POLITECNICO DI TORINO

Course in Automotive Engineering

Autonomous and connected vehicle

Master's Degree Thesis

BEV Target setting tool

BEV Architecture and vehicle optimization

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1 Introduction

The thesis work presented describes an innovative way of using simulation tools for the development of new battery electric vehicle architectures. The aim of process is to help electric vehicle developers adapt to change, by creating a standardized procedure to obtain an overall picture in the phase of choosing and designing the electric vehicle, in the shortest possible time and with the minimum cost. This procedure will be applied to define the main performance targets and the vehicle target in the early phase of an electric vehicle design (virtual prototyping / model-based design).

The procedure aims to define a list of sequential / iterative steps to provide a target setting for a battery electric vehicle, using a Simulink model to run acceleration and range simulations. The goal of defining a standard procedure collides with the interaction with the customer, who must choose between different strategies: for that reason, the process involves iterative steps. Based on the strategies and possibly major changes to the vehicle configuration, the procedure must adapt. Ultimately, the process must deliver the vehicle's performance (acceleration and range) and objectives.

The process includes a first generic analysis in the phase of understanding the objectives, then defining them for the specific car in question.

The design of an architecture for a BEV involves the definition of the components that constitute it, for which standard schemes used in the various applications are available in the literature. In this thesis project, a vehicle model developed on MATLAB / Simulink will be used as a reference.

Once the architecture of interest has been defined, we then move on to the sizing of the main components of the architecture such as battery packs, inverters, electric motors and related transmissions.

In the literature there are texts that provide an explanation on the procedure for choosing electrical architectures with the particularity of being static procedures and defined a priori, in this thesis, however, a procedure is developed that we will call target setting tool that will make it possible to make a standard procedure from static to dynamic taking into consideration the needs of the customer and the various structural constraints of the architecture to be developed. With this regard, the work aims to develop a procedure which will define the target values, considering the design constraints. The procedure analyses the effects of the various choices of components and vehicle parameters. Subsequently, the optimal values will be sought through a sensitivity analysis that allows you to have a clear idea of the effects of each variation of the parameters / components of the vehicle.

The fundamental objective of the thesis, in line with the customer's needs, is to design a model-based vehicle with a considerable reduction in the analysis and development times of the various projects.

Another objective of the thesis is to be able to develop models of battery electric vehicles which goal is not necessarily maximizing the performance but allows the right compromise between range and performance.

The thesis elaborates a procedure for the choice of priorities that must be taken into consideration in the vehicle development phase, according to the vehicle class and the business choices made by the customer.

Having developed the idea of the layout of the architecture, based on the targets to be reached and the priorities defined by the customer, a feasibility study is carried out regarding the performance and range of the vehicle through numerous simulations that cover most of the scenarios of interest for the type approval of the vehicle in question.

The work ends with vehicle dynamics simulations to evaluate the results obtained in terms of performance and range.

The second chapter introduces the reference vehicle model of this project. The model has been entirely developed for this thesis project. In particular, I will illustrate the main functions of the various blocks , their representation and the main input variables that will allow the calculation and estimation of the results useful for defining the performance and range of the vehicle in question, referring to the main essential blocks for modeling the various components of the architecture. In particular, the sub-systems covered are the following:

- the input parameters
- the driver model
- the high voltage battery system
- the DC line
- the electric drive unit

- the charger model
- The DCDC model
- the brake model
- the longitudinal dynamics estimator;
- the vehicle control unit.

The third and last chapter explains the methodology used to obtain an iterative procedure in the choice of targets, in the definition of priorities and finally in the optimization of the various components of the vehicle in question with the aim of reaching the target values defined at the beginning of the procedure. The procedure was created using the App design tool in order to allow anyone to use the tool without having any specific computer knowledge.

2 Battery Electric Vehicle Simulink model

The electric vehicle, also called EV from the English Electric vehicle, as mentioned in the previous chapter, is a vehicle that properly uses electricity stored in special batteries to move the vehicle. The main elements that make up an electric vehicle are the High Voltage Battery (paragraph 2.3), the electric drive unit that includes the inverter (paragraph 2.5.1), the electric motor (paragraph 2.5.2), the transmission (paragraph 2.5.3) and the DCDC (paragraph 2.7). The figure below shows an Electric vehicle Sketch.

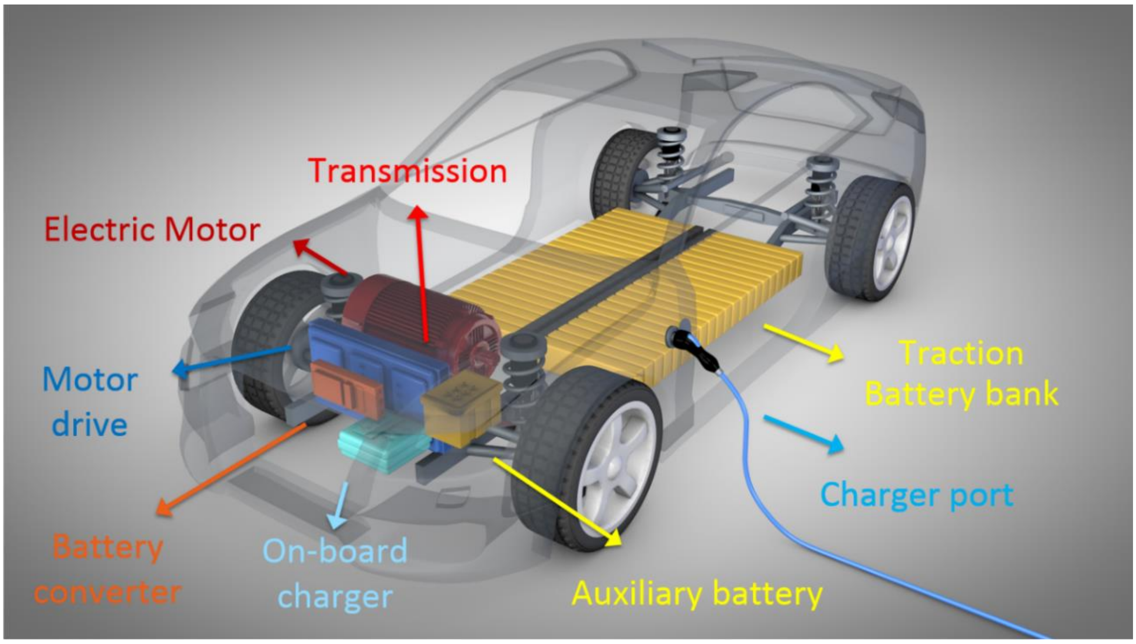


Figure 1 - BEV block diagram

What is important, for policy makers, climate scientists, and environmentally minded consumers is the fact that EVs produce zero emissions when they operate using electricity drawn from renewable electricity systems, including solar, wind, hydro, and tidal power.

BEVs are limited in their range when compared to HEVs and PHEVs. However, their range is expected to increase significantly due to ongoing advanced research and development in the areas of lightweight materials, high-energy-density storage devices, and electric propulsion motor drives.

The procedure requires multiple inputs to perform realistic simulations. These inputs depend on the accuracy desired and the vehicle target to inspect. Once the mission is known, the model requirements can be defined, and so the input parameters.

To estimate the performance and range of a vehicle architecture, a model developed in Simulink will be used which will allow obtaining reliable results for the analysis. To work, the model needs many parameters such as the maps of the battery (R_0, R_1, tau_1 map), the maps and the parameters of the motors, the inverter maps, the vehicle parameters, the tire coefficients, the cooling system maps and parameters, the general setting parameters and finally control unit parameters.

The figure below shows the Battery Electric Vehicle model.

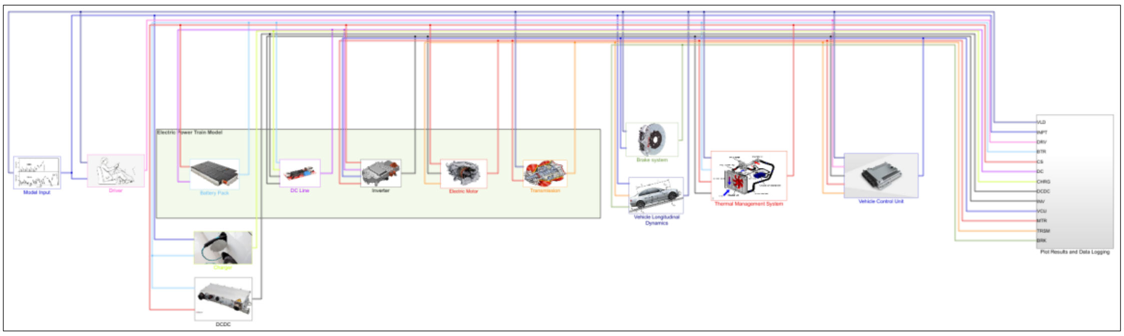


Figure 2 - Battery Electric Vehicle Model

In this chapter all the sub-systems present in the Simulink model will be described, the treatment will be at high level for reasons of corporate secrecy. The sub-systems present in the model are listed below:

- Input model
- Driver model
- Battery pack model
- Inverter model
- Electric motor model
- Transmission model
- DC line model
- Charger model
- DCDC model
- Brake system model
- Vehicle longitudinal dynamic model
- Thermal management system
- Vehicle control unit

In the following chapters all the sub-systems necessary for the development of the Simulink model will be illustrated, describing the main characteristics.

2.1 Input parameters

The procedure requires multiple inputs to perform realistic simulations. The following figure shows the model input block.

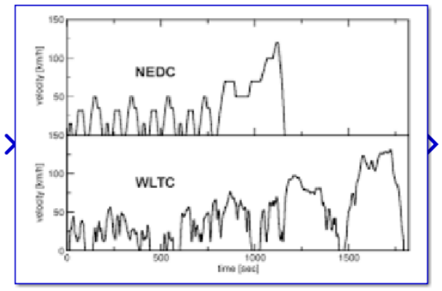


Figure 3 - Input block

These inputs depend on the accuracy desired and the vehicle target to inspect. Once the mission is known, the model requirements can be defined, and so the input parameters. In the following figure the input parameter subsystem overview is shown.

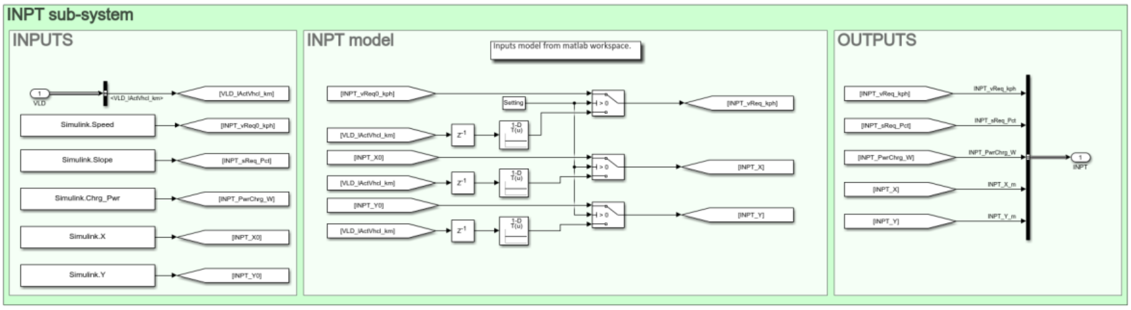


Figure 4 - Input sub-system

The INPT block Converts the input parameters present in the MATLAB workspace into Simulink signals.

The input signals are the actual speed, the required speed, the required slope, the charging power, X and Y position. It outputs the required speed, the road slope, the charging power, the X and Y position.

2.2 Driver model

The driver can be modelled as a PID, which reference signals are given by the speed cycles or tracks to follow. In terms of pure performance, the model of the driver does not require more than a PI with instantaneous response so no lateral dynamics simulation is introduced. The figure below shows the driver sub-system.

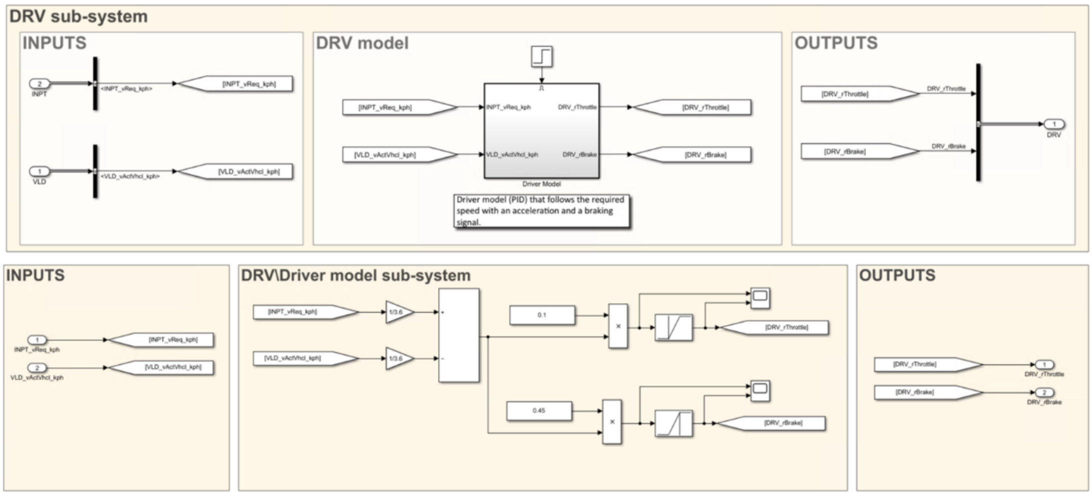


Figure 5 - Driver sub-system

2.3 High Voltage Battery System model

One way that can be used to accumulate energy is using electrochemical conversion. In practice, there are devices capable of converting chemical energy into electricity. The conversion is achieved through chemical reactions that develop between two electrodes (cathode and anode). The most common of these devices are those that are accumulators that once discharged can store chemical energy again and then be reused several times. The different types of batteries are named depending on the materials that make up the electrodes: Nickel-Cadmium, Lithium, etc. batteries.

The figure below shows an example of a high voltage battery pack.

Figure 6 - High Voltage Battery Pack

An accumulator consists of:

- Two electrodes, one positive and one negative
- An electrolyte that allows electrons to be transported from pole to pole
- Current collectors which serve to convey electrical current to and from the electrodes
- Separators that prevent the two electrodes coming into contact from causing a short circuit

An accumulator is made up of several elements connected in series or parallel and the voltage depends on such connections. For example, a 400V battery may consist of one hundred 4V elements connected in series. The main parameters that describe the potential and functioning of an electrochemical accumulator are the following:

- **Capacity (C):** It is measured in Ampère-hours (Ah) and represents the quantity of electric charge that can be stored, the Capacity is given by the product of the intensity of the current supplied for the time necessary for the accumulator to discharge, supplying continuously that current (1 Ah = 3600 coulombs). To obtain the energy in watt hours it is necessary to multiply the capacity in Ah by the nominal voltage. A 1 Ah battery can deliver 0.1 amps of current for ten hours before discharging. The real capacity is very dependent on the discharge rate, C decreases with the increase of the required current. Therefore a 1 Ah battery usually fails to deliver 1 amp for an hour.

- State of energy (SoE): this is the percentage of residual energy stored in the batteries.
- Discharge rate (C/x): it is the current that completely discharges the battery in x hours, remembering that dimensionally it is [A] = [C / t].
- Specific energy: energy that can be supplied by the accumulator per unit of mass (Wh/kg) or per unit of volume (Wh/dm^3), once the energy in Wh has been obtained, simply divide by the size of the battery or for its mass.
- Working voltage: it is the average voltage present between the two positive and negative terminals when the accumulator supplies current.
- Deliverable power: it is the product of the average discharge voltage and the current. It is measured in watts (W). The specific power per unit of mass (W/kg) and per unit of volume (W/dm^3) can also be considered.
- Amperometric efficiency: it is the ratio between the number of amper hours delivered during the discharge and those absorbed during the previous charge.
- Energy efficiency: it is the ratio between the energy delivered during the discharge and the energy absorbed during the previous charge.
- Life span: it strongly depends on the operating conditions of the accumulator and therefore can only be assigned for certain charge/discharge conditions that must be specified.
- Final discharge voltage: this is the working voltage at which the discharge should be stopped for technical and/or economic reasons.

The accumulator technology used in this project is based on lithium, which is quite common in nature, but unfortunately, due to its reactivity, it is not found in the metallic state but only linked to other elements. Fifty percent of the commercially exploitable reserves of lithium are found in South America. Thanks to its low atomic weight and extremely high specific capacity, it is one of the most suitable elements for the development of batteries with high specific energy. Lithium batteries can be divided into three main types:

- Li-ion batteries with liquid electrolyte: they are the most mature and widespread ones

- lithium-ion polymer batteries: they have a solid polymer-type electrolyte and present fewer risks in terms of safety
- lithium metal-polymer batteries: lithium is in metallic form in the liquid state and present greater safety problems, their development is still backward

All types of lithium batteries are carefully managed through the Battery Monitoring and Management System (BMS).

The aim of the battery model is to estimate the voltage variation, the deliverable current / power during operation, the temperature of the cells and of the busbar (and the heat exchanged with the cooling liquid). These outputs are required both for acceleration and range performance. The figure below shows the HVBS block.

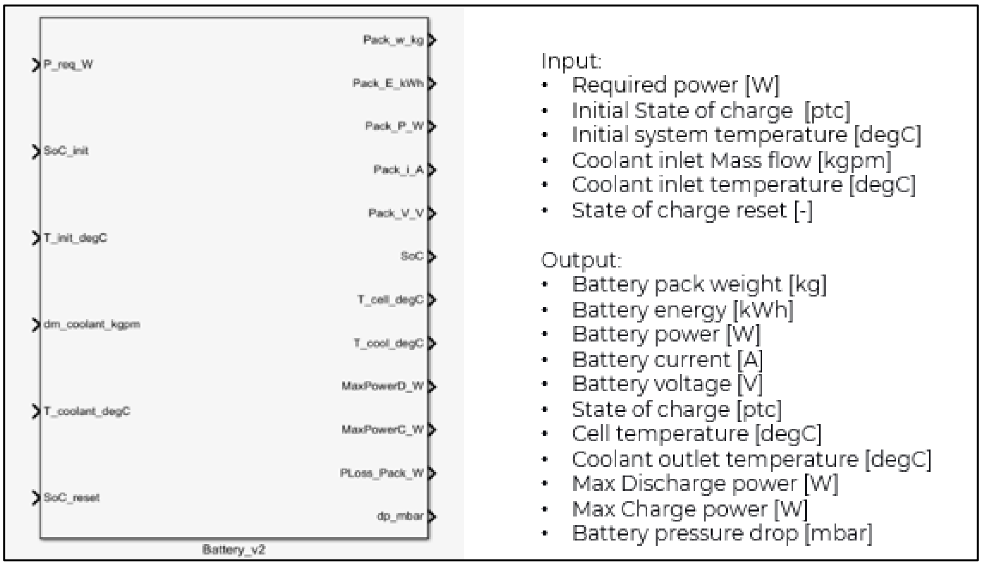


Figure 7 - The HVBS block

The HVBS block consists in the 1RC battery model with simple BMS for c-rate, temperature, and voltage limitations, includes simple thermal model and battery pack weights estimation. The main HVBS block outputs the Battery energy, the Battery power, the Battery current, the cell temperature and the SoC estimation. The main formulas used to model the battery pack are the following:

$$E_{pack} = V_{nominal} \cdot C_{cell} \cdot N_{series}$$

$$P_{actual} = I_{pack,act} \cdot VoP$$

$$I_{Cell} = \frac{P_{req}}{(VoP \cdot N_{parallel})} \text{ with Max discharge and charge limits}$$

$$SoC = SoC_{start} - \int \frac{I_{cell}}{C_{Cell}} dt$$

$$T_{cell} = \int \frac{P_{loss,pack} - P_{Rej}}{(c_{cell} \cdot N_{cell})} dt$$

The figures below show the HVBS Simulink model overview.

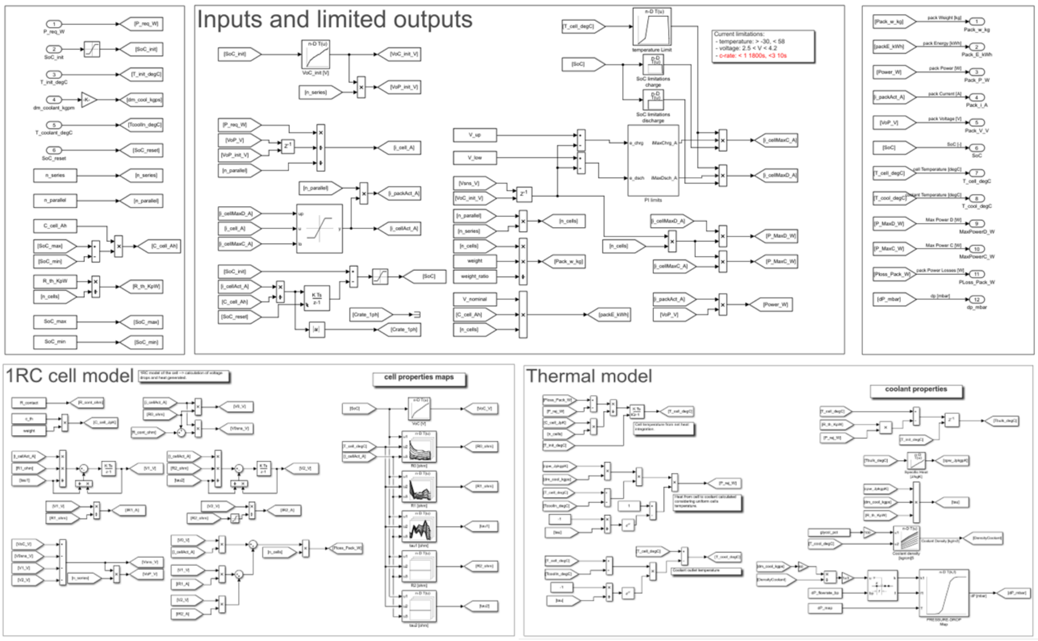


Figure 8 - the HVBS Simulink model overview

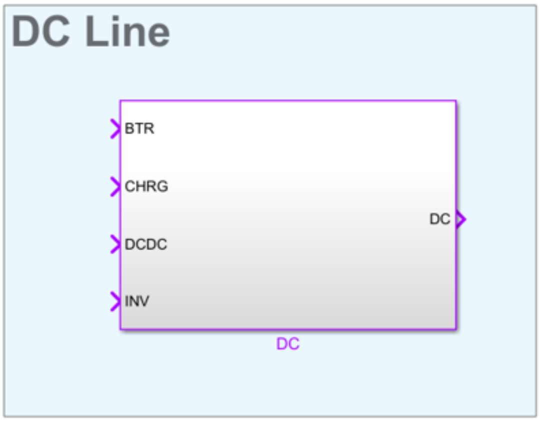
Finally, the main model functions used to model the battery pack are listed in the table below.

Table 1 - HVBS model functions description

Model Function	Description
SoC estimation	Mathematical formula function of the actual cell current, the cell capacity and SoC_start
Battery energy	mathematical formula function of the nominal voltage, the cell capacity and the total number of cells
Battery power	mathematical formula function of the VoP (Voltage of pack) evaluated with the second Kirchhoff's law applied to the RC circuit and the battery current
Battery current	mathematical formula function of the number of parallel modules and the cell current (with charge and discharge current limit), the cell current is based on the required power
Battery Voltage	Second Kirchhoff's law applied to the RC circuit
Cell Temperature	Thermal law, the cell temperature derives from the net heat integration
Outlet coolant temperature	Mathematical formula with an exponential form function of the cell temperature, the inlet coolant temperature and time constant (depends on the thermal capacity, the coolant mass flow, and thermal resistance)
Charge power limit	Mathematical formula function of max charge current and Vsns (Voltage at cell level)
Discharge power limit	Mathematical formula function of max discharge current and Vsns (Voltage at cell level)
Battery power loss	Mathematical formula function of the power loss across the 2RC model
Battery pressure drop	The battery pressure drop function is taking as input the coolant inlet mass flow and with a 1D-Lookup table is outputting pressure drop [mbar]
Heat rejected	The heat from cell to coolant is calculated considering uniform temperature
Coolant density	The coolant density function is taking as input the coolant inlet temperature and the percentage of glycol with a 2D-Lookup table is outputting coolant density [kg/m3]
Charge cell current limit	The Charge cell current limit is modelled as a PI and considering the SoC limitation charge and the cell temperature limit
Discharge cell current limit	The Charge cell current limit is modelled as a PI and considering the SoC limitation discharge and the cell temperature limit
Open Circuit Voltage	The VoC function is taking as input the SoC with a 1D-Lookup table is outputingThe VoC [V]
R0	The R0 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe R0 [ohm]
R1	The R1 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe R1 [ohm]
Tau 1	The tau 1 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe tau 1

2.4 DC line

The DC line block take all the power request to the battery block. The figure below shows the DC line block.



Input:
- BTR – Battery power [W]
- BTR – max discharge power [W]
- BTR – max charge power [W]
- BTR – Battery voltage [V]
- CHRG – Charge power consumption [W]
- DCDC – Auxiliary power consumption [W]
- INV – Inverter inlet power [W]

Output:
- DC battery power [W]
- Max DC discharge battery power [W]
- Max DC charge battery power [W]
- DC battery voltage [V]
- Required DC battery power [W]
- Required DC battery energy [kWh]
- Positive DC battery energy [kWh]
- Negative DC battery energy [kWh]

Figure 9 - The DC line block.

In the following figure the DC line subsystem overview is shown.

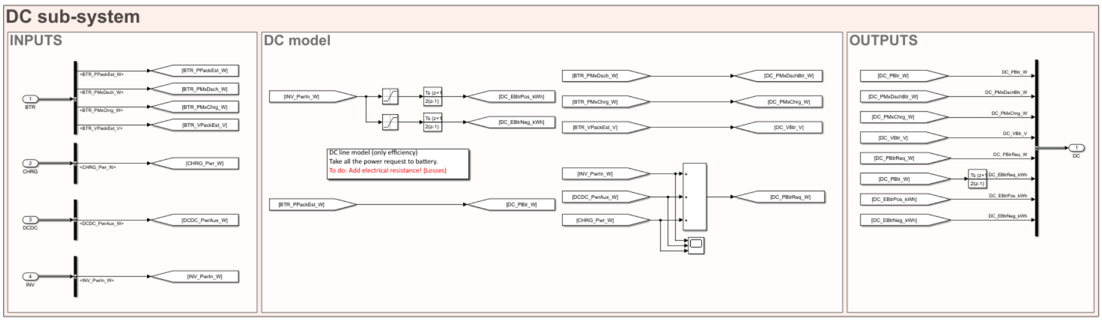


Figure 10 - The DC line subsystem overview

2.5 Electric Drive Unit model

An Electric Drive Unit (EDU) consists of three main modules: the power electronics, the gearbox, and the electric motor. All three must work in perfect harmony to get the vehicle moving.

The main purpose is the effective conversion of electrical energy into motion. The type of energy source used can vary on a case-by-case basis - from conventional electricity from charging stations or power outlets, stored in batteries, to fuel cells - anything is possible.

The power electronics are responsible for the overall control of the e-drive and convert the DC voltage of high-power batteries into a three-phase AC voltage. This subsystem carries the logic of the entire EDU system and regulates the current to the motor. For electric drive systems, achieving maximum efficiency is considered more important than maximum power. The inverter is expected to achieve high flexibility, durability, power availability and allow variable and maximum voltage utilization at the same time. To deliver steady torque even at the highest performance levels, strict safety requirements and compliance with ISO standards must be met.

Other prominent topics are charging times and charging speed. Demands for high charging capabilities require a new generation of inverters that keep losses as low as possible during the charging process while also coping with extremely high voltages. Because power electronics manage the flow of current between the battery and the motor, its design must be able to manage these high currents effectively. For this reason, 800 V inverter, allowing twice the charging speed of 400 V inverter, are gaining popularity.

The transmission is responsible for the torque transfer from the motor to the wheels with the most effective gear ratio. When choosing an EDU, the number of gears in transmission has a significant impact on the design complexity, functionalities, overall performance, and efficiency of the system, influencing other factors such as the size of the e-motor and the system costs. The focus lies on two performance aspects in particular: the acceleration power and the driving range. For a wide range of applications, the 1-2 gear transmissions are the most effective. In contrast to the 1-gear transmission, a 2-gear transmission allows an increase in driving range and top speed with the same acceleration power. With multi-gear transmissions, the transmission must be capable of changing gears to ensure acceleration without traction interruption, which is known to be typical for electric vehicles.

An overarching functional element, particularly relevant in this highly connected and digital time, is the control software. It includes the functions for regulating and monitoring the drive unit of the vehicle. The control unit, located in the power electronics, communicates with the high-level vehicle systems. In vehicles, the demand for software is skyrocketing. Drive units need to be controlled in a manner that ensures the highest possible efficiency. However, since the inverter has a limit depending on its power capacity, it is the control software's job to reach this edge to fully utilize the potentials and deliver maximum performance.

The efficiency of electric drive systems benefits enormously from advances in software control. Excellent accuracy in the recording of currents, voltages and temperatures is required. Precise control software reduces the amount of hardware and materials required within a vehicle.

Algorithms are used to optimize the range, always determining the most efficient driving characteristics. High-grade software design is essential. Beginning in the development phase, the models must be able to represent all desired software functions in detail and take them into account at an early stage.

The Electric Drive Units differ in their power capacities, drive torque, transmission ratios. They can accommodate everything from 12V systems to high power categories of up to 300 / 400 / 500 kW. Based on the electric machines used, they deliver different degrees of torque, ranging from 220 Nm to 300 Nm to 450 Nm and more. These specifications of an EDU depend on the vehicle's requirements, weight, size, and available installation space - SUVs require a larger electric drive unit than small vehicles. The figure below shows an Electric Drive Unit (EDU).

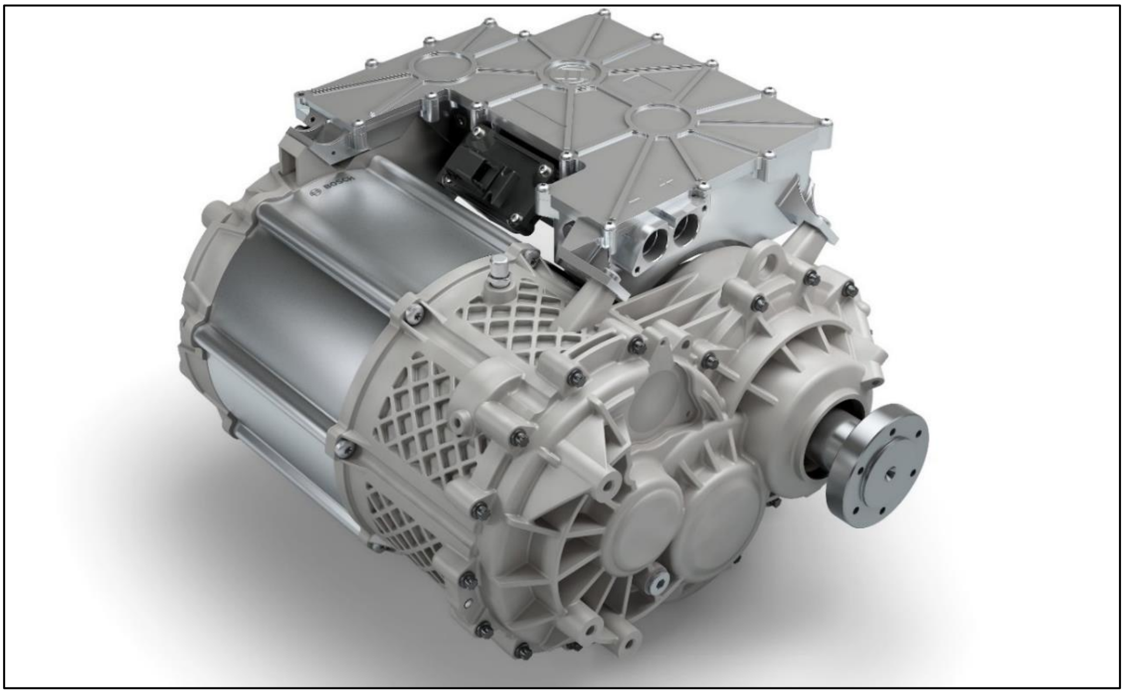


Figure 11 - Electric Drive Unit (EDU)

2.5.1 Inverter model

The inverter is an essential element in electric vehicles because it converts the voltage of a bus into direct, coming from the electric battery, into alternating. The latter in turn is used to power the electric motor. In particular, the inverter can adjust, both in voltage and in current, the amplitude and frequency.

The inverter is normally used to power accumulators, electric motors for vehicles. The term "Inverter" can also be understood as a "rectifier-inverter" set, powered by alternating current and used to vary the voltage and frequency of the alternating current output as a function of the input one.

There are three main types of inverters used to power alternating current loads:

- square wave inverter - suitable for purely resistive loads
- modified sine wave inverter - suitable for resistive and capacitive loads, with inductive loads they can produce noise
- pure sine wave inverter - suitable for all types of loads because they faithfully reproduce a sine wave equal to that of our home electrical network.

The figure below shows an example of inverter.

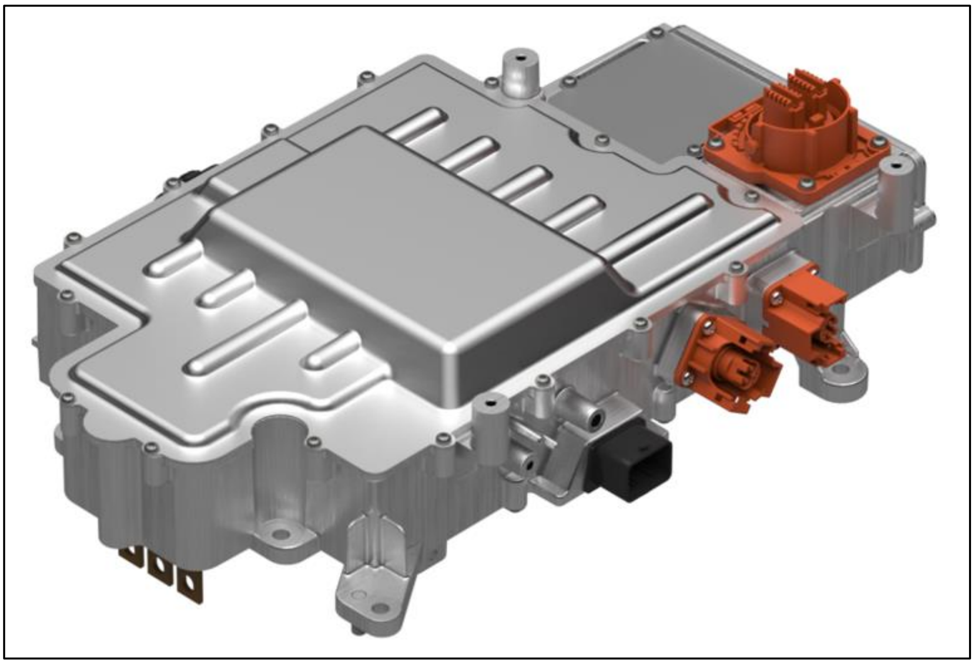
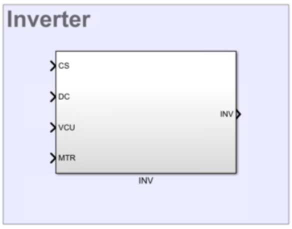


Figure 12 - Inverter sketch

The inverter is modelled as an efficiency map. Once the efficiency is known, the power losses can be calculated.

Due to the high frequency dynamics of the inverter, its model does not need to be physical. The only required output of the inverter is the efficiency (function of power and frequency requested). The figure below shows the inverter block.

Input:
- DC – Discharge battery power [W]
- DC – Charge battery power [W]
- DC – Battery voltage [V]
- VCU – split torque ratio [-]
- VCU – Front required torque [Nm]
- VCU – Rear required torque [Nm]
- MTR – Front electric power [W]
- MTR – Rear electric power [W]
- MTR – Front motor torque [Nm]
- MTR – Rear motor torque [Nm]
- MTR – Front motor RPM [RPM]
- MTR – Rear motor RPM [RPM]
- CS – Initial system temperature [degC]
- CS – Front EDU pump mass flow [kgpm]
- CS – Rear EDU pump mass flow [kgpm]
- CS – Front inlet inverter coolant temperature [degC]
- CS – Rear inlet inverter coolant temperature [degC]



Output:
- The inlet inverter power [W]
- The outlet power [W]
- The power losses [W]
- Front INV torque request [Nm]
- Rear INV torque request [Nm]
- The inverter voltage [V]
- The front efficiency [-]
- The rear efficiency [-]
- The front power loss [W]
- The front power loss [W]
- The actual discharge power [W]
- The actual charge power [W]
- The discharge energy loss [W]
- The charge energy loss [W]
- The front inverter temperature [degC]
- The rear inverter temperature [degC]
- The front IGBT temperature [degC]
- The rear IGBT temperature [degC]
- The front DIODE temperature [degC]
- The rear DIODE temperature [degC]
- The outlet front coolant temperature [degC]
- The outlet rear coolant temperature [degC]
- The front inverter power [W]
- The rear inverter power [W]
- The inverter discharge energy losses [kWh]
- The inverter charge energy losses [kWh]

Figure 13 - The inverter block

The inverter block is a device that simulates the operation of the inverters present on the electric vehicle. The figure below shows the inverter Simulink model overview.

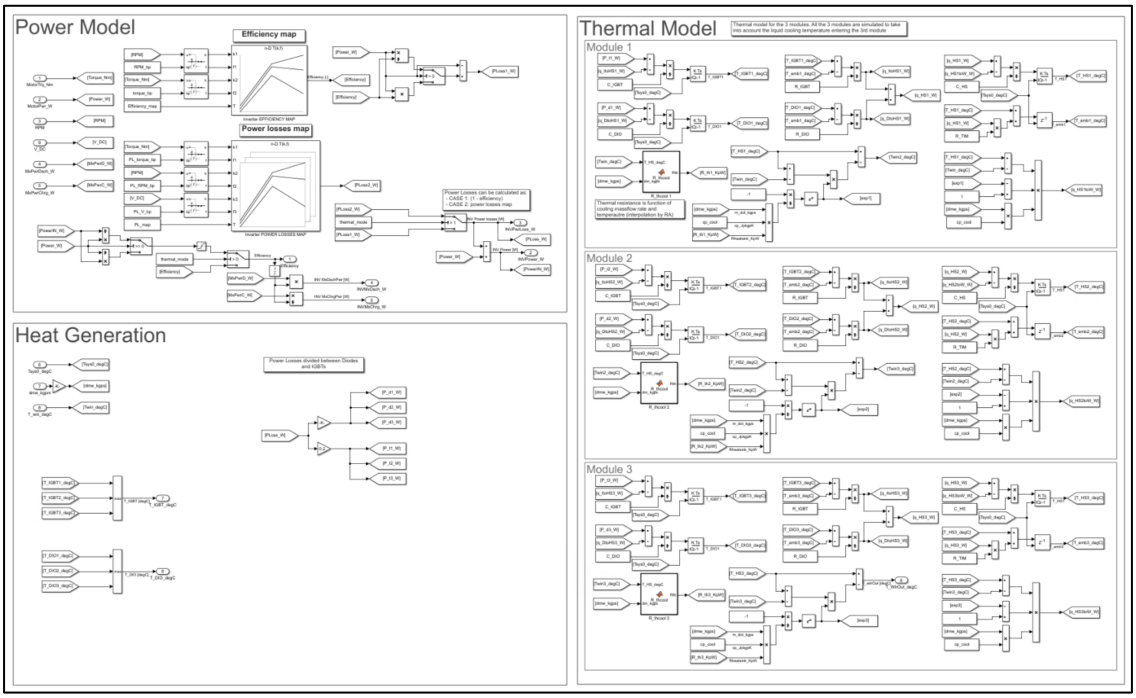


Figure 14 - The inverter Simulink model overview

Finally, the main model functions used to model the inverter are listed in the table below.

Table 2 - inverter model functions description

Model Function	Description	Model Function	Description
Inlet power	The inlet power is the sum of the front and rear inverter power required from the battery	Charge energy loss	The discharge energy loss is the integral of the difference between the outlet power and the inlet power
Outlet power	The outlet power is the sum between the electric power of the motors (Front and rear)	Front inverter temperature	The front inverter temperature is the maximum temperature between the IGBT temperature and the DIODE temperature
Power Losses	The power losses is the difference between the inlet power and the outlet power	Rear inverter temperature	The rear inverter temperature is the maximum temperature between the IGBT temperature and the DIODE temperature
Front INV torque request	The front inverter torque request is a signal that comes directly from the VCU	The rear IGBT temperature	The IGBT temperature is evaluated with a dedicated thermal model based on a thermal resistence and the cooling temperature entering in the modules (3 modules)
Rear INV torque request	The rear inverter torque request is a signal that comes directly from the VCU	The front IGBT temperature	The IGBT temperature is evaluated with a dedicated thermal model based on a thermal resistence and the cooling temperature entering in the modules (3 modules)
Inverter Voltage	The inverter voltage is equal to the DC battery voltage	The front DIODE temperature	The DIODE temperature is evaluated with a dedicated thermal model based on a thermal resistence and the cooling temperature entering in the modules (3 modules)
Front INV efficiency	The inverter efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the Motor power and outlet inverter power when the inverter power is positive and viceversa when the inverter power is negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 2D look-up table and it is function of thr RPM and the torque required	The rear DIODE temperature	The DIODE temperature is evaluated with a dedicated thermal model based on a thermal resistence and the cooling temperature entering in the modules (3 modules)
Rear INV efficiency	The inverter efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the Motor power and outlet inverter power when the inverter power is positive and viceversa when the inverter power is negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 2D look-up table and it is function of thr RPM and the torque required	Outlet front coolant temperature	The outlet front coolant temperature is calculated taking into account the modules heat of the components, the exchanged heat between the components and the coolant and the exponential dependency ofthe mass flow, the specific heat and the thermal resistence
Front power loss	The power losses can be calculated in two ways depending on the thermal mode value. Case 1: is calculated as "1-efficiency"; Case 2: is evaluated through a 3D look up table and it is function of torque, RPM and Voltage	Outlet rear coolant temperature	The outlet front coolant temperature is calculated taking into account the modules heat of the components, the exchanged heat between the components and the coolant and the exponential dependency ofthe mass flow, the specific heat and the thermal resistence
Rear power loss	The power losses can be calculated in two ways depending on the thermal mode value. Case 1: is calculated as "1-efficiency"; Case 2: is evaluated through a 3D look up table and it is function of torque, RPM and Voltage	Front inverter power	The front inverter power is the input inveeter power plus the inverter power loss
Actual discharge power	The inverter discharge power is the sum between the front and rear input discharge power multiplied by the efficiency	Rear inverter power	The rear inverter power is the input inveeter power plus the inverter power loss
Actual charge power	The inverter charge power is the sum between the front and rear input discharge power multiplied by the efficiency	Inverter discharge energy loss	The inverter discharge energy loss is the integral of the difference between the positive inverter power and the positive electric motor power
Discharge energy loss	The discharge energy loss is the integral of the difference between the inlet power and the outlet power	Inverter charge energy loss	The inverter charge energy loss is the integral of the difference between the negative inverter power and the negative electric motor power

2.5.2 Electric Motor model

In the choice and design of an electric propulsion system for electric vehicles, as in general for all road vehicles, an attempt is made to achieve a mechanical characteristic as close as possible to the ideal hyperbolic one, with constant power as speed increases and with a constant torque initial region. While for internal combustion engines this requires the installation of a gearbox in the case of the electric motor this is not necessary. By adopting control systems, it is possible to obtain precise adjustments of torque and speed according to the operating conditions in which one is found. The motor types used in electric traction are the following:

- DC motors - initially used for electric propulsion due to reduced regulation requirements, they are now of limited use in vehicle on-board equipment such as windscreen wipers, etc.
- Squirrel cage asynchronous motors (AC) Induction motors are very robust and have a low cost; on the other hand, they have a low efficiency and specific torque.
- synchronous motors (AC) maintain high efficiency over a wide operating range, and like DC motors, they can be deflexed and require greater maintenance due to the 16/48 power brushes of the excitation winding.
- permanent magnet synchronous motors (AC) are the most promising category in the field of electric traction thanks to the notable developments that are affecting the permanent magnet sector: the absence of conventional excitation increases the efficiency of the machine, moreover the specific torque is extremely high. on the other hand, it is not possible, in the event of a fault, to completely exclude it.

The figure below shows a general mechanical characteristic of electric motors.

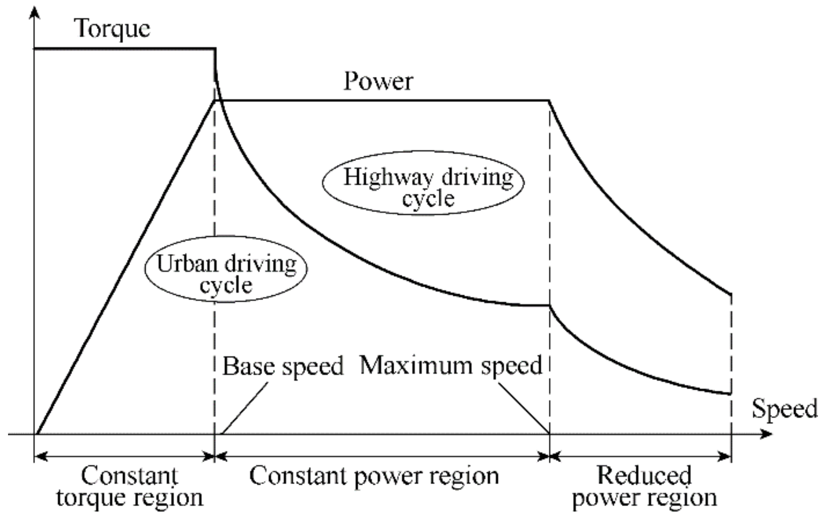


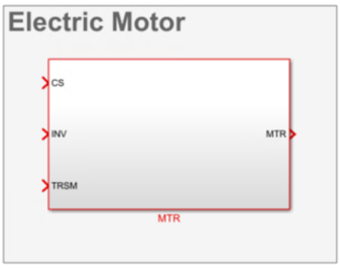
Figure 15 - Electric motor characteristic

The motor, as the battery, is one of the biggest limiters of the vehicle acceleration performances. A physical model of the motor gives an accurate output in terms of torque responsiveness and electric power losses, but still a friction losses map is required. If the motor model is physical, a control in current is required (and so are the windings resistance, self and mutual inductances, flux linkage values). If the motor is modelled as torque and efficiency maps, the accuracy of the simulation depends on the accuracy of these maps (the torque responsiveness could be introduced as a simple model based on experimental data, but its contribute is negligible in terms of acceleration and range performance).

The estimation of the motor temperature is function of the motor capacity and the heat exchanged with the cooling liquid. So, if the cooling is not a sub-system to design, the thermal resistance (constant value or map) between the motor and the cooling liquid is required.

The figure below shows the electric motor block.

Input:
- CS – front EDU mass flow [kgpm]
- CS – rear EDU mass flow [kgpm]
- CS – initial system temperature [degC]
- MTR – front required torque [Nm]
- MTR – rear required torque [Nm]
- MTR – MTR inverter voltage [V]
- MTR – front outlet coolant temperature [degC]
- MTR – rear outlet coolant temperature [degC]
- TRSM – front motor RPM [RPM]
- TRSM – rear motor RPM [RPM]



Output:
- The total electric motor power [W]
- The total mechanical motor power [W]
- The total thermal motor power loss [W]
- The front MTR required torque [Nm]
- The rear MTR required torque [Nm]
- The MTR inverter voltage [V]
- The front efficiency [-]
- The rear efficiency [-]
- The front mechanical power [W]
- The rear mechanical power [W]
- The front electric power [W]
- The rear electric power [W]
- The front thermal power loss [W]
- The rear thermal power loss [W]
- The front motor RPM [RPM]
- The rear motor RPM [RPM]
- The front external temperature [degC]
- The rear external temperature [degC]
- The outlet front coolant temperature [degC]
- The outlet rear coolant temperature [degC]
- The front MTR output torque [Nm]
- The rear MTR output torque [Nm]
- The MTR discharge thermal energy losses [kWh]
- The MTR charge thermal energy losses [kWh]
- The front MTR discharge thermal energy losses [kWh]
- The front MTR charge thermal energy losses [kWh]
- The rear MTR discharge thermal energy losses [kWh]
- The rear MTR charge thermal energy losses [kWh]
- The front motor pressure drop [mbar]
- The rear motor pressure drop [mbar]

Figure 16 - The electric motor block

An electric motor is a particular rotating electric machine that transforms the incoming electrical energy, applied to the power supply terminals, into mechanical output energy made available on the motor axis. This type of electric machine is based on the electromagnetic forces that interact between a system of currents and a magnetic field. The figure below shows the motor Simulink model overview.

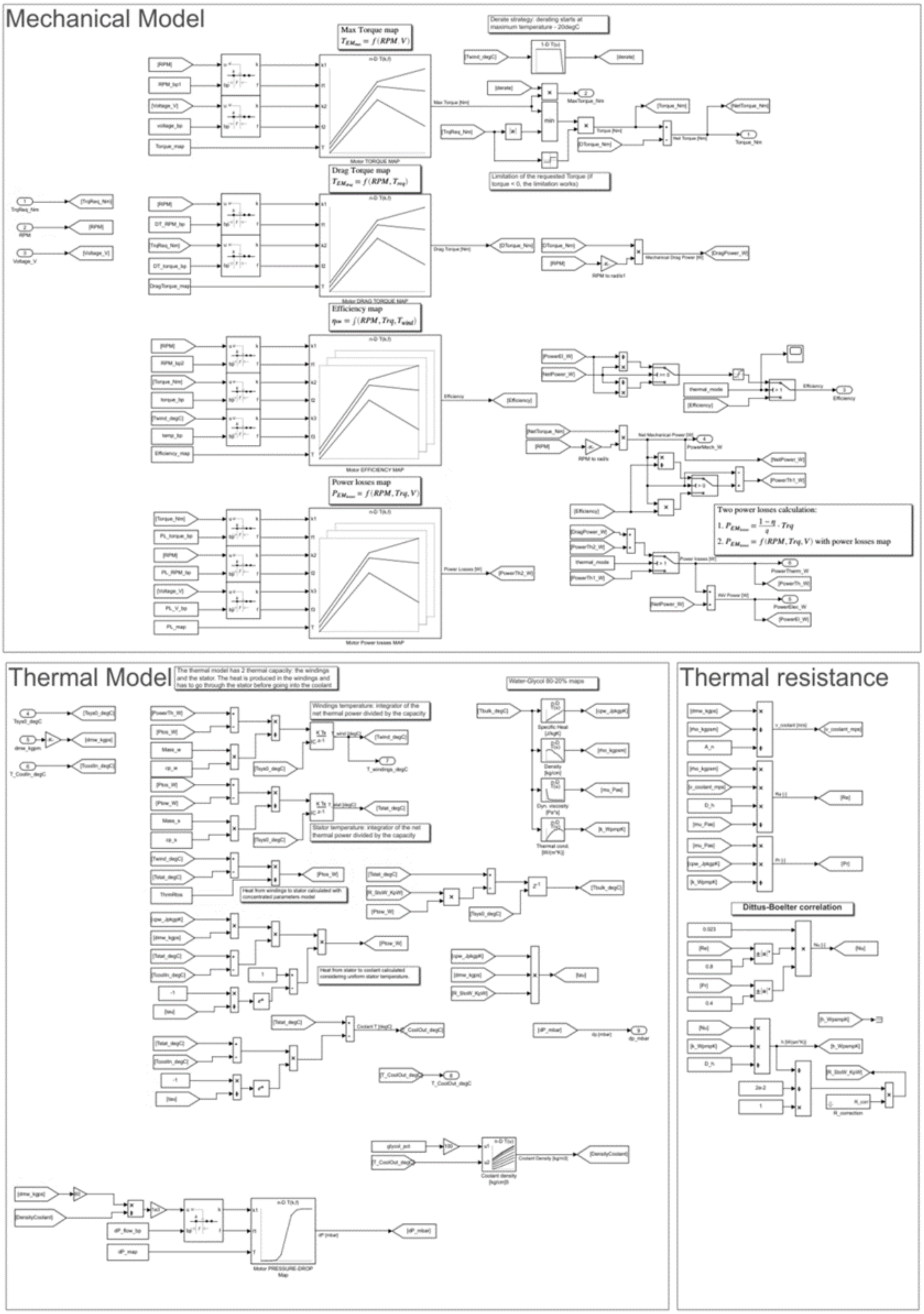


Figure 17 - The electric motor Simulink model overview

Finally, the main model functions used to model the motor are listed in the table below.

Table 3 - Electric motor model functions description

Model Function	Description	Model Function	Description
Electric motor power	The electric motor power is taking as input the rear and front electric motor power and it outputs the total electric motor power	Front motor external temperature	The front motor external temperature is taking as input the power loss,the front motor mass and the specific heat and it outputs the front external motor temperature
Mechanical motor power	The mechanical motor power is taking as input the rear and front electric motor power and it outputs the total mechanical motor power	Rear motor external temperature	The rear motor external temperature is taking as input the power loss,the rear motor mass and the specific heat and it outputs the rear external motor temperature
Thermal motor power	The thermal motor power is taking as input the rear and front thermal motor power and it outputs the total thermal motor power	Front motor outlet cooling temperature	The front motor cooling temperature is taking as input the stator temperature,the inlet cooling temperature and front tau parameter and it outputs the front motor cooling temperature
Front motor torque	The front motor power is taking as input the torque (minimum between the required torque and the maximum torque) and the drag torque and it outputs the front motor torque	Rear motor outlet cooling temperature	The rear motor cooling temperature is taking as input the stator temperature,the inlet cooling temperature and rear tau parameter and it outputs the rear motor cooling temperature
Rear motor torque	The rear motor power is taking as input the torque (minimum between the required torque and the maximum torque) and the drag torque and it outputs the rear motor torque	Front maximum motor torque	The maximum front motor torque is taking as input the front motor torque, the derate parameter(function of the exthernal front motor temperature) and it outputs the maximum front motor torque
Front motor RPM	The front motor RPM is equal to the transmission front RPM signal	Rear maximum motor torque	The maximum rear motor torque is taking as input the rear motor torque, the derate parameter(function of the exthernal rear motor temperature) and it outputs the maximum rear motor torque
Rear motor RPM	The rear motor RPM is equal to the transmission rear RPM signal	Thermal discharge motor energy	The thermal discharge motor energy is taking as input the total electric power, the total mechanic power and it outputs the thermal discharge motor energy
Front motor efficiency	The front motor efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the net motor power and electrical motor power when the net front power is positive and viceversa when the net front power negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 3D look-up table and it is function of the RPM, the wind temperature and the torque required	Thermal charge motor energy	The thermal charge motor energy is taking as input the total electric power, the total mechanic power and it outputs the thermal charge motor energy
Rear motor efficiency	The rear motor efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the net motor power and electrical motor power when the net rear power is positive and viceversa when the net rear power negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 3D look-up table and it is function of the RPM, the wind temperature and the torque required	Front thermal discharge motor energy	The thermal discharge front motor energy is taking as input the front electric power, the front mechanic power and it outputs the thermal discharge front motor energy
Mechanical front motor power	The mechanical front motor power is taking as input the net front power and the front motor RPM and it outputs the front mechanical motor power	Rear thermal discharge motor energy	The thermal discharge rear motor energy is taking as input the rear electric power, the rear mechanic power and it outputs the thermal discharge rear motor energy

Mechanical rear motor power	The mechanical rear motor power is taking as input the net rear power and the rear motor RPM and it outputs the rear mechanical motor power	Front thermal charge motor energy	The thermal charge front motor energy is taking as input the front electric power, the front mechanic power and it outputs the thermal charge front motor energy
Electric front motor power	The electrical front motor power is taking as input the net front power, the front motor drag power and the front motor thermal power loss and it outputs the electrical front motor power	Rear thermal charge motor energy	The thermal charge rear motor energy is taking as input the rear electric power, the rear mechanic power and it outputs the thermal charge rear motor energy
Electric rear motor power	The electrical rear motor power is taking as input the net rear power, the rear motor drag power and the rear motor thermal power loss and it outputs the electrical rear motor power	Front motor pressure drop	The front motor pressure drop function is taking as input the coolant inlet mass flow, and with a 1D-Lookup table is outputing pressure drop [mbar]
Thermal front motor power loss	The thermal front motor power loss is taking as input the rear motor drag power and the front motor thermal power loss(map) and it outputs the thermal front motor power loss	Rear motor pressure drop	The rear motor pressure drop function is taking as input the coolant inlet mass flow, and with a 1D-Lookup table is outputing pressure drop [mbar]
Thermal rear motor power loss	The thermal rear motor power loss is taking as input the rear motor drag power and the rear motor thermal power loss(map) and it outputs the thermal rear motor power loss		

2.5.3 Transmission model

The e-Mobility is leading to a substantial change in the way manufacturing companies approach transmission design. Where previously six-speed manual or eight-speed automatic transmissions were standard in the automotive industry, state-of-the-art electric vehicles use different types of automatic transmissions, such as two-stage spur gearboxes, integrated pitch planetary gearboxes or continuously variable transmissions (CVT), also known as gearless transmissions, to ensure optimum efficiency.

Electric motors, power electronics and transmissions often share a single housing, reducing the overall number of powertrain components and overall system weight. In battery electric vehicles (BEVs) this integrated device can directly power a combined electric axle drive.

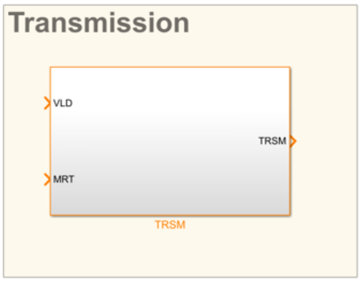
While many principles of operation of electric vehicle transmissions differ from their combustion engine vehicle counterparts, at the component level there are many similarities in the required design and manufacturing processes. Key components such as straight, helical gears and housings are common to both types of drivetrains. The main challenge in making such components for electric vehicle transmissions is managing the higher torque and rotational speed that can be achieved with electric motors. The tolerances involved in precision manufacturing of transmission components such as straight and helical gears or planetary drive systems are typically tighter for electric vehicle components. The surface finish of the gears also acquires new importance, as the noise emission of the transmission is a critical factor in electric vehicles due to the quietness of the electric motor.

The transmission model scope is to give the output torque at wheels, function of the gear ratio and power losses. The gear ratio is a constant value (if a CVT is not implemented), the power losses can be calculated with a function or an efficiency map.

The figure below shows the transmission block.

Input:
- MTR – front required torque [Nm]
- MTR – rear required torque [Nm]
- MTR – front mechanical motor power [W]
- MTR – rear mechanical motor power [W]

- VLD – front wheel RPM [RPM]
- VLD – rear wheel RPM [RPM]



Output:
- The total electric motor power [W]
- The total wheel power [W]
- The total thermal motor power loss [W]
- The transmission power loss [W]
- The TRSM discharge energy losses [kWh]
- The TRSM charge energy losses [kWh]
- The front transmission RPM [RPM]
- The rear transmission RPM [RPM]
- The front wheel RPM [RPM]
- The rear wheel RPM [RPM]
- The front motor torque [Nm]
- The rear motor torque [Nm]
- The front wheel torque [Nm]
- The rear wheel torque [Nm]
- The front efficiency [-]
- The rear efficiency [-]
- The front tau [-]
- The rear tau [-]
- The front TRSM discharge energy losses [kWh]
- The front TRSM charge energy losses [kWh]
- The rear TRSM discharge energy losses [kWh]
- The rear TRSM charge energy losses [kWh]

Figure 18 – The transmission block

The transmission model goal is to give the output torque at wheels, function of the gear ratio and power losses. The gear ratio is a constant value, the power losses can be calculated with a function or an efficiency map. Inside it has two blocks taken from the library called "Gearbox" which identify the front gearbox (s) and the rear gearbox (s).

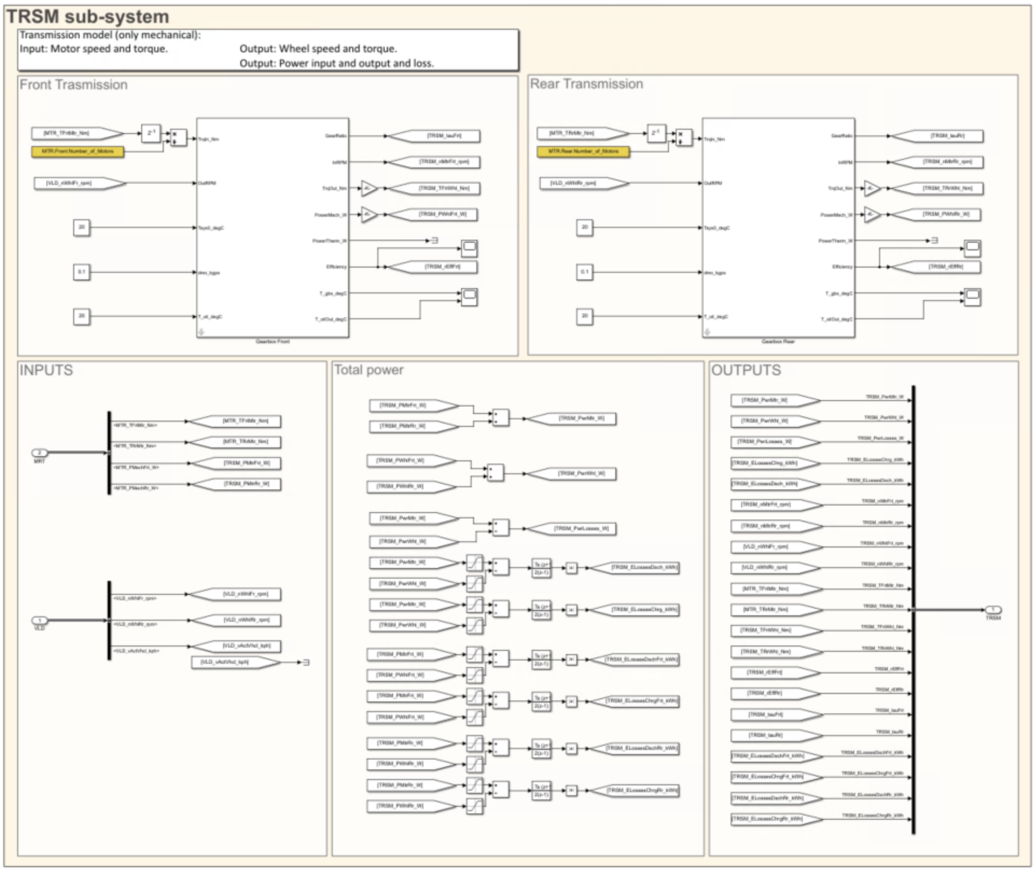


Figure 19 - The electric motor Simulink model overview

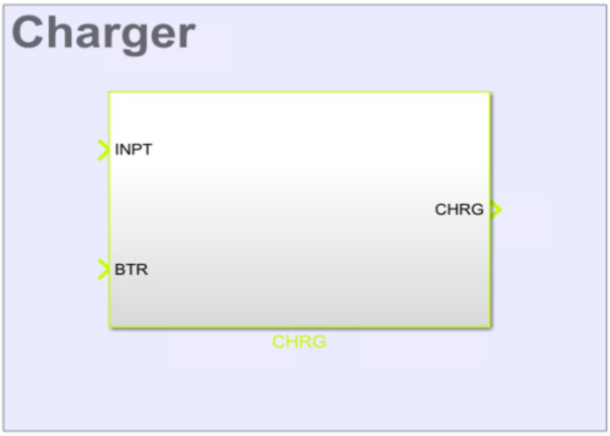
Finally, the main model functions used to model the transmission are listed in the table below.

Table 4 - Transmission model functions description

Model Function	Description	Model Function	Description
Electric motor power	The electric motor power is taking as input the rear and front electric motor power and it outputs the total electric motor power	Front tau	The front tau is chosen in function of the input rpm
total wheel power	Total wheel power is taking as input the rear and front RPMs, the input torque, the loss torque, tau and it outputs the total wheel power	Rear tau	The rear tau is chosen in function of the input rpm
Transmission power loss	The transmission power loss is taking as input the total motor power, the total wheel power and it outputs the transmission power loss	Front discharge transmission energy	The discharge front transmission energy is taking as input the front motor power, the front wheel power and it outputs the discharge front transmission energy
Discharge transmission energy	The discharge transmission energy is taking as input the total electric motor power, the total wheel power and it outputs through an integral function the discharge transmission energy	Rear discharge transmission energy	The discharge rear transmission energy is taking as input the rear motor power, the rear wheel power and it outputs the discharge rear transmission energy
Charge transmission energy	The charge transmission energy is taking as input the total electric motor power, the total wheel power and it outputs through an integral function the charge transmission energy	Front charge transmission energy	The charge front transmission energy is taking as input the front motor power, the front wheel power and it outputs the charge front transmission energy
Front transmission RPM	The front transmission RPM is equal to the wheel front RPM multiplied by tau	Rear charge transmission energy	The charge rear transmission energy is taking as input the rear motor power, the rear wheel power and it outputs the charge rear transmission energy
Rear transmission RPM	The rear transmission RPM is equal to the rear wheel RPM multiplied by tau	R1	The R1 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe R1 [ohm]
Front wheel torque	The front wheel torque is taking as input the front tau, the front torque loss and the input torque and it outputs the front wheel torque	Tau 1	The tau 1 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe tau 1
Rear wheel torque	The rear wheel torque is taking as input the rear tau, the rear torque loss and the input torque and it outputs the rear wheel torque	R2	The R2 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe R2 [ohm]
Front motor efficiency	The front motor efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the net motor power and electrical motor power when the net front power is positive and viceversa when the net front power negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 3D look-up table and it is function of thr RPM, the wind temperature and the torque required	Tau 2	The tau 2 function is taking as input the the SoC, cell temperature and actual cell current with a 3D-Lookup table is outputingThe tau 2
Rear motor efficiency	The rear motor efficiency is calculated in two ways depending on thermal mode variable. 1) When the thermal mode is higher of the value 1 the efficiency is the ratio between the net motor power and electrical motor power when the net rear power is positive and viceversa when the net rear power negative. 2) When the thermal mode is equal to zero the efficiency is calculated through a 3D look-up table and it is function of thr RPM, the wind temperature and the torque required		

2.6 Charger model

The CHRG block consists in a simple efficiency model with an input the charge power and it outputs the charge power to the DC line. The figure below shows the charger block.



Input:
- INPT – Input charged power [W]
- BTR – Battery voltage [V]
- BTR – Max charged power [W]
- BTR - Battery SoC [ptc]

Output:
- Charger power [W]
- Charger current [A]
- Charger port temperature [degC]

Figure 20 - The CHRG block

The figure below shows the Charger Simulink model overview.

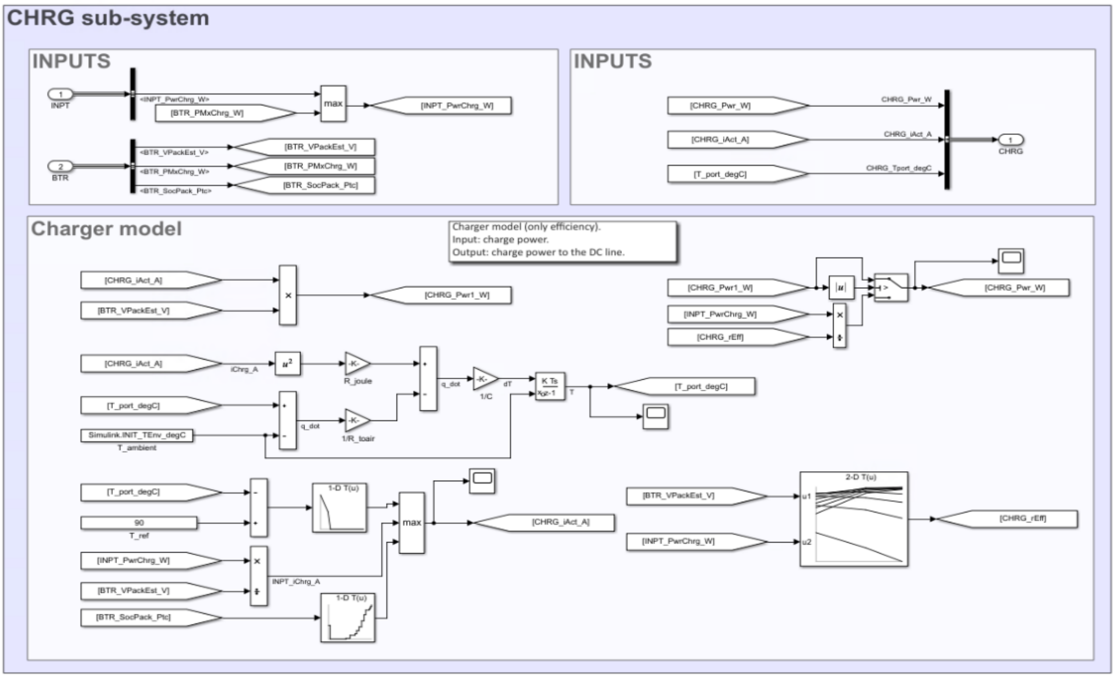


Figure 21 - The CHRG Simulink model overview

Finally, the main model functions used to model the charger are listed in the table below.

Table 5 – CHRG model functions description

Model Function	Description
Charger efficiency	The efficiency function is taking as input the the battery voltage and the input charging power (saved into the speed profile workspace) with a 3D-Lookup table is outputing the efficiency of the charger
Actual charge current	The actual charge current function is taking as input the the port current (function of the different temperature between the limit temperature 90 degC and the port temperature), The input current from the workspace input and the impose current profile with a maximum function (The current has a negative sign) is outputing the actual charge current [A]
Port temperature	The port temperture function is taking as input the actual charge current and the difference btw the port temperature and the initial enviromental temperature with a mathematical function is outputing port temperature [degC]
Actual charge power	The actual charge power function is taking as input the the input charge power and the available charge power with a switch function is outputing the charge power [W]

2.7 DC-DC model

The DC-DC power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as dc motor drives. The input to a dc-dc converter is an unregulated dc voltage Vg. The converter produces a regulated output voltage V, having a magnitude (and possibly polarity) that differs from Vg.

The ideal DC-DC converter exhibits 100% efficiency; in reality, efficiencies of 70% to 95% are typically obtained. This is achieved using switched-mode, or chopper, circuits whose elements dissipate negligible power. Pulse-width modulation (PWM) allows control and regulation of the total output voltage. This approach is also employed in applications involving alternating current, including high-efficiency dc-ac power converters (inverters and power amplifiers), ac-ac power converters, and some ac-dc power converters (low-harmonic rectifiers).

Many DC-DC converter circuits that can increase or decrease the magnitude of the DC voltage and/or invert its polarity are available. The main types of converters will be illustrated below.

The first converter is the buck converter, which reduces the dc voltage and has conversion ratio M(D) = D. The figure below shows a buck converter circuit.

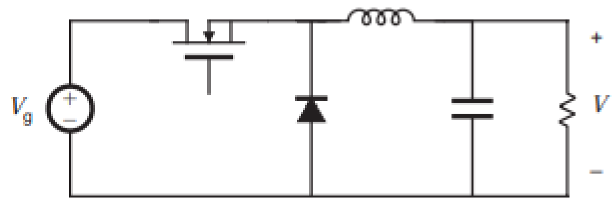


Figure 22 - Buck converter

In a similar topology known as the boost converter, the positions of the switch and inductor are interchanged. This converter produces an output voltage V that is greater in magnitude than the input voltage Vg. Its conversion ratio is $M(D) = \frac{1}{1-D}$. The figure below shows a boost converter circuit.

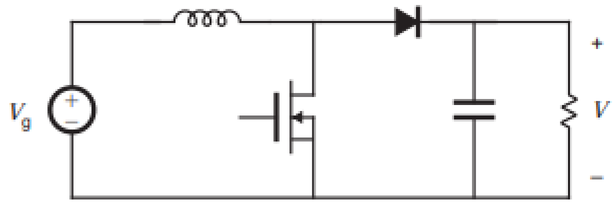


Figure 23 - Boost converter

In the buck-boost converter, the switch alternately connects the inductor across the power input and output voltages. This converter inverts the polarity of the voltage and can either increase or decrease the voltage magnitude. The figure below shows a buck-boost converter circuit.

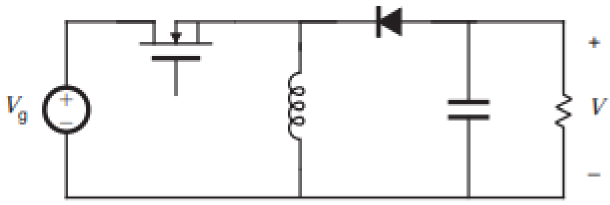
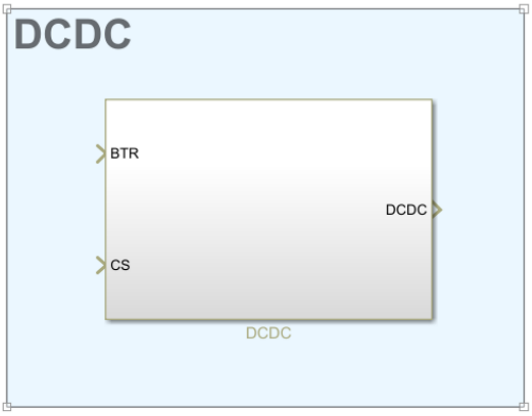


Figure 24 - Buck-boost converter

The DC-DC block consists in a simple efficiency model with an input the aux, EE12V, pumps and fan power consumption and it outputs the DCDC auxiliary power consumption and the DCDC energy consumption to the DC line. The figure below shows the DC-DC block.



Input:
- BTR – Battery voltage [V]
- CS – Fan power [W]
- CS – EDU Pump power [W]
- CS – HVBS pump power [W]

Output:
- Auxiliary DCDC power consumption [W]
- DCDC efficiency [-]
- DCDC EE12V power consumption [W]
- DCDC EE12V energy [kWh]
- DCDC auxiliary energy [kWh]

Figure 25 - The DC-DC block

The figure below shows the DC-DC Simulink model overview.

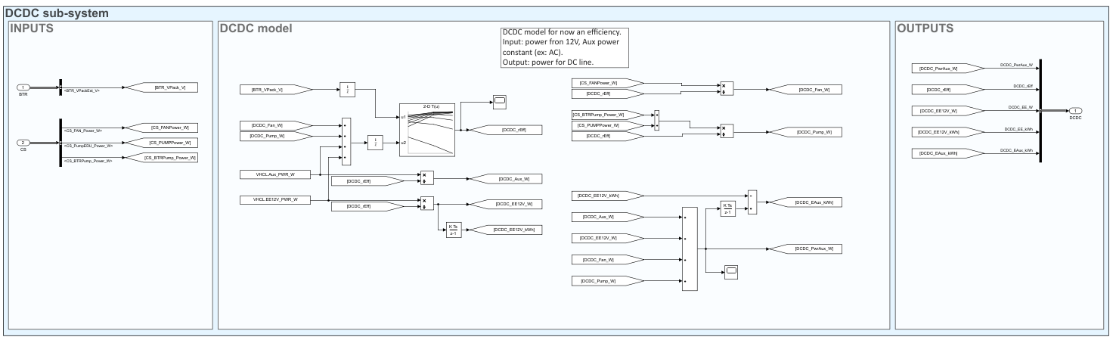


Figure 26 - The DC-DC Simulink model overview

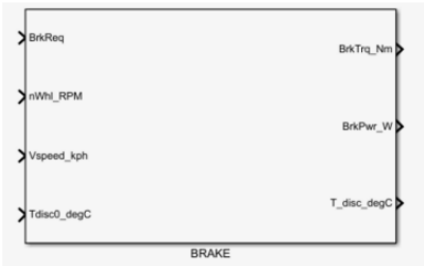
Finally, the main model functions used to model the DC-DC are listed in the table below.

Table 6 – DCDC model functions description

Model Function	Description
Fan power consumption	The fan power function is taking as input the CS\fan power and the DCDC efficiency and it outputs the DCDC fan power [W]
Pump power consumption	The pump power function is taking as input the sum between the HVBS and EDU pumps power and outputs the DCDC pump power [W]
Total auxiliary power consumption	Total auxiliary power consumption is a sum function of the all DCDC power consumptions (EE12V, pumps, fan and aux)
Auxiliary power consumption	The aux power consumption function taking as input the input aux power consumption and the DCDC efficiency and it outputs the auxiliary power consumption at DCDC level
EE12V power consumption	The EE12V power consumption function taking as input the input power consumption and the DCDC efficiency and it outputs the EE12V at DCDC level
EE12V energy	The EE12V energy function taking as input the EE12V power consumption with an integral function outputs the EE12V energy
Auxiliary energy	The auxiliary energy function taking as input the total auxiliary power consumption with an integral function outputs the auxiliary DCDC energy
Efficiency	The DCDC efficiency function taking as input the Battary voltage and the EE12V, pumps, fan and aux power consumptions wit a 2D-look up table outputs the DCDC efficiency

2.8 Brake model

The braking sub-system purpose is to provide the output braking power, function of the braking command from the VCU. Inside it has two blocks taken from the library called “Brake" which identifies the front braking system (s) and the rear braking system. The main variables obtained from this block are the actual front torque, the actual rear torque, the braking power, the braking energy, the front braking temperature, and the rear braking temperature. The figure below shows the brake block.



Input:
- Braking request command [-]
- Wheel RPM [RPM]
- Vehicle speed [kph]
- Initial disc temperature [degC]

Output:
- Braking torque [Nm]
- Braking power [W]
- Disc temperature [degC]

Figure 27 – The brake block

The figure below shows the brake Simulink model overview.

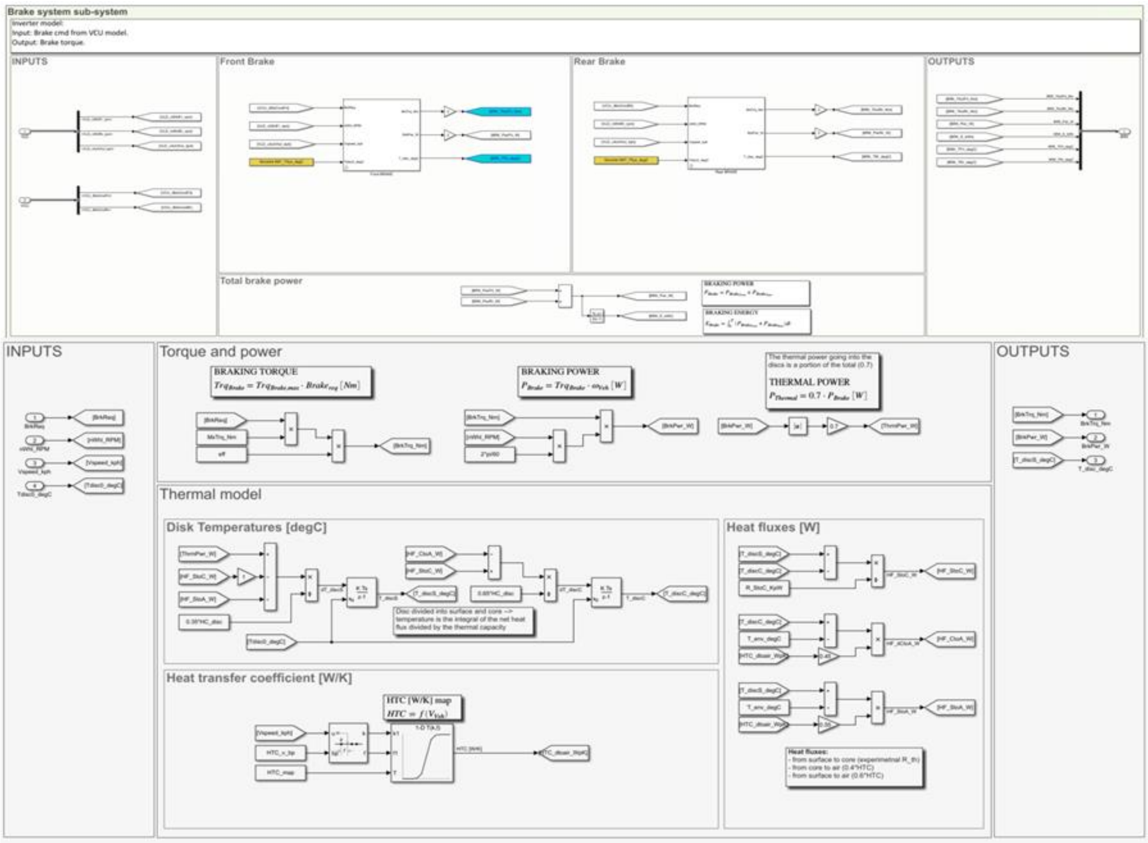


Figure 28 - The DC-DC Simulink model overview

Finally, the main model functions used to model the DC-DC are listed in the table below.

Table 7 – The brake model functions description

Model Function	Description
Front actual braking torque	The front actual braking torque is taking as input the required braking command, the maximum torque, the efficiency and it outputs the front actual braking torque
Rear actual braking torque	The rear actual braking torque is taking as input the required braking command, the maximum torque, the efficiency and it outputs the rear actual braking torque
Braking power	The braking power is taking as input the front braking power, the rear braking power and it outputs the braking power
Braking energy	The braking power is taking as input the front braking power, the rear braking power and it outputs through an integral function the braking energy
Front braking Temperature	The front braking temperature is taking as input the front thermal power, the front surface to core heat fluxes, the front surface to air heat fluxes, the disc thermal capacity and it outputs through an integral function the front braking temperature
Rear braking Temperature	The rear braking temperature is taking as input the rear thermal power, the rear surface to core heat fluxes, the rear surface to air heat fluxes, the rear disc thermal capacity and it outputs through an integral function the rear braking temperature

2.9 Longitudinal dynamics estimator

The longitudinal dynamics estimator is the core model of the performance simulations. In the case of acceleration simulation, the slip losses are not negligible. So, it is important to have a slip model that considers the difference of speed between the tires and the vehicle required to transmit a certain torque. In the case of range simulation, instead, the required torque is well below the tire limits, so the slip losses are negligible (no need of slip model and tires data). Both for acceleration and range performance, a high contribute of the energy required is given by the mass and rotational inertia acceleration of the vehicle: if these parameters are fixed, they need to be accurate. The figure below shows the longitudinal dynamics estimator block.

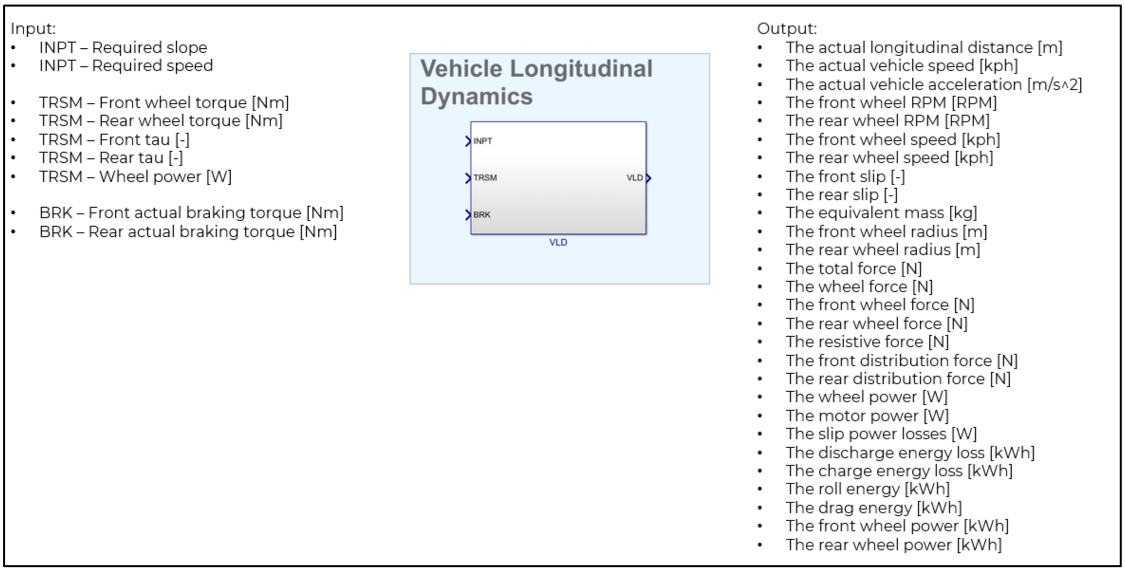


Figure 29 - The longitudinal dynamics estimator block

The main blocks of the longitudinal dynamics model are the wheels (front and rear), the inertia of the driveline and the equations that regulate the movement of the vehicle. The figure below shows the longitudinal dynamics estimator Simulink model overview.

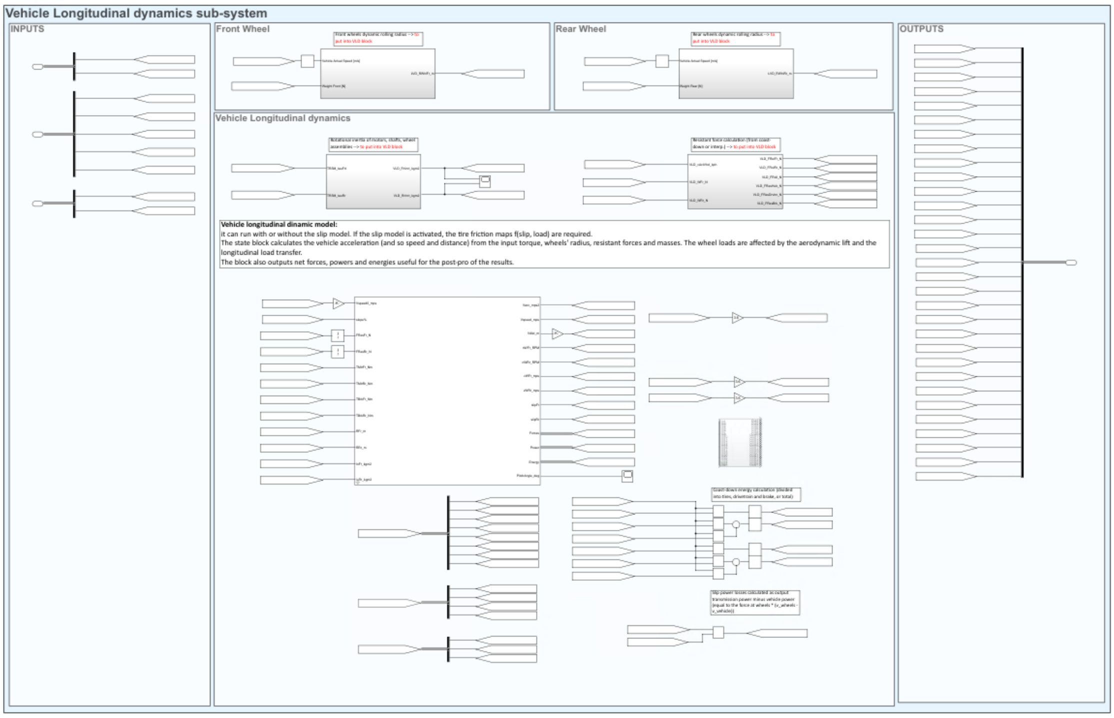


Figure 30 - The longitudinal dynamics estimator model overview

Finally, the main model functions used to model the longitudinal dynamics estimator are listed in the table below.

Table 8 - longitudinal dynamics estimator functions description

Model Function	Description	Model Function	Description
Actual longitudinal distance	slip model: The actual longitudinal distance is taking as input the long. friction coefficients, the wheel forces, the rolling resistive force, the slope force, the tow force, the toe mass and total vehicle mass and through a double integration function, it outputs the actual longitudinal distance. No slip model: The actual longitudinal distance is taking as input the wheel forces, the rolling resistive force and total vehicle mass and through a double integration function, it outputs the actual longitudinal distance	Front wheel force	The front wheel force is taking as input the front wheel torque, the front wheel radius and it outputs the front wheel force.
Actual vehicle speed	slip model: the actual vehicle speed is taking as input the long. friction coefficients, the wheel forces, the rolling resistive force, the slope force, the tow force, the toe mass and total vehicle mass and through an integration function, it outputs the actual vehicle speed. No slip model: the actual vehicle speed is taking as input the wheel forces, the rolling resistive force and total vehicle mass and through an integration function it outputs the actual vehicle speed.	Rear wheel force	The rear wheel force is taking as input the rear wheel torque, the rear wheel radius and it outputs the rear wheel force.
Actual vehicle acceleration	slip model: the actual vehicle acceleration is taking as input the long. friction coefficients, the wheel forces, the rolling resistive force, the slope force, the tow force, the toe mass and total vehicle mass and it outputs the actual vehicle acceleration. No slip model: the actual vehicle acceleration is taking as input the wheel forces, the rolling resistive force and total vehicle mass and it outputs the actual vehicle acceleration.	Total resistive force	The total resistive force is taking as input the front resistive force, the rear resistive force, the drag force, the slope force, the tow force and it outputs the total resistive force.
Front wheel RPM	slip model: the front wheel RPM is taking as input the front wheel inertia, the front torque, the front wheel radius, the long. friction coeff., the vehicle speed and the the front wheel applied force and it outputs through an integrator function the front wheel RPM. No slip model: the front wheel RPM is taking as input the front wheel speed and the front wheel radius and it outputs front wheel RPM.	Front distribution force	The front distribution force is taking as input the front wheel total force, the load distribution of vertical force and the load distribution due the toe angle and it outputs the front distribution force.

Rear wheel RPM	slip model: the rear wheel RPM is taking as input the rear wheel inertia, the rear torque, the rear wheel radius, the long. friction coeff., the vehicle speed and the the rear wheel applied force and it outputs through an integrator function the rear wheel RPM. No slip model: the rear wheel RPM is taking as input the rear wheel speed and the rear wheel radius and it outputs rear wheel RPM.	Rear distribution force	The rear distribution force is taking as input the rear wheel total force, the load distribution of vertical force and the load distribution due the toe angle and it outputs the rear distribution force.
Front wheel speed	slip model: the front wheel speed is taking as input the front wheel inertia, the front torque, the front wheel radius, the long. friction coeff., the vehicle speed and the the front wheel applied force and it outputs through an integrator function the front wheel speed. No slip model: the front wheel speed is taking as input the front wheel speed and the front wheel radius and it outputs front wheel speed.	Wheel power	The wheel power is taking as input the vehicle speed and the wheel force and it outputs the wheel power.
Rear wheel speed	slip model: the rear wheel speed is taking as input the rear wheel inertia, the rear torque, the rear wheel radius, the long. friction coeff., the vehicle speed and the the rear wheel applied force and it outputs through an integrator function the rear wheel speed. No slip model: the rear wheel speed is taking as input the rear wheel speed and the rear wheel radius and it outputs rear wheel speed.	Motor power	The motor power is taking as input the front and rear motor torque and the wheel radius and it outputs the motor power.
Front slip	The front slip is taking as input the vehicle speed and the front wheel speed and it outputs the front slip.	Slip power losses	The slip power losses calculated as output transmission power minus vehicle power (equal to the force at wheels * (v_wheels - v_vehicle))
Rear slip	The rear slip is taking as input the vehicle speed and the rear wheel speed and it outputs the front slip.	Discharge energy loss	The discharge energy loss is taking as input the motor power and it outputs through an integral function (only negative part) the discharge energy loss.
Equivalent mass	The equivalent mass is taking as input the vehicle mass, the front wheel inertia, the rear wheel inertia, the front wheel radius and the rear wheel radius and it outputs (kinetic energy theorem) the equivalent mass.	Charge energy loss	The discharge energy loss is taking as input the motor power and it outputs through an integral function (only positive part) the discharge energy loss.
Front wheel radius	The front wheel radius is taking as input the vehicle speed, the front wheel force and it outputs through the Pacejka formula (same coefficient) the front wheel radius.	Coast down energy	Coast-down energy calculation (divided into tires, drivetrain and brake, or total)

Rear wheel radius	The rear wheel radius is taking as input the vehicle speed, the rear wheel force and it outputs through the Pacejka formula (same coefficient) the rear wheel radius.	Drag energy	The drag energy is taking as input the vehicle speed and drag force and it outputs through an integral function the drag energy.
Total force	The total wheel force is taking as input the wheel force, the resistive force and it outputs the total force.	Front wheel power	The front wheel power is taking as input the vehicle speed and the front wheel force and it outputs the front wheel power.
Wheel force	The wheel force is taking as input the front wheel force, the rear wheel force and it outputs the total wheel force.	Rear wheel power	The rear wheel power is taking as input the vehicle speed and the rear wheel force and it outputs the rear wheel power.

2.10 Thermal management model

The cooling model aims to estimate the input liquid cooling temperature of battery and motors (and inverter if required). The hydraulic dynamics of the system is not required, because the aim of the model is to know the temperature for a given volumetric / mass flow and not to understand how this flow is achieved. Given the input temperature of the radiator, the heat exchanged is calculated. This requires a heat exchange map of the radiator, function of the liquid and air flows (or similar experimental data).

The pump dynamics implementation gives more accuracy in terms of cooling responsiveness. A map of the pump power consumption must be implemented to estimate the battery power request. The thermal management system sub-system is a complex block that includes several components such as the radiator, the EDU pump, the HVBS pump, the thermal models of the motors, the chiller, the high voltage heater, and the thermal model of the battery.

The figure below shows the thermal management system scheme.

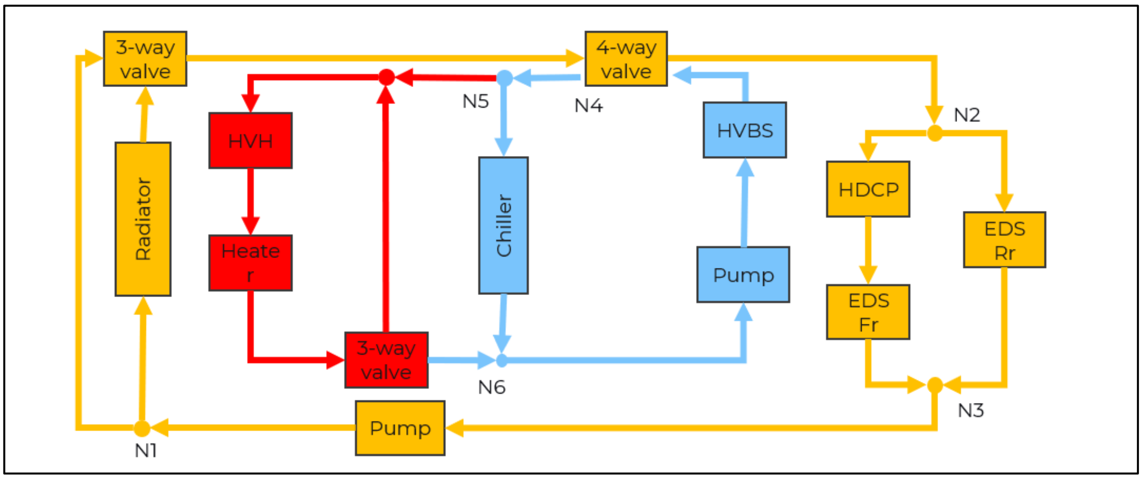


Figure 31 - The thermal management system scheme

The TMS is divided into two macro loops called EDU and HVBS.

The EDU loop is the circuit identified by the yellow colour in the previous figure.

The HVBS loop instead is identified by the colours red and blue respectively they are the heating circuit and the cooling circuit of the HVBS loop.

The two circuits have a single node in common represented by a 4-way valve that allows the entire system to work in two different modes based on the needs of the battery and the surrounding conditions. The figure below shows the longitudinal dynamics estimator Simulink model overview.

The TMS block communicates with the following model blocks:

- The HVBS block provides information on the HVBS coolant outlet temperature, the cells temperature and the coolant pressure drop across the battery ducts
- The MTR block provides information on the front and rear motor, precisely on the output coolant temperature of the motors, the external temperatures, the motor RPMs, and the coolant pressure drops across the motor ducts
- The VLD block provides the vehicle speed
- The INV block provides information on the front and rear output coolant temperature of the inverters
- Simulink provides information about the initial system temperature and the initial environment temperature

The EDU loop mainly consists of seven blocks:

- Radiator
- EDU pump
- HDCP
- EDS Front
- EDS Rear
- 3-way valve
- 4-way valve
- Pressure drops

The connections between the components are characterized in the model as pressure drops of The various connection pipes.

The HVBS loop mainly consists of seven blocks:

- HVBS
- HVBS pump
- Chiller
- HVH
- Heater
- 3-way valve
- Pressure drops

The connections between the components are characterized in the model as pressure drops of the various connection pipes.

Finally, the main model functions used to model the thermal management system are listed in the table below.

Table 9 The thermal management system functions description

Model Function	Description	Model Function	Description
Actual cooling pressure	The cooling pressure is a function present in each block, the real calculation is inside the pump block that takes as input the initial pressure (1 bar) and througth the pump head the pressure increase, indeed for the other components we take into account the pressure drop of the component	Pressure drop	The pressure drop function is present for each component of the circuit and is based on a 1D lookup table which outputs the pressure drop as a function of the mass flow that passes through the component.
Actual cooling temperature	The cooling temperature is a function present in each block and takes as input the inlet temperature, the heat rejection (if present), the specific coolant heat and as output the outlet cooling temperature	EDU pump power consumption	The EDU pump power function is based on a 2D lookup table which outputs the power consumption as a function of the mass flow and the RPM.
Actual cooling mass flow	The cooling mass flow is a function present in each block, the real calculation is inside the pump block that takes as input the pressure drop of the system, the coolant mass flow end the tune parameter and outputs the coolant mass flow inside the pump block. The mass flow pass througth all the blocks and finally we need to have the continuity of the mass flow.	Fan power consumption	The fan power function is based on a 1D lookup table which outputs the power consumption as a function of the fan RPM.
RAD enable	The radiator enable is taking as input the outlet coolant radiator temperature and it outputs througth a relè (25 degC) the radiator enable	HVBS pump power consumption	The HVBS pump power function is based on a 2D lookup table which outputs the power consumption as a function of the mass flow and the HVBS pump RPM.
EDU pump control	The EDU pump control is taking as input the components temperatures (front INV, rear INV, front MTR, rear MTR, cell HVBS) and it outputs througth a 1D lookup table and a max function the EDU pump RPM	Chiller heat rejected	The chiller heat rejected is based on a 2D lookup table which outputs theheating power derating as a function of the mass flow and the inlet chilller temperature.
EDU pump control	The HVBS pump control is taking as input the cell HVBS temperature and it outputs througth a 1D lookup table the HVBS pump RPM	Chiller power consumption	The chiller power consumption taking as inputs the HR and the COP coefficient and it outputs the CHLR power consumption.
HVH enable	The high voltage heater control is taking as input the cell HVBS temperature and it outputs througth a 1D lookup table the HVH control command	Radiator heat rejected	The radiator heat rejected taking as inputs the air temperature, the coolant temperature, the frontal radiator area, the normalized radiator heat rejected and it outputs the raddiator heat rejected.
CHLR enable	he chiller enable is actived when tThe EDU and HVBS loops work togheter, The radiator is disabled and the coolant HVBS temperature is higher of *40°C or when the HVBS loop works in isolaton mode and the coolant HVBS temperature is higher of *40°C	HVH power consumption	The chiller heat rejected taking as inputs the HP and the HVH efficiency and it outputs the HVH power consumption.
HVBS isolation	The four way valve (valve that joins the EDU loop with the HVBS loop) control, takes as input the temperature difference between the battery and the system, the battery temperature and the radiator enable and through logical operators is capable of opening and closing the valve	Air mass flow	The air mass flow is a function present in the radiator block and takes as input the vehicle speed, the pressure variations due to the presence of the condenser and the fan, the air pressure, the air density and as output there air mass flow

2.11 Vehicle Control Unit

The Vehicle Control Unit gives the logic of action of the vehicle. A base VCU must be implemented to ensure the functioning of the model (torque request, torque limitations, cooling liquid flow, etc.). More accurate controls are required to simulate different study cases. The figure below shows the Vehicle Control Unit block.

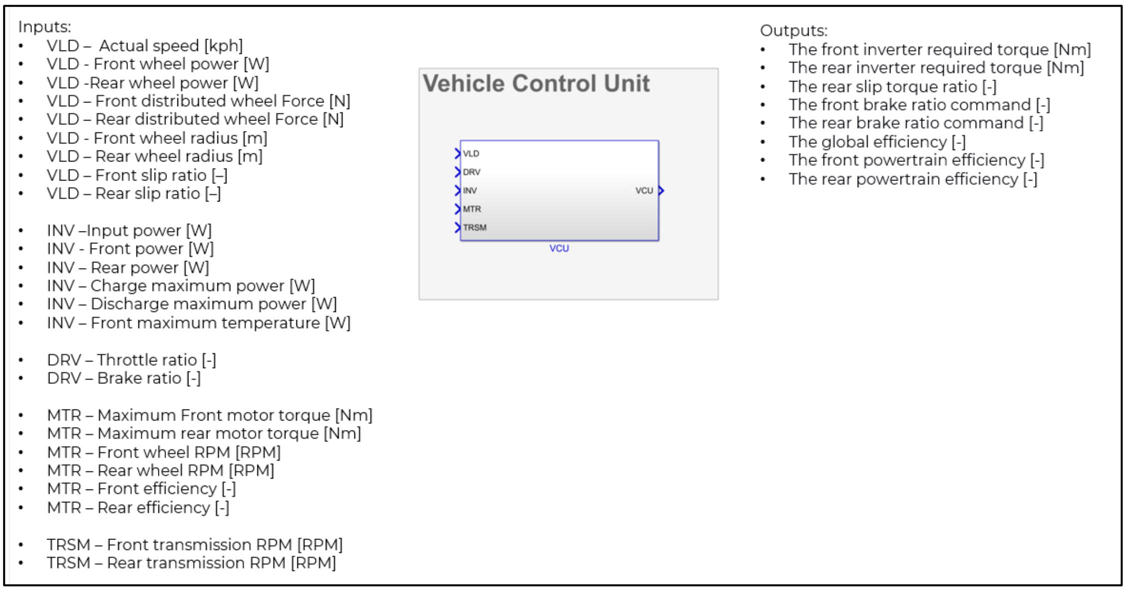


Figure 32 - The Vehicle Control Unit block

The vehicle control unit block is a device that simulates the operation of control unit on the electric vehicle. The main variables obtained from vehicle control unit block are the inverter required torque, the slip torque ratio, the brake ratio command, the global efficiency, and the powertrain efficiency. The figure below shows the vehicle control unit Simulink model overview.

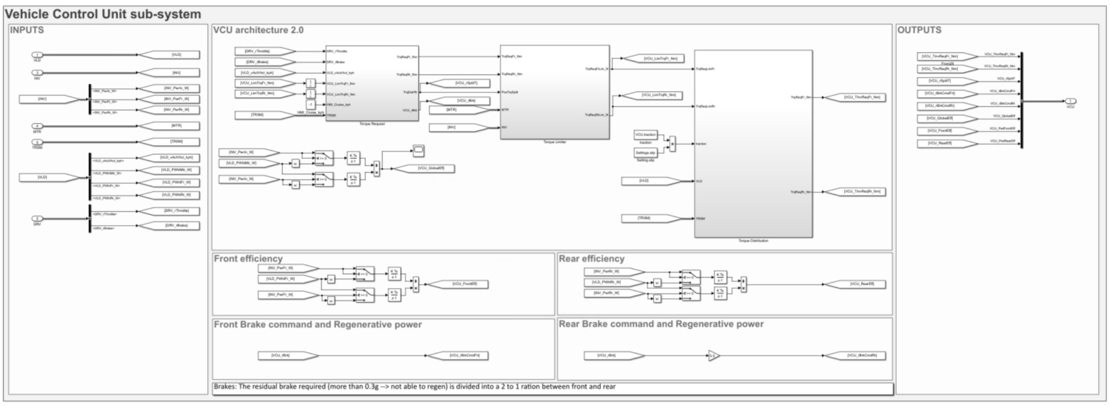


Figure 33 - The vehicle control unit model overview

Finally, the main model functions used to model the vehicle control unit are listed in the table below.

Table 10 – The vehicle control unit functions description

Model Function	Description
Front inverter required torque	The front inverter required torque function taking as input the front slip, the front tau, the front wheel radius, the front long. Friction coefficient, the front weight distribution, the number of the motors, the front maximum torque and througth several mathematical formulas it outputs the front inverter required torque
Rear inverter required torque	The rear inverter required torque function taking as input the rear slip, the rear tau, the rear wheel radius, the rear long. Friction coefficient, the rear weight distribution, the number of the motors, the rear maximum torque and througth several mathematical formulas it outputs the rear inverter required torque
Front regenerated brake ratio command	The front regenerated brake ratio function taking as input the actual speed, the driver brake ratio and it outputs the front regenerated brake ratio
Rear regeneratedbrake ratio command	The rear regenerated brake ratio function taking as input the actual speed, the driver brake ratio and it outputs the front regenerated brake ratio
Global efficiency	The global efficiency function taking as input the inverter power, the wheel power and it outputs the global powertrain efficiency
Front powertrain efficiency	The front efficiency function taking as input the front inverter power, the front wheel power and it outputs the front efficiency
Rear powertrain efficiency	The rear efficiency function taking as input the rear inverter power, the rear wheel power and it outputs the rear efficiency

3 Target setting Tool

Target setting tool is an app developed in MATLAB with the aim of making the most of the potential of the Simulink model to provide customers with adequate engineering advice for the choice of vehicle architecture based on the various customer needs.

The tool provides complete support starting from the choice of architecture to the creation of a vehicle model based on the parameters provided by the customer, to the optimization of the powertrain and other characterizing parameters to improve the performance and range of a vehicle.

The application has been developed in a modular way to unlock the various phases of the procedure for choosing the vehicle architecture.

The complete procedure is divided into the following stages:

- Targets definition
- Priority definition
- Architecture definition
- Vehicle definition
- Vehicle optimization
- Test and vehicle validation

In the following chapters we will deal with all the phases and the various logics and strategies used at the base of each of them. The following figure shows the application user interface.

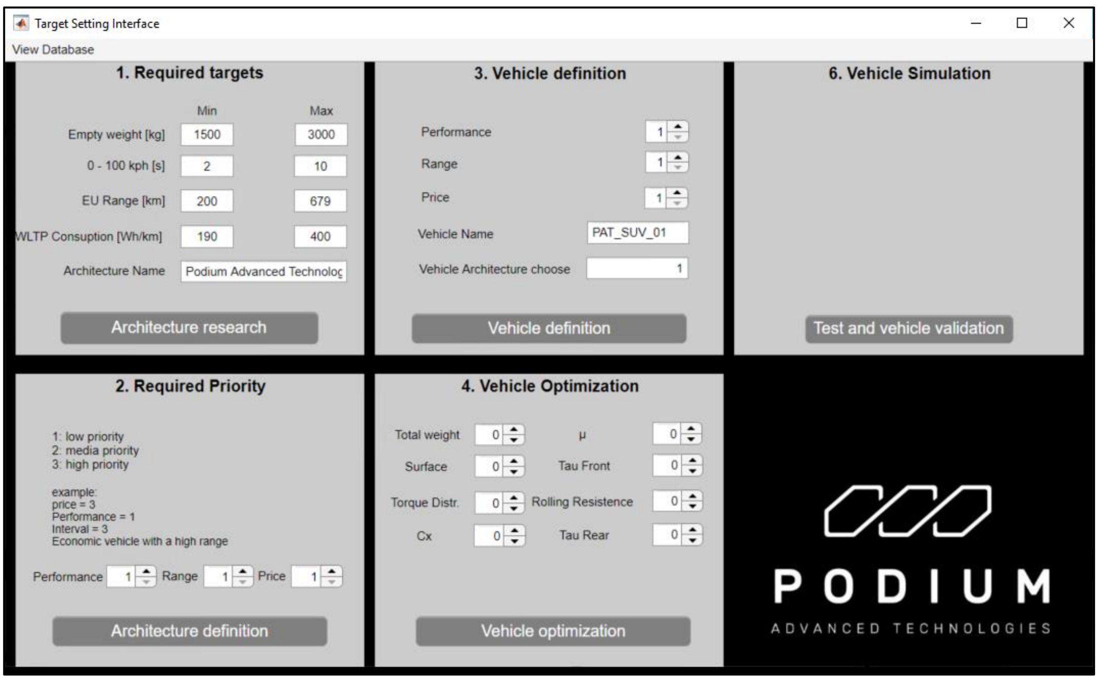


Figure 34 - Target setting interface

From the figure above you can see the various areas of the interface that will allow the user to use the tool without the need to have IT skills.

3.1 Targets definition

Targets definition is the first phase of the procedure for choosing a vehicle architecture, The starting point is the definition of the targets of the vehicle that the client wants to design, to do this a panel has been created for the definition of the starting parameters. the figure below shows the panel for the definition of the starting targets.

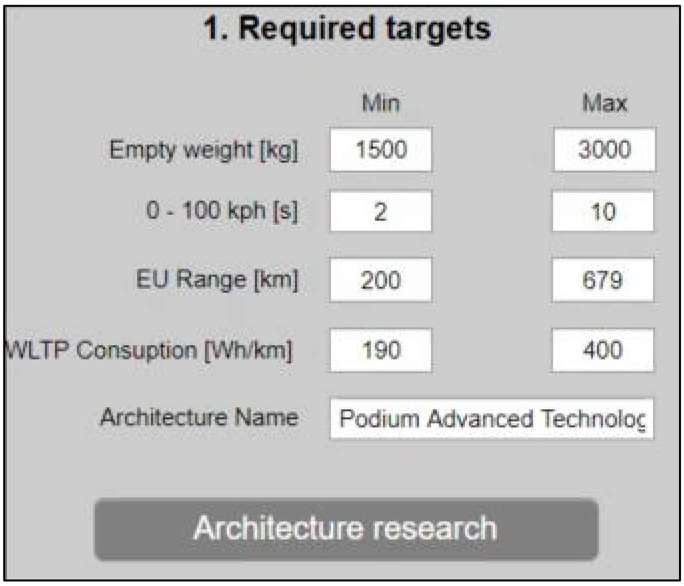


Figure 35 - Starting target panel

The user who will use the tool can easily fill in the various fields with the desired values, once the various fields have been filled in, a name will be chosen that will be assigned to an excel file that will save in a structured way all the user's choices and the various results obtained.

Once the Architecture research button has been pressed, the app will create the file in which it will automatically enter all the architectures, present in a dedicated database (described in 3.1.1), which match the targets previously entered.

The app will also create a table that will be visible to the user in which there will be all the architectures that match the chosen and selected targets.

The figure below shows an example of a table that is created after selecting the targets.

Architecture_Podium Advanced Technology_23-Oct-2022_18-23

Parameters	1	2	3	4	5	6	7	8	9
HVBS	1	1	1	1	1	1	1	1	1
VHCL	1	1	1	1	1	1	1	2	2
AERO	1	1	1	1	1	1	1	2	2
WHL_Front	1	1	1	1	1	1	1	2	2
WHL_Rear	1	1	1	1	1	1	1	2	2
TRSM_Front	1	1	1	2	2	2	2	1	1
MTR_Front	1	1	1	2	2	2	2	1	1
INV_Front	0	0	0	0	0	0	0	0	0
MTR_Rear	2	2	2	2	2	2	2	2	2
TRSM_Rear	2	2	2	2	2	2	2	2	2
INV_Rear	0	0	0	0	0	0	0	0	0
Num_MTR_...	1	2	2	1	1	2	2	1	1
Num_MTR_...	1	1	2	1	2	1	2	1	2
UBE [Wh]	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04	4.6049e+04
Curb weight...	2.0553e+03	2.0553e+03	2.0553e+03	2.1108e+03	2.1108e+03	2.1108e+03	2.1108e+03	2.3993e+03	2.3993e+03
S [m2]	2.4400	2.4400	2.4400	2.4400	2.4400	2.4400	2.4400	2.8000	2.8000
Cx [-]	0.2300	0.2300	0.2300	0.2300	0.2300	0.2300	0.2300	0.2800	0.2800
Rollling radi...	0.2899	0.2899	0.2899	0.2899	0.2899	0.2899	0.2899	0.3903	0.3903
Rollling radi...	0.2898	0.2898	0.2898	0.2898	0.2898	0.2898	0.2898	0.3902	0.3902
Tire rolling r...	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000
Tire rolling r...	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000	8.4000
Tire μ front [-]	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500
Tire μ rear [-]	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500	1.1500
Aux. Cons. ...	300	300	300	300	300	300	300	300	300
Front Tau1	9.1900	9.1900	9.1900	13.6450	13.6450	13.6450	13.6450	9.1900	9.1900
Rear Tau1	13.6450	13.6450	13.6450	13.6450	13.6450	13.6450	13.6450	13.6450	13.6450
Front.RollR...	0.2899	0.2899	0.2899	0.2899	0.2899	0.2899	0.2899	0.3903	0.3903
Rear.RollRa...	0.2898	0.2898	0.2898	0.2898	0.2898	0.2898	0.2898	0.3902	0.3902
1foot rollout...	0.2700	0.2720	0.2700	0.2790	0.2780	0.2730	0.2790	0.2710	0.2720
0 - 60mph [s]	3.1980	3.6140	3.1980	3.4090	3.2930	3.7970	3.4090	3.5040	3.4150
0 - 60mph ...	2.9280	3.3420	2.9280	3.1300	3.0150	3.5240	3.1300	3.2330	3.1430
0 - 100 kph [s]	3.3670	3.8020	3.3670	3.5860	3.4700	3.9760	3.5860	3.6990	3.6080

Figure 36 - Architecture table

As can be seen from the previous figure, the table is divided into three different sections:

1. Components IDs
2. Main parameters (UBE, Cx, etc.)
3. Performance and range results

All architectures were simulated in the database creation phase.

3.1.1 Architecture database

The architecture database is composed of 865 diversified architectures based on the various components of the power train.

The following table lists show the main components with the main characterizing parameters on which the architectures have been developed.

Table 11 - Main parameters of Architecture components

HVBS		
Battery cell type	Configuration	Battery energy [kWh]
Molicel	162p20s	53
Molicel	170s32p	88
Molicel	188s36p	110
Molicel	192s40p	124
LG	154s20p	53
LG	170s30p	88
LG	186s34p	110
LG	188s38p	124

Vehicle			
ID	NePT Mass [kg]	Wheelbase [mm]	CG_height [m]
Sedan	1300	3100	0.5
SUV	1644	5151	0.55
Sport	1200	4430	0.45

Motor		
ID	Max Torque [Nm]	Power [kW]
1	360	280
2	600	465
3	505	350

Aerodynamic		
ID	Frontal Area [m^2]	Cx [-]
Sedan	2.44	0.23
SUV	2.8	0.28
Sport	2.2	0.33

Transmission		
ID	Max Torque [Nm]	Max RPM
1	360	17000
2	600	14000
3	500	20000

Wheel	
ID	Wheel code
Sedan	195/45R16
SUV	275/50R20
Sport	225/45R18

In the previous table it can be seen how the various parameters have been chosen to have a wide choice and variability.

All simulations in the database are based on the components described in the previous table.

The database has been organized in status, with the term status all the simulations performed are grouped to obtain information about the performance and the range of the architectures.

All the statuses present in the database have been estimated through the use of the Simulink model created specifically for the app, the following table shows the database structure.

Table 12 - Database structure

Simulation Code	1111111011011	...	3222233011012	...	8111133011012
HVBS code	1	...	3	...	8
VHCL code	1	...	2	...	1
AERO code	1	...	2	...	1
Front WHL code	1	...	2	...	1
Rear WHL code	1	...	2	...	1
Front TRSM code	1	...	3	...	3
Front MTR code	1	...	3	...	3
Front INV code	0	...	0	...	0
Rear MTR code	1	...	1	...	1
Rear TRSM code	1	...	1	...	1
Rear INV code	0	...	0	...	0
# of front MTR	1	...	1	...	1
# of rear MTR	1	...	2	...	2
UBE [kWh]	46	...	96	...	116
Curb weight [kg]	2000	...	2759	...	2457
frontal surface [m2]	2.44	...	2.8	...	2.44
Cx [-]	0.230	...	0.280	...	0.230
Front rollling radius [m]	0.290	...	0.390	...	0.290
Rear rollling radius [m]	0.290	...	0.390	...	0.290
Front tire rolling resistance [kg/ton]	8.4	...	8.4	...	8.4
Rear tire rolling resistance [kg/ton]	8.4	...	8.4	...	8.4
Front tire friction coefficient [-]	1.15	...	1.15	...	1.15
Rear tire friction coefficient [-]	1.15	...	1.15	...	1.15
Aux. Cons. [W]	300	...	300	...	300
Front gear ratio [-]	9.2	...	8.4	...	8.4
Rear gear ratio [-]	9.2	...	9.2	...	9.2
1foot rollout [s]	0.290	...	0.324	...	0.309
0 - 60mph [s]	3.5	...	4.9	...	4.4
0 - 60mph w/o 1 foot [s]	3.2	...	4.6	...	4.0
0 - 100 kph [s]	3.7	...	5.1	...	4.5
0 - 100 kph w/o 1 foot [s]	3.4	...	4.7	...	4.2
0 - 200 kph [s]	11.6	...	12.7	...	11.2
0 - 200 kph w/o 1 foot [s]	11.3	...	12.3	...	10.9
1/4 miles [s]	11.6	...	12.6	...	12.0
1/4 miles w/o 1 foot [s]	11.3	...	12.3	...	11.7
1/4 miles exit speed [kph]	201	...	200	...	209
EU Range (WLTC_3b DS2) [km]	283	...	494	...	682
WLTP Cons. (WLTC_3b DS2) [Wh/km]	163	...	195	...	170
Powertrain system efficiency in WLTP	87%	...	90%	...	90%
Torque Distribution in WLTP (front)	0.5	...	0.3	...	0.3
Maximum speed [kph]	266	...	278	...	279
CS range @150kph [km]	164	...	277	...	411

The database is divided into three parts, starting from the top:

- ID components (grey)
- Main parameters (green)
- Performance and range results (yellow)

The speed profiles that identify the type of simulation carried out to define the status in this phase of the procedure are the following:

- Constant speed @ 150 kph – used to define the range at constant speed
- WLTC – used to estimate the range and consumption of the architecture
- WOT @ 300 kph – used to estimate vehicle performance
- WOT @ 400 kph – It is used to define the maximum speed of the vehicle as an initial approximation

The decision to use a database for the choice of architecture was made as all components are based on real tests and in addition the database will evolve as more types of components are added.

3.2 Priority definition

The priority definition is the second phase of the procedure for choosing a vehicle architecture, The starting point is the definition of the priorities of the architecture that the client wants to design, to do this a panel has been created for the definition of the performance and the range priority. the figure below shows the panel for the definition of the priorities.

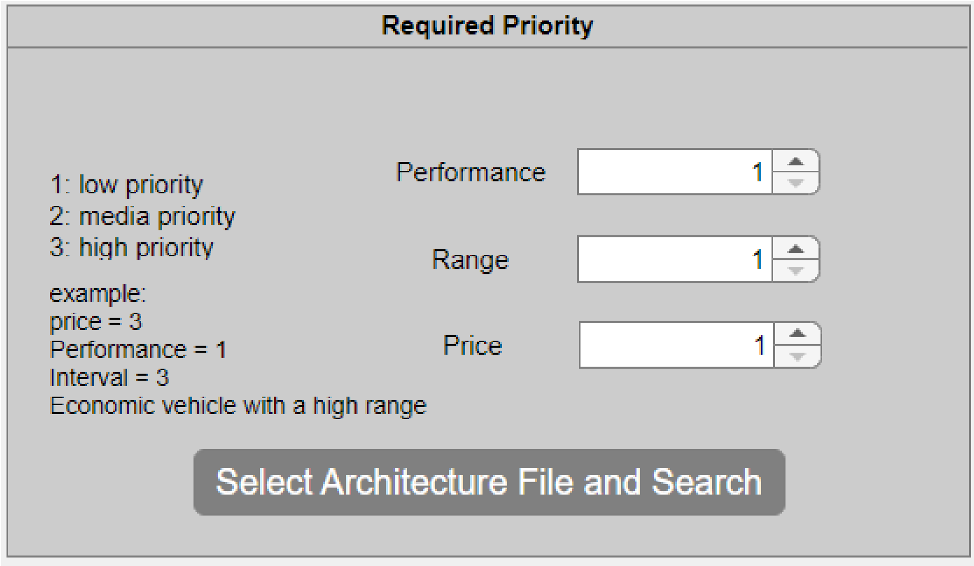


Figure 37 – Required priority panel

The user who will use the tool can easily fill in the various fields with the desired value of priority (from 1 to 3).

Once the priorities have been chosen and the button is pressed, the software will generate a file containing all the architectures that can be used by the customer to reach their targets through a cost function and a clustering of the architectures.

The methodology used to choose the architecture will be illustrated in the following sub-chapter.

3.2.1 Architecture cluster

The architectures present in the database have been included in a cluster based on the three main variables for choosing the architecture listed below:

- Range: the variable taken into consideration is the range of the architecture for the WLTC cycle.
- Performance: the variable taken into consideration is the time taken to reach 100 kph starting from a standstill considering the one foot.
- Cost: the cost of the main components of the architecture.

The cluster scheme is shown in the figure below.

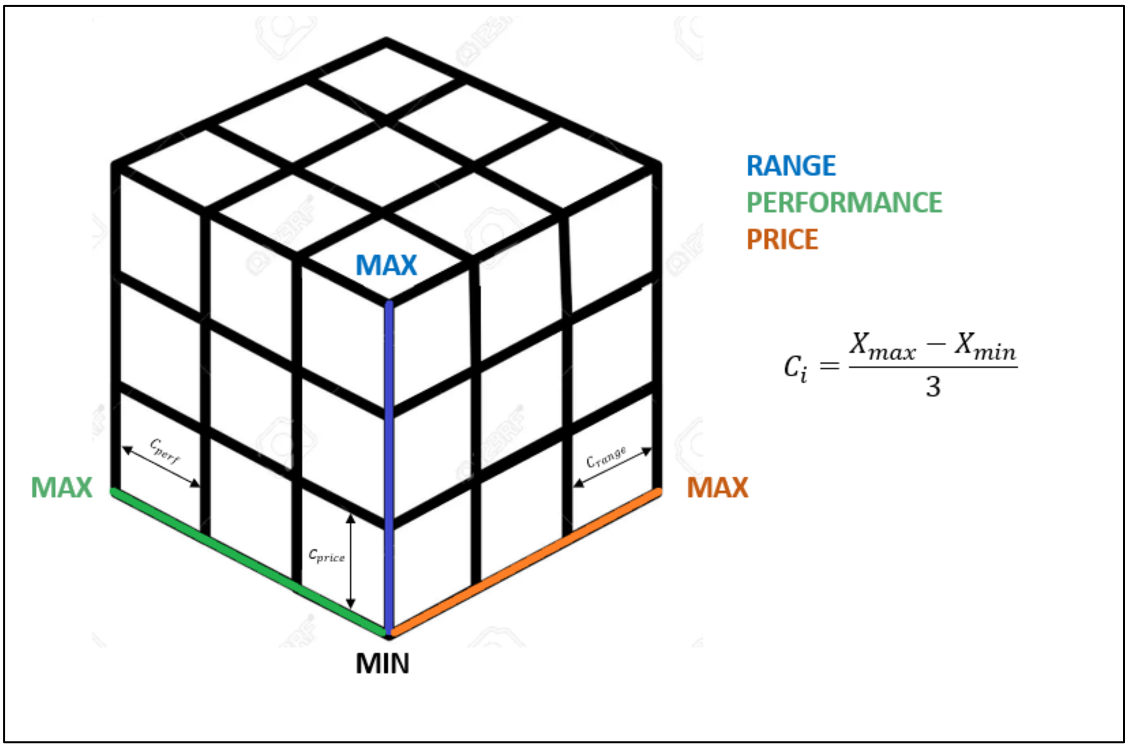


Figure 38 - Cluster scheme

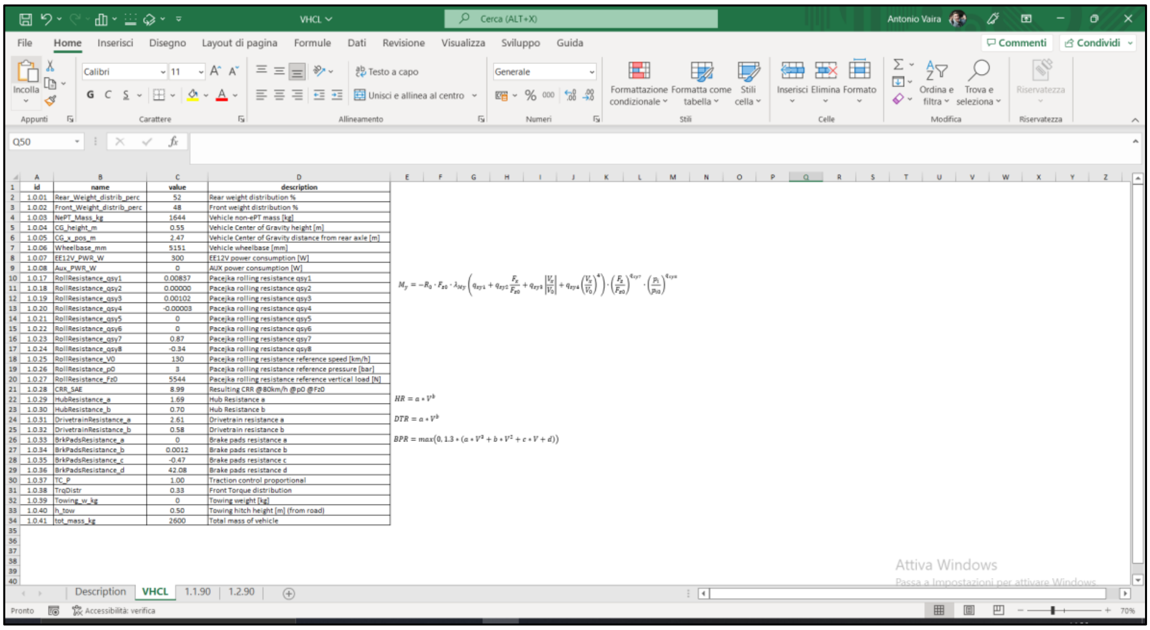
The dimensions of the cluster depend on the simulations inserted in the database and in this first version of the project each dimension (performance, range, and cost) is divided into three equal parts.

Once the database has been clustered, through the user's choice of the architecture priorities, the app will automatically eliminate all the architecture clusters that do not have the appropriate characteristics for the customer. This operation is developed through linear interpolations of the clusters.

3.3 From database architecture to vehicle of interest

Once the architecture has been selected, the software automatically generates a folder containing several excel files containing all the parameters of the architecture components and various maps that will then be loaded into the lookup tables of the Simulink model.

The figure below shows an example of the excel files generated once the basic architecture has been chosen.



id	name	value	description
1.0.01	Rear_Weight_distrib_perc	52	Rear weight distribution %
1.0.02	Front_Weight_distrib_perc	48	Front weight distribution %
1.0.03	NePT_Mass_kg	1644	Vehicle non-ePT mass [kg]
1.0.04	CG_height_m	0.55	Vehicle Center of Gravity height [m]
1.0.05	CG_x_pos_m	2.47	Vehicle Center of Gravity distance from rear axle [m]
1.0.06	Wheelbase_mm	5151	Vehicle wheelbase [mm]
1.0.07	EE12V_PWR_W	300	EE12V power consumption [W]
1.0.08	Aux_PWR_W	0	AUX power consumption [W]
1.0.17	RollResistance_qsy1	0.00837	Pacejka rolling resistance qsy1
1.0.18	RollResistance_qsy2	0.00000	Pacejka rolling resistance qsy2
1.0.19	RollResistance_qsy3	0.00102	Pacejka rolling resistance qsy3
1.0.20	RollResistance_qsy4	-0.00003	Pacejka rolling resistance qsy4
1.0.21	RollResistance_qsy5	0	Pacejka rolling resistance qsy5
1.0.22	RollResistance_qsy6	0	Pacejka rolling resistance qsy6
1.0.23	RollResistance_qsy7	0.87	Pacejka rolling resistance qsy7
1.0.24	RollResistance_qsy8	-0.34	Pacejka rolling resistance qsy8
1.0.25	RollResistance_V0	130	Pacejka rolling resistance reference speed [km/h]
1.0.26	RollResistance_p0	3	Pacejka rolling resistance reference pressure [bar]
1.0.27	RollResistance_Fz0	5544	Pacejka rolling resistance reference vertical load [N]
1.0.28	CRR_SAE	8.99	Resulting CRR @80km/h @p0 @Fz0
1.0.29	HubResistance_a	1.69	Hub Resistance a
1.0.30	HubResistance_b	0.70	Hub Resistance b
1.0.31	DrivetrainResistance_a	2.61	Drivetrain resistance a
1.0.32	DrivetrainResistance_b	0.58	Drivetrain resistance b
1.0.33	BrkPadsResistance_a	0	Brake pads resistance a
1.0.34	BrkPadsResistance_b	0.0012	Brake pads resistance b
1.0.35	BrkPadsResistance_c	-0.47	Brake pads resistance c
1.0.36	BrkPadsResistance_d	42.08	Brake pads resistance d
1.0.37	TC_P	1.00	Traction control proportional
1.0.38	TrqDistr	0.33	Front Torque distribution
1.0.39	Towing_w_kg	0	Towing weight [kg]
1.0.40	h_tow	0.50	Towing hitch height [m] (from road)
1.0.41	tot_mass_kg	2600	Total mass of vehicle

$$M_y = -R_0 \cdot F_{z0} \cdot \lambda_{My} \left(q_{sy1} + q_{sy2} \frac{F_x}{F_{z0}} + q_{sy3} \left| \frac{V_x}{V_0} \right| + q_{sy4} \left(\frac{V_x}{V_0} \right)^4 \right) \cdot \left(\frac{F_z}{F_{z0}} \right)^{q_{sy7}} \cdot \left(\frac{p_i}{p_{i0}} \right)^{q_{sy8}}$$

$$HR = a * V^b$$

$$DTR = a * V^b$$

$$BPR = max(0, 1.3 * (a * V^3 + b * V^2 + c * V + d))$$

Figure 39 - Vehicle parameters example

The choice of creating different excel files for the various vehicle components was made to simplify the customization of the vehicle according to the customer's needs.

In this phase of the procedure the vehicle model is created which in the next phase will be optimized, tested, and validated until it reflects the expected targets.

3.4 Sensitivity analysis

The core process of the target setting procedure is given by the sensitivity analyses. These analyses aim to inspect the effect of a certain parameter's change on the performance of the vehicle. It is important to understand, before proceeding, which parameters are fixed, and which are design ones and so parameters to analyse.

Note that the fixed parameters must be as precise as possible, to avoid irrelevant results.

Follows the list of design parameters (not to be considered binding):

- Vehicle total mass
- Tires friction coefficient
- Aerodynamics parameters (Cx, Cl, front surface)
- Gear ratios (front & rear)
- Inverter efficiency
- Battery capacity
- Torque distribution
- Gear ratios
- Battery configuration

As for the parameters, a list of simulations to evaluate performance is defined:

- WOT 0 – 300kph: output 0 – 100kph, 0 – 200kph, 0 – 400m times
- Drivability 40 – 70 kph: output time
- Drivability 60 – 130 kph: output time
- Drivability 80 – 150 kph: output time
- Drivability 100 – 230 kph: output time
- Constant speed @ 150 kph: output range
- WLTP: output cycle consumption and range
- WOT 0 - 400kph: output maximum vehicle speed
- Gradeability mission: avoid derating
- AC and DC charge: output 5 – 85% time

From now on, when we talk about all the simulations referring to an architecture, the term status will be used.

For this analysis, three different architectures were chosen (a sedan, an SUV, and a sport car). The following table illustrates the status of the three baseline architectures.

Table 13 - Architectures for sensitivity analysis

Simulation Code	1111111011011	5222211011021	8333333022012
Class	Sedan	SUV	Sport
Battery code	1	5	8
Vehicle parameters code	1	2	3
Aerodynamic code	1	2	3
Front wheel code	1	2	3
Rear wheel code	1	2	3
Front transmission code	1	1	3
Front motor code	1	1	3
Front inverter code	0	0	0
Rear motor code	1	1	2
Rear transmission code	1	1	2
Rear inverter code	0	0	0
Number of front motors	1	2	1
Number of front motors	1	1	2
UBE [kW]	46	50	116
Number of series	20	20	38
Number of parallel	162	154	188
Curb weight [kg]	2000	2326	2412
Front surface [m2]	2.44	2.80	2.20
Cx [-]	0.230	0.280	0.330
Front rollling radius [m]	0.290	0.390	0.329
Rear rollling radius [m]	0.290	0.390	0.329
Front and rear tire rolling resistance [kg/ton]	8.4	8.4	8.4
Tire μ [-]	1.15	1.15	1.15
Auxiliary Consumption [W]	300	300	300
Front gear ratio	9.19	9.19	8.40
Rear gear ratio	9.19	9.19	13.65
One foot rollout [s]	0.290	0.312	0.269
0 - 60mph [s]	3.5	4.6	2.7
0 - 60mph w/o 1 foot [s]	3.2	4.2	2.5
0 - 100 kph [s]	3.7	4.8	2.8
0 - 100 kph w/o 1 foot [s]	3.4	4.5	2.6
0 - 200 kph [s]	11.6	17.3	7.4
0 - 200 kph w/o 1 foot [s]	11.3	17.0	7.2
1/4 miles [s]	11.6	13.1	10.1
1/4 miles w/o 1 foot [s]	11.3	12.8	9.9
1/4 miles exit speed [kph]	201	177	237
EU Range (WLTC_3b DS2) [km]	283	266	564
WLTP Cons. (WLTC_3b DS2) [Wh/km]	163	188	206
Powertrain system efficiency in WLTP	87%	88%	84%
Torque Distribution in WLTP	0.50	0.67	0.33
Maximum speed [kph]	266	262	277
Range @150kph [km]	164	145	360

In order to obtain reliable results, it was decided to carry out a univariate analysis by independently varying each variable value in an appropriate range. To do this, ten simulations were carried out to generate each status and to obtain a detailed analysis seven statuses were generated for each parameter variation. In total 2100 simulations were carried out.

The first sensitivity results show how the test results vary as a function of the parameter variation. This type of result shows how the various tests are influenced by the parameters entered in the vehicle components. The following tables show the averaged results between the three vehicle architectures.

Table 14 - Frontal area behaviour

Variable \ Fr. area var.	5%	3%	2%	-2%	-3%	-5%	Trend
Vehicle max speed (60s) [kph]	-0.17%	-0.11%	-0.06%	0.06%	0.12%	0.17%	
0 - 60 kph w/o 1 foot [s]	0.04%	0.01%	0.01%	-0.01%	-0.02%	-0.02%	
0 - 100 kph w/o 1 foot [s]	0.04%	0.02%	0.00%	-0.02%	-0.03%	-0.03%	
0 - 200 kph w/o 1 foot [s]	0.43%	0.28%	0.14%	-0.14%	-0.28%	-0.42%	
1/4 miles w/o 1 foot [s]	0.06%	0.04%	0.02%	-0.02%	-0.04%	-0.06%	
80-120 kph [s]	0.00%	0.00%	0.00%	0.00%	-0.17%	-0.31%	
100-140kph [s]	0.36%	0.25%	0.25%	0.00%	0.00%	-0.11%	
100-200 kph [s]	0.56%	0.43%	0.16%	-0.20%	-0.40%	-0.56%	
Constant speed range @150kph [km]	-2.86%	-1.92%	-0.97%	0.99%	2.00%	3.04%	
EU Range (WLTC_3b DS2) [km]	-1.51%	-1.01%	-0.51%	0.52%	1.04%	1.56%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	1.54%	1.02%	0.51%	-0.51%	-1.02%	-1.54%	
Powertrain system efficiency in WLTP [%]	0.04%	0.03%	0.02%	-0.02%	-0.04%	-0.06%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	0.01%	0.00%	0.00%	0.00%	0.00%	-0.01%	
Min Voltage during HP Discharge [V]	-0.01%	-0.01%	0.00%	0.00%	0.01%	0.01%	
Max Mech P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	

From the summary table of the variation of the frontal area, the constant speed range @ 150 kph, the consumption in the WLTC cycle and the range in the same cycle are sensitive to the variation of the frontal area.

Table 15 - Cx behaviour

Variable \ Cx var.	5%	3%	2%	-2%	-3%	-5%	Trend
Vehicle max speed (60s) [kph]	-0.17%	-0.11%	-0.06%	0.06%	0.12%	0.17%	
0 - 60 kph w/o 1 foot [s]	0.04%	0.01%	0.01%	-0.01%	-0.02%	-0.02%	
0 - 100 kph w/o 1 foot [s]	0.04%	0.02%	0.00%	-0.02%	-0.03%	-0.03%	
0 - 200 kph w/o 1 foot [s]	0.43%	0.28%	0.14%	-0.14%	-0.28%	-0.42%	
1/4 miles w/o 1 foot [s]	0.06%	0.04%	0.02%	-0.02%	-0.04%	-0.06%	
80-120 kph [s]	0.00%	0.00%	0.00%	0.00%	-0.17%	-0.31%	
100-140kph [s]	0.36%	0.25%	0.25%	0.00%	0.00%	-0.11%	
100-200 kph [s]	0.56%	0.43%	0.16%	-0.20%	-0.40%	-0.56%	
Constant speed range @150kph [km]	-2.86%	-1.92%	-0.97%	1.00%	2.00%	3.04%	
EU Range (WLTC_3b DS2) [km]	-1.51%	-1.01%	-0.51%	0.52%	1.04%	1.56%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	1.54%	1.02%	0.51%	-0.52%	-1.02%	-1.54%	
Powertrain system efficiency in WLTP [%]	0.04%	0.03%	0.02%	-0.02%	-0.04%	-0.06%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	0.01%	0.00%	0.00%	0.00%	0.00%	-0.01%	
Min Voltage during HP Discharge [V]	-0.01%	-0.01%	0.00%	0.00%	0.01%	0.01%	
Max Mech P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	

From the summary table of the variation of the Cx, the constant speed range @ 150 kph, the consumption in the WLTC cycle and the range in the same cycle are sensitive to the variation of the aerodynamic coefficient.

Table 16 - Rolling resistance behaviour

Variable \ Rolling resist. var.	10%	7%	3%	-3%	-7%	-10%	Trend
Vehicle max speed (60s) [kph]	-0.06%	-0.04%	-0.02%	0.02%	0.04%	0.06%	
0 - 60 kph w/o 1 foot [s]	0.09%	0.05%	0.03%	-0.03%	-0.05%	-0.09%	
0 - 100 kph w/o 1 foot [s]	0.09%	0.06%	0.02%	-0.02%	-0.05%	-0.10%	
0 - 200 kph w/o 1 foot [s]	0.23%	0.15%	0.08%	-0.07%	-0.15%	-0.22%	
1/4 miles w/o 1 foot [s]	0.05%	0.03%	0.02%	-0.02%	-0.03%	-0.05%	
80-120 kph [s]	0.00%	0.00%	0.00%	-0.12%	-0.30%	-0.30%	
100-140kph [s]	0.24%	0.24%	0.24%	0.00%	-0.09%	-0.09%	
100-200 kph [s]	0.31%	0.15%	0.09%	-0.09%	-0.19%	-0.35%	
Constant speed range @150kph [km]	-1.77%	-1.19%	-0.60%	0.61%	1.23%	1.85%	
EU Range (WLTC_3b DS2) [km]	-2.85%	-1.92%	-0.97%	0.99%	2.00%	3.03%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	2.94%	1.96%	0.98%	-0.98%	-1.96%	-2.94%	
Powertrain system efficiency in WLTP [%]	0.07%	0.05%	0.03%	-0.04%	-0.07%	-0.11%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Min Voltage during HP Discharge [V]	-0.01%	-0.01%	0.00%	0.00%	0.01%	0.01%	
Max Mech P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	

From the summary table of the variation of the rolling resistance, the constant speed range @ 150 kph, the consumption in the WLTC cycle and the range in the same cycle are sensitive to the variation of the rolling resistance.

Table 17 - Torque distribution behaviour

Variable \ Trq distr. var.	10%	7%	3%	-3%	-7%	-10%	Trend
Vehicle max speed (60s) [kph]	0.37%	0.30%	0.19%	-0.21%	-0.43%	-0.65%	
0 - 60 kph w/o 1 foot [s]	-3.81%	-2.75%	-1.46%	1.53%	3.09%	4.69%	
0 - 100 kph w/o 1 foot [s]	-3.77%	-2.72%	-1.44%	1.52%	3.06%	4.66%	
0 - 200 kph w/o 1 foot [s]	-3.21%	-2.31%	-1.30%	1.40%	2.85%	4.37%	
1/4 miles w/o 1 foot [s]	-1.29%	-0.92%	-0.49%	0.52%	1.05%	1.59%	
80-120 kph [s]	-3.12%	-2.17%	-1.08%	1.36%	2.85%	3.94%	
100-140kph [s]	-3.30%	-2.30%	-1.21%	1.09%	2.52%	3.95%	
100-200 kph [s]	-3.11%	-2.29%	-1.34%	1.35%	2.86%	4.37%	
Constant speed range @150kph [km]	-0.08%	-0.05%	-0.03%	0.04%	0.08%	0.13%	
EU Range (WLTC_3b DS2) [km]	-0.06%	-0.04%	-0.02%	0.02%	0.05%	0.08%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	0.06%	0.04%	0.02%	-0.02%	-0.05%	-0.08%	
Powertrain system efficiency in WLTP [%]	-0.03%	-0.02%	-0.01%	0.01%	0.03%	0.02%	
Max HVBS P (3s / 35°C) [kW]	9.90%	6.88%	3.01%	-3.01%	-6.88%	-9.90%	
Max HVBS I (3s / 35°C) [A]	3.68%	2.45%	1.22%	-1.23%	-2.46%	-3.69%	
Min Voltage during HP Discharge [V]	-0.35%	-0.24%	-0.14%	0.17%	0.35%	0.54%	
Max Mech P (3s / 35°C) [kW]	2.87%	2.05%	1.04%	-1.07%	-2.16%	-3.27%	

From the summary table of the variation of the torque distribution, the performance test results are sensitive to the variation of the torque distribution.

Table 18 - weight behaviour

Variable \ Weight var.	5%	3%	2%	-2%	-3%	-5%	Trend
Vehicle max speed (60s) [kph]	-0.06%	-0.03%	-0.01%	0.01%	0.02%	0.02%	
0 - 60 kph w/o 1 foot [s]	4.88%	2.97%	1.58%	-1.54%	-2.71%	-3.59%	
0 - 100 kph w/o 1 foot [s]	5.07%	2.97%	1.60%	-1.47%	-2.65%	-3.81%	
0 - 200 kph w/o 1 foot [s]	4.93%	3.21%	1.61%	-1.56%	-3.09%	-4.44%	
1/4 miles w/o 1 foot [s]	2.01%	1.29%	0.66%	-0.63%	-1.20%	-1.65%	
80-120 kph [s]	4.96%	1.15%	0.00%	-1.15%	-2.74%	-2.74%	
100-140kph [s]	4.20%	2.23%	0.00%	-0.90%	-3.14%	-5.10%	
100-200 kph [s]	4.64%	2.58%	1.64%	-2.32%	-3.96%	-4.89%	
Constant speed range @150kph [km]	-0.78%	-0.52%	-0.26%	0.27%	0.53%	0.80%	
EU Range (WLTC_3b DS2) [km]	-1.60%	-1.07%	-0.54%	0.54%	0.62%	1.17%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	1.63%	1.08%	0.54%	-0.54%	-0.61%	-1.15%	
Powertrain system efficiency in WLTP [%]	0.27%	0.18%	0.09%	-0.09%	-0.41%	-0.33%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	0.05%	0.04%	0.02%	-0.02%	-0.04%	-0.06%	
Min Voltage during HP Discharge [V]	-0.08%	-0.05%	-0.02%	0.03%	0.05%	0.07%	
Max Mech P (3s / 35°C) [kW]	0.04%	0.02%	0.01%	-0.01%	-0.03%	-0.04%	

By observing the summary table of the vehicle weight, it is clear that the variation in the mass affects the range tests, even if only minimally. Furthermore, it can be seen that the performance results vary significantly as the mass varies.

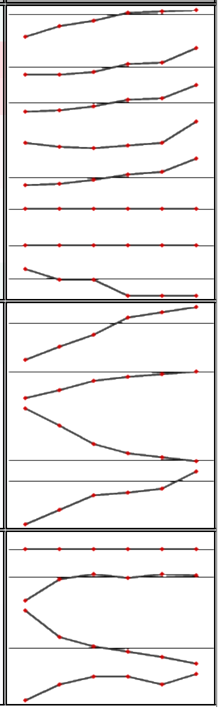
Table 19 - Front gear ratio behaviour

Variable \ Fr. gear ratio var.	10%	7%	3%	-2%	-3%	-5%	Trend
Vehicle max speed (60s) [kph]	-4.68%	-2.47%	-1.36%	0.53%	0.87%	1.10%	
0 - 60 kph w/o 1 foot [s]	-0.74%	-1.12%	-0.44%	0.85%	1.85%	3.14%	
0 - 100 kph w/o 1 foot [s]	-0.71%	-0.92%	-0.27%	1.00%	2.00%	3.07%	
0 - 200 kph w/o 1 foot [s]	0.61%	0.29%	0.25%	0.25%	0.47%	0.73%	
1/4 miles w/o 1 foot [s]	-0.13%	-0.19%	-0.05%	0.24%	0.52%	0.81%	
80-120 kph [s]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
100-140kph [s]	0.00%	0.00%	0.00%	-0.90%	-0.90%	-0.90%	
100-200 kph [s]	0.52%	0.26%	0.00%	-0.68%	-0.68%	-0.93%	
Constant speed range @150kph [km]	-0.75%	-0.49%	-0.23%	0.11%	0.23%	0.35%	
EU Range (WLTC_3b DS2) [km]	-0.03%	0.02%	0.04%	-0.04%	-0.09%	-0.14%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	0.03%	-0.02%	-0.04%	0.04%	0.09%	0.14%	
Powertrain system efficiency in WLTP [%]	-0.15%	-0.09%	-0.04%	0.02%	0.04%	0.23%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	-0.83%	-0.63%	-0.30%	0.12%	0.20%	0.25%	
Min Voltage during HP Discharge [V]	0.07%	0.04%	0.02%	-0.02%	-0.05%	-0.08%	
Max Mech P (3s / 35°C) [kW]	-0.46%	-0.31%	-0.17%	0.08%	0.16%	0.23%	

Observing the summary table of the front gear ratio it is clear that the parameters that varies significantly with the variation of the gear ratio are the maximum speed reached by the vehicle, the 0 – 60 kph test result and the 0 – 100 kph test result.

Table 20 - Rear gear ratio behaviour

Variable \ Rr. gear ratio var.	10%	7%	3%	-2%	-3%	-5%	Trend
Vehicle max speed (60s) [kph]	-4.07%	-2.17%	-1.15%	0.34%	0.64%	0.83%	
0 - 60 kph w/o 1 foot [s]	-1.03%	-0.95%	-0.65%	0.37%	0.50%	2.49%	
0 - 100 kph w/o 1 foot [s]	-0.93%	-0.85%	-0.36%	0.35%	0.54%	2.04%	
0 - 200 kph w/o 1 foot [s]	0.15%	0.06%	0.05%	0.08%	0.14%	0.59%	
1/4 miles w/o 1 foot [s]	-0.22%	-0.19%	-0.07%	0.10%	0.17%	0.54%	
80-120 kph [s]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
100-140kph [s]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
100-200 kph [s]	0.42%	0.00%	0.00%	-0.68%	-0.68%	-0.68%	
Constant speed range @150kph [km]	-0.61%	-0.40%	-0.19%	0.09%	0.18%	0.27%	
EU Range (WLTC_3b DS2) [km]	-1.59%	-1.05%	-0.51%	-0.21%	-0.07%	0.04%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	1.62%	1.06%	0.52%	0.22%	0.07%	-0.04%	
Powertrain system efficiency in WLTP [%]	-0.52%	-0.34%	-0.16%	-0.13%	-0.09%	0.12%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	-0.06%	-0.01%	0.01%	0.00%	0.01%	0.01%	
Min Voltage during HP Discharge [V]	0.02%	0.00%	0.00%	0.00%	0.00%	-0.01%	
Max Mech P (3s / 35°C) [kW]	-0.06%	-0.03%	-0.01%	-0.01%	-0.02%	0.00%	



Observing the summary table of the rear gear ratio it is clear that the parameters that varies significantly with the variation of the gear ratio are the maximum speed reached by the vehicle, the 0 – 60 kph test result, the 0 – 100 kph test result, the EU range and the WLTP consumption.

Table 21 - Number of series of the battery configuration variation

Variable \ Series conf. Var.	2%	1%	1%	-1%	-1%	-2%	Trend
Vehicle max speed (60s) [kph]	0.04%	0.03%	0.01%	-0.02%	-0.04%	-0.08%	
0 - 60 kph w/o 1 foot [s]	-0.50%	-0.15%	-0.09%	0.00%	0.06%	0.22%	
0 - 100 kph w/o 1 foot [s]	-0.39%	-0.27%	0.00%	0.06%	0.21%	0.21%	
0 - 200 kph w/o 1 foot [s]	-1.44%	-0.98%	-0.51%	0.54%	1.10%	1.64%	
1/4 miles w/o 1 foot [s]	-0.30%	-0.22%	-0.11%	0.11%	0.27%	0.38%	
80-120 kph [s]	-1.15%	0.00%	0.00%	0.00%	0.00%	1.15%	
100-140kph [s]	-0.90%	-0.90%	-0.90%	0.00%	0.00%	1.33%	
100-200 kph [s]	-1.87%	-1.61%	-0.93%	0.26%	0.93%	1.61%	
Constant speed range @150kph [km]	1.77%	1.18%	0.59%	-0.59%	-1.18%	-1.77%	
EU Range (WLTC_3b DS2) [km]	1.77%	1.18%	0.59%	-0.59%	-1.18%	-1.77%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	0.03%	0.02%	0.01%	-0.01%	-0.02%	-0.03%	
Powertrain system efficiency in WLTP [%]	-0.01%	-0.01%	0.00%	0.00%	0.01%	0.19%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	0.06%	0.05%	0.02%	-0.03%	-0.05%	-0.09%	
Min Voltage during HP Discharge [V]	1.86%	1.25%	0.63%	-0.63%	-1.25%	-1.88%	
Max Mech P (3s / 35°C) [kW]	1.52%	1.00%	0.50%	-0.62%	-1.31%	-1.97%	

Observing the summary table of the battery configuration serial number, we observe, as expected, a variation in the results both in the performance tests and in the performance range and obviously the minimum HVBS voltage during the discharge and the HVBS mechanical power varies.

Table 22 - Number of parallel of the battery configuration variation

Variable \ Parallels conf. Var.	15%	10%	5%	-5%	-10%	-15%	Trend
Vehicle max speed (60s) [kph]	0.03%	0.02%	0.02%	-0.25%	-0.83%	-1.57%	
0 - 60 kph w/o 1 foot [s]	-1.47%	-1.06%	-0.91%	0.57%	1.46%	2.54%	
0 - 100 kph w/o 1 foot [s]	-1.72%	-1.10%	-0.87%	1.02%	1.92%	3.11%	
0 - 200 kph w/o 1 foot [s]	-3.84%	-2.78%	-1.52%	2.03%	4.75%	7.99%	
1/4 miles w/o 1 foot [s]	-0.94%	-0.70%	-0.41%	0.55%	1.15%	1.84%	
80-120 kph [s]	-5.47%	-2.74%	-2.74%	2.74%	5.47%	7.06%	
100-140kph [s]	-5.37%	-3.14%	-2.23%	2.23%	5.80%	8.04%	
100-200 kph [s]	-5.32%	-4.28%	-2.83%	2.28%	6.63%	10.68%	
Constant speed range @150kph [km]	12.63%	8.42%	4.21%	-4.21%	-8.42%	-12.63%	
EU Range (WLTC_3b DS2) [km]	12.63%	8.42%	4.21%	-4.21%	-8.42%	-12.67%	
WLTP Consumption (WLTC_3b DS2) [Wh/km]	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	
Powertrain system efficiency in WLTP [%]	0.00%	0.00%	0.00%	-0.05%	-0.71%	-0.91%	
Max HVBS P (3s / 35°C) [kW]	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
Max HVBS I (3s / 35°C) [A]	5.30%	3.81%	2.11%	-2.68%	-5.39%	-8.22%	
Min Voltage during HP Discharge [V]	1.20%	0.83%	0.43%	-0.48%	-0.96%	-1.33%	
Max Mech P (3s / 35°C) [kW]	5.25%	3.75%	2.08%	-2.76%	-5.58%	-8.43%	

Observing the summary table of the battery configuration parallel number, we observe, as expected, a variation in the results both in the performance tests and in the performance range and obviously the maximum HVBS current and the HVBS mechanical power varies.

The sensitivity results make us understand how the vehicle responds to the variation of some fundamental parameters, for a better understanding of the results, a summary table is provided below which highlights the parameters that most influence the range and performance of the vehicle.

Table 23 - Summary trend table

Test \ Variable	Frontal surface	Cx	Rolling resistance	Torque distribution	Weight	Front gear ratio	Rear gear ratio	Series configuration	Parallel configuration
Vehicle max speed (60s) [kph]									
0 - 60 kph w/o 1 foot [s]									
0 - 100 kph w/o 1 foot [s]									
0 - 200 kph w/o 1 foot [s]									
1/4 miles w/o 1 foot [s]									
80-120 kph [s]									
100-140kph [s]									
100-200 kph [s]									
Constant speed range @150kph [km]									
EU Range (WLTC_3b DS2) [km]									
WLTP Consumption (WLTC_3b DS2) [Wh/km]									
Powertrain system efficiency in WLTP [%]									
Max HVBS P (3s / 35°C) [kW]									
Max HVBS I (3s / 35°C) [A]									
Min Voltage during HP Discharge [V]									
Max Mech P (3s / 35°C) [kW]									

As can be seen from the summary table, we have a clear view on how the parameters taken into consideration affect the performance of the vehicle.

The representation of the effects of parameter’s change on the performance must be intuitive and quick to read, hence a matrix is chosen. The sensitivity value is defined as follow:

$$\text{sensitivity} = \frac{\text{performance}_{\text{var},\%}}{\text{parameter}_{\text{var},\%}}$$

The resulting matrix is shown in the following table.

Table 24 - Summary indicator table

Test \ Variable	Frontal surface	Cx	Rolling resistance	Torque distribution	Weight	Front gear ratio	Rear gear ratio	Series configuration	Parallel configuration
Vehicle max speed (60s) [kph]	0.03	0.03	0.01	0.05	0.01	0.34	0.27	0.03	0.04
0 - 60 kph w/o 1 foot [s]	0.01	0.01	0.01	0.42	0.88	0.34	0.22	0.12	0.14
0 - 100 kph w/o 1 foot [s]	0.01	0.01	0.01	0.42	0.88	0.35	0.18	0.13	0.17
0 - 200 kph w/o 1 foot [s]	0.08	0.08	0.02	0.38	0.94	0.04	0.03	0.84	0.38
1/4 miles w/o 1 foot [s]	0.01	0.01	0.01	0.14	0.38	0.09	0.05	0.18	0.09
80-120 kph [s]	0.02	0.02	0.02	0.35	0.57	0.00	0.00	0.21	0.46
100-140kph [s]	0.05	0.05	0.03	0.34	0.67	0.17	0.00	0.57	0.45
100-200 kph [s]	0.12	0.12	0.03	0.37	1.04	0.15	0.13	0.98	0.53
Constant speed range @150kph [km]	0.59	0.59	0.18	0.01	0.16	0.07	0.06	0.95	0.84
EU Range (WLTC_3b DS2) [km]	0.31	0.31	0.29	0.01	0.29	0.01	0.06	0.96	0.84
WLTP Consumption (WLTC_3b DS2) [Wh/km]	0.31	0.31	0.29	0.01	0.29	0.01	0.06	0.02	0.00
Powertrain system efficiency in WLTP [%]	0.01	0.01	0.01	0.00	0.07	0.02	0.01	0.02	0.02
Max HVBS P (3s / 35°C) [kW]	0.00	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00
Max HVBS I (3s / 35°C) [A]	0.00	0.00	0.00	0.36	0.01	0.07	0.00	0.04	0.46
Min Voltage during HP Discharge [V]	0.00	0.00	0.00	0.04	0.02	0.01	0.00	1.01	0.09
Max Mech P (3s / 35°C) [kW]	0.00	0.00	0.00	0.30	0.01	0.05	0.00	0.93	0.47

This matrix gives a clear idea of which parameters are more efficient to work with, but it must be noted that the influence of a parameter on the others is neglected. For example, changing the configuration of the battery pack by modifying the number of modules in parallel will consequently vary the weight of the battery pack and therefore of the vehicle.

Taking this aspect into consideration, it is always advisable to perform one optimization at a time to analyse the effects of the variation on the other parameters.

Note that the only sensitivity is not enough to choose an action strategy, because some parameters have strong constraints (not known at the start of the process). So, from the sensitivity analysis, the output is a series of action strategies. These strategies must take in account the priority target of the vehicle. If the most important target to achieve is a range of 500km, the parameters to work with are the ones with high sensitivity on the range [km] and low sensitivity on the acceleration times [s]. Note that a strategy can be the mix of two or more strategies based on a single parameter's change.

Due to the high quantity of performance and vehicle target to set, the solution is not unique. The expectation is to get a high number of combinations of vehicle settings which give a set of performance (still not fixed). The process is highly variable and, so, its description requires a list of assumption to eventually confirm during the process itself. Given the starting inputs and a set of simulations to ensure the plausibility of these assumptions, a performance setting is performed. If the performance targets are not defined, the process must reiterate until no more improvement is possible (due to unfeasibility of vehicle targets).

3.5 Vehicle Optimization

As described in the previous paragraph, there is a high number of combinations of vehicle settings which give the performance desired. The viability of these combinations is not known in this phase, so, based on the sensitivity matrix, a limited set of action strategies is defined.

Note that the efficiency of the strategies is known thanks to the sensitivity matrix.

Given the set of action strategies, a choice is required to move forward in the process. The vehicle components / sub-systems are optimized based on the changes required to achieve the performance targets. If these changes are not achievable, the process needs to reiterate with new inputs and a new set of action strategies is defined.

In case of major changes in the project, the process must be re-performed with the new inputs.

After the main targets are defined (and achieved), it could be possible to perform the optimization of the vehicle based on different criteria:

- Reduction of the constraints without losing the achieved performance
- Enhancement of the performance due to slack constraints.

3.5.1 Rule based strategy

After developing the sensitivity analysis, a rule based strategy was created for the optimization of the vehicle selected during the use of the app based on the linear interpolation of each parameter with respect to the results obtained averaged for the three architectures taken as a reference.

The following illustrates, through an application example, the reliability of the optimization implemented in the software based on the rule based strategy.

The main parameters of the vehicle taken as a reference are illustrated in the table below.

Table 25 - Vehicle parameter for optimization procedure

Parameter	Baseline
UBE [kW]	105
Cx [-]	0.260
S [m2]	2.7
Curb weight [kg]	2326
Tire μ front [-]	1.15
Tire rolling resistance [kg/ton]	8.4
Aux. Cons. [W]	300
Front gear ratio [-]	9.19
Rear gear ratio [-]	9.19
Front rollling radius [m]	0.390
Rear rollling radius [m]	0.390

The percentages of parameter variation used for the optimization of the vehicle architecture are listed below.

Table 26 - Parameter variation table for the EGO vehicle

Parameter	Parameter variation [%]
Cx	3.00%
Frontal surface	-3.00%
Vehicle mass	5.00%
Tire longitudinal friction coefficient	-2.00%
Rolling coefficient	5.00%
Torque distribution	0.00%
Front gear ratio	-2.00%
Rear gear ratio	-4.00%
Series - HVBS configuration	0.00%
Parallel - HVBS configuration	0.00%

The optimization result is shown in the table below.

Table 27 - Rule based example results

Test	Baseline	Rule based	Simulated	Reliability
Vehicle max speed [kph]	266	269	274	98.18%
0 - 60 kph w/o 1 foot [s]	4.9	5.3	5.2	98.08%
0 - 100 kph w/o 1 foot [s]	5.1	5.5	5.4	98.15%
0 - 200 kph w/o 1 foot [s]	13.0	13.8	13.6	98.53%
1/4 miles w/o 1 foot [s]	12.7	13.0	13.0	100.00%
80 - 120 kph	2.2	2.3	2.3	100.00%
100 - 140 kph	2.5	2.6	2.6	100.00%
100 - 200 kph	8.0	8.3	8.3	100.00%
Constant speed range @ 150 kph	323	319	320	99.69%
EU Range (WLTC_3b DS2) [km]	578	560	562	99.64%
WLTP consumption (WLTC_3b DS2)	182	188	187	99.47%
Powertrain system efficiency in WLTP	88%	88%	88%	100.00%
Max HVBS P (3s / 35°C)	491	492	499	98.60%
Max HVBS I (3s / 35°C)	739	740	753	98.27%
Min Voltage during HP Discharge	664	664	663	99.85%
Max Mech P (3s / 35°C)	449	449	454	98.90%
Mean reliability				99.21%

The results table is divided into four main columns: baseline, rule based, simulated and reliability.

The baseline column shows the results of the simulation of the status of the starting architecture taken as a reference, the rule based column shows the results obtained by using the linear interpolations carried out for each test based on the sensitivity matrix, the simulated column shows the results of the status of the optimized vehicle actually simulated through the Simulink model and finally the reliability column represents the reliability of the rule based with respect to the results obtained by simulating the vehicle architecture through Simulink.

The number of modified parameters in this example is eight and despite this the average reliability of the rule based is 99.21%.

3.6 Case Study

In the following paragraph the whole procedure developed will be illustrated with a practical example.

The main features of the vehicle to be designed are the following:

- The vehicle mass must be between 2300 and 2400 kg
- 0 - 100 kph must be less than 3.5 seconds
- the vehicle range in the WLTC must be greater than 500 km
- The aerodynamic coefficient Cx must be less than 0.314.

Once the targets to be reached have been identified, let's enter the minimum and maximum parameters in the "required targets" mask (see figure).

It is important to note that in this phase it is good to leave a wide tolerance in the choice of ranges.

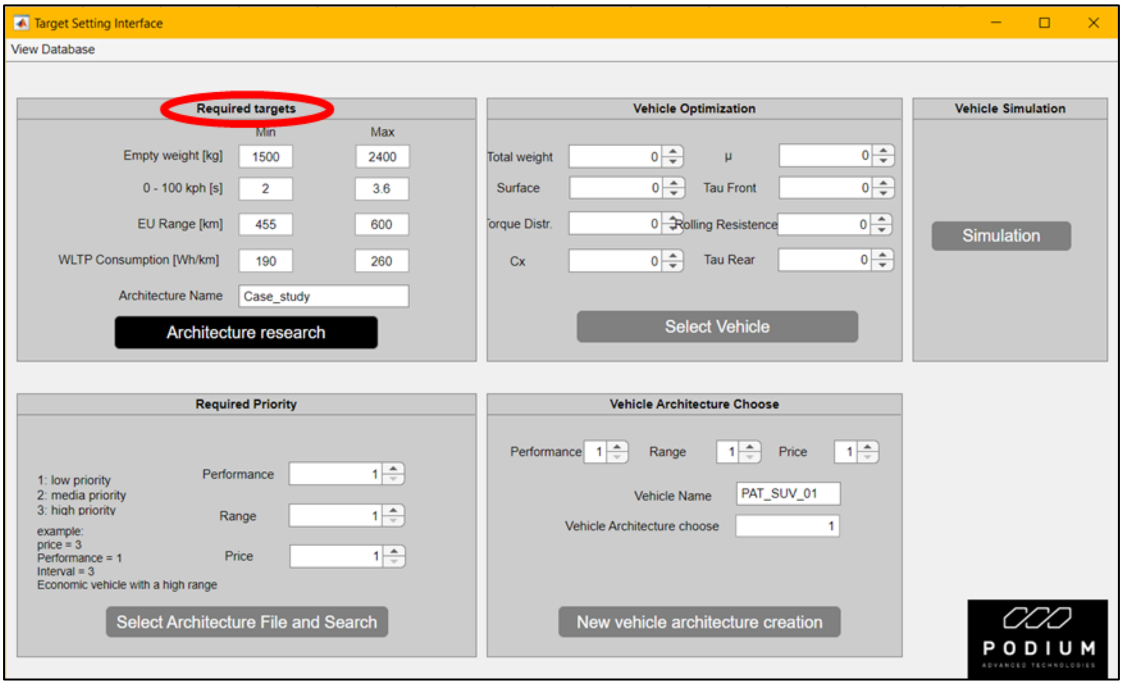


Figure 40 - Case study - step 1: Required targets

By pressing the "Architecture research" button, the app will generate a table containing all the architectures that meet the targets entered, in detail the vehicle mass, the 0 - 100 kph, WLTP range and consumption.

The table below illustrates the architectures present in the database that satisfy the targets entered.

Table 28 - Case study - step 1 results

Status / #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
HVBS code	3	3	3	3	3	3	3	3	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	8	8	8
VHCL code	3	3	3	3	3	3	3	3	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
AERO code	3	3	3	3	3	3	3	3	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Front WHL code	3	3	3	3	3	3	3	3	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Rear WHL code	3	3	3	3	3	3	3	3	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Front TRSM code	1	2	2	2	3	3	3	3	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	1	1	1
Front MTR code	1	2	2	2	3	3	3	3	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	1	1	1
Front INV code	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rear MTR code	2	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	2	2	2	2
Rear TRSM code	2	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	2	2	2	2	2	2	2
Rear INV code	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
# of front MTR	1	1	1	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	1	1	2	2	1	1	2
# of rear MTR	2	1	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
UBE [kW]	96	96	96	96	96	96	96	96	103	103	103	103	103	103	103	103	103	103	103	103	103	103	103	103	103	103	103	116	116	116
Curb weight [kg]	2349	2370	2370	2370	2370	2370	2370	2370	2400	2400	2400	2400	2300	2300	2300	2300	2355	2355	2355	2355	2321	2321	2321	2321	2321	2321	2321	2391	2391	2391
frontal surface [m2]	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.44	2.44	2.44	2.44	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
Cx [-]	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.230	0.230	0.230	0.230	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330	0.330
Front rolling radius [m]	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.290	0.290	0.290	0.290	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329
Rear rolling radius [m]	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.290	0.290	0.290	0.290	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329	0.329
Front tire rolling resistance [kg/ton]	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
Rear tire rolling resistance [kg/ton]	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
Front tire friction coefficient [-]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Rear tire friction coefficient[-]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Aux. Cons. [W]	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Front gear ratio [-]	9	14	14	14	8	8	8	8	9	9	9	9	9	9	9	9	14	14	14	14	14	14	14	8	8	8	8	9	9	9
Rear gear ratio [-]	14	8	8	8	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	8	8	8	14	14	14	14	14	14	14
1foot rollout [s]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0 - 60mph [s]	2.8	3.6	3.5	3.6	2.6	2.7	2.8	2.6	2.6	2.6	3.3	2.6	2.8	2.8	3.2	2.8	3.0	2.9	3.1	3.0	3.6	3.4	3.6	2.7	2.7	2.8	2.7	2.8	2.9	3.2
0- 60mph w/o 1 foot [s]	2.6	3.3	3.2	3.3	2.3	2.5	2.6	2.3	2.4	2.4	3.0	2.4	2.5	2.6	2.9	2.5	2.7	2.6	2.9	2.7	3.3	3.1	3.3	2.4	2.4	2.6	2.4	2.6	2.6	3.0
0 - 100 kph [s]	2.9	3.7	3.6	3.7	2.7	2.8	3.0	2.7	2.8	2.7	3.4	2.8	2.9	2.9	3.3	2.9	3.1	3.0	3.3	3.1	3.7	3.6	3.7	2.8	2.8	3.0	2.8	2.9	3.0	3.4
0 - 100 kph w/o 1 foot [s]	2.7	3.5	3.3	3.5	2.4	2.6	2.7	2.4	2.5	2.5	3.2	2.5	2.7	2.7	3.0	2.7	2.8	2.7	3.0	2.8	3.4	3.3	3.4	2.5	2.5	2.7	2.5	2.7	2.7	3.1
0 - 200 kph [s]	7.8	8.3	9.0	8.3	7.2	7.5	8.4	7.2	8.2	7.8	10.2	8.2	8.2	7.9	10.0	8.2	7.4	7.6	8.0	7.4	8.4	9.2	8.4	7.4	7.4	8.6	7.4	8.1	8.0	9.7
0 - 200 kph w/o 1 foot [s]	7.5	8.0	8.8	8.0	6.9	7.2	8.2	6.9	7.9	7.5	9.9	7.9	7.9	7.6	9.7	7.9	7.1	7.4	7.8	7.1	8.1	8.9	8.1	7.2	7.2	8.3	7.2	7.8	7.7	9.5
1/4 miles [s]	10.3	10.8	11.0	10.8	10.0	10.1	10.5	10.0	10.3	10.2	11.2	10.3	10.4	10.3	11.1	10.4	10.2	10.3	10.5	10.2	10.9	11.0	10.9	10.1	10.1	10.6	10.1	10.4	10.4	11.1
1/4 miles w/o 1 foot [s]	10.0	10.5	10.7	10.5	9.7	9.9	10.2	9.7	10.1	9.9	11.0	10.1	10.2	10.1	10.8	10.2	10.0	10.0	10.2	10.0	10.6	10.8	10.6	9.8	9.9	10.3	9.8	10.1	10.1	10.8
1/4 miles exit speed [kph]	232	235	223	235	238	236	224	238	226	230	210	226	226	231	211	226	242	236	234	242	232	221	232	235	236	222	235	228	229	214
EU Range (WLTC_3b DS2) [km]	456	483	480	483	463	471	461	463	508	511	504	508	488	491	484	488	460	458	458	460	518	516	518	498	499	496	498	544	547	540
WLTP Cons. (WLTC_3b DS2) [Wh/km]	211	199	200	199	208	204	209	208	202	201	204	202	211	209	212	211	223	224	224	223	198	199	198	206	206	207	206	213	212	215
Powertrain system efficiency in WLTP	82%	84%	83%	84%	84%	84%	83%	84%	81%	82%	81%	81%	81%	82%	81%	81%	77%	77%	77%	77%	83%	83%	83%	83%	84%	83%	83%	82%	82%	81%
Torque Distribution in WLTP (front)	0.33	0.50	0.33	0.50	0.50	0.33	0.67	0.50	0.50	0.33	0.67	0.50	0.50	0.33	0.67	0.50	0.50	0.33	0.67	0.50	0.50	0.33	0.50	0.50	0.33	0.67	0.50	0.50	0.33	0.67
Maximum speed [kph]	275	276	277	276	277	277	278	277	276	276	275	276	275	275	274	275	276	276	275	276	276	277	276	277	277	278	277	275	275	275
CS range @150kph [km]	290	300	301	300	300	299	301	300	355	355	356	355	311	311	312	311	311	312	312	311	321	322	321	321	321	322	321	349	349	351

the next step is the choice of priorities to select only the architectures that best reflect the needs of the customer. In our example, the priorities chosen for the range and performance are respectively 3 and 1. The figure below graphically represents the choice of priorities through the "Required priority" mask.

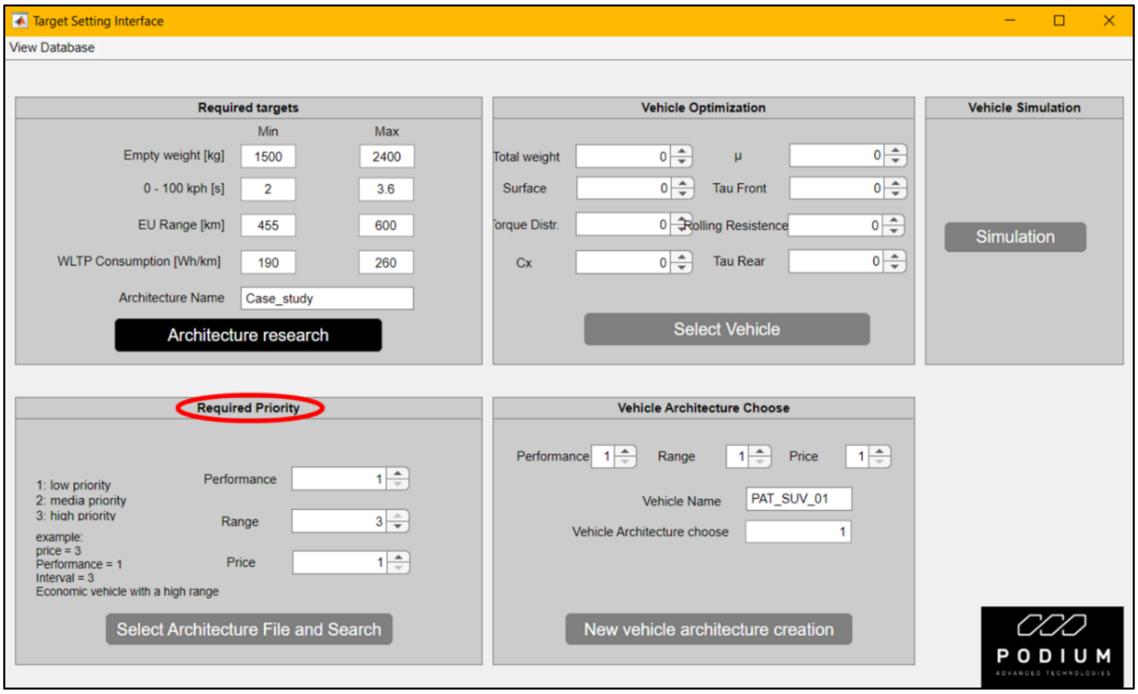


Figure 41 - Case study - step 2: Required priority

Once the priorities have been selected, the app will generate a new table based on the clustering previously illustrated. In our example we will get a table with 8 different architectures. Once the priorities have been selected, the app will generate a new table based on the clustering previously illustrated. In our example we will get a table with 8 different architectures as can be seen from the table below.

Table 29 - Case study - step 2 results

Status \ #	1	2	3	4	5	6	7	8
HVBS code	7	7	7	7	7	8	8	8
VHCL code	1	1	1	3	3	3	3	3
AERO code	1	1	1	3	3	3	3	3
Front WHL code	1	1	1	3	3	3	3	3
Rear WHL code	1	1	1	3	3	3	3	3
Front TRSM code	1	1	1	2	2	1	1	1
Front MTR code	1	1	1	2	2	1	1	1
Front INV code	0	0	0	0	0	0	0	0
Rear MTR code	2	2	2	3	3	2	2	2
Rear TRSM code	2	2	2	3	3	2	2	2
Rear INV code	0	0	0	0	0	0	0	0
# of front MTR	1	1	2	1	1	1	1	2
# of rear MTR	1	2	1	1	2	1	2	1
UBE [kW]	103	103	103	103	103	116	116	116
Curb weight [kg]	2400	2400	2400	2321	2321	2391	2391	2391
frontal surface [m2]	2.44	2.44	2.44	2.20	2.20	2.20	2.20	2.20
Cx [-]	0.230	0.230	0.230	0.330	0.330	0.330	0.330	0.330
Front rollling radius [m]	0.290	0.290	0.290	0.329	0.329	0.329	0.329	0.329
Rear rollling radius [m]	0.290	0.290	0.290	0.329	0.329	0.329	0.329	0.329
Front tire rolling resistance [kg/ton]	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
Rear tire rolling resistance [kg/ton]	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
Front tire friction coefficient [-]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Rear tire friction coefficient[-]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Aux. Cons. [W]	300	300	300	300	300	300	300	300
Front gear ratio [-]	9	9	9	14	14	9	9	9
Rear gear ratio [-]	14	14	14	8	8	14	14	14
1foot rollout [s]	0.27	0.27	0.28	0.29	0.28	0.27	0.27	0.28
0 - 60mph [s]	**2.64**	**2.64**	3.30	3.59	3.43	**2.83**	2.85	3.23
0 - 60mph w/o 1 foot [s]	**2.38**	**2.37**	3.02	3.31	3.14	**2.55**	2.58	2.95
0 - 100 kph [s]	**2.76**	**2.75**	3.44	3.72	3.55	**2.94**	2.96	3.36
0 - 100 kph w/o 1 foot [s]	**2.49**	**2.48**	3.16	3.43	3.27	**2.66**	2.69	3.08
0 - 200 kph [s]	8.15	**7.80**	10.22	8.43	9.16	**8.11**	**8.01**	9.75
0 - 200 kph w/o 1 foot [s]	7.89	**7.53**	9.94	8.15	8.87	**7.84**	**7.73**	9.47
1/4 miles [s]	**10.32**	**10.21**	11.23	10.87	11.04	10.41	**10.39**	11.09
1/4 miles w/o 1 foot [s]	**10.06**	**9.95**	10.95	10.59	10.75	10.14	**10.11**	10.81
1/4 miles exit speed [kph]	226	**230**	210	**232**	221	228	**229**	214
EU Range (WLTC_3b DS2) [km]	508	511	504	518	516	**544**	**547**	**540**
WLTP Cons. (WLTC_3b DS2) [Wh/km]	202	**201**	204	**198**	**199**	213	212	215
Powertrain system efficiency in WLTP	81%	82%	81%	**83%**	**83%**	82%	**82%**	81%
Torque Distribution in WLTP (front)	0.50	0.33	0.67	0.50	0.33	0.50	0.33	0.67
Maximum speed [kph]	276	**276**	275	**276**	**277**	275	275	275
CS range @150kph [km]	**355**	**355**	**356**	321	322	349	349	351

The highlighted cells are representing the top 3 for each row.

Once all the architectures have been observed and analysed, number 4 was chosen as the best architecture. To communicate our choice to the app, simply select the architecture using the "Vehicle architecture choose" mask as shown in the figure below.

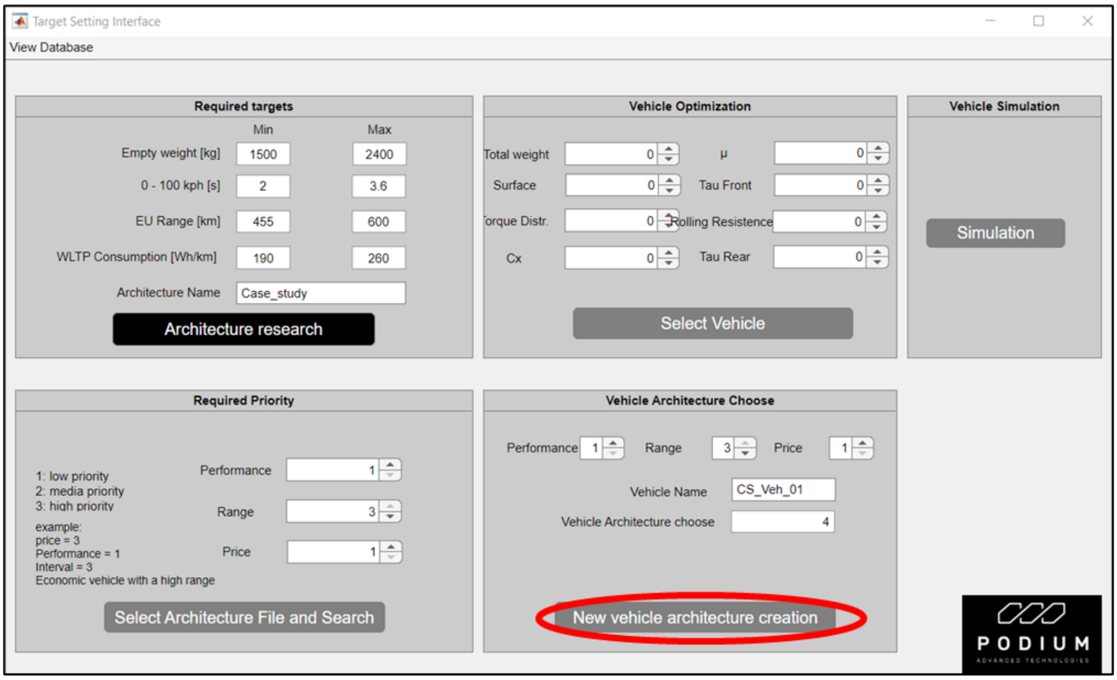


Figure 42 - Case study - step 3: new vehicle architecture creation

After selecting the required architecture, the app has generated a folder with all the useful information to customize, analyse, simulate, and optimize our vehicle called "CS_Veh_01". The table below shows the status of the new vehicle.

Table 30 – CS_veh_01 status

Status \ #	4
HVBS code	7
VHCL code	3
AERO code	3
Front WHL code	3
Rear WHL code	3
Front TRSM code	2
Front MTR code	2
Front INV code	0
Rear MTR code	3
Rear TRSM code	3
Rear INV code	0
# of front MTR	1
# of rear MTR	1
UBE [kW]	103
Curb weight [kg]	2321
frontal surface [m2]	2.20
Cx [-]	0.330
Front rollling radius [m]	0.329
Rear rollling radius [m]	0.329
Front tire rolling resistance [kg/ton]	8.4
Rear tire rolling resistance [kg/ton]	8.4
Front tire friction coefficient [-]	1.15
Rear tire friction coefficient [-]	1.15
Aux. Cons. [W]	300
Front gear ratio [-]	14
Rear gear ratio [-]	8
1foot rollout [s]	0.29
0 - 60mph [s]	3.59
0 - 60mph w/o 1 foot [s]	3.31
0 - 100 kph [s]	3.72
0 - 100 kph w/o 1 foot [s]	3.43
0 - 200 kph [s]	8.43
0 - 200 kph w/o 1 foot [s]	8.15
1/4 miles [s]	10.87
1/4 miles w/o 1 foot [s]	10.59
1/4 miles exit speed [kph]	232
EU Range (WLTC_3b DS2) [km]	518
WLTP Cons. (WLTC_3b DS2) [Wh/km]	198
Powertrain system efficiency in WLTP	83%
Torque Distribution in WLTP (front)	0.50
Maximum speed [kph]	276
CS range @150kph [km]	321

As we can see from the table, not all the predetermined targets have been reached, in fact the Cx of the starting vehicle is higher than 0.314.

The selected vehicle could be customized according to the needs in our case it will be enough to optimize only the aerodynamic coefficient Cx.

To re-enter the Cx target, you can use the "vehicle optimization" function and obtain reliable results without the aid of any simulation tool, to better estimate the changes to be made to the vehicle parameters. The "vehicle optimization" procedure is illustrated in the figure below.

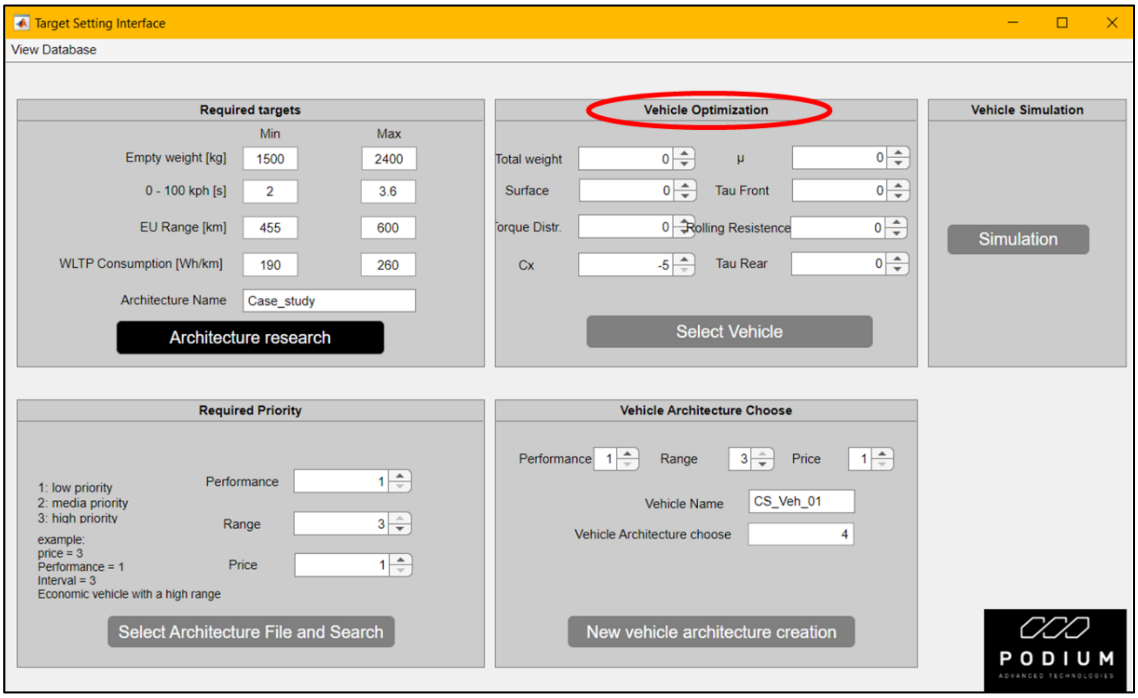


Figure 43 - Case study - step 3: vehicle optimization

Finally, the table below shown the status of the vehicle CS_vehi_01 in the baseline version, with the optimization carried out through the rule based and finally the status was also launched to verify the results obtained.

Table 31 - CS_veh_01 results

CS_Veh_01	Baseline	Rule based	Simulation
HVBS code	7	7	7
VHCL code	3	3	3
AERO code	3	3	3
Front WHL code	3	3	3
Rear WHL code	3	3	3
Front TRSM code	2	2	2
Front MTR code	2	2	2
Front INV code	0	0	0
Rear MTR code	3	3	3
Rear TRSM code	3	3	3
Rear INV code	0	0	0
# of front MTR	1	1	1
# of rear MTR	1	1	1
UBE [kW]	103	103	103
Curb weight [kg]	2321	2321	2321
frontal surface [m2]	2.2	2.2	2.2
Cx [-]	0.330	0.314	0.314
Front rollling radius [m]	0.329	0.329	0.329
Rear rollling radius [m]	0.329	0.329	0.329
Front tire rolling resistance [kg/ton]	8.4	8.4	8.4
Rear tire rolling resistance [kg/ton]	8.4	8.4	8.4
Front tire friction coefficient [-]	1.15	1.15	1.15
Rear tire friction coefficient[-]	1.15	1.15	1.15
Aux. Cons. [W]	300	300	300
Front gear ratio [-]	13.6	13.6	13.6
Rear gear ratio [-]	8.4	8.4	8.4
0 - 60mph w/o 1 foot	3.3	3.3	3.3
0 - 100 kph w/o 1 foot	3.4	3.4	3.4
0 - 200 kph w/o 1 foot	8.1	8.1	8.1
1/4 miles w/o 1 foot	10.6	10.6	10.6
EU Range (WLTC_3b DS2)	518	526	526
WLTP Consuption (WLTC_3b DS2)	198	195	195
Powertrain sys efficiency in WLTP	83%	83%	83%
Torque Distribution in WLTP	0.50	0.50	0.50
Maximum speed [kph]	276	277	276
CS range @150kph [km]	321	331	331

Considering the results obtained and that every time a status is launched the MATLAB / Simulink takes about 25 minutes to generate all the results and instead with the "rule-based method" the results are estimated in no more than 3 seconds, we can conclude that for more complex optimizations, where it would be necessary to launch more status for many parameters, we would save a lot of computational and working time.

Obviously, it is important to validate the results at the end of the analysis using the simulation tool as the simulation not only returns the numerical results but also the graphs that illustrate the trends of the variables during the test.

The WLTP test is used as an illustrative example.

The figure below illustrates some fundamental variables to observe after performing a WLTP simulation.

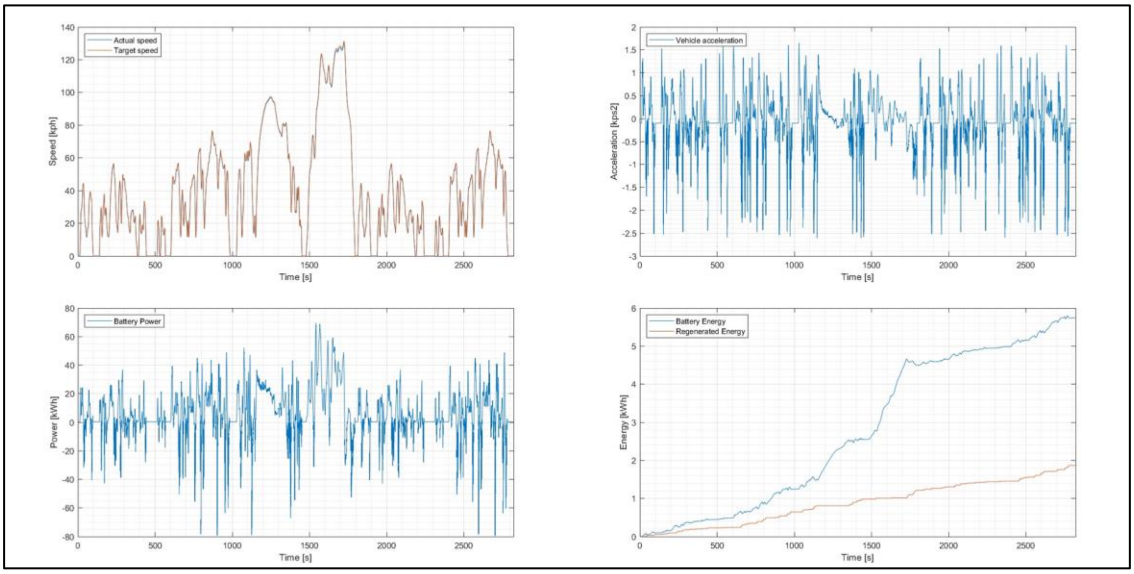


Figure 44 - Main variables results

4 Conclusion

The target setting procedure output is a list of vehicle and performance targets, whose feasibility is ensured by the loops performed. The end of the process is to be defined by a certain tolerance of performance change after a loop, or by the unfeasibility of the vehicle targets of the last loop.

The thesis project developed was treated as a pilot study for target setting strategies useful for the design of electrical architectures by exploiting company databases, automation software to optimize time during the design phase, clustering techniques to organize user choices, sensitivity analysis to obtain a clear picture of the influence of the various parameters on vehicle performance, taking into account the variation percentages of the various parameters and the use of a rule-based strategy to obtain an estimation of the results without using software based methods on complex models and with high computational times.

The entire analysis considers only architectures for battery electric vehicles, but hybrid architectures should also be introduced for future developments.

In conclusion, the results show a high reliability of the tool that allows the user to make decisions in the design phase based on the results obtained from the app.

At work, there is no need to carry out a multivariate sensitivity analysis that would allow the tool to consider the influence that each parameter has on the others.

The app created during the developed analysis will be used as a starting point for future studies that will include the following features:

- Enrich the database of basic architectures
- the parameterization of the maps used for the battery and for the motors
- a choice of the architecture clustering strategy to be used
- Multivariate sensitivity analysis
- Vehicle optimization using machine learning techniques.

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