POLITECNICO DI TORINO

Master science degree
in Automotive Engineering

Development and validation of a model of regenerative braking and acceleration in co-simulation environment

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Acknowledgments

This thesis is dedicated to my beloved family, whom sustained me along the university career, and to my grandparents.

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Abstract

The project that I started and developed at the INSIA (Instituto universitariòn del automovil de investigacion del automovil) has the purpose to create a model of an existing vehicle with the method of the co-simulation. The project has been carried out using as modelling software AVL Cruise and CarSim for the modelling of the vehicle subsystems and Simulink as communication channel between the two. A set of experimental tests was available and was used to verify the accuracy of the response of the modelled vehicle. The development of the project started with the definition of the modelling environment in which each sub-system of the vehicle have to be placed; the choices taken in this phase were motivated by the accuracy that the software can offers in the modelling of the considered component. At this point the design of each component model and of the environment of experimental tests is done. Once the model is defined and operative a calibration of its parameters is carried out comparing experimental and simulated results. Finally the advantages encountered during the design process and the numerical results obtained from the validation process are resumed.

Introduction

Nowdays complex engineered systems that integrate physical, software and network aspects are emerging. Due to external pressure, the development of these systems has to be concurrent and distributed, that is, divided between different teams; each team develops a partial model of the whole system, that needs to be integrated with all the other partial models. A good solution able to manage this way of modelling is the co-simulation method. It consists in the development of coupled software systems, in this way different models can be designed separately and at the same time focusing on the characteristic features of the considered sub-model. Further more, with this method, the needs to build prototypes board circuits to validate the composition of the software and of the hardware is decreased [1]. As well as co-simulation allows to integrate the modelling of different system on different simulation environment, it is used also as design tool during all the stages of the development process, from early system validation to the X-in the loop co-simulation, bringing hard real-time constraints to the set of challenges.
Since co-simulation method show this versatility, the development of a model able to simulate accurately the behaviour of powertrain and driveline of vehicle can be carried out exploiting all the advantages of co-simulation; the main purpose of the project, consequently, is based on the model development, with the mentioned method, using as simulation environments the ones of AVL and CarSim. In this way the powertrain can be modelled on AVL Cruise, since it is able to model electric powertrains, and the driveline is modelled on CarSim for its capacity to built a detailed model of the driveline and to represent the testing conditions of the experimental tests performed by an existing vehicle. So doing, the model design, is placed at the end of the development process of the vehicle and so the model can be considered as a tool to test the vehicle in particular manoeuvres that in real life can be hard or expensive to reproduce. The control of the model is performed by the time evolutions of the positions of steering wheel, accelerator and brake pedals measured by sensors during experimental tests. Since the simulation of the two models occurs in two different simulation environment, a communication channel have to be designed in order to exchange and process signals between the powertrain and driveline models. A Software able to perform this action is Simulink, in fact both AVL Cruise and CarSim are provided by standard interface to Matlab/Simulink; in this way the tree software simulate at the same time the behaviour of each subsystem interacting one with the other.
Dividing and modelling the entire vehicle systems in AVL Cruise and in CarSim, it is possible to exploit the strenghts of each simulation environment obtaining a comprehensive representation of the complex system through the integration and the validation of the systems.

The project starts with the definition of the vehicle that have to be modelled and with the definition of the exmperimental tests that it will perform in order to validate the components of the subsystems of powertrain and driveline. At this point the design on CarSim of the driveline's model and testing environment is described focusing on the working principle of the main component's models and on the model's interface with respect to others simulation environment. Later also the powertrain's model implemented on AVL Cruise is described pointing out the math models that control each component's block and the signals that it exchanges with the external simulation environment. Finally the scheme of the model in Simulink for the communication between AVL Cruise and CarSim is presented; in particular the working principle of each subsystem block and the way in which they have been designed is explained.

Once the global model of the system is completely described, the results of the simulations are compared with the experimental ones and a degree of the robustness of the model is evaluated.

1. Vehicle characteristics and experimental tests

The vehicle used to perform the experimental tests is the Mitsubishi iMiEV, a city car belonging to the categories of A-class vehicles with a full electric powertrain. The particularity of this vehicle, as in quite all the electric vehicles, is the capability to perform a regenerative braking; this means that during the phases in which the engine is not delivering power to the wheels, it recovers kinetic energy from them and store it in the battery under electrical form. This regeneration can be exploited using the electric machine as a generator during the braking or coast down phase through a suitable control on the inverter; in this way the wheels, that are mechanical connected to the electric machine, transfer their kinetic energy to the generator that converts it in electrical energy opposing a resisting torque that tends to stop the vehicle. In the following the main characteristics and properties of the vehicle are presented in Table 1.1 [2]

Length	[mm]	3475
Width	[mm]	1475
Height	[mm]	1610
Height from ground	[mm]	150
Front track	[mm]	1310
Rear track	[mm]	1270
Vehicle mass	[kg]	1110
Maximum speed	[km/h]	130
Steering radius	[m]	4,5
Maximum power	[kW]	49 @ 2500-8000 rpm
Maximum torque	[Nm]	180 @ 0-2000 rpm
Traction type	[-]	RWD
Engine	[-]	Electric synchronous motor with permanent magnets
Traction battery		Lithium-ion , 88 cells

Battery voltage	[V]	330
Battery capacity	[kWh]	16
Final ratio	[-]	6,066
Steering system	[-]	Rack-and-pinion (Electric power assisted)
Front suspension	[-]	Mac Pherson
Rear suspension	[-]	3-Link de Dion
Front brakes	[-]	Ventilated brake disks
Rear brakes	[-]	Drum brakes
Front tires	[-]	145/65R15
Rear tires	[-]	175/55R15

Table 1.1 – Main characteristics of the vehicle

The vehicle is provided by three driving modes that the driver can select with the same stick that select the motion mode (for instance forward, neutral and reverse):

- D-Mode
- ECO Mode
- B-Mode

The D-mode position is the standard one and it provides full power access and a normal regenerative braking. In this mode the vehicle deliver a direct response, this means that at full throttle the engine is delivering is actual maximum torque [3]. However it has to be underlined that in the first instants after take-off the delivered torque by the engine (considering a constant pedal position) assumes value grater than the ones that it would have in normal condition and than decrease until the it reaches the value proportional to the pedal stroke; this kind of control is employed to facilitate the take-off and reduce the effect of jerk[4].

In ECO Mode position the vehicle slightly reduces the response of the engine in order to save the energy stored in the battery and the regenerative braking efficiency is increased with respect to the D-Mode. This mode is useful in urban driving where accelerations and braking are frequent, in this way all the energy dissipations can be exploited to further reduce the energetic consumption [3].

The B-Mode position provides the same torque response as the D-Mode, but has the strongest regenerative braking capability [3]; this mode is useful when the vehicle is driven downhill.
The experimental tests are performed in such a way the features of the three driving mode can be highlighted; consequently tests are three, one for each driving mode, and can be subdivided in three phases:

- Acceleration
- Coast down
- Braking

Each test is performed with all the optional in off-mode and is representative of a smooth acceleration in urban environment; in fact the vehicle reaches a maximum speed of maximum speed of 40 km/h in ten seconds and returns to 0 km/h in more or less the same time, condition similar to the one in the UDC of the NEDC. In order to collect the experimental results of the tests the vehicle has been provided with a set of sensors that provide the following data:

- Vehicle speed
- Accelerator pedal position
- Brake pedal position
- Current at battery ends
- Voltage at battery ends
- Angular position of steering wheel

All the signals coming from sensors are collected by a data collector and than elaborated for the design of the model.

2. Simulink model

The Simulink model is the core of the model of the entire system, it contains the two interfaces of AVL Cruise and CarSim and moreover elaborates the data coming from the two environments performing the acceleration and the regenerative braking control.

The model scheme is shown in Figure 2.1

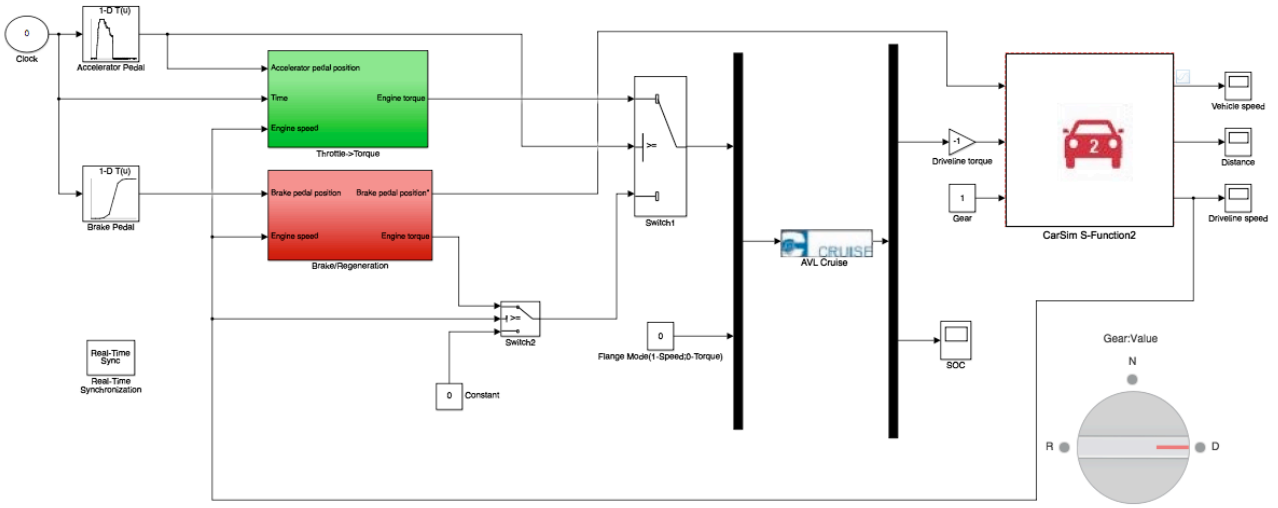


Figure 2.1 – Simulink model scheme

Looking at the scheme above it is possible to identify the interfaces of AVL Cruise and CarSim on the right and the blocks representative of the acceleration control, in green, and the regenerative brake control in red. The accelerator control block receives as input the accelerator pedal position, the time and the driveline angular speed, as output returns the torque required to the engine. The brake block, instead, receives as input the driveline angular speed and the brake pedal position and returns the engine torque and the brake pedal position adapted to the brake system model in CarSim (the position interval of the brake pedal position have to match with the one defined in CarSim).

The working principle of the two blocks combined identifies four working phases:

- Stall
- Drive
- Coast down
- Braking

The shift between different phases is performed by switches, in particular the Switch 1 selects between stall/coast down and drive mode using as criteria the accelerator pedal position (if greater than 0 the drive phase is active, if equal to 0 the stall/coast down phase is active); than the Switch 2 selects between stall/coast-down and braking receiving as choosing criteria the engine speed (if greater than 0 regenerative braking phase is active, if equal to 0 stall phase is active). In this way stall mode occurs when accelerator pedal position and engine speed are equal to 0 and the coast down mode occurs when the accelerator pedal is 0 but the engine speed is grater than 0.

2.1 Accelerator control

The accelerator block model receives the signal of the accelerator pedal position and returns the torque required from the engine. The accelerator pedal position is provided by an angular position sensor mounted on the pedal; since the pedal position is related to the torque delivered by the engine, it is useful to normalize (equation 2.1.1) the signal *p(t)* in order to obtain a 0 value when the signal reach its minimum value.

$$x(t) = \frac{p(t)}{0.498} - 1 \qquad (2.1.1)$$

In this way when the accelerator pedal is in rest position the accelerator block returns a 0 value torque. Than the modified signal *x(t)* is stored in a 1-D Look-up Table which receives as input the current simulation time at each simulation step from the clock block (Port 1 in Figure 2.1) and returns the stored signal.

The accelerator pedal position is employed to define the amount of torque delivered by the engine, the relation between pedal position and torque can be of three types depending on the selected driving mode. As explained in Chapter 1, in fact, the vehicle presents three different driving modes:

- In D-Mode the relation is direct, this means that at full throttle the engine is delivering the maximum torque deliverable
- In ECO Mode the relation isn't direct but at the same pedal position, with respect to the previous mode, the engine delivers a lower torque
- In B-Mode the relation pedal position-torque is the same of the D-Mode

Although the relations in D and B modes are direct, during take-off the delivered torque shows a transitory; at first, considering a constant pedal position, the demanded torque is maximum. Than, after the vehicle starts to gain speed, the demanded torque at the same pedal position is reduced until a constant value; from this instant the proportionality between the pedal position signal and demanded torque remains constant over time. As state before the pedal position *x(t)* is useful to determine the amount of torque that that the driver is requesting, this can be performed multiplying the pedal position with the maximum deliverable torque at the actual engine angular speed. In order to obtain the right *pedal position-torque* relation the pedal signal is modified to take into account the properties of the selected driving mode; to this purpose the model show in Figure 2.2 has been built.

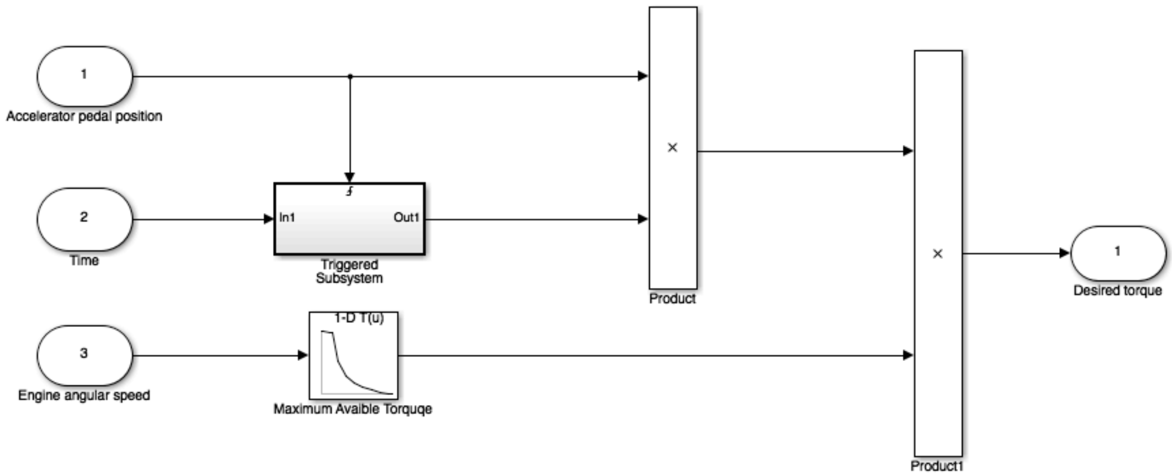


Figure 2.2 – Accelerator model with triggered subsystem for the definition of the right relation *Pedal position-Torque*

As it is possible to see the signal of pedal position coming out from Look-up table is sink into an event triggered subsystem which contains a polynomial function that receives as input the time signal; the control signal of the trigger is the pedal position one and the event that activate the subsystem is the passage of the pedal position from 0 to a positive value. When the subsystem is triggered the polynomial function generates a signal that will be multiplied with the pedal position one; in this way it possible to obtain a signal represenatione of the *pedal position-torque* relationship that takes into account of the transitory during take off and of the proportionality between pedal position and torque expected by the driving mode. The expression of the polynomial function has been designed starting from a rough approximation of the signal that it should be generated (a comparison between computed and experimental results is done at each modification in order to get closer to the right relationship), this has been performed thanks to a signal builder shown in Figure 2.3.

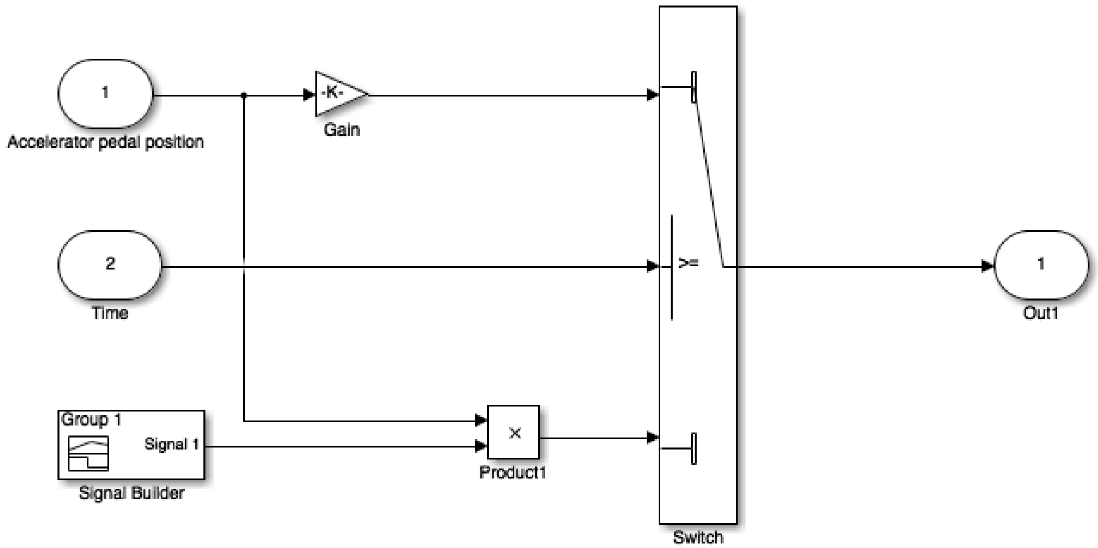


Figure 2.3 – Accelerator model with signal builder block for the rough approximation of the modified pedal position signal

Once a suitable signal is built, it is fitted by a polynomial function defined by the Matlab command *polyfit.*

The maximum torque available at the actual engine speed is provided by a second 1-D Look-up table, in which the mechanical characteristic of the engine is stored, that receives as input the driveline angular speed from the CarSim simulation environment (through Simulink).

2.2 Regenerative brake control

The brake control works likewise the acceleration control with the difference that it provides a second output equal to a signal proportional to the brake pedal position. Again the position signal is normalized using equation (2.2.1)

$$x(t) = \frac{p(t)}{27} - 1 \qquad (2.1.1)$$

In this way the stroke in the experimental test is adapted to the one defined in the CarSim braking system. Since the vehicle can exploit a regenerative braking, it is possible to define two types of phases:

- Coasting down phase, in which the vehicle regenerate current thanks to the residual kinetic energy of the vehicle
- Braking phase, in which the total braking power is given by the mechanical brakes and from the braking torque opposed by the generator

The evaluation of the braking torque in the first phase is performed using a 1-D Look-up table in which the mechanical characteristic of the engine (in regeneration mode) is stored. The Look-up table receives as input the actual engine speed from the CarSim simulation environment and returns the braking torque that the engine is transmitting to the driveline (Figure 2.4). Than the braking torque is sent to the AVL Cruise model interface in order to compute the recovered current.

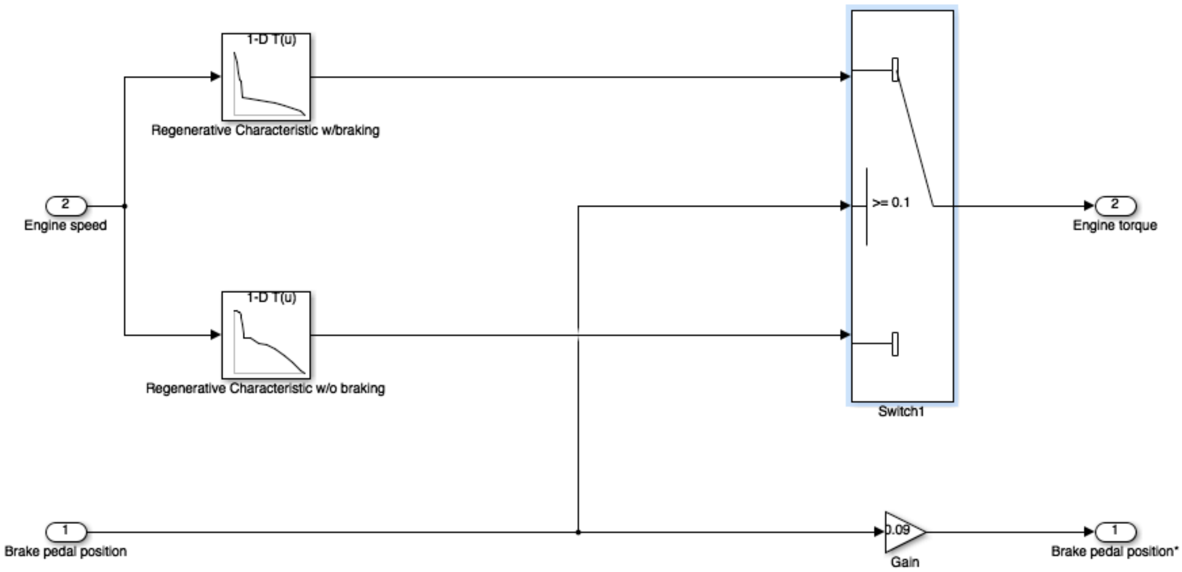


Figure 2.3 – Brake model subsystem

For what concerns the braking phase, the contributes to the braking torque are two:

- Braking torque due to the disc and drum brake
- Braking torque due to a further regeneration

The first contribute is evaluated by sending as input to CarSim model the brake pedal position properly modified as stated before. The second contribute is due to the fact that a light pressure on the brake pedal (as in the testing case) the regeneration control allows the electric machine (generator) to increase its efficiency recovering more energy; to simulate this behaviour a second regeneration characteristic is stored in a second 1-D Look-up table [5]. The selection between the two regenerative characteristics is performed by a switch that switches the input signal (that is the output of the Look-up tables) when the brake pedal position is different from 0. Comparing the experimental current signal with the experimental pedals positions signals of brake and accelerator as shown in Figure 2.4, is possible to see an increase of the regenerated current in the moment in which the brake pedal is pushed; this can demonstrate this particular control of the vehicle.

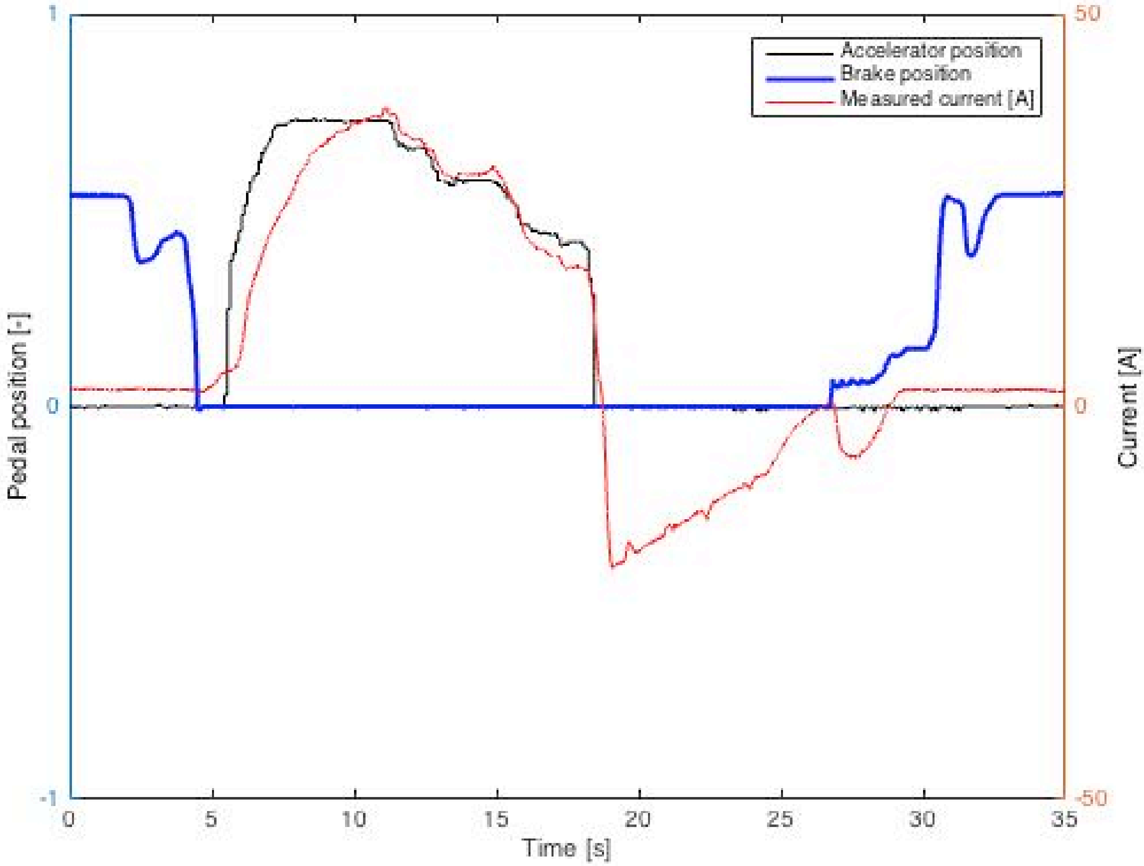


Figure 2.4 – Comparison between brake pedal position, accelerator pedal position and current delivered by the battery

The regeneration characteristic has been evaluated considering an approximated characteristic and modifying it in order to obtain a regenerated current equal to the one of the experimental result; these steps has been performed for each of the three driving modes of the vehicle. The model detect the working modes thanks to a switch that receives as choosing criteria the value of brake pedal position and than select the correspondent working principle; in particular for a position equal to 0 the model works in coast down phase, for a position value greater than 0 the model enters in braking phase.

2.3 AVL Cruise and CarSim interfaces

AVL Cruise provides interface through a DLL created by the Simulink coder, in this way we can link the two simulation environments. This interface receives as inputs three signals:

- Engine torque
- Engine rotational speed
- Flange mode

And two output signals:

- State of charge
- Driveline torque

The torque input signal is used by AVL Cruise to evaluate the current requested by the engine and consequently the state of charge and the voltage at battery terminals. The flange mode signal, instead, is a constant that can be equal to 0 or 1 and it is employed to define the type of exchanged signal; in this model we select the torque mode and so the constant value will be equal to 0. So doing, AVL Cruise knows that is receiving a torque signal as input rather than a speed signal.
The CarSim interface is an S-Function block and presents four input ports:

- Driveline torque
- Gear selection (forward, neutral and reverse)
- Brake pedal position

And three output ports:

- Engine rotational speed
- Vehicle speed

- Covered distance

The torque input signal is used by CarSim to evaluate the speed of the vehicle in function of the driving conditions and consequently returns the vehicle speed and the speed of the propeller shaft (i.e the engine rotational speed, since the vehicle hasn't a gearbox).
The driving mode signal is provided by a dashboard which can select among the values of -1, 1 and 0 that correspond o the respectively driving modes: reverse, drive and neutral.

3. AVL Cruise engine and battery model

The powertrain of the vehicle has been modelled on AVL Cruise simulator, in this way the analysis effort is reduced through a ready-to-use platform. In the considered case the powertrain is electric and so the elements that will compose it are the electric engine, the battery and the DC/AC inverter; the scheme with which all blocks are arranged is shown in Figure 3.1

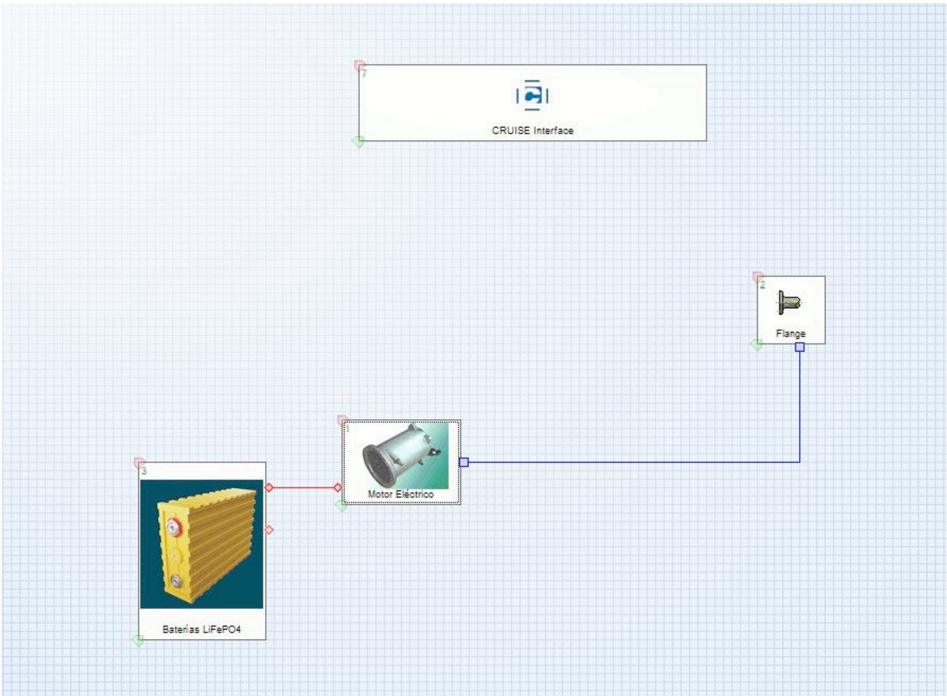


Figure 3.1 – AVL Cruise model, in red the electrical connection and in blue the mechanical connection

3.1 Electric machine block

Concerning the electric engine AVL Cruise is provided with the "Electric machine" block that is able to behave as motor or as generator; inside the block there are two sub-models: the inverter and the electric machine itself.

The modelling of the component starts setting the following properties:

- Selection button losses
- Selection button temperature
- Selection current limit
- Selection button control variable

The selection button losses it's a property that consider the losses through the efficiency or through the power loss; in this model the efficiency mode has been selected. Selection button temperature, instead, allow to evaluate the temperature of the machine through an internal mathematical model or loading the value of temperature from an external model through a data BUS. The current limit selection is a property that can disable the set of a maximum current; since during the experimental tests the vehicle never reaches heavy load condition, the property has been disabled since it has no influence. Finally the selection control variable defines the type of input control variable that the model will receive; two types of signal can be selected: load signal or desired torque signal. Since Simulink simulation environment provides the signal of the torque requested to the engine, the suitable control variable will be of the second type and consequently a data BUS channel with this kind of signal have to be connected to the block as it will be described in next chapters.
Once the properties of interest have been set, the next step is the design of the user-defined variables, an example of the configuration screen is shown in Figure 3.2. In this model the following variables have been considered and designed:

- Type of machine
- Nominal voltage
- Machine inertia
- Maximum machine speed

The library of the software has two type of electric machine: an asynchronous machine and a synchronous machine with permanent magnets, the second solution has been selected. Concerning the nominal voltage it should be the same as in on-board network; since it is composed by the battery and the electric machine, the nominal voltage will be equal to the one of the battery. The machine inertia is useful to compute the torque transmitted to the driveline, this time the value of the variable isn't available, so the moment of inertia of a similar machine has been set. This approximation can be acceptable since the acceleration performed by the engine are not so high, consequently the inertia torque doesn't affect too much the torque delivered to the driveline. Maximum engine speed has been taken from vehicle's technical data sheet.

E_{EM}	Type of machine	PSM
$U_{EM,nom}$	Nominal voltage [V]	330
$\Theta_{EM,nom}$	Moment of inertia [kgm^2]	0,31
$\omega_{EM,mot,max}$	Maximum speed [rpm]	9000

Table 3.1 – User-defined variables, electric machine model

As stated before the electric machine is provided with an internal thermal model, consequently also the user-defined variable useful for the considered case has to be defined [6]:

- Mass of the machine
- Initial temperature
- Specific heat transition
- Specific heat capacity
- Temperature coefficient of remanence induction

All these variables are employed by the electric machine in order to evaluate the evolution of temperature of the machine and consequently its induction reduction. Varying the variable's values the output of the simulation isn't affected, for this reason the thermal model is not considered. The insensitivity of the model to the variation of thermal variables could be due to the fact that the experimental tests have been performed for a very short time (tens of second) in cold condition and without a heavy load, for this reason the energy losses are small and so the performance of the machine remains invariant. The same consideration has been done about the thermal model of the inverter [6].

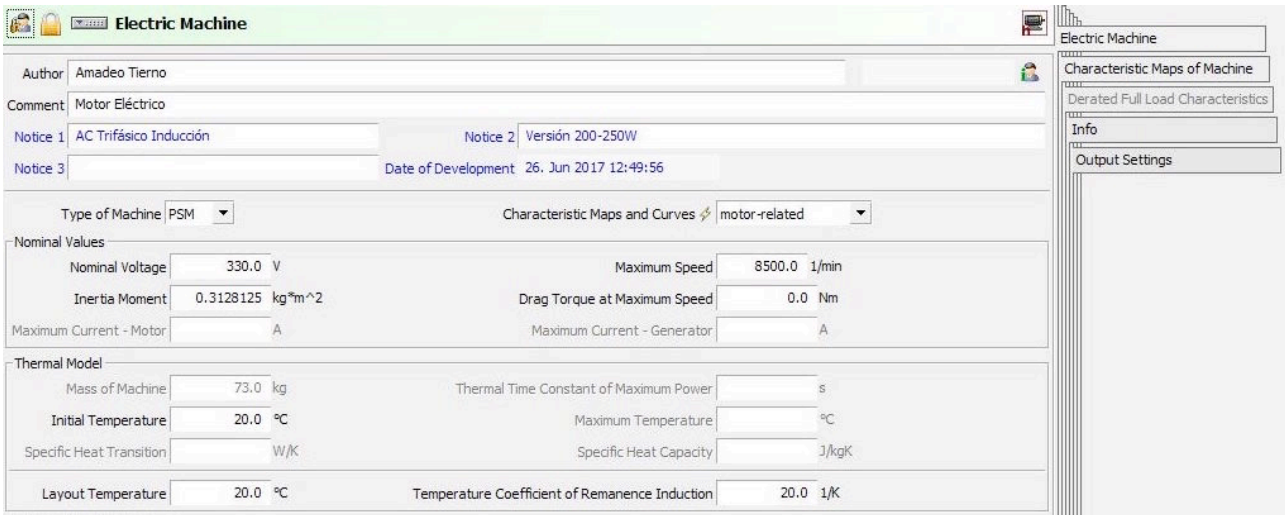


Figure 3.0.2 – Example of User-defined variables figuration screen

At this point it is possible to proceed with the definition of the mechanical characteristic of the engine (torque in function of rotational speed of the shaft); since the electric motor can perform a regenerative braking the characteristic should have two curves, one in the first quadrant and one in the third quadrant as shown in Figure 3.3. As reported on the technical sheet in chapter one the torque remains quite constant at the maximum value until a rotational speed of 2500 rpm, for higher speeds the torque decrease at constant power. For what concerns the generator characteristic (the one in the third quadrant) there weren't any useful data to define it, for this reason a generic characteristic was implemented. Than, comparing the simulated recovered current with the experimental one, a correct shaping of the generator characteristic was possible.

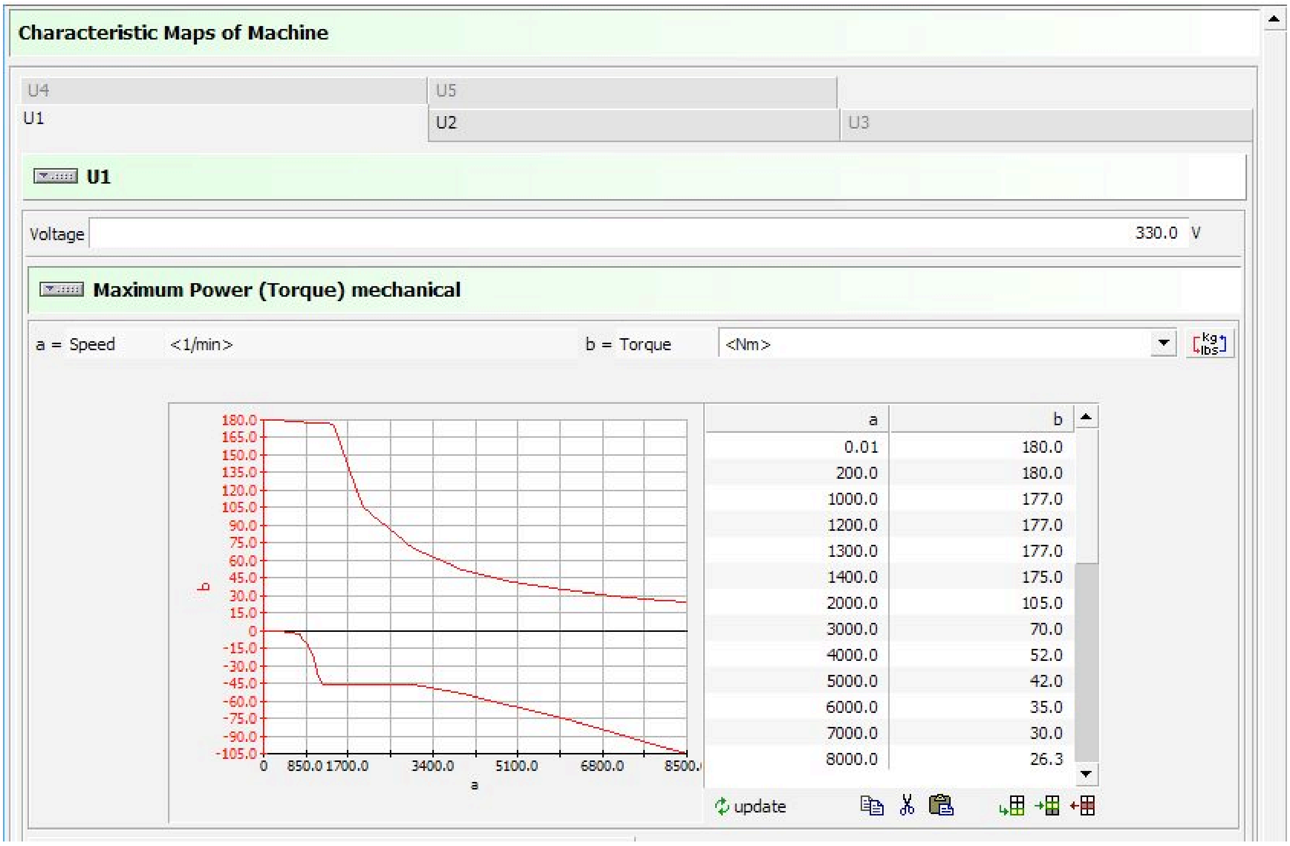


Figure 3.0.3 – Engine and generator mechanical characteristic

As explained before the selection losses have been set in efficiency mode, for this reason a map of the efficiency, as the one in Figure 3.3, function of the engine working condition have to be defined. The efficiency, in fact, depends on the temperature and on the load and since in the considered tests the vehicle works at low load for short time there isn't a significant increase of temperature; consequently the efficiency can be considered constant over the whole simulation.

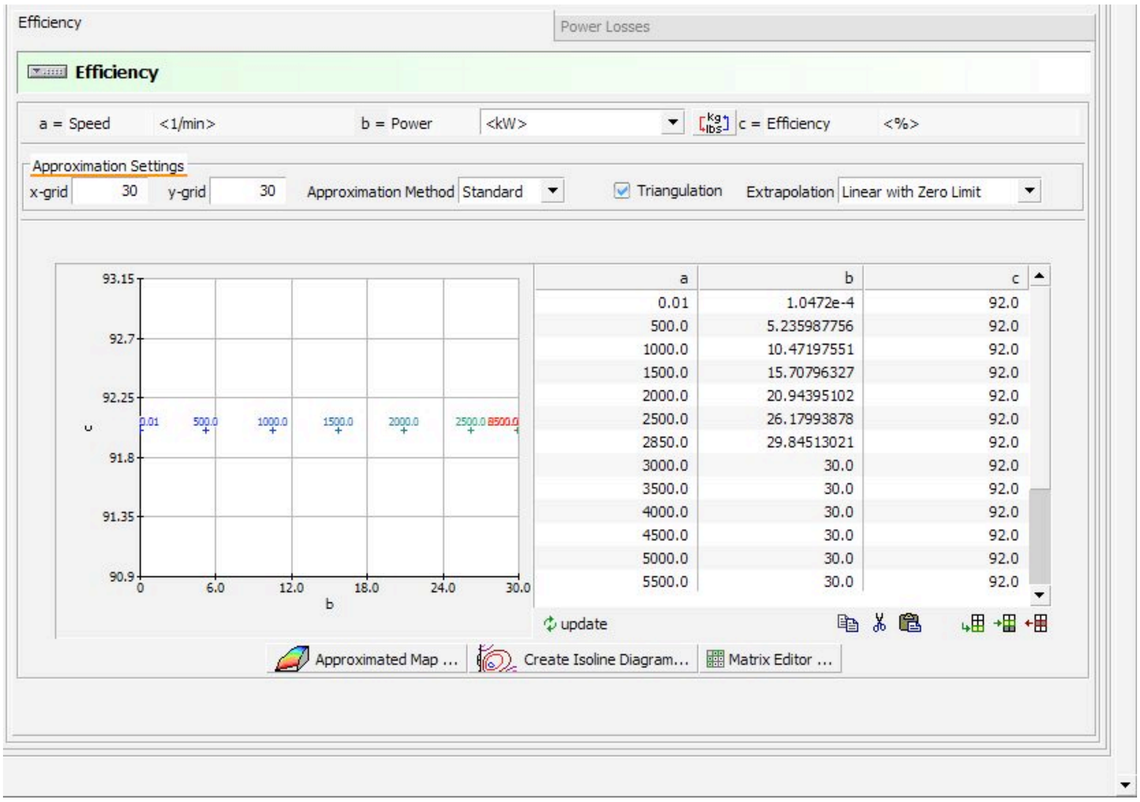


Figure 3.4 – Map of the efficiency in function of the engine power

Than the connections with the others blocks of the model have to be defined, they are subdivided in two typologies [6]:

- Electrical connections
- Mechanical connections

The first type is used to connect the battery block model to the one of the electric machine, in particular this connection exchange the variables shown in Table 3.2.

$U_{EM,net}$	Net voltage	V
I_{EM}	Current	A

Mechanical connections connect the electric machine block with the flange block that is a link element between the powertrain and the driveline. The variables exchanged by means of mechanical connection are shown in Table 3.3

ω_{EM}	Angular speed	Rad/s
α_{EM}	Angular acceleration	Rad/s^2
$\omega_{EM,max}$	Maximum angular speed	Rad/s
M_{EM}	Torque	Nm

Table 3.3 – Output variables of the electric machine block

3.1.1 Equation system of the electric machine block

The system of equation stored in the math model of the block can be subdivided in two part, mechanical part and electrical part.

For what concerns the mechanical part, the torque delivered by the engine to the driveline, and so to the Simulink environment, is computed with the relation in equation (3.1.1) [6]

$$M_{EM,dt} = M_{EM} - \Theta_{EM}\alpha \qquad (3.1.1)$$

Where M_{EM} is the desired torque input signal generated by the accelerator block in Simulink environment. In the electrical parts, instead, the mechanical and electrical powers are related together with the power losses [6]

$$P_{EM,el} = P_{EM,mech} - P_{EM,loss} \qquad (3.1.2)$$

Where the mechanical power is given by equation (3.1.3)[6]

$$P_{EM,mech} = M_{EM}\alpha \qquad (3.1.3)$$

About the power losses they can be considered in two separated condition, in motor-related and in generator-related condition. To this purpose the smallest data point of the mechanical characteristic of the engine are considered ($M_{EM,1}$ that is a torque and $\omega_{EM,1}$ that is the angular acceleration). In motor-related condition are presents two cases [6]:

If $M_{EM} > M_{EM,1}$, $\omega_{EM} > \omega_{EM,1}$

$$P_{EM,loss,act} = P_{EM,mech,act}\left(1/\eta_{EM} (M_{EM}\omega) - 1 \right) \quad (3.1.4)$$

If $M_{EM} < M_{EM,1}$, $0 < \omega_{EM} < \omega_{EM,1}$

$$P_{EM,loss,act} = \omega_{EM,1} M_{EM}\left(1/\eta_{EM} (\omega_{EM} M_{EM}) - 1 \right) \quad (3.1.5)$$

In generator-related condition, instead, the power losses can be again subdivided in two cases assuming that for values of $M_{EM,1}$ greater than the drag torque opposed by the generator the value of $M_{EM,1}$ is set equal to the drag torque [6]:

If $M_{EM} >> 0$, $\omega_{EM} >> 0$

$$P_{EM,loss} = \left| P_{EM,mech}(1 - \eta_{EM}(\omega_{EM} M_{EM})) \right| \quad (3.1.6)$$

If $M_{EM} >>=$, $\omega_{EM} \approx 0$

$$P_{EM,loss} = \left| \omega_{EM,1} M_{EM}(1 - \eta_{EM}(\omega_{EM} M_{EM})) \right| \quad (3.1.7)$$

Once the electrical power and the net voltage computed by the battery block are known the current requested to the battery is computed with equation (3.1.8).

$$I_{EM} = P_{EM,el} / U_{EM,net} \quad (3.1.8)$$

3.2 Battery block model

The battery model presents in AVL Cruise is useful to design models of hybrid or electric vehicles and it is connected to the electric machine by means of an electrical connection as explained in the previous chapter. As in electric machine block a list of properties can be enabled or disabled [6]:

- Selection button temperature
- Selection button ohmic resistance
- Switch resistance RC concentration overvoltage
- Switch resistances RC transfer overvoltage

The first selection button allows to chose between a computation of battery's temperature by means of an internal model or by means of an external source. Since thermal contribution is very low in experimental test the second options is selected providing a constant temperature value. The ohmic resistance property can be temperature-dependent, temperature/SOC-dependent or constant; since temperature is constant and any relation SOC-ohmic resistance was known the constant option has been selected. Regarding the two switches they have been disabled, in this way the RC concentration and transfer overvoltage aren't considered.
Defined all the desired properties, it is possible to proceed with the definition of the user-defined variables for the single cell

- Maximum charge
- Initial charge
- Nominal voltage
- Minimum voltage
- Maximum voltage
- Operating temperature
- Number of cells and rows

The maximum charge value limit the amount of charge that the battery can deliver until the complete discharge; the initial charge instead is the charge stored in the battery at the beginning of the simulation and it is expressed as percentage of the maximum charge [6]. The operating temperature value is equal to the temperature of the environment in which the experimental test is performed. All the values of user-defined variables are taken from the technical sheet of the battery and their values are reported in Table 3.4

$Q_{QH,max}$	Maximum charge [A s]	100
$Q_{QH,init}$	Initial charge [%]	89
$U_{QH,nom}$	Nominal voltage [V]	3,7
$U_{QH,min}$	Minimum voltage [V]	2,8
$U_{QH,max}$	Maximum voltage [V]	4
$T_{qh,op}$	Operating temperature [°C]	24
$N_{QH,cells\ in\ row}$	Number of cells per row [-]	88
$N_{QH,rows}$	Number of rows [-]	1

Table 3.4 – User-defined variable for the battery block

At this point the characteristic map of the component can be designed, in particular the map represents the idle voltage (voltage when no current is delivered out of the battery) in function of the state of charge. The maps are two, one for the charging case and the other for the discharging phase as shown in Figure 3.5

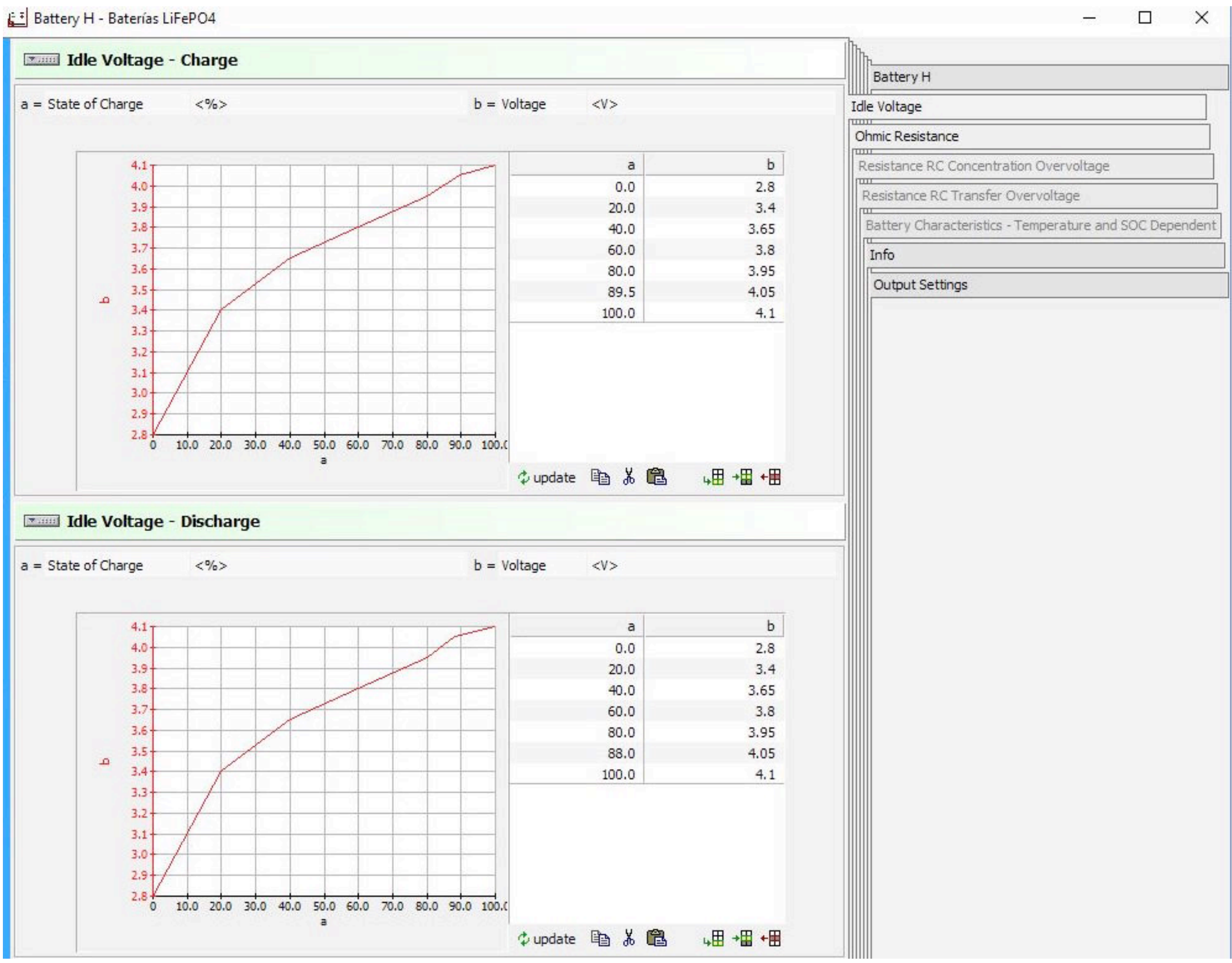


Figure 3.5 – Characteristic maps for the battery block

The design of these characteristic started considering the maximum and minimum voltage defined in the user-defined variable, than the other parts of the curve have been adjusted comparing the simulation output with the experimental results. Once the voltage-state of charge characteristic is defined the values of ohmic resistance in charging and discharging mode have to be set, their values are shown in Table 3.5

$R_{QH,charge}$	Ohmic resistance-discharge [Ω]	0.0017
$R_{QH,dischagre}$	Ohmic resistance-discharge [Ω]	0.0028

Table 3.5 – Ohmic resistances

Than the inputs and the outputs of the block are defined among a list of signal (Figure 3.3) that can be produced or received by the block considered.

As for the model of the electric machine connection with surrounding elements have to be established and differently from the electric machine the battery block is equipped only with electrical connections; the variables exchanged in this connection are the same presented in the previous chapter (net voltage and current for instance).

3.1.2 Equation system of the battery block

Inside the battery model the following system equation are stored, in particular they compute the voltage at the battery terminals receiving as input the current demanded by the engine. The expression of the voltage in function of the current is showed in equation (3.1.9) [6]

$$U_{QH,term} = U_{QH,idle}(I_{QH,term}, SOC) - R_{QH} I_{QH,term} \tag{3.1.9}$$

The value of current at the terminals is provided by the electric machine block in function of the desired torque and will be used to compute the amount of charge still present in the battery multiplying the current by the time of charge/discharge. Than it is possible to evaluate the actual state of charge with equation (3.1.10) [6]

$$SOC_{QH} = {Q_{QH,init}}/{Q_{QH,\max}} \tag{3.1.9}$$

At this point the value of open circuit voltage is taken from the characteristic maps and inserted in equation (3.1.9) to compute the value of voltage at the battery's terminals.

3.3 AVL Cruise interface

Interface block in AVL Cruise allows to design an interface able to organize all the data Bus connection for the blocks present in the model. For each block the software shows what are the possible variables that it can be exchange (Figure 3.5), the following one have been set for the electric machine block:

- Desired torque
- Angular speed

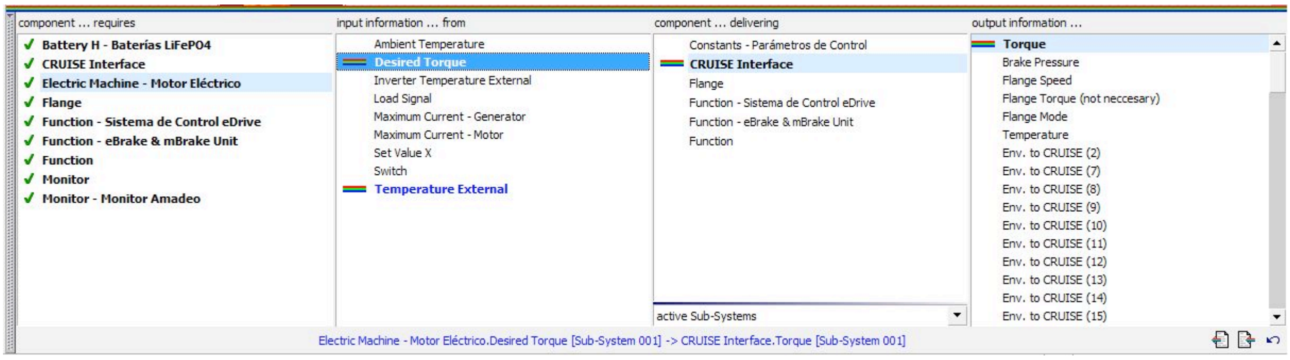
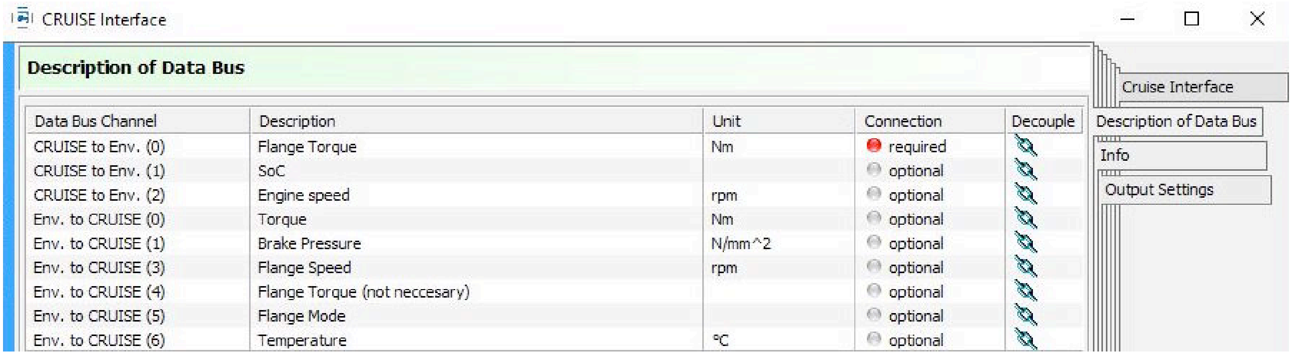


Figure 3.5 – Example of data bus configuration among different blocks in AVL Cruise

Both the signals have to be taken from Simulink simulation environment, for this reason a description of the data Bus have to be performed. More precisely each signal exchanged through data Bus have to characterized in terms of environment provenience and type of signal (torque or speed for example) and the direction (input/output). The correspondent interface block in Simulink environment will have all the inputs and inputs in the same order defined in the AVL Cruise environment. An example of the screen menu in which it is possible to characterize the connections is shown in Figure 3.6; the description of the adopted data Bus network is already present in Chapter 2 at paragraph 2.3.



Data Bus Channel	Description	Unit	Connection	Decouple
CRUISE to Env. (0)	Flange Torque	Nm	required	
CRUISE to Env. (1)	SoC		optional	
CRUISE to Env. (2)	Engine speed	rpm	optional	
Env. to CRUISE (0)	Torque	Nm	optional	
Env. to CRUISE (1)	Brake Pressure	N/mm^2	optional	
Env. to CRUISE (3)	Flange Speed	rpm	optional	
Env. to CRUISE (4)	Flange Torque (not neccesary)		optional	
Env. to CRUISE (5)	Flange Mode		optional	
Env. to CRUISE (6)	Temperature	°C	optional	

Figure 3.6 - Example of data Bus characterization

3.4 Flange block

The flange block is a coupling tool that connects the powertrain to the driveline and at the same time provides a bridge between the electric machine block and the AVL Cruise interface one [6]. The flange, in fact, has a mechanical interconnection with the electric machine and exchange with it the rotational speed of the driveline (depending on the signal selection made in the Simulink model as explained in chapter 2) and the driveline torque computed by equation (3.1.1) in the electric machine equation system. The same signals are exchanged with the AVL interface block through data us connections.

4. CarSim body and driveline model

The CarSim simulation environment is the one in which the driveline, the steering system and the driving environment are modelled. This simulation environment can represents the dynamical behaviour of different type of vehicle's class; each vehicle class is a generic model and is a starting point for the development of the model of the considered vehicle. To this purpose the software presents a set of vehicle parts and systems arranged in menu screens, as shown in Figure 3.1, whose characteristics can be modified in order to create a model as close as possible to the real vehicle.

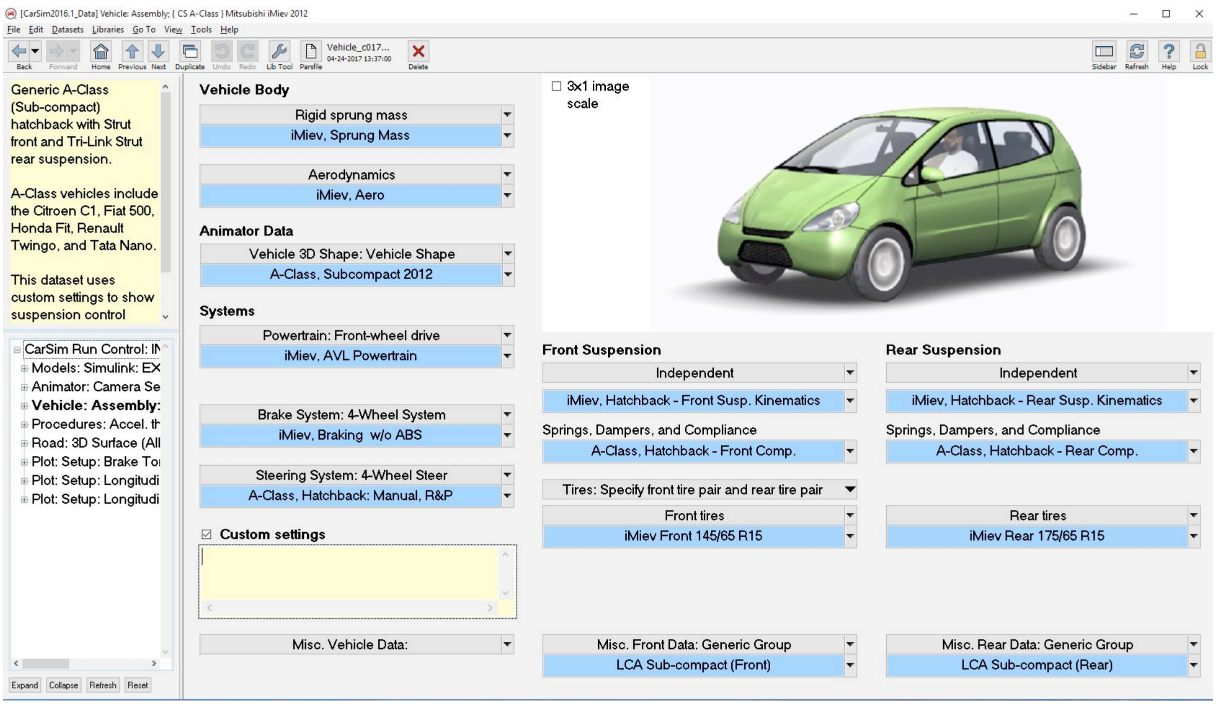


Figure 4.1 – Vehicle parts and systems

CarSim allows to perform also control actions and so for the considered model the control of the braking system and of the steering system is performed here. Moreover, in this window, it is possible to set the frequency at which CarSim returns the signal's values and the frequency at which it performs its iterations.

4.1 Vehicle body

The vehicle body is modelled considering the following characteristics

a	Distance of mass center from front axle [mm]	1402,5
b	Distance of mass center from rear axle [mm]	1147,5
h_g	Height of mass center [mm]	300
m	Mass of the vehicle [kg]	1100
$R_{u,rear}$	Rear wheels unloaded radius [mm]	286,75
$R_{u,front}$	Front wheels unloaded radius	284,75
l	Wheelbase [mm]	2550

Table 4.1 – sprung mass main dimensions

Their definition can be easily done through a screen menu in which the scheme of the sprung mass is shown (Figure 4.2)

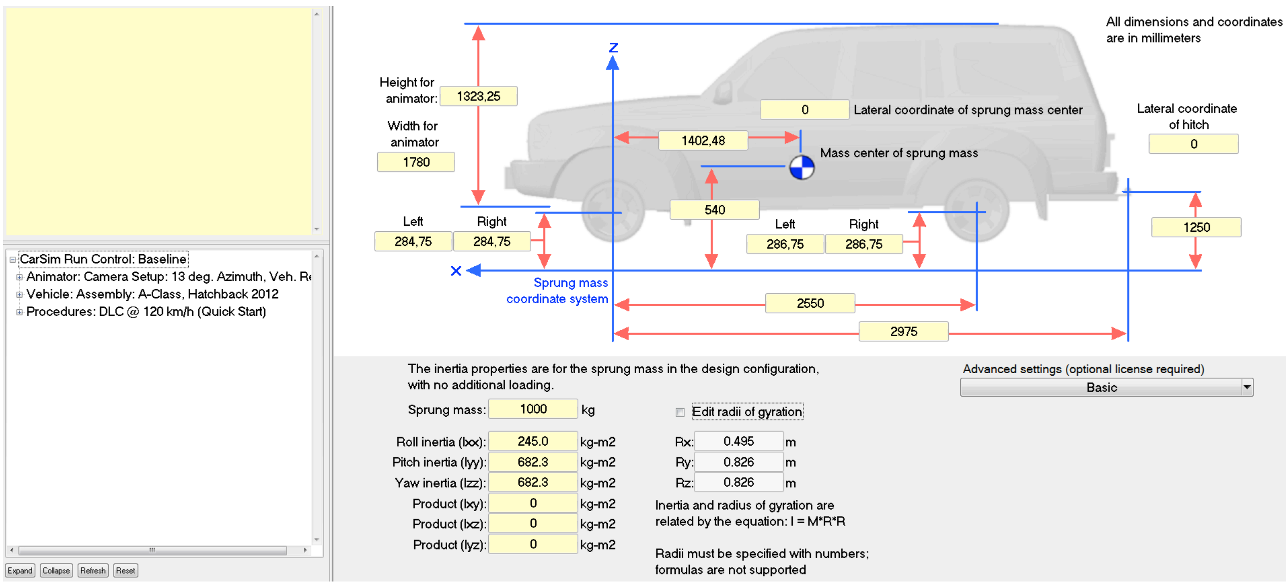


Figure 4.2 – Sprung mass characteristics definition

All the values of each characteristic can be easily taken from the technical sheet of the car except for the distance of the center of gravity from the two axles. The evaluation of the distances a and b (where a is the distance from the front axle and b the one from the rear axle) can be performed considering the vehicle in stand still position and drawing a free body diagram. Than the equilibrium equation of the moment with respect to the center of gravity is defined in equation (4.1), knowing that the sum of *a* and *b* is equal to the wheelbase their values can be computed

$$F_{z1}b - F_{z2}a = 0 \tag{4.1}$$

$$a + b = l \tag{4.2}$$

About the height of the center of mass, instead, it has been considered between the driver seats and the battery since the latter, with its weight, shift the center downward.

The modelling of the body regards also its aerodynamic behaviour as shown in Figure 4.3. All the aerodynamic characteristics can be changed in a window of the same type of the sprung mass model. Since in experimental tests the trajectory of the vehicle was practically straight, the drag force contribution in *y* direction is very small and so they can be considered insensitive to the variation of C_y. The aerodynamic momenta with respect to the vehicle reference frame have been neglected since the simulation results were insensitive to their variation. About the drag coefficient *z* direction C_z it has been set to a low value since the vehicle is a common city car and so its shape is made in such a way the down-force is minimum in order to save energy.

The others definable characteristics are the following:

- Aerodynamic reference point
- Frontal area
- Reference length
- Air density

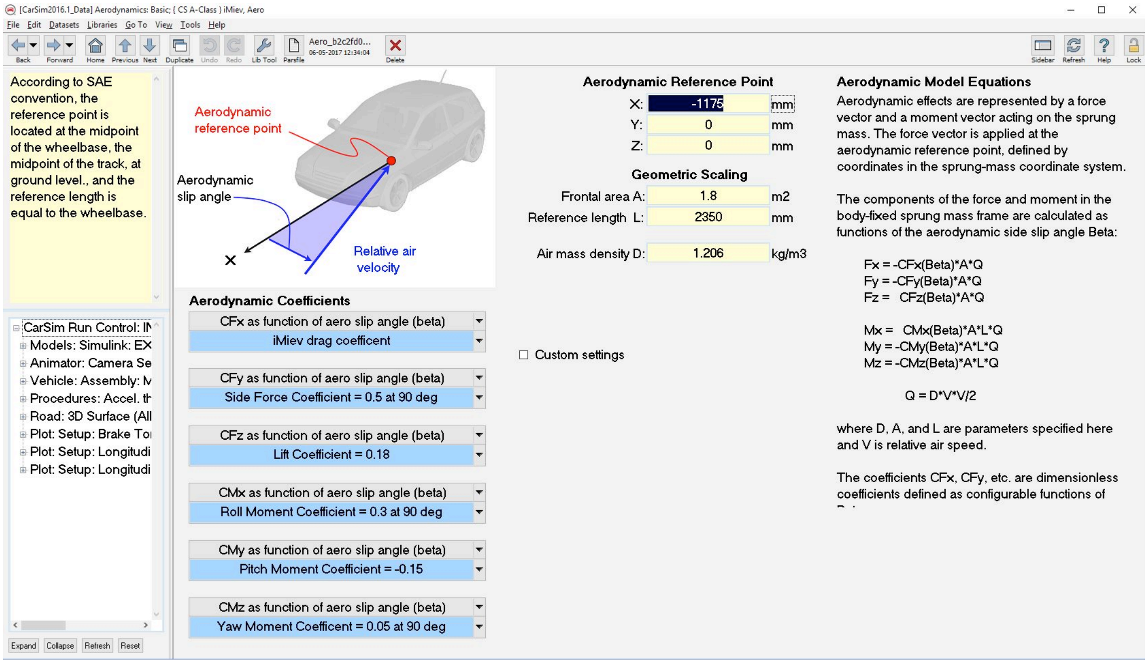


Figure 4.3 – Aerodynamic characteristic

The aerodynamic reference point is the point in which the aerodynamic forces and moments are applied and it is defined on the ground plane at the center of the wheels; the reference length, instead, is used to scale the aerodynamic moments applied to the sprung mass and it is equal to the wheelbase.

For what concerns the values of frontal area and longitudinal aerodynamic coefficient, they have been taken from technical sheets.

4.2 Driveline and powertrain structure definition

In this section the general structure of the system composed by powertrain and driveline in CarSim environment is explained. As shown in the model window illustrated in Figure 4.4, it is possible to define the element that will compose the entire system of the vehicle; in this case the engine is modelled on AVL Cruise and so the external engine mode is selected. The torque transmission element is also neglected since the vehicle has a fixed gear transmission and so hasn't any device of this kind.

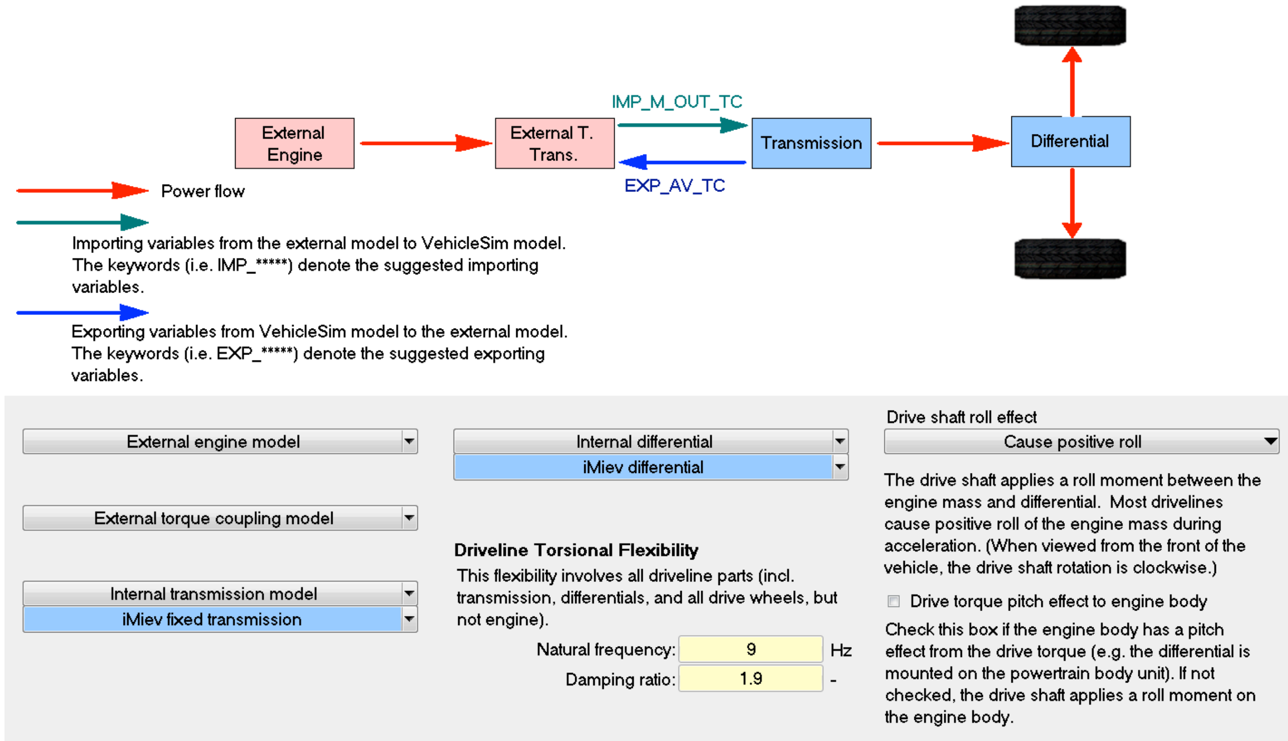


Figure 4.4 – Powertrain model structure

Once the powertrain model is set in external model, CarSim provide the type of signal that the driveline model have to exchange with AVL; in this case the model will receive the torque of the engine as input and will return the angular speed of the driveline (that is equal to the one of the engine) as output.

Regarding gearbox and differential, they are considered internal components of the model; in particular, in order to represent a fixed gear transmission, the gearbox has only the neutral position and two gear ratios equal and opposite as shown in Figure 4.5:

- Reverse
- Direct drive

The transmission ratio of the direct drive speed is equal to the overall transmission ratio; the transmission ratio of the differential is consequently equal to 1.

In order to select among the neutral position, reverse and forward an the external shift schedule mode is selected. This schedule associates a constant value called IMP_GEAR_TRANS to each driving mode (for instance 1 for the direct drive, 0 for the neutral position and -1 for the reverse as Shown in Figure 3.5) allowing CarSim to know in which selection the vehicle is [7]; the different constant values are provided by a selector block in Simulink.

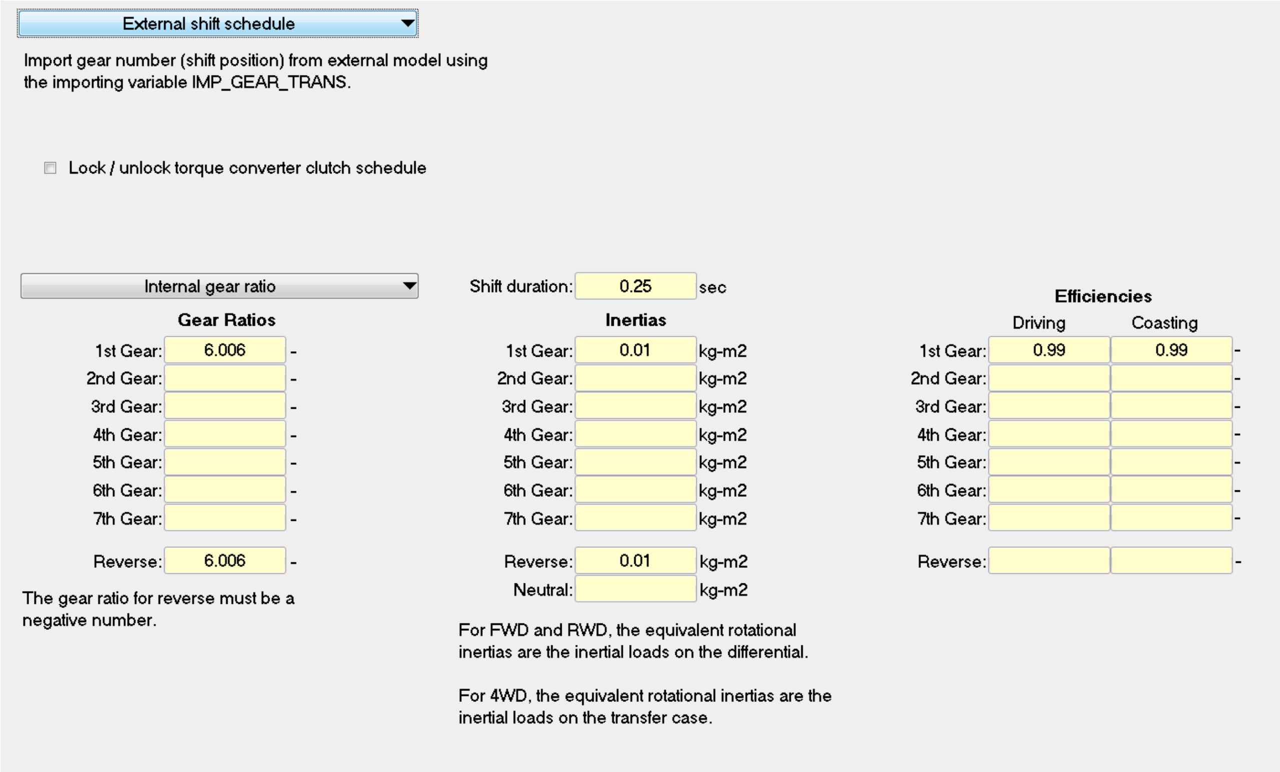


Figure 4.5 – Driving modes definition and scheduling

4.4 Brake system

Brake system configuration window is presented in Figure 3.6 and takes into account the following characteristics:

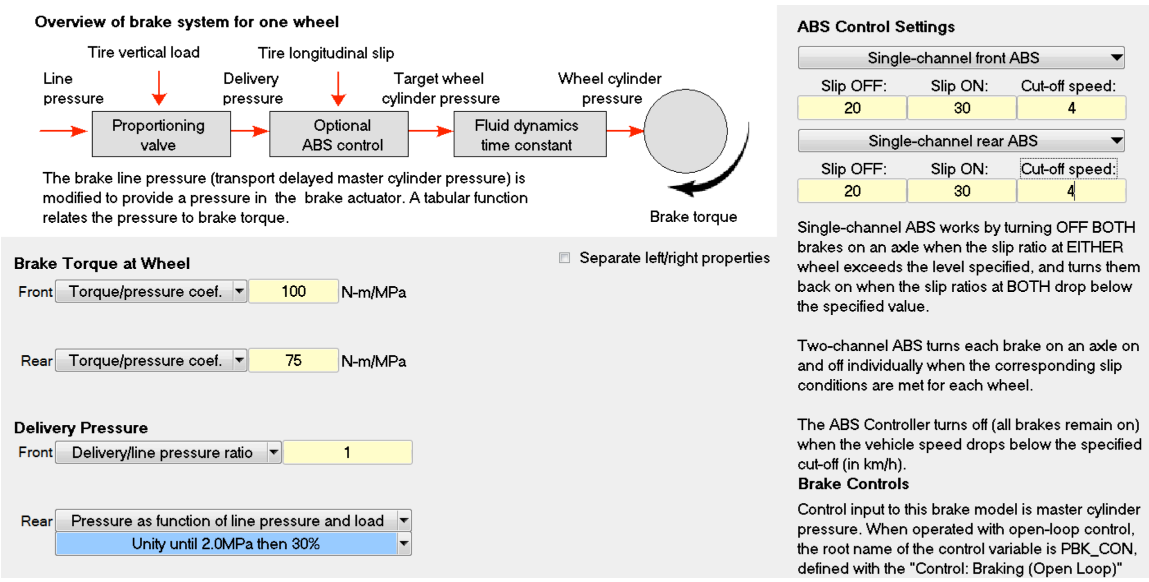


Figure 4.0.6 – Brake system configuration

The brake torque at wheel for front and rear axle is considered linear with respect to the delivered pressure and the coefficients of proportionality are reported in the yellow field. Coefficients are chosen comparing the deceleration of the vehicle with the one of experimental test and assuming that rear and front brakes are equal since the mechanical braking phase of the test is very small and so braking torques are very low. The delivery pressure is defined as linear function of the line pressure with linear coefficient equal to 1 [7]; others values of the coefficient didn't show any changes in the computed results. Fluid dynamics characteristics are set with default values since their variation has no impact on the driving condition considered in the model.

In the brakes system configuration is possible also to design the ABS control settings, in this case the slip limits are set at 20% and 30% with a Cut-off speed of 10 km/h.

The control of the whole brake system model is performed sending as input the brake pedal position signal from Simulink, than CarSim is able to compute the correspondent line pressure and consequently the braking torque to apply to the wheels.

4.5 Steering system

About the steering system, configuration parameters are taken for the libraries of the software considering a power-steered manual rack-pinion type of an A-class vehicle; and this because the steering action during the condition considered by the model has no influence on the outputs of the model. The unique modified property is the transmission ratio, since it can affect heavily the trajectory if higher values are set and its values was available on technical sheets. Concerning the control of the steering system, it is performed uploading the angular position signal of the steering wheel as shown in Figure 4.7

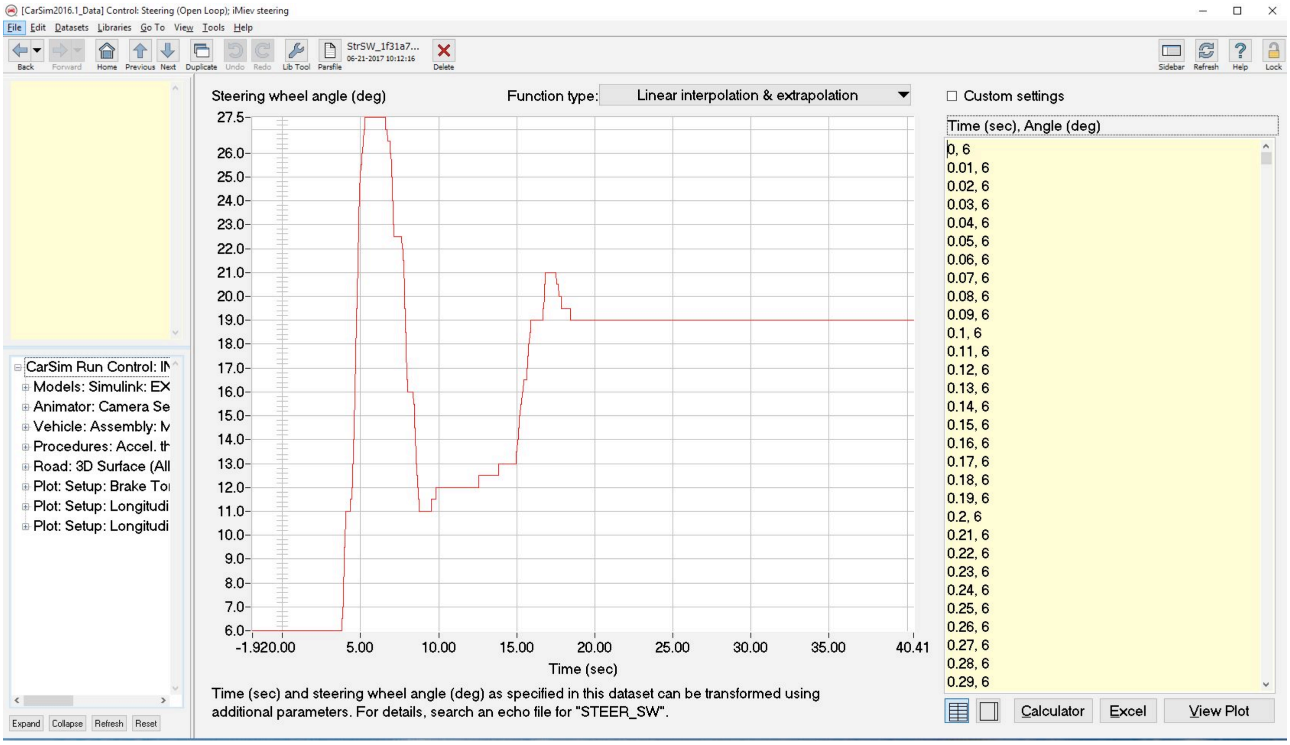


Figure 4.7 – Angular position of the steering wheel

4.7 Road modelling

CarSim provides a wide library of roads and the possibility to change their parameters such as elevation, inclination and friction coefficient as shown in Figure 4.9. In this case the modelled road is similar to the one in which experimental results were performed, and so a dry asphalt in good condition with a flat surface has been modelled. The friction coefficient is used to compute the maximum power transmissible to the ground through equation (4.3) [8]

$$P_{\max,trans} = V\mu_{ip}\left(mg\cos(\alpha) - \frac{1}{2}\rho V^2 SC_z\right) \tag{4.3}$$

From this equation is possible to see that the maximum power transmissible to the ground is function of the speed and its trend can be represented in general form in Figure 4.8.

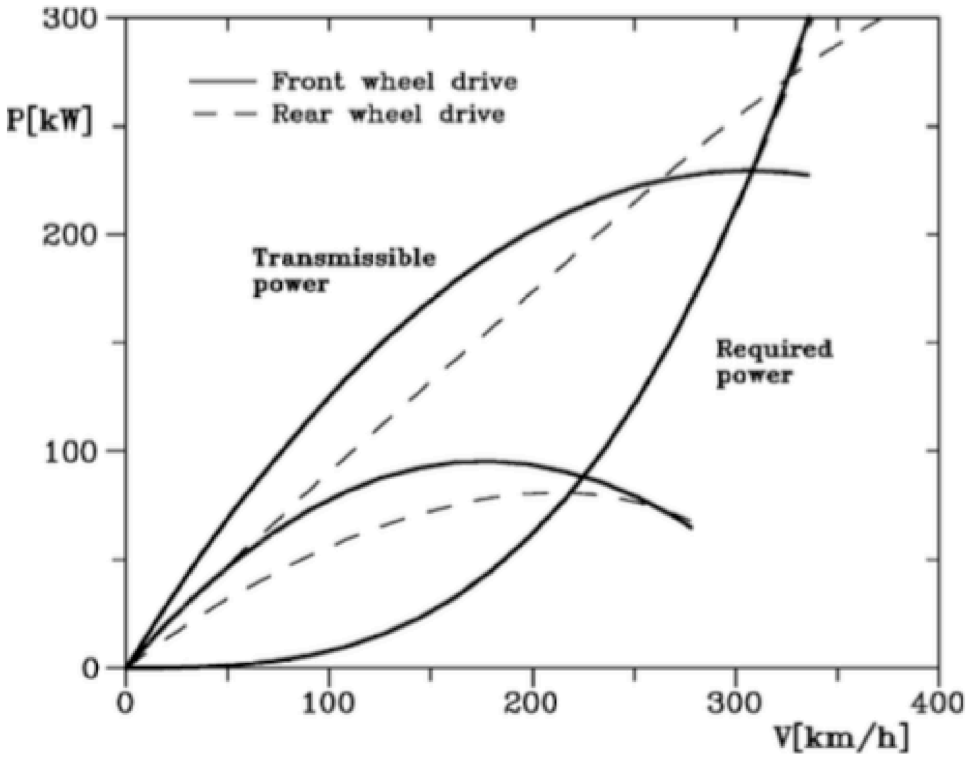


Figure 4.8 – Maximum power transmissible to the ground and power needed for motion for rear and front wheel driven vehicles

Increasing the speed the maximum power transmissible will equal the one needed for the motion, at these point all the power in excess is converted in heat by the tire material and high slip; this condition is characterized by a precise value of speed. Since during experimental tests the speed at which the power needed to motion equals the maximum power transmissible is never reached, it is sufficient to set a friction coefficient sufficiently high in order to never overcome the power limit.

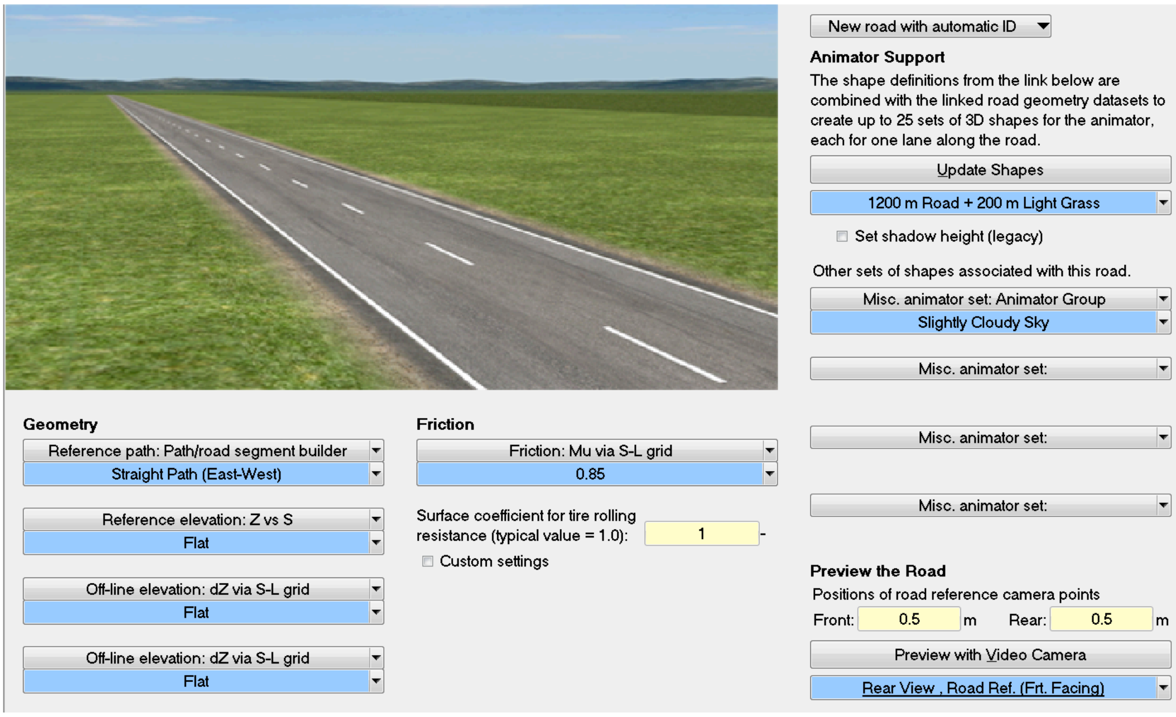


Figure 4.9 – Screen of road configuration

4.8 Tires model

The tire model screen offers several type of tire model option, in fact in the upper part of Figure 4.10 it is possible to select the suitable model and consequently the software create screens in which insert the tire characteristic.

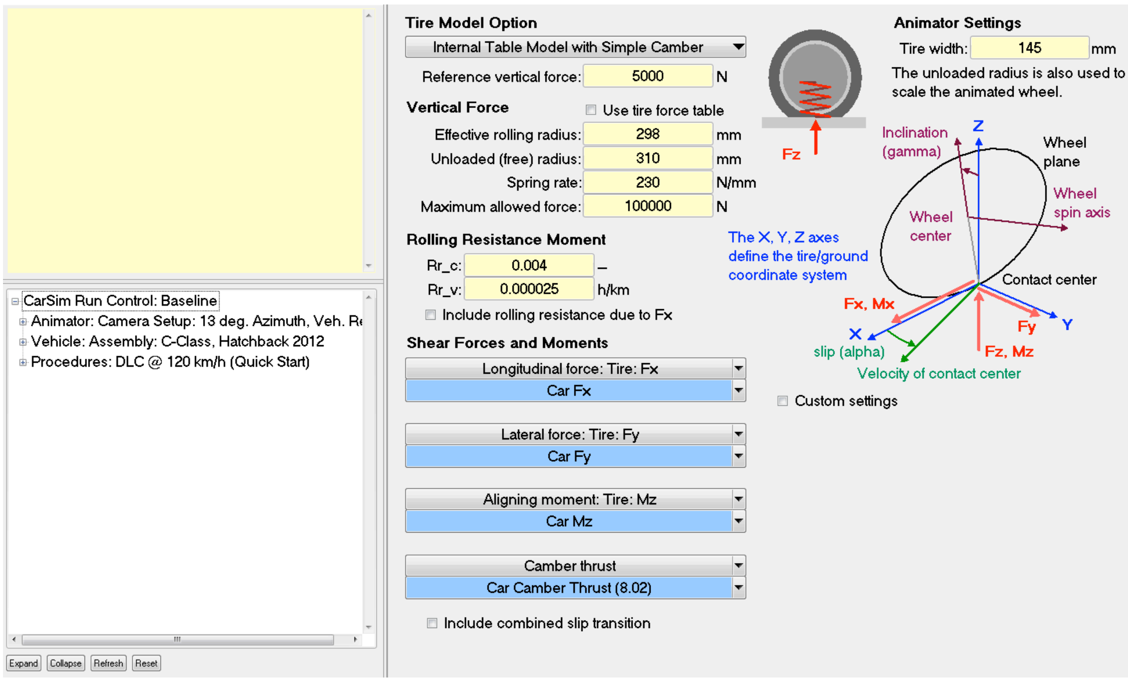


Figure 4.10 – Tire model screen

In this case the internal table model with simple camber is selected and it allows to define the following parameters [7]:

- Reference vertical force; it is not used in calculations by the solver but is provided as standard property that can be used as a built-in reference for scaling others tire properties that are related to force
- Effective rolling radius; evaluated through the measured engine and vehicle speed
- Unloaded radius; evaluated considering the tire with which the vehicle is sold
- Spring rate; is a coefficient used to develop table for tire deflection vs. load, used in the model to calculate change in vertical load due to tire compression
- Maximum allowed vertical force

5. Calibration and validation of the model

Once the three models structures are defined, a simulation of each experimental test is performed; in this way is possible to compare the experimental test with the simulated one to quantify the error of the model with respect the real vehicle behaviour. The validation is performed among three types of simulated signals:

- Current of the battery
- Voltage of the battery
- Vehicle speed

In this way both the powertrain and the driveline are considered in the validation process since the amount of delivered/recovered current by the engine is related to the torque transmitted to the driveline and consequently to the vehicle speed. The validation of the battery voltage signal is useful to calibrate the relation between voltage and state of charge.
In order to validate the model a relative error and an absolute error are defined (equation 5.1 and 5.2 respectively

$$\varepsilon_{abs} = \int_{t_0}^{t_1} \sqrt{\left(y_{\exp} - y_{comp}\right)^2}\, dt \tag{5.1}$$

$$\varepsilon_{abs} = \frac{\int_{t_0}^{t_1} \sqrt{\left(y_{\exp} - y_{comp}\right)^2}\, dt}{\int_{t_0}^{t_1} \sqrt{y_{\exp}^2}\, dt} \tag{5.2}$$

where $t_0<t<t_1$ is the time span of interest for the response history, y_{exp} is the time response of the experimental signal and y_{comp} is the output signal of the simulation.
In this way, after each simulation, it is possible to see if the actual model behaviour is close enough to the experimental one; if the result isn't satisfactory a further calibration is performed basing on the comparison between the two signals.

5.1 ECO driving mode validation results

Below are showed the validation results and the graphs of current (Figure 5.1), voltage (Figure 5.2) and speed (Figure 5.3) for the first experimental test. It has to be noticed that when the vehicle is stand still, the current delivered by the battery isn't null because some electric and electronic components of the vehicle are active even in this case (for example the ECU and the screen of the dashboard)

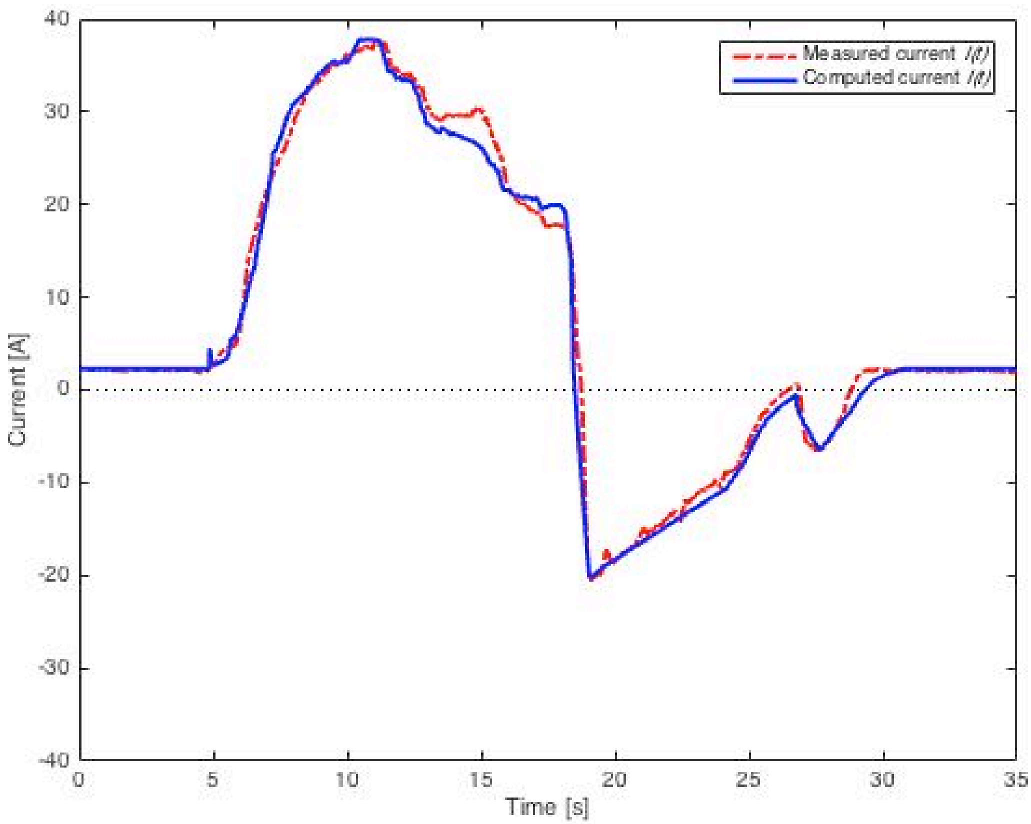


Figure 5.1 – Computed and measured current delivered by the battery in ECO driving mode

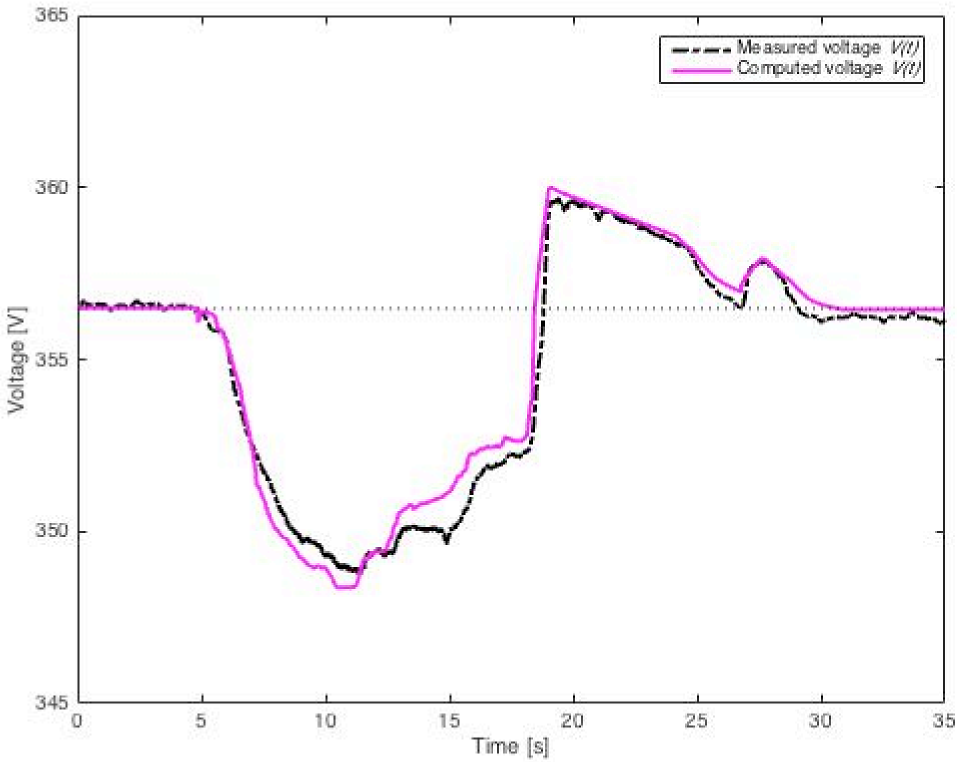


Figure 5.2 – Measured and computed voltage at the battery terminals in ECO driving mode

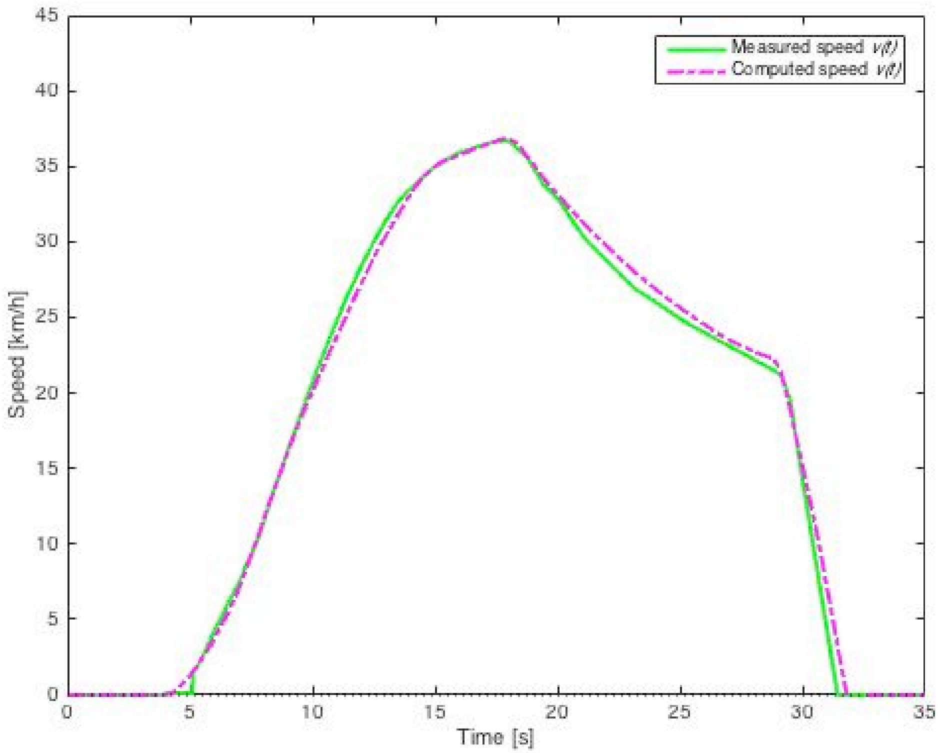


Figure 5.3 – Computed and measured vehicle speed in ECO driving mode

	Current	Voltage	Speed
ε_{rel} [%]	7,6	0,1	4,8
ε_{abs}	34,9 [A]	13,6 [V]	2,9 [km/h]

Table 5.1 – Numerical results for the absolute and relative error of the computed signals (B-Mode condition) with respect to the simulated ones

5.2 B-Driving mode validation results

In the following the validation results for the current (Figure 5.4), for the voltage (Figure 5.5) and for the speed (Figure 5.6) are reported below.

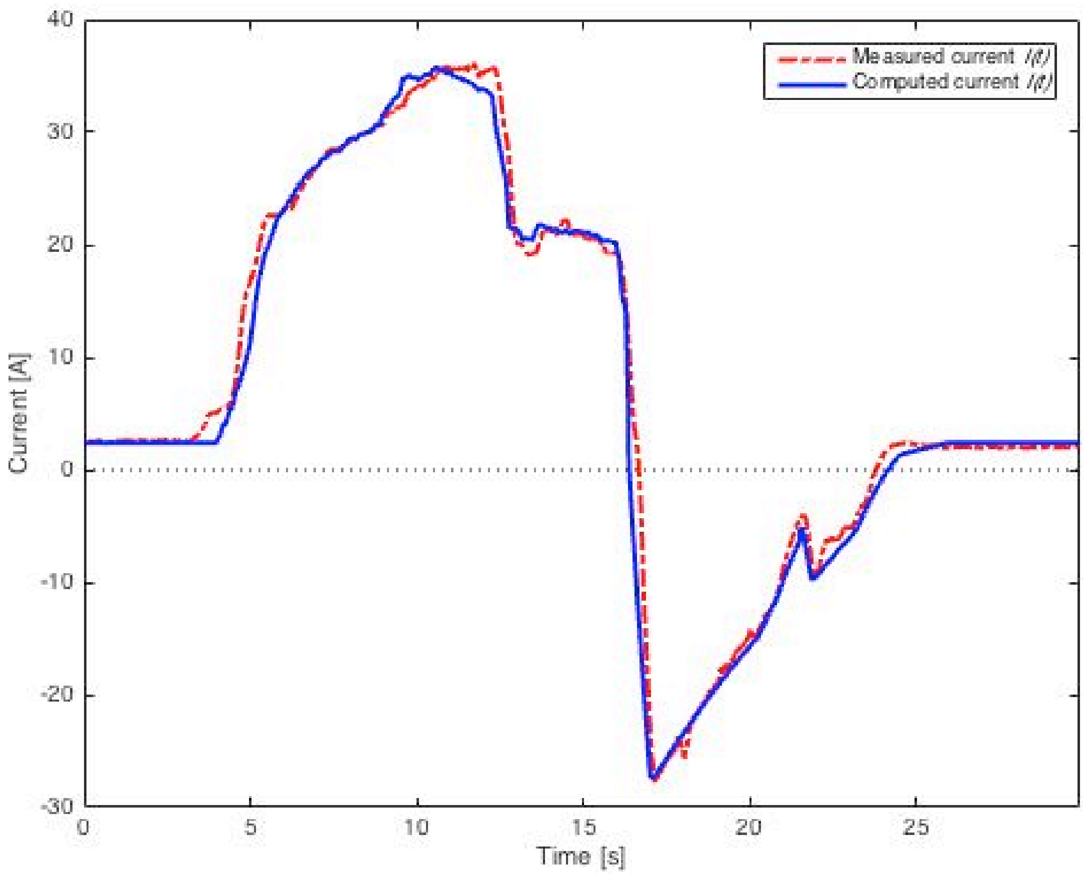


Figure 5.4 – Measured and computed current delivered by the battery in B-Driving mode

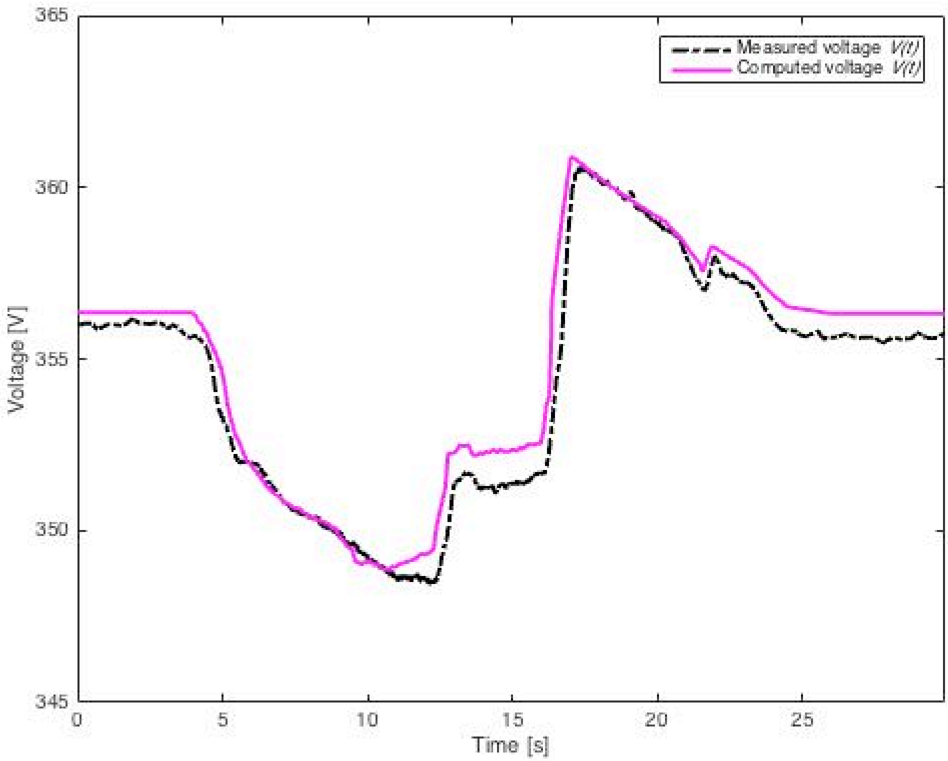


Figure 5.5 – Computed and measured voltage at the battery terminals in B-Driving mode

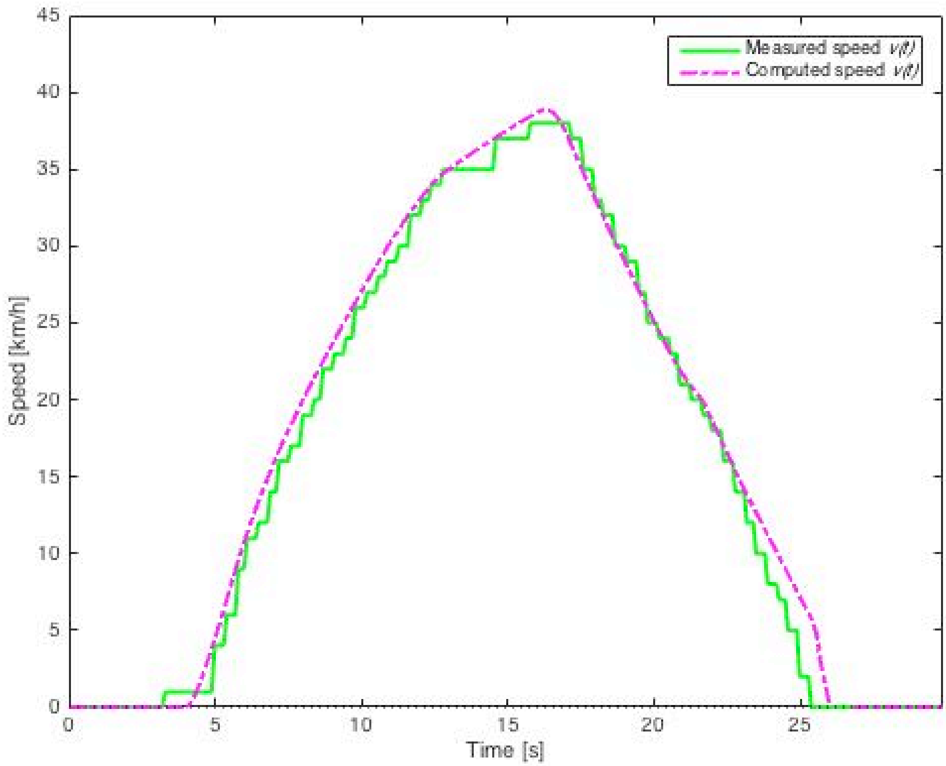


Figure 5.6 – Measured and computed vehicle speed in B-Driving mode

	Current	**Voltage**	**Speed**
ε_{rel} [%]	7,6	0,16	5,3
ε_{abs}	31,9 [A]	13,4 [V]	2,7 [km/h]

Table 5.2 – Numerical results for the absolute and relative error of the computed signals (in B-Mode condition) with respect to the simulated ones

5.3 D-Driving mode validation results

In the following the validation results for the current (Figure 5.7), for the voltage (Figure 5.8) and for the speed (Figure 5.9) are reported below.

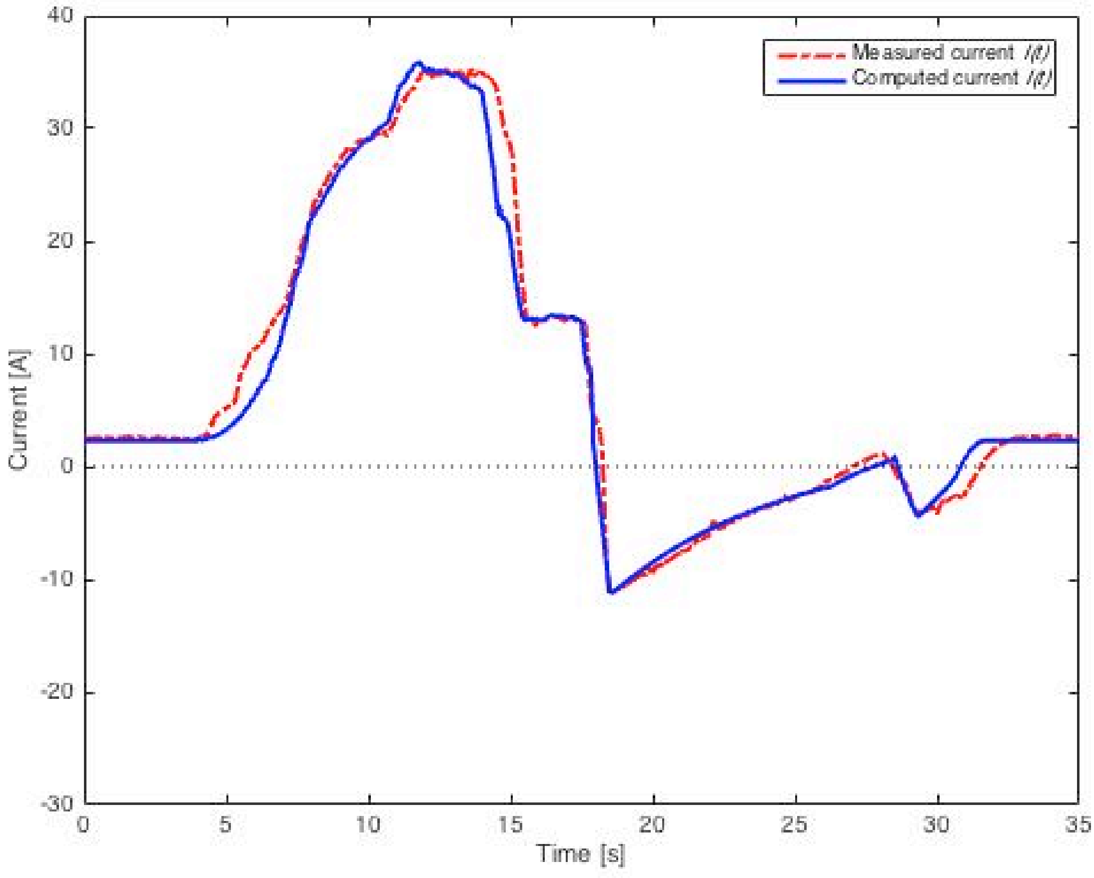


Figure 5.7 – Computed and measured current delivered by the battery in D-Driving mode

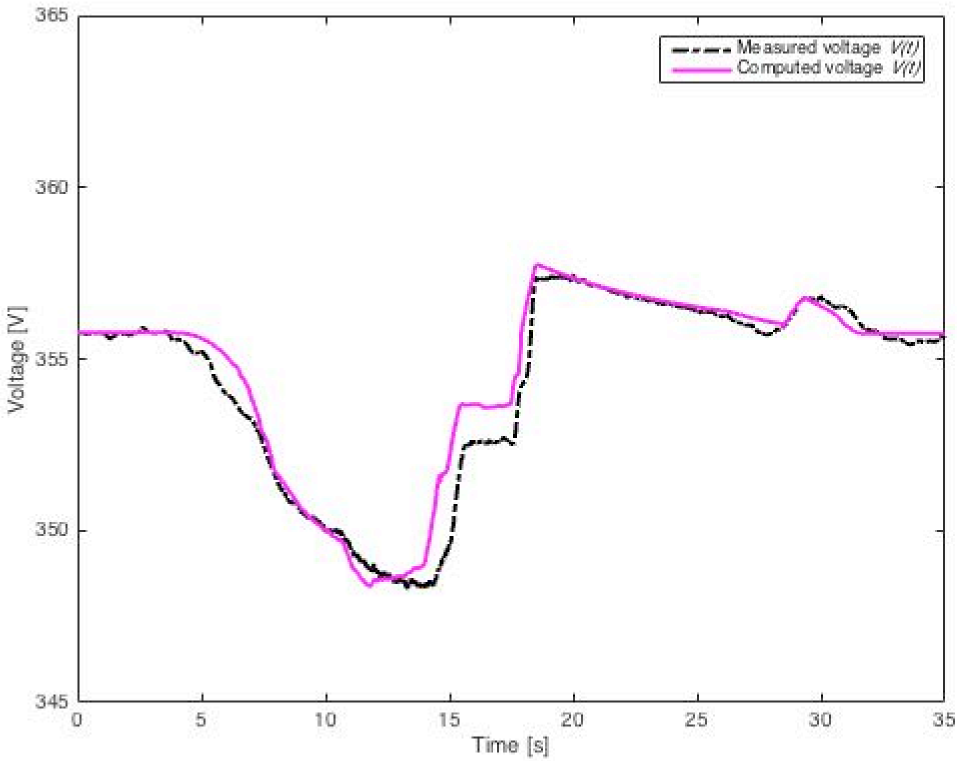


Figure 5.8 – Computed and measured voltage at the battery terminals in D-Driving mode

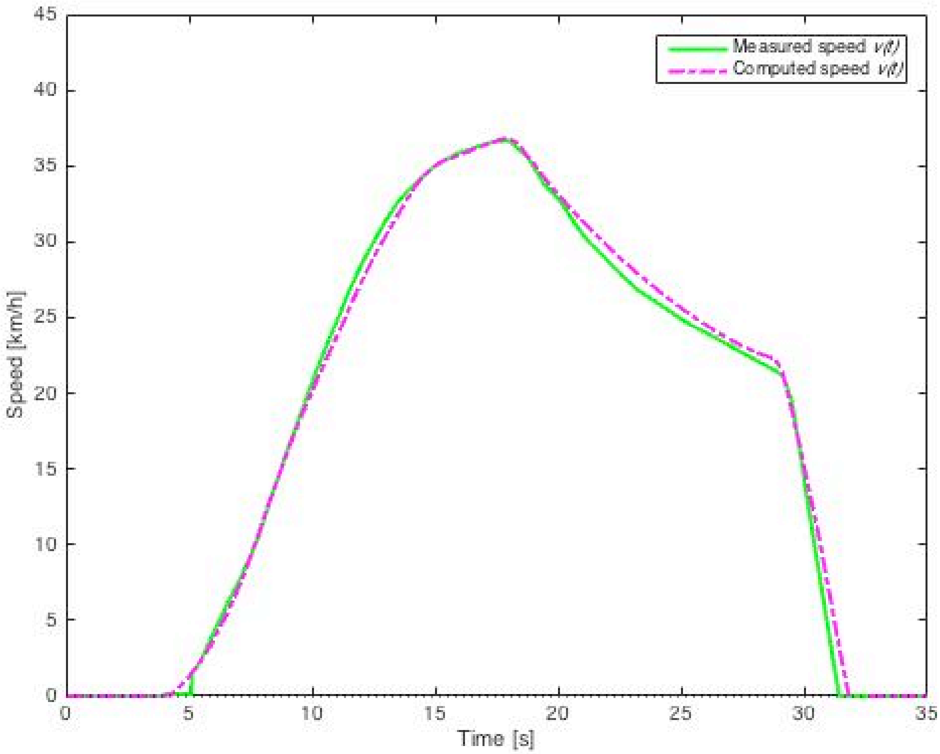


Figure 5.9 – Computed and measured vehicle speed in D-Driving mode

	Current	**Voltage**	**Speed**
ε_{rel} [%]	10,7	0,1	2,6
ε_{abs}	37 [A]	13,4 [V]	8,5 [km/h]

Table 5.3 – Numerical results for the absolute and relative error of the computed signals (in D-Mode condition) with respect to the simulated ones

Conclusions

The objective to create a model of the whole vehicle with the co-simulation method has been achieved experiencing all the advantages that this kind of method offers. The possibility to choose different simulation environment and to combine them allowed to choose AVL Cruise for its capacity to model electric powertrains and CarSim for its capacity to simulate experimental conditions and for its vastness of libraries related to drivelines. In this way the behaviour of the real sub-system can be simulated in a more accurate way. The co-simulation method offered also advantages for what concerns the development process of the model; in the first stages of the project, in fact, it was possible to model components on different simulation environment in order to check which is the solution that works better with a very low waste of time. Further more, thanks to co-simulation method, it was possible to model controls that the AVL Cruise and CarSim can't handle or can't exploit in easy way. All these characteristics make the model very adaptable to the requirements of the considered vehicle and experimental tests. In the first stages of the design process of a vehicle this method can be useful to simulate in advance, without the need of prototypes, what would be the general performances of the vehicle even in particular operating conditions.

Concerning the results obtained from the comparison between the simulated results and the experimental ones emerges that the model is a good representation of the behaviour of the vehicle in the considered operating conditions. The validation method described and applied in chapter 4 and 5 show relative errors that are in the range of the 7% for what concerns the electric machine model, the accelerator and regenerative braking control, of the 0,1% for what concerns the modelling of the *Voltage-State of Charge* characteristic of the battery and of the 5% for what concerns the driveline, body and testing condition models. For these reason the model could be eventually used to simulate the behaviour of the vehicle in different conditions from the one considered in this project and see how the powertrain and driveline behave in these conditions. In this way it could be possible to obtain good previsions, overcoming all the limitations introduced by the most widespread type approval tests, and eventually try to improve the controls of the vehicle (as accelerator or regenerative braking) in order to achieve a predetermined target in terms of energetic consumption.

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