/iveco-daily-doble-cabina-unico-mercado-utilitarios-2016595/. [Accessed 2023 May 31].

[33] "F1C Light Commercial Vehicles," F1C | FPT Industrial, [Online]. Available: https://www.fptindustrial.com/en/engines/Onroad/Light-Commercial-Vehicles/F1C. [Accessed 11 April 2023].

[34] J. van Boekel, I. Besselink and H. Nijmeijer, “Design and realization of a One-Pedal-Driving algorithm for the TU/e Lupo EL,” *World Electric Vehicle Journal - ISSN 2032-6653,* vol. 7, pp. 6-8, 2015.

[35] Mathworks, “Progettazione Model Based con Simulink,” [Online]. [Accessed 22 May 2023].

[36] AVL, “AVL CRUISE™ M,” [Online]. [Accessed 22 May 2023].

[37] AVL Cruise M, “CRUISE M User Manual,” 2020.

[38] C. Six, G. Silberholz, J. Fredriksson, B. Geringer and S. Hausberger, “Development of an exhaust emissions and CO2 measurement test prodecure for heavy-duty hybrids (HDH),” Chalmers University Of Technology, Graz University of Technology, Vienna University of Technology, Vienna, 2014.

[39] U. Wiki, “HDH General Files - Transport - Vehicle Regulations - UNECE Wiki,” 30 May 2014. [Online]. Available: https://wiki.unece.org/display/trans/HDH+General+Files. [Accessed 01 03 2023].

[40] S. Mobility, “Increasing the range of EV with the same battery - Part II - More efficiency with better software - Silicon Mobility,” [Online]. Available: https://www.silicon-mobility.com/increasing-the-range-of-ev-with-the-same-battery-part-ii-more-efficiency-with-better-software/. [Accessed September 2023].

[41] L. E. Schwer, "Validation metrics for response histories: perspectives and case studies," *Engineering with Computers ,* pp. 23:295-309, 2007.