POLITECNICO DI TORINO

Master of Science in Mechatronic Engineering

Master Degree Thesis

Hybrid electric vehicles analysis and implementation of a rule-based control strategy for a lightweight commercial vehicle

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Summary

The role of environmental protection is crucial also in the automotive field and the hybridization of commercial vehicles is a current trend. The thesis is made in cooperation with AMET; its purpose is to investigate the various solutions and to define and control a model of a hybrid electric lightweight commercial vehicle. The state of the art of hybrid electric vehicles is studied, classifying them according to the hybridization factor and the powertrain structure. The potentialities of each configuration are collected, and the main pros e cons are deduced. Usually, these solutions lead to improvements in terms of fuel consumption and CO_2 emissions with respect to conventional vehicles, by ensuring the same performances. Therefore, a reference conventional vehicle model is implemented in TruckSim. Here the vehicle is defined at the system level and is validated over the main driving cycles. Then, it is selected a parallel P2 hybrid architecture to develop the proposed hybrid electric vehicle model. All the additional components proper of the hybrid powertrain are implemented in MATLAB/Simulink. Especially, the electric machine and the battery models are defined in Simulink, using a model-based approach. A PMSM as electric machine and a Li-ion battery, modelled with the Thevenin model (or Dual Polarization), are proposed. One of the crucial points in hybrid electric vehicles is the control strategy. An accurate control algorithm is fundamental to exploit all the hybrid powertrain potentialities. In this work, a power management strategy to optimize the power flow between the power sources is proposed. It is a rule-based control strategy implemented through Stateflow charts; based on the requested power at the wheels, four different operating modes are defined. Lastly, the hybrid electric vehicle is co-simulated between Simulink and TruckSim. Compared to the conventional vehicle model, an improvement

in terms of fuel consumption in the hybrid vehicle model is achieved and discussed.

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Chapter 1

Introduction

The European Green Deal aims to achieve a carbon-neutral Europe by 2050. This requires the decarbonization of all sectors. The transport sector is responsible for nearly a quarter of Europe's greenhouse gas emissions. Indeed, in recent years the transport sector (Figure 1.1) has not followed the general trend of the overall reduction in greenhouse gas emission. Specifically, according to the European Environment Agency, road transport constitutes the highest proportion of overall transport emissions [1]. In this context, manufacturers develop new products like hybrid electric vehicles, electric vehicles, or fuel cell hybrid electric vehicles to invert this trend. Thus, road transport is expected to decrease relatively quickly.

In the last 10 years, hybrid electric vehicles are quickly grown up. The need to reduce environmental pollution is such that hybrid electric vehicles are the perfect trade-off between the high CO_2 emissions of conventional vehicles and the not too cost-effective solution of electric vehicles. In this direction, hybrid traction is a smart choice for lightweight commercial vehicles too.

Thanks to the combination of the two complementary propulsion systems, lightweight commercial vehicles are suitable for different missions. The performances very near to the conventional vehicles guarantee the transport over the medium distance, but, at the same time, the pure electric

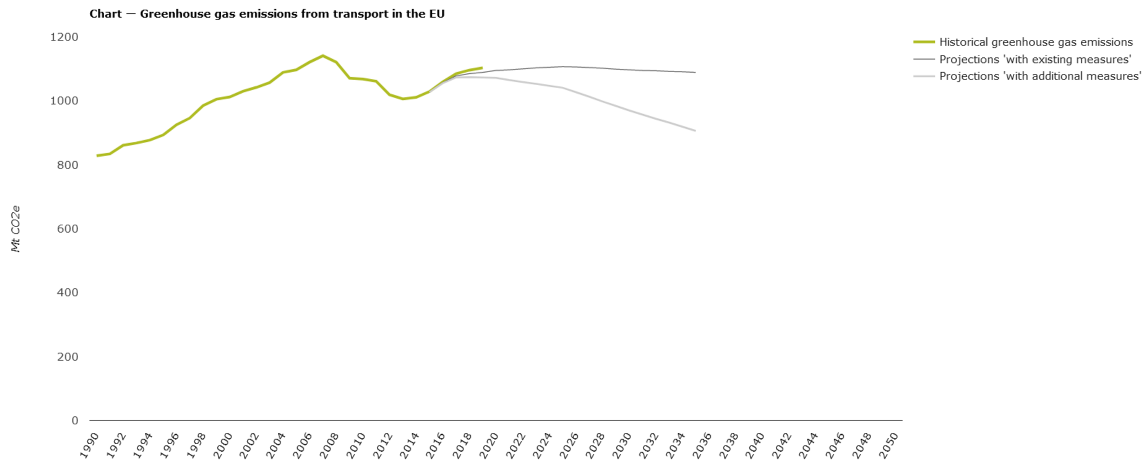


Figure 1.1: Greenhouse gas emission from transport in UE [1]

mode is more appropriate to the urban driving. In this way, it is possible to take care of the increasingly more restrictive goals related to fuel consumption and CO_2 emissions. The additional cost of the hybrid electric vehicle is balanced by the reduced fuel consumption and the highest operability in front of commercial activity limitations.

Hybrid vehicles are based on three main powertrain architectures. Depending on the automotive sector of the hybrid electric vehicle, one is more appropriate than the others. The main challenge is to control optimally the hybrid vehicle. A fundamental role is reserved for the control algorithms since it is essential to optimize the cooperation of the two energy sources and, at the same time, guarantee robust driveability and vehicle road performances.

All these features are considered in the following sections. A first description of the hybrid technology and an analysis of the actual state of the art are described in Chapter 2. Then, the reference model of the conventional vehicle is presented in Chapter 3. Chapter 4 contains the analysis of the electric domain components proposed to hybridize the vehicle and in Chapter

5 is presented the rule-based control strategy implemented. Finally, the experimental results are shown and discussed in Chapter 6, and in the last section the achieved objectives and possible future works are described.

Chapter 2

State of Art of Hybrid Electric Vehicles

A vehicle with more than one power source is called hybrid vehicle. There are different kinds of hybrid vehicles according to the types of power used to propel them. The most common are hybrid electric vehicles and fuel cell vehicles. The latter are based on a relatively innovative technology but too expensive, whereas the formers are widely spread in the industry. Hybrid electric vehicles are characterized by a primary power source (the combustion engine) and one or more electric motors. There are conditions in which the engine does not provide optimal performance, so it is useful to support it with the electric motor. The flexibility of these vehicles represents a good trade-off between performance and environmental protection, unlike pure electric vehicles, which are optimal in terms of emissions and fuel consumption but often do not guarantee the same road performances of the conventional vehicles.

2.1 HEV classification

Depending on the hybridization factor (HF), i.e. the ratio between the electric power and the overall power of the system, hybrid electric vehicles are classified into [2]:

1. *Micro hybrid*: vehicles equipped with a small electric motor (belt alternator starter) used for support operations without affecting the propulsion. It is mainly exploited as a starter of the vehicle. Indeed, it is usually integrated with the Start-Stop system: the Internal Combustion Engine (ICE) is turned off during the stop to reduce its inactivity time, decreasing emissions and fuel consumption. This configuration is convenient primarily for a vehicle that spends a lot of time in traffic.

2. *Mild hybrid*: architecture in which the conventional ICE cooperates with an electric motor, and both can power the vehicle simultaneously. The power provided by the electric motor is such as to support the ICE in operations like braking or stopping. These vehicles implement some features typical of full hybrid vehicles, but unlike the latter, they do not implement a purely electric propulsion mode, nor do they achieve the same levels of fuel economy.

3. *Full hybrid*: vehicles made up of an internal combustion engine as the primary source of power and one or more electric motors. Full hybrid vehicles can move in pure electric mode and, depending on the powertrain structure, there are different configurations [2]: series hybrid, parallel hybrid, series-parallel hybrid.

2.1.1 Series HEV

The series hybrid propulsion is one of the powertrain configurations for full-hybrid electric vehicles. In series electric hybrid vehicles (Figure 2.1) the electric motor gives motion to the wheels and the ICE is not mechanically connected to the transmission. In this way, since the ICE speed is totally independent of that of the vehicle, it works in the range of greater efficiency, ensuring a significant reduction in terms of fuel consumption. In series hybrid electric vehicles, the generator converts the engine mechanical power

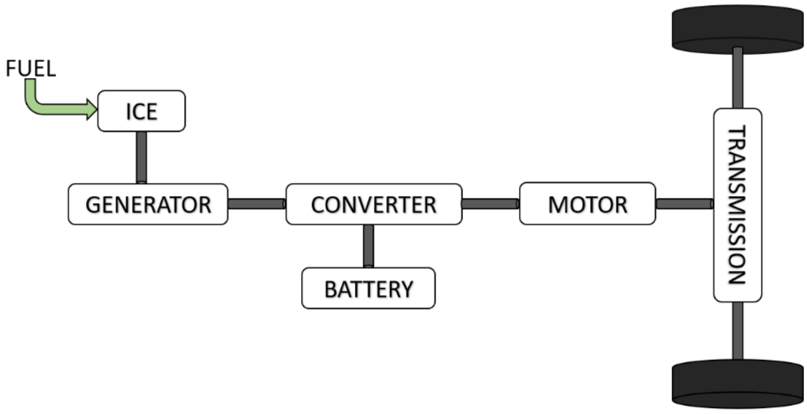


Figure 2.1: Series HEV architecture

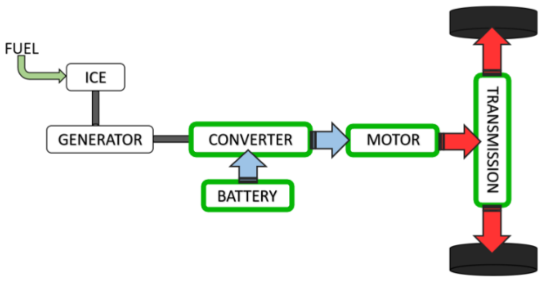
into electricity, and the power flow is combined with the electric power supplied by the battery. The electric power is then converted by the electric motor into mechanical power to move the vehicle. Usually, during urban driving, the ICE is turned off and the battery provides the necessary power to the engine. When, on the other hand, the battery level is low or during extra-urban driving, the ICE is turned on. In that case, if the power required by the electric motor is less than the amount supplied by the generator, the surplus power is used to charge the battery pack; otherwise, the battery provides the difference.

The main drawbacks of series hybrid vehicles are the low efficiency due to multiple power conversions and the use of large components, necessary to provide high power and suitable vehicle performance. Indeed, this configuration is not much used in lightweight vehicles, while it is often implemented in vehicles such as city buses or locomotives, where it is easier to arrange the powertrain and implement the control strategy.

Depending on the driving condition, the power flow of the series hybrid electric vehicle (Figure 2.2) is the following:

- Start: the ICE stands turned off and only the electric motor is used; all the power comes from the battery.

- Passing: the electric motor gets power from the battery and the ICE, whose torque is converted into electricity via the generator.
- Cruising: at a constant speed, the ICE provides the energy required by the electric motor for traction and the surplus is used to charge the battery.
- Brake: the braking power is regenerated by the electric motor and is used to charge the battery. The ICE can also continue to charge the battery if needed.



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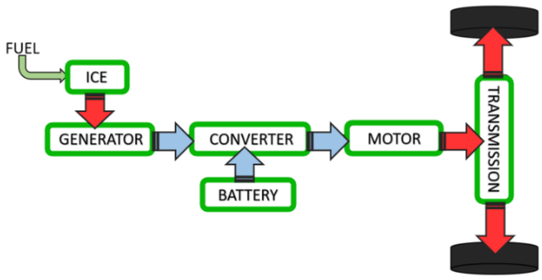

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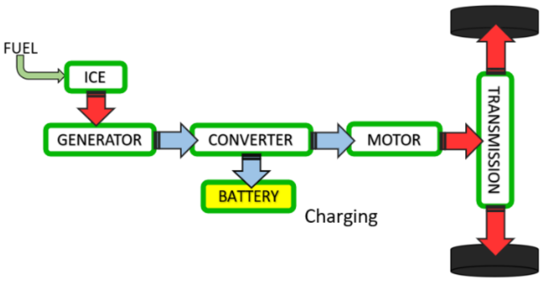

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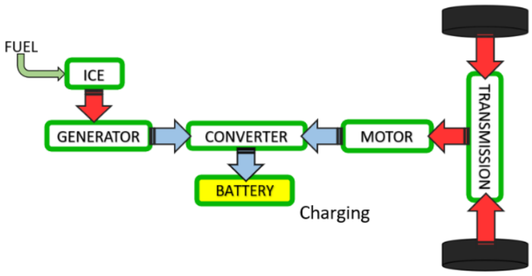


Figure 2.2 d.

Figure 2.2: Power flow in series HEV: in red colour the mechanical power flow, in blue colour the electric power flow (a. start, b. passing, c. cruising, d. brake)

2.1.2 Parallel HEV

In parallel hybrid electric vehicles (Figure 2.3) the ICE and the electric motor are both mechanically linked to the transmission. With this configuration, the power flow is mainly mechanical. Indeed, the vehicle propulsion takes place with only the thermal engine or in pure electric mode, especially when the ICE is not efficient - at low speeds; when the power demand is higher, the electric motor and the ICE supply the transmission together. Therefore, it is clear how it is necessary to introduce a mechanical coupling before the transmission, to handle the torques of both sources. As a result, the overall vehicle structure and the control strategy are more complex.

However, the parallel hybrid vehicle structure, compared to the series architecture, allows reducing the size of the ICE and the electric machine, ensuring the same performance. But, unlike series hybrids, the rotation speed of the ICE is correlated with the vehicle speed; hence, the ICE does not always work in the maximum efficiency area.

The electric machine position defines different configurations of parallel hybrid, classifying them in three groups:

- P1, when the electric machine is placed before the transmission and before the clutch.
- P2, when the electric machine is placed before the transmission but after the clutch.
- P3: when the electric machine is placed after the transmission, maximizing the regenerative braking.

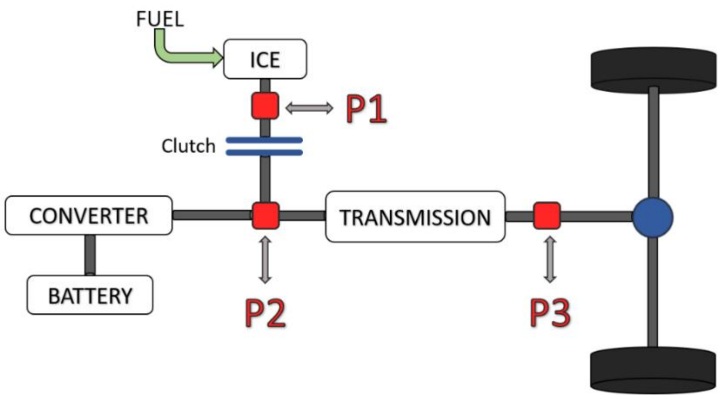


Figure 2.3: Parallel HEV architecture

Referring to a P2 parallel hybrid configuration, the power flow in the main missions (Figure 2.4) is the following:

- Start the only electric motor handles the start, exploiting the electric power coming from the battery. The clutch prevents the activation of the ICE for the transmission.
- Passing: both sources supply the propulsion, by adding together the torques. The electric motor gets power from the battery.
- Cruising at a constant speed the engine provides the required power for propulsion and to recharge the battery, through the electric motor that works in generator mode.
- Brake: the braking power is regenerated by the electric motor, and it is used to recharge the battery.

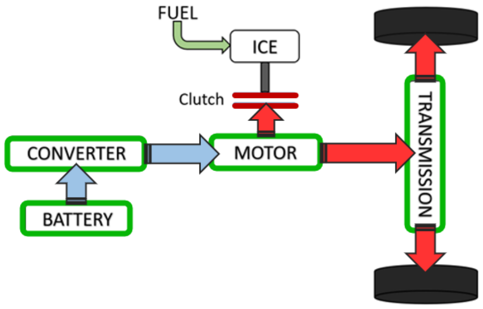
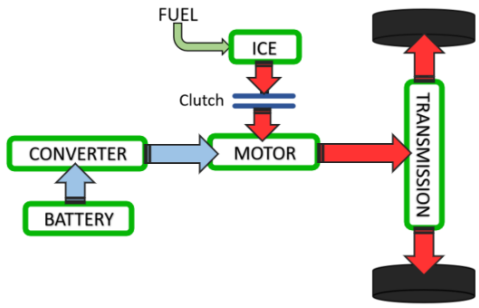


Figure 2.4 a.



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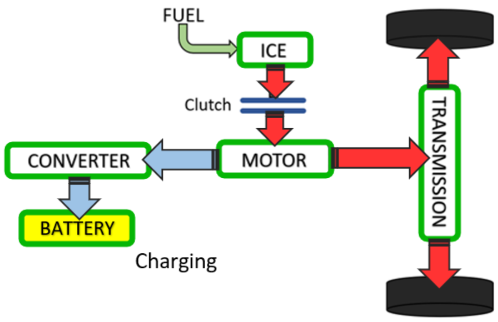

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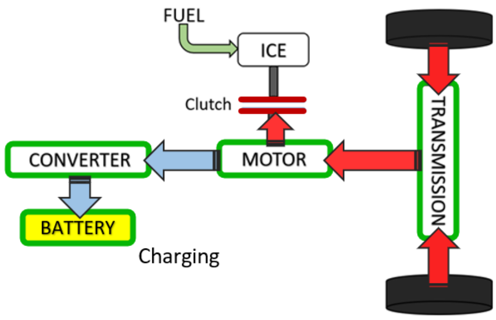


Figure 2.4 d.

Figure 2.4: Power flow in parallel HEV: in red colour the mechanical power flow, in blue colour the electric power flow (a. start, b. passing, c. cruising, d. brake)

2.1.3 Series-parallel HEV

The series-parallel or power-split configuration (Figure 2.5) combines features typical of series and parallel hybrid electric vehicles. It increases the flexibility of the vehicle, but the structure is more complex. Two electric machines are introduced: a motor-generator placed between the ICE and the battery pack – mainly intended to recharge the battery – and an electric motor that provides the necessary power for propulsion. The mechanical axes are joined by a planetary gear, which handles the power flow according to different driving conditions. In this way, part of the power supplied by the ICE is used to move the vehicle directly, the other to recharge the battery.
Therefore, it is possible to power the vehicle in hybrid mode or in full-electric mode, taking advantage of the electric motor and, when needed, the motor-generator (in motor mode).

Using this architecture, it is possible to exploit the advantages of series and parallel architectures. The whole system works optimally and deletes the drawbacks of previous configurations, at the expense of greater complexity in terms of control and vehicle structure.

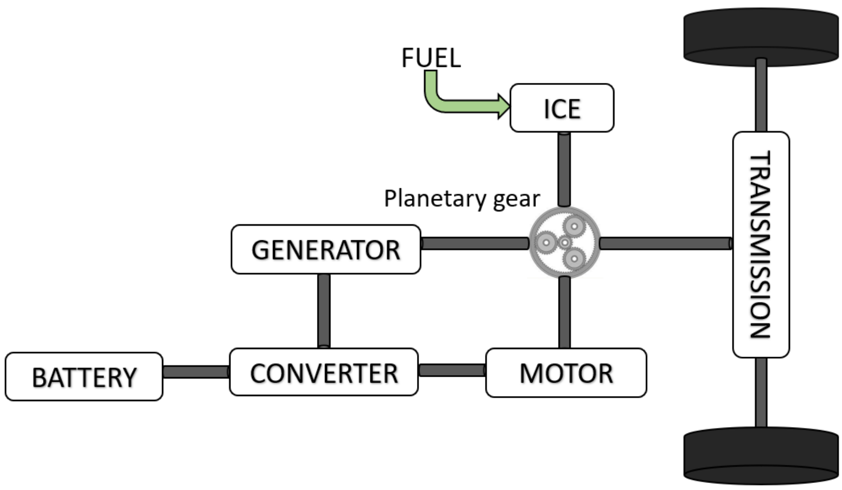


Figure 2.5: Series-parallel (power-split) HEV architecture

The power flow of the series-parallel hybrid electric vehicles (Figure 2.6) is the following:

- Start: only the electric motor is used, exploiting the electric power coming from the battery.
- Passing: both sources supply the propulsion, by adding together the torques. The electric motor gets power from the battery.
- Cruising: at a constant speed the ICE provides the required power for propulsion and to recharge the battery, through the motor-generator. Unlike the parallel architecture, thanks to the motor-generator, the engine can work in the range of greater efficiency.
- Brake: the braking power is regenerated by the motor-generator, and it is used to recharge the battery.

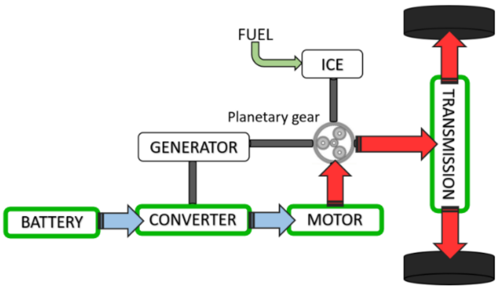
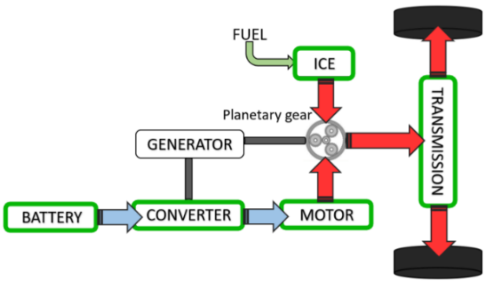


Figure 2.6 a.



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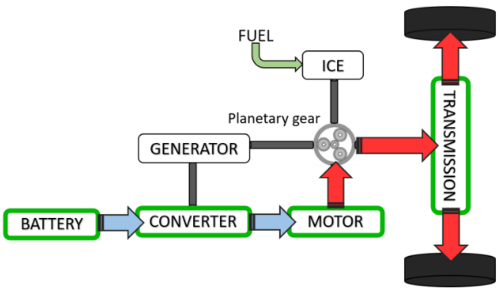

Figure 2.6 c.

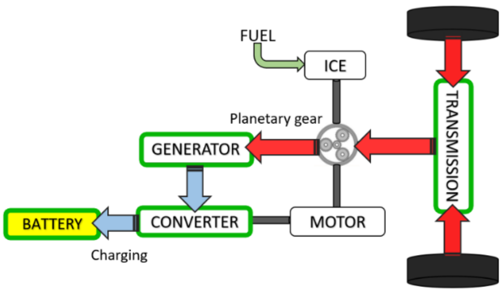

Figure 2.6 d.

Figure 2.6: Power flow in series-parallel HEV: in red colour the mechanical power flow, in blue colour the electric power flow (a. start, b. passing, c. cruising, d. brake)

Table2.1: Full hybrid architectures comparison

Architecture	Pros	Cons
Series	Good control of the ICE working point Low constraints in control strategy Pure electric mode	Low energetic efficiency Full ICE mode not enabled
Parallel	Good energy efficiency One electric motor only Pure electric mode	Complex control strategy The ICE could not be in high efficiency range
Series-parallel	Very good control of the ICE working point Pure electric mode	Many constraints in control strategy More than one electric motor Complex structure

It can be noted that, in addition to the pros and cons of the different configurations of full hybrid vehicles shown in Table 2.1, as the main drawback in common to all types is that the batteries are only recharged by recovering power from the primary resource or by regenerative braking. This critical issue is not valid for Plug-in hybrid vehicles, i.e. vehicles that meet the following requirements [2]:

– A battery system of at least 4kWh to power motion.
– A means of recharging from an external electrical source.
– An ability to drive 10 miles (16 km) in pure electric mode.

Plug-in hybrid vehicles arrange their powertrain in one of the previous architectures, but thanks to the possibility to recharge the battery from an external grid, optimize the control strategy for reducing consumption, rather than giving priority to maintaining the state of charge above a minimal level. In addition, unlike pure electric vehicles, the battery must not be recharged from an external source, making them more flexible than electric vehicles.

Lastly, the types of hybridization described have lower consumption and emissions than a conventional vehicle powered only by the thermal engine, although they retain almost the same performance. At the same time, each architecture brings with it advantages and disadvantages, such that it is necessary to make a trade-off in the choice of one rather than the other. Typically, to hybridize a vehicle already configured with a thermal engine, parallel architecture is used, as it is enough to integrate the electrical part. However, the main drawback of this approach is that the ICE is sized for standard uses, so it turns out to be oversized for a hybrid electric vehicle. Therefore, the choice of car makers often falls on the implementation of power-split HEV [3], which even with greater complexity in terms of components adopted, ensure optimal performance in the most controversial driving conditions too.

Chapter 3

Reference vehicle model

3.1 Model environment

The objective of the thesis is to propose a suitable hybridization of a conventional lightweight commercial vehicle (LCV). To do that, first the conventional model is defined starting from a reference one. The model should reproduce accurately the physics of the vehicle, to simulate its dynamic behaviour and perform consistent analysis according to several missions. Therefore, the environment used to define the conventional model is TruckSim (Figure 3.1). It is a software provided by Mechanical Simulation, useful for analysing vehicle dynamics, developing active controllers, and computing performance characteristics. The TruckSim math models are represented at the system level, meaning the vehicle data are intended to be measured or computed and do not depend on detailed knowledge of component materials or other too much low-level information. This approach is an appropriate solution to the high number of components involved in the overall design of the vehicle. All the components will be treated as a set of rigid bodies and the VehicleSim (VS) Solver solves their equation of motion, as sub-systems of the full vehicle model. The equations of motion for multibody models are machine-generated by a symbolic multibody program called VS Lisp. For this purpose, the main components are defined through parameters (measurable properties) and variables. The model of the conventional LCV is presented including sprung and unsprung mass, engine transmissions, and wheels. All the required data are introduced according to the reference model, a 35 quintals LCV with 3 dm^3 of cubic capacity, 150 kW of maximum power, and rear-wheel drive (RWD).

Figure 3.1: TruckSim logo

3.2 Vehicle dynamics

An accurate definition of the vehicle model requires an appropriate description of the vehicle dynamics. The longitudinal dynamic is mainly considered since it is possible to derive the traction force needed by the vehicle in presence of all the friction losses and knowing the weight of the vehicle. The schematic representation is reported in Figure 3.2, where the aerodynamic drag force is applied at the centre of gravity of the vehicle, the rolling friction force at the intersection between the tire wheel and the road surface. Then, L is the wheelbase – the length between the centre of the front and rear wheels – hg is the height of the centre of gravity from the ground. These features are implemented to reproduce accurately the vehicle behaviour; however, some parameters are obtained directly from the datasheet of the reference vehicle, others result from vehicle dynamic theory. All the future considerations are referred to an inertial reference frame fixed on the road (X,Y,Z) and a right-hand vehicle-fixed reference frame (x,y,z), that moves with the vehicle and is centred in its sprung mass. The forward direction is along the x-axis, whether the z-axis points upwards, and the y-axis is perpendicular to the other two, oriented in the lateral direction of the vehicle.

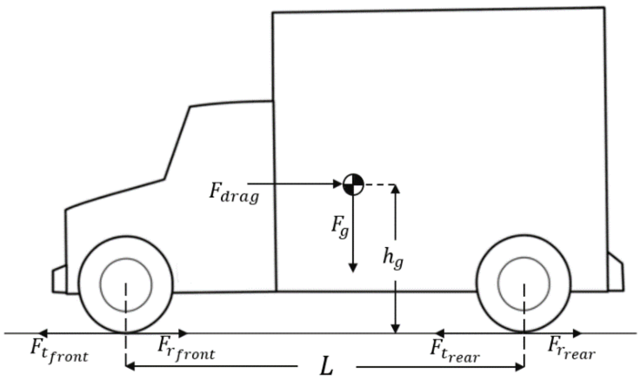

Figure 3.2: Vehicle dynamic diagram

3.2.1 Aerodynamics

The aerodynamic force acts on the vehicle when it moves, especially its contribution is relevant when the velocity increase since it is proportional to the square of the velocity. To evaluate properly its effects, it is necessary to test the vehicle in the wind tunnel and analyse the effect of the air flow around it. From this kind of experimental testing, the aerodynamic force F_a is expressed as:

$$F_a = \frac{1}{2}\, \rho\, V^2 S\, C_a \tag{3.1}$$

where $\frac{1}{2}\, \rho\, V^2$ is the dynamic air pressure, $\rho = 1.225\ kg/m^3$ is the air density, V is the relative airspeed, S is the aerodynamic cross-section and C_a is the drag coefficient, based on the geometry of the vehicle concerning the wind flow. Its numerical value strictly depends on the aerodynamic cross-section S, which should include the tires and the underbody part [4], as reported in the following figure (Figure 3.3):

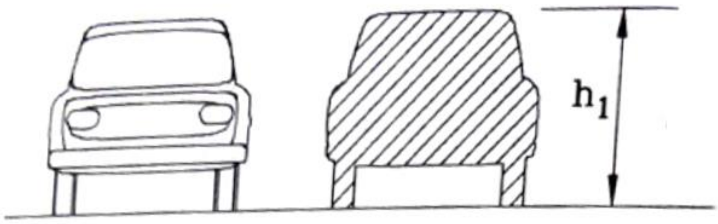

Figure 3.3: Definition of the surface S and of the overall height h [4]

The numerical value is obtained from the following expression:

$$S = \psi \, t \, h_1 \tag{3.2}$$

where ψ is a coefficient that takes a value between 0.85 and 0.95, t is the front track and h_1 is the overall height of the vehicle.

In the math model proposed in TruckSim aerodynamics effects are represented by a force vector acting on a point in the sprung mass. The point is called the aerodynamic reference point and is placed in the ground plane at the centre of the wheels. With this convention, the force is always applied at the same point in the sprung mass regardless of its orientation in space.

3.2.2 Tires

The pneumatic tires have an important role in the dynamic behaviour of the vehicle. When the vehicle moves forward a normal force is generated between the tire and the road contact surface. It is assumed to be located at the centre of the contact area and is proportional to the weight of the vehicle. Therefore, the tire is fundamental in distributing the vertical load to ensure adherence on the road. The increase of the normal force produces a deformation of the tire. To take into consideration this phenomenon, should differentiate the radius of a rigid wheel R with respect to the effective rolling radius R_e. R_e is the radius of a rigid wheel that travels and rotates at the same speed as the pneumatic wheel [4]. Accordingly, the following relation holds:

$$R_l < R_e < R \tag{3.3}$$

where R_e is the effective rolling radius, R is the rigid wheel radius – also called unloaded radius – and R_l is the loaded radius. Hence, R_e does not correspond to the loaded radius R_l nor to the unloaded radius R, and the centre of instantaneous rotation is different from the centre of contact A (Figure 3.4).

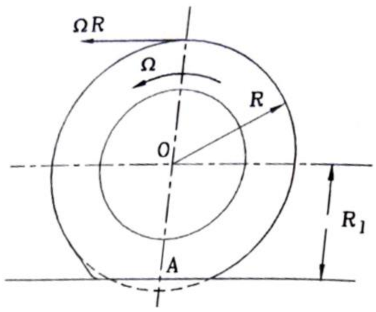

Figure 3.4: Loaded and unloaded tire radius [4]

The effective rolling radius depends on many factors, like the structure of the tire. Basing on this data, it is designed in the TruckSim math model. In general, a tire is defined by a group of indexes that refer to some properties, as shown in the following figure (Figure 3.5):

Figure 3.5: Tires indexes

The first number refers to the section width and it is expressed in millimetres, whether the second value is the ratio between the sidewall and the section width, in percentage. Then the letter R stands for the type of tire (R = radial in this case) and the number 17 for the rim diameter, expressed in inches. The last couple of values are, respectively, the load index – in pounds – and the speed index.

The tire structure of the reference model is:

$$195/75 \quad R\,16 \quad 110/108 \quad R$$

where the two load indexes refer to single or dual tire structures. 108 is the load index used for the computation of parameters on the rear wheels, since there is a dual tire, while 110 is used for the values on single front wheels. Basing on the previous data, the tires parameters are defined. Particularly, for radial tires it is possible to define R_e and R_l respectively equal to 98% and 92% of R [4]. Hence, the effective rolling radius used in the simulation is:

$$R_e = 342{,}46\ mm$$

And the unload radius is:

$$R = 349{,}45\ mm$$

As it is stated above, when the vehicle moves the tire is continuously deformed in the contact zone with the road. This deformation is produced by an energy dissipation, which in turn causes rolling resistance. It is the force applied at the centre of the wheel directed opposite to the vehicle's direction. For practical purposes, rolling resistance is expressed as:

$$F_r = -f\ F_z \tag{3.4}$$

where f is the rolling resistance coefficient and depends on various factors. For this reason, it is experimentally determined and is strictly related to the kind of tire and its efficiency consumption, since the dissipated energy impacts the fuel consumptions too. In the math model designed, all these features are considered to define the rolling coefficient f equal to 0,0098.

It is obtained from the efficiency consumption index 'E' declared by the OEM, which corresponds to the previous value according to the EU regulation on the labelling of tires concerning fuel efficiency [5].

3.2.3 Size and weight distribution

The weight distribution into a vehicle is crucial to provide realistic behaviour in terms of stability and performance analyses. In the math model defined in TruckSim first is described the vehicle in unloaded condition. Rather than the 3500 kg of the lightweight truck, the mass of the vehicle in running order is used, i.e. 2491 kg. A relevant analysis is reserved for the sprung mass since the vehicle-fixed reference frame is attached to it.

Describing it in more detail, the origin of the sprung mass coordinate system is located at ground level and aligned with the front axle of the vehicle. With this assumption, the x-axis points forward along the longitudinal direction, the z-axis points up parallel to gravity, and the y-axis points to the left along the lateral direction. By knowing the centre of gravity of the whole unloaded vehicle, the sprung mass is defined as reported in Figure 3.6, where the lateral coordinate is null since the vehicle is laterally symmetric.

Finally, the defined mass for the sprung mass is 2191 kg. This value is the mass of the vehicle without payloads as previously mentioned – also called curb mass – minus the contributions of tires, axes, and other components related to the unsprung mass.

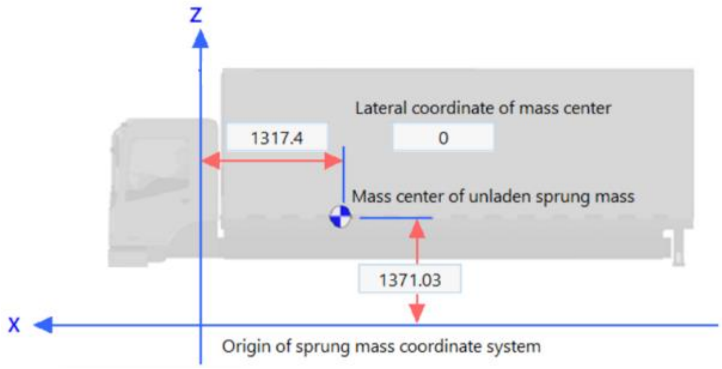

Figure 3.6: Sprung mass dimension in TruckSim (all values are expressed in millimeters)

All these values influence the roadholding of the vehicle but also the fuel consumption. Indeed, in Chapter 6 the rigorous validation of the reference vehicle model will be done according to some requirements on the fuel consumption declared by the OEM.

3.3 Powertrain model

In this section are described all the components that constitute the powertrain of the conventional reference vehicle, i.e. the chain of elements that transfer the power generated by the power source to the wheels of the vehicle. This is the core of the present work, meaning that it is the vehicle model part that will be modified by the proposed hybrid model.

Usually, a conventional powertrain is made up of the engine, the mechanical clutch, and the transmission, divided into gearbox and differential (Figure 3.7). Basing on both the reference values from the OEM and the theoretical/experimental modelling, these components are suitably defined in the TruckSim math model.

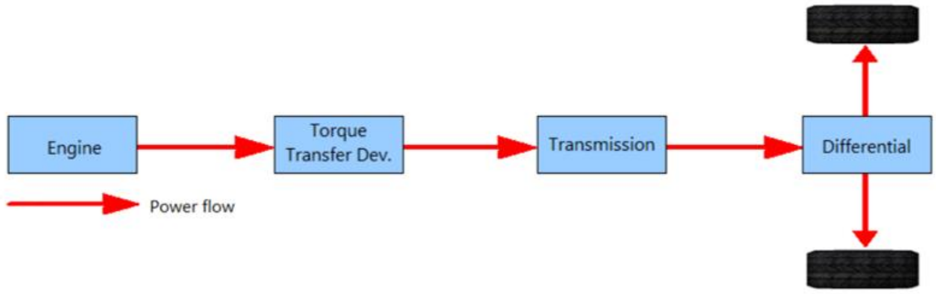

Figure 3.7: Powertrain model in TruckSim

3.3.1 Internal Combustion Engine

The internal combustion engine is the power source of the conventional vehicle. Its characteristics depend on the combustion process, a non-linear process and so difficult to be expressed into a math model. To consider the conversion of the chemical energy of fuel into mechanical energy on the output shaft, usually two modelling methods exist: theoretical and experimental-data-based modelling. The former is based on the engine dynamic model in which many aspects related to thermodynamic and fluid dynamic must be considered. This approach is too complex due to the amount of information needed and has a time-consuming computation. On the other hand, the experimental-data-based modelling is more generic and based on the input-output relationship of the model [6]. Through experimental measurements, the data collected into look-up tables are used to quantify and simulate the engine working features. The accuracy of the experimental data is not optimum, so this is the main drawback of this approach.

In the presented work, an experimental-data approach is used. Particularly, the main aspects analysed to reproduce an accurate model of the engine are related to its torque characteristic and its fuel consumption.

These features are slightly connected since the torque is produced by burning the right amount of fuel. Thus, a common way to present the engine operating conditions is to plot brake specific fuel consumption (BSFC) over engine full load and speed range [7]. Generally, the BSFC map is measured through a bench test based on the amount of fuel required by the engine to produce mechanical power. The fuel mass flow rate is measured on a dynamometer. By dividing the fuel mass flow rate by the engine output power, the brake specific fuel consumption is obtained:

$$BSFC = \frac{\dot{m}_f}{P_e} \tag{3.5}$$

where $\dot{m}_f$ is the fuel flow rate in kg/s, P_e is the engine output power in W and so the BSFC is expressed in kg/J. Conventionally, the brake specific fuel consumption is expressed in g/kWh, hence the following relation holds:

$$BSFC = \frac{\dot{m}_f}{P_e}\,3600 \tag{3.6}$$

where $\dot{m}_f$ is in g/s and P_e in kW.

However, based on the available data it is not possible to reproduce accurately the efficiency map of the reference vehicle engine. An experimentally derived efficiency map is adapted to the engine of the proposed model (Figure 3.8). It represents the brake mean effective pressure (BMEP) versus engine speed, with brake specific fuel consumption contours. It is referred to as a diesel engine too, but with 2.5-liter of cubic capacity with respect to the 3-liter of the reference vehicle. The maximum torque and the engine speed are proportionally shifted of a factor proportional to the given maximum brake mean effective pressure, expressed as:

$$p_{me} = T_e \frac{2\pi}{V} i \tag{3.7}$$

where T_e is the engine torque in Nm, V is the engine cubic capacity in dm³ and, i is the number of revolutions per cycle ($i = 1$ for two-stroke engines, $i = 2$ for four-stroke engines).

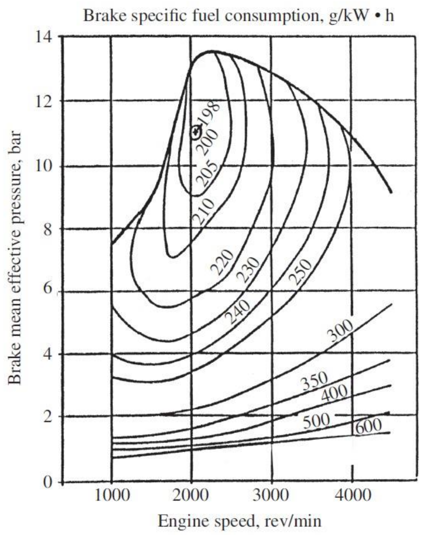

Figure 3.8: BMEP plot from "ICE fundamentals" [8]

From these considerations, the efficiencies about the conventional model are collected and processed on MATLAB, obtaining the BSFC map reported in Figure 3.9, in which are reported the brake specific fuel consumption contours and the maximum torque characteristic versus the engine speed.

Therefore, from the efficiencies defined in Figure 3.9, the fuel mass flow rate is defined. In this way, TruckSim VS Solver can compute the fuel rate of the vehicle in a defined mission.

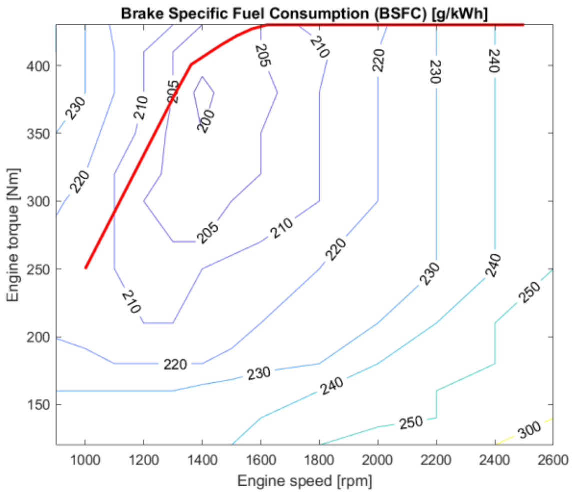

Figure 3.9 a: BSFC MAP contour plot

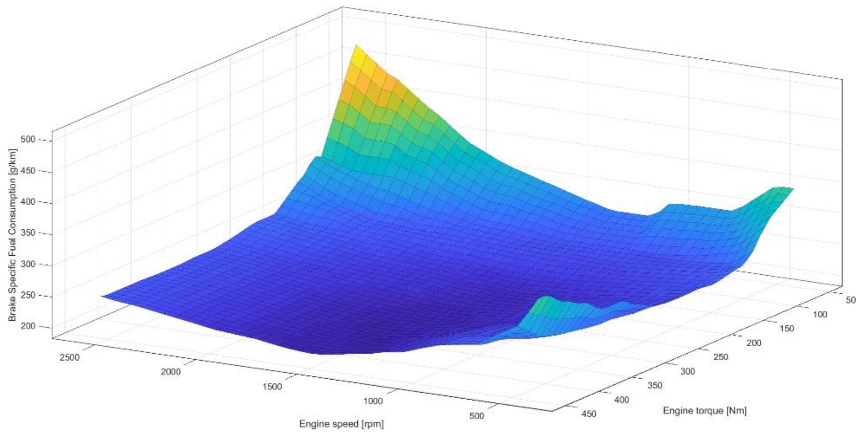

Figure 3.9 b: BSFC MAP 3D curve

As will be shown in Chapter 6, this feature will be exploited in the validation phase by checking if the TruckSim model of the conventional vehicle is compliant with fuel consumption parameters declared by the OEM. The fuel flow rate $\dot{m}_f$ is obtained from the inverse of Equation 3.6, as follow:

$$\dot{m}_f = \frac{BSFC\ T_e\ w_e}{3600x9549} \tag{3.8}$$

where $\dot{m}_f$ is expressed in g/s and T_e and w_e are respectively the engine torque and engine speed.

These data are not properly about the reference model. It is an approximation of the presented model, but the obtained values are compliant with the more common results about a diesel engine since, usually, the brake specific fuel consumption efficiencies are around 200 g/kWh.

3.3.2 Transmission

The transmission system in this dissertation is referred to the entire drivetrain, including clutch, gearbox, and differential. It is intended to transfer the torque from the engine to the wheel and to allow the traction of the vehicle. There are different kinds of transmissions, such as manual transmission (MT), automatic transmission (AMT), and continuous variable transmission (CVT). In the first, the driver decides to change gear according to the driving conditions, while the AMT allows changing the gear directly according to the torque provided by the engine. These two types are both limited to fixed steps of gear ratios, whereas the CVT is defined as an automatic transmission but allows gear shifting through an infinite number of gear ratios in a continuous range. It is evident how the flexibility of the CVT may allow the engine to optimize its working points independently of the driving wheels operations.

In the developed model a manual transmission is adopted, therefore, a mechanical clutch is implemented. Its function is to engage and disengage the engine from the output shaft when it is required from the driving conditions. It is made up of a friction disc and a pressure plate in such a way that, when the clutch lever is pressed, the torque is no longer transmitted to the drivetrain. So, the driver can change the gear or simply stop the vehicle motion without turn off the engine. When the clutch is engaged the torque is stored into a mechanical component – called flywheel – before it is transmitted again. The torque capacity depends on the clutch friction disc and its friction coefficient. These parameters are only determined from experimental tests, hence in the TruckSim implemented model is used a default mechanical clutch, intended for a vehicle very similar to the one under analysis.

The power provided by the engine for the transmission enters the gearbox. It uses a series of fixed gears to proportionally outputs the engine torque and speed. Indeed, the internal combustion engine achieves good performance at high rotational speeds, which are inappropriate for the normal motion conditions of the vehicle. Therefore, getting the right gear ratio is a crucial task. In the manual transmission, the fixed gear ratios usually are 5 or 6 ratios which value depends on many aspects, from the kind of traction required by the vehicle, to the driving style. In the presented model are used 6 gears with the following gear ratios (Table 3.1):

Table3.1: Gear ratios

Gear number	Gear ratio
1	5.004
2	2.94
3	1.52
4	1
5	0.86
6	0.68

To accurately describe the transmission model, the shift schedule should be defined too. It specifies the upshift/downshift boundary of transmission speed as a function of the throttle position. However, the TruckSim vehicle model is not customized but just uses the ones referred to a vehicle with same sizes of the one analysed.

The last element of the drive train is the differential. It allows controlling the applied torque and the rotational speed of the wheels. Employing a series of gears that combine their rotation, the differential enables a pair of wheels to rotate at a different speed without slipping while turning in a curve, for example. However, there are various types of differentials depending on how are actuated. In the TruckSim model, it is presented as an open differential with a fixed gear ratio equal to 3,16 : 1, the value declared by the OEM for the reference vehicle.

Chapter 4

Hybrid electric vehicle model

This chapter describes the proposed hybridization of the LCV. Generally, the OEMs decide to adapt a conventional thermal vehicle into a hybrid one; this is exactly the approach followed in this work. Starting from the conventional vehicle model presented in the previous section, the electric domain components are modelled and integrated with it. The main challenge now is to combine accurately the different kinds of power flows, optimizing the number of transformations and providing the requested mechanical power at the wheels.

4.1 Definition of the hybrid solution

In this work, a parallel P2 configuration of the hybrid electric powertrain is implemented (Figure 4.1). The internal combustion engine is the primary source, although it is introduced an electric motor, and both directly power the drivetrain. In the P2 configuration, the electrical machine is located after the clutch, which enables the ICE detachment when the purely electric mode is selected. In addition to the electric mode, the parallel architecture allows propelling the vehicle in pure thermal mode – in which the mechanical power is entirely provided by the ICE – and in assist mode, with both the motor and the engine combined for the traction.

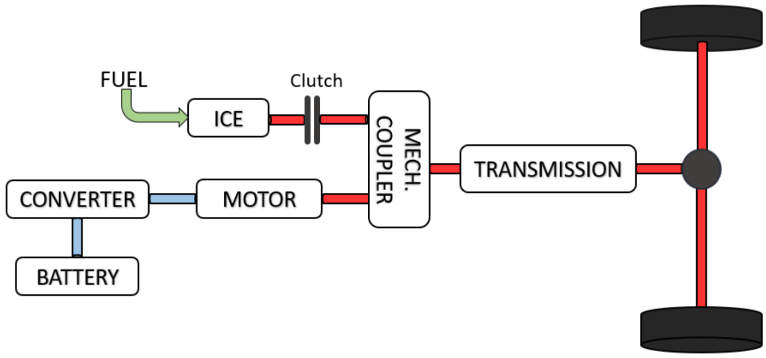

Figure 4.1: Parallel P2 HEV architecture

This solution is the most used by OEMs when the goal is to hybridize an existing vehicle since it is necessary to assemble the electric components in parallel with the mechanical branch. However, the main drawback is that, usually, the internal combustion engine is oversized, meaning that a lower sized ICE could be enough to achieve the same performances and even better efficiencies in terms of fuel consumption. It also impacts weight distribution and deprives, for instance, the introduction of a more powerful energy storage system. This aspect is crucial in the case of the LCV, where the best design choice is to use components as lightweight as possible to take full advantage of its weight capacity without affecting the performance. In the proposed model, the ICE is the same as the conventional vehicle, while the size of the electric motor is chosen to improve the fuel consumption and to maintain the drivability.

The main parameter used to set the size of the electric motor is the Hybridization Factor (HF), expressed as follow:

$$HF = \frac{P_{EM}}{P_{EM} + P_{ICE}} \tag{4.1}$$

Where P_{EM} is the electrical machine power and P_{ICE} is the combustion engine power. It is a value that can oscillate from 0 to 1. Particularly, is used to classify the kind of hybrid vehicle according to the following table [9]:

Table 4.1: Hybridization factor

Type of hybrid	HF
Micro-hybrid	$0 < HF < 0.05$
Mild-hybrid	$HF \leq 0.1$
Full-hybrid	
Parallel	$0.1 < HF < 0.5$
Series	$0.5 < HF < 0.75$
Electric vehicle	$HF = 1$

To maintain the same performance of the conventional model but trying to reduce the fuel consumption, it is introduced a hybridization factor equal to 0.38. Together with the previously defined internal combustion engine, the electric motor is sized with a continuous power equal to 80 kW.

By increasing the HF, the powertrain potentialities increase too. Theoretically, the consumptions decrease with a bigger electrical machine, since the global efficiency grows up too. It is possible to demonstrate that with a bigger size motor, the torque capacity of the motor increases consequently. However, must be set a trade-off between electric motor and the energy storage system sizes. Indeed, with higher HF can be noticed improvements in vehicle performances until a critical point, that corresponds to the maximum capacity of the battery system.

Therefore, it is chosen to use an electric motor with 80 kW of continuous power and a battery model with a capacity equal to 40 Ah. To take into account these devices, the HEV model is 600 kg heavier, according to the weights of the components sized as the implemented ones. Then, in this work, are not considered all the aspects related to the power converters, that are expected in a real hybrid powertrain.

4.2 Model environment

To propose the hybrid solution are used various tools. The idea is to exploit all the features of the reference vehicle modelled in TruckSim, as described in Chapter 3 but modifying the powertrain. The electric components of the new powertrain are implemented in Simulink using a model-based approach. Simulink is a software intended for modelling and simulation of dynamic systems. It uses a graphical programming language based on functional blocks and allows to perform advanced analysis also thanks the integration with MATLAB – a powerful textual programming language. Thus, it is possible to use both the software in parallel at run time or analyse the simulation results in post-processing in MATLAB. Simulink also enables some extended features, like the Stateflow charts. Stateflow allows the implementation of a finite-state machine for the development of algorithms for combinatorial and sequential logic. The flow charts can be easily integrated with other Simulink blocks and share signals information. In this work, Stateflow is used for the implementation of the power management strategy.

The components modelled in Simulink are integrated with the existing elements of the powertrain. Indeed, to implement the hybrid model a co-simulation is performed within TruckSim and Simulink. The latter inherits the step-size from the one defined in TruckSim and the two development environments are linked by modelling externally, in Simulink, a component of the powertrain. In that case, the torque converter is externally defined as reported in Figure 4.2; it is a hydraulic component used in an automatic transmission that allows changing gear directly according to the torque provided by the engine. Thus, the variables of interest are exported from the TruckSim model to Simulink, where are processed according to the dynamic behaviour of the electric domain components and the control strategy requirements.

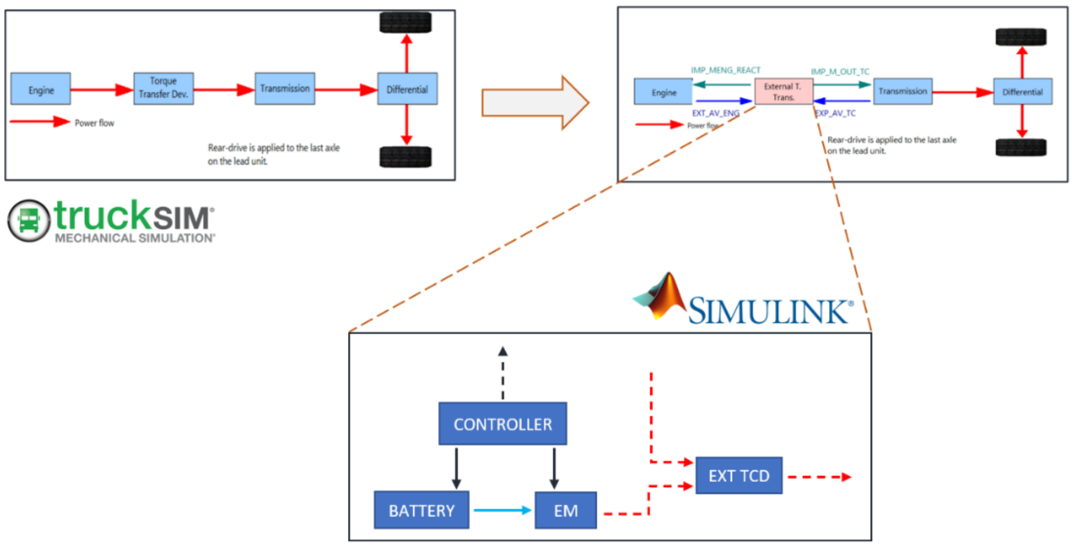

Figure 4.2: Co-simulation interface

4.3 Electric motor model

In the literature, there are various types of electrical machines adopted for HEV applications. Generally, electrical machines can be classified based on their operation in Direct Current (DC) or Alternating Current (AC) machines. They work on the principle of the transformation of mechanical energy into electricity – and vice versa – through a rotating magnetic field. For the proposed hybrid model, a brushless permanent magnet synchronous motor (PMSM) is used as a reference.

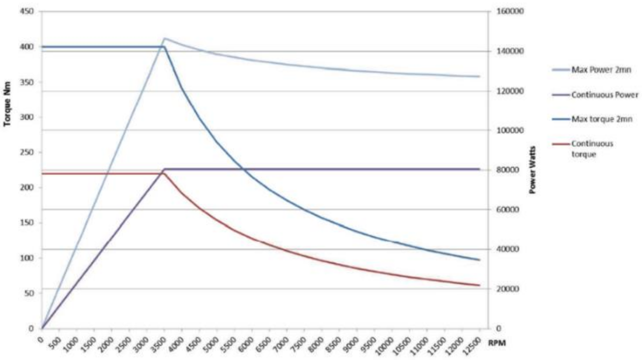

Figure 4.3: PMSM torque-power characteristic

The PSMSs are AC synchronous machines with a permanent magnet rotor. They are characterized by high efficiency and good reversibility thereby can optimally work as motors and generators. The only drawback is due to their high cost. However, in this work, the full dynamics of the electric motor is not reproduced. It is used experimental-data-based modelling where through look-up tables are defined the input-output relationships of the model. The data used are obtained from the torque characteristic of an 80 kW continuous power electric motor (Figure 4.3). The torque output of the motor and the generator are obtained from the following relationship:

$$T_{em\_out} = \begin{cases} min\{T_{dem}, T_{em}(w_{em}, P_{em})\}, & if\ T_{dem} \geq 0, motorizing\ mode \\ \\ max\{T_{dem}, T_{em}(w_{em}, P_{em})\}, & if\ T_{dem} < 0, generation\ mode \end{cases} \tag{4.2}$$

where T_{dem} is the demand torque from the controller based on the requested torque at the wheels, and $T_{em}(w_{em}, P_{em})$ is the deliverable torque by the electrical machine at the current working condition (Figure 4.5). P_{em} is the power available to the motor and it is a variable linked to the State of Charge of the battery (SoC).

The relationship between the battery power and the electric machine power is given by the following equation:

$$P_{batt} = \frac{P_m}{n} \qquad motorizing\ mode \tag{4.3}$$

This relationship holds when the power demand at the wheel is positive, so the motor gets power from the battery; while when the power is negative, and the electrical machine recharges the battery, the following equation holds:

$$P_{batt} = P_m\, n \qquad generation\ mode \tag{4.4}$$

In which P_m is the effective power requested or absorbed by the motor, whereas the efficiency n is considered as constant value. This is an assumption introduced into the model due to the lack of information since the efficiency depends on the working point of the electrical machine. However, the PMSM high efficiency is such that their global efficiency is almost the same and never below 0.9, thus in the model it is not introduced a high approximation.

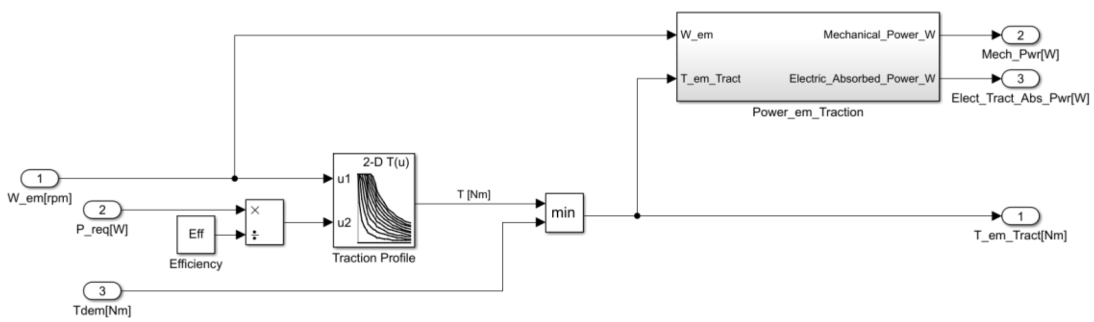

Figure 4.4: Simulink model of the electric machine in motorizing mode

4.4 Battery model

In the HEVs the internal combustion engine is still not the only power source, but it cooperates with the battery. One of the main challenges is to implement a high-performance energy storage system. Many kinds of materials have been combined to find the best solution, such as Lithium-based or Nickel-based batteries. In general, the battery is an electrochemical device that stores chemical energy and gives it out in the form of electrical energy. It has two electrodes – cathode and anode – connected by an electrolyte, and the charge flows from the anode (-) to the cathode (+) in discharging phase, vice versa when the cell is charging. In this work, a Lithium-ion battery (Li-ion) is used as a reference.

Li-ion batteries benefit from high power and energy density, even if the main drawbacks are related to their lifespan and sensibility to high temperatures. Hence, to overcome these effects usually the Li-ion batteries are oversized and equipped with a complex cooling system. All the electrochemical reactions of a battery are not easily modelled. However, based on the dynamic characteristics and working principles of the battery, have been developed various equivalent circuits models [10]. By using electrical circuit components, it is possible to describe the dynamic behaviour of the battery.

In the proposed solution, the Thevenin model (or Dual Polarization model) is used (Figure 4.5). It consists of several parallel RC networks in series with a resistance. R_o represents the ohmic resistance and RC blocks are described as the following [10]:

- R_{pa} is the effective resistance that reproduces the electrochemical polarization.
- R_{pc} is the effective resistance that reproduces the concentration polarization.
- C_{pc} and C_{pa} reproduce the transient response during the power flow to/from the battery.

According to Kirchhoff's law, the electrical behaviour of the circuit can be expressed by the following equations:

$$\begin{cases} \dot{U}_{pa} = -\dfrac{U_{pa}}{R_{pa}C_{pa}} + \dfrac{I_L}{C_{pa}} \\ \\ \dot{U}_{pc} = -\dfrac{U_{pc}}{R_{pc}C_{pc}} + \dfrac{I_L}{C_{pc}} \\ \\ U_L = U_{oc} - U_{pa} - U_{pc} - I_L R_o \end{cases} \tag{4.5}$$

By using the Laplace transform, results:

$$I_L = \frac{U_{px}}{R_{px}} + sC_{px}U_{px} \tag{4.6}$$

And the voltage on both the RC networks, in the s-domain, are the following:

$$\begin{gathered} U_{pa} = \frac{1}{s}\left[\frac{I_L}{C_{pa}} - \frac{U_{pa}}{R_{pa}C_{pa}}\right] \\ \\ U_{pc} = \frac{1}{s}\left[\frac{I_L}{C_{pc}} - \frac{U_{pc}}{R_{pc}C_{pc}}\right] \end{gathered} \tag{4.7}$$

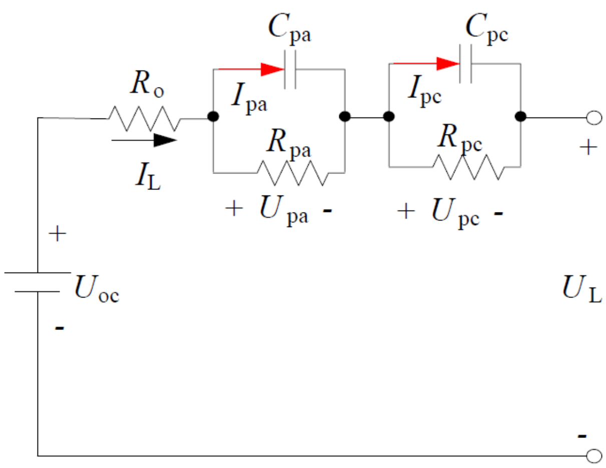

Figure 4.5: Battery model: Thevenin circuit model (Dual Polarization model)

The parameters depend on the State of Charge, the current, and the temperature. However, this work has not reproduced the effects of the temperature on the components. All the evaluations are based on the SoC and the sign of the current (positive in discharging phase, negative in charging phase). Thus, a relevant parameter to be considered is the SoC.

The State of Charge is defined as the ratio of the available quantity of charge Q to the nominal charge capacity of the battery Q_0 (in Ah). It is a dimensionless variable and assumes values in the range between 0 and 1 – or 0-100 if expressed in percentage. It is expressed as:

$$SoC = \frac{Q}{Q_0} \tag{4.8}$$

The SoC can be estimated using the coulomb counting method [11]:

$$SoC = SoC_0 - \frac{1}{3600}\int \frac{I_L}{Q_0} \tag{4.9}$$

In the presented model, the SoC is defined in percentage. Generally, a battery is used in the range of 20% and 80% of SoC, otherwise undesired chemical reactions or damages to the battery can occur. All the values of the above components are in function of the SoC. However, to characterize them are needed a large amount of information, so for the designed model, the data are extrapolated from a reference model proposed in the literature [12]. The battery used is a Li-ion battery which characteristics are proper of batteries often used in HEV applications (Table 4.2).

Table 4.2: Experimental characteristics of battery

Parameters	Cell	Module
Nominal Capacity (Ah)	40	40
Nominal Voltage (V)	3.7	26.9

The experimentally obtained values are defined in function of the SoC and the charging or discharging condition of the battery. Therefore, for the purpose of the presented model, the values of the components are stored in look-up tables. The Simulink model implements the previously obtained electrical equations defining at each time step the actual SoC and the available power of the battery (Figure 4.6). The model is divided in sub-systems, in which are defined the equivalent circuit (Figure 4.7), the RC networks – for the determination of the battery voltage, and the SoC computation sub-module.

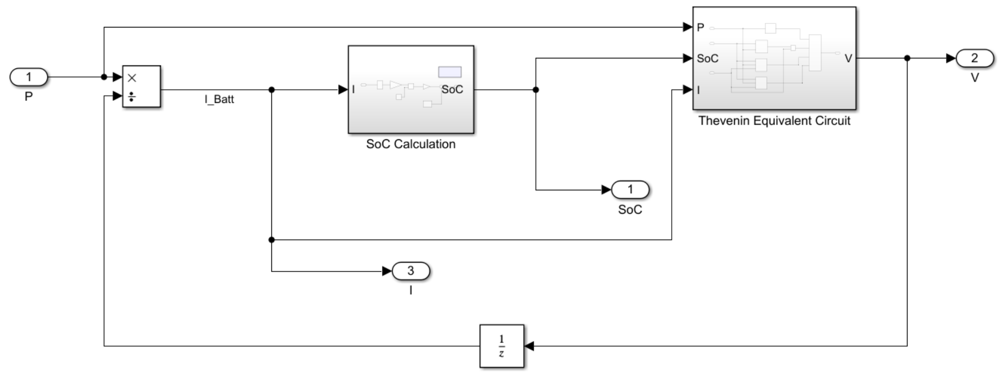

Figure 4.6: Battery model: Simulink model

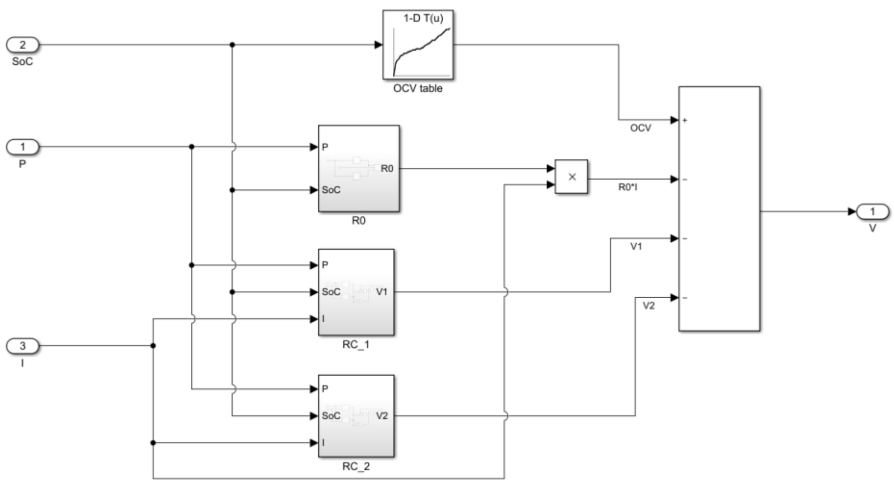

Figure 4.7: Battery model: Thevenin model subsystem

Lastly, the model is validated by comparing the simulation results with the experimental data from the paper [12]. The simulations output a very close behaviour of the implemented model to the reference one, based on the two kinds of tests performed: a charge test and a discharge test.

The charge test is made with current pulses of 80 A amplitude, 200 s width, and 1800 s rest period (Figure 4.8).

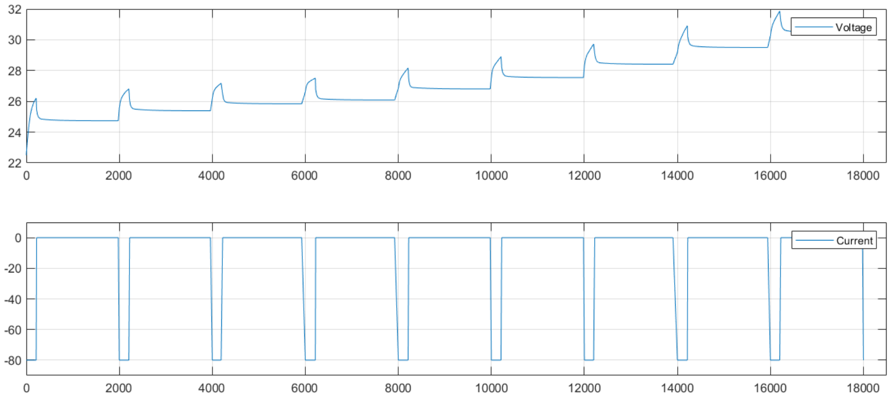

Figure 4.8: Battery model validation: charge test

The discharge test is made with current pulses of 40 A amplitude, 360 s width and 1800 s rest period, as shown in Figure 4.9.

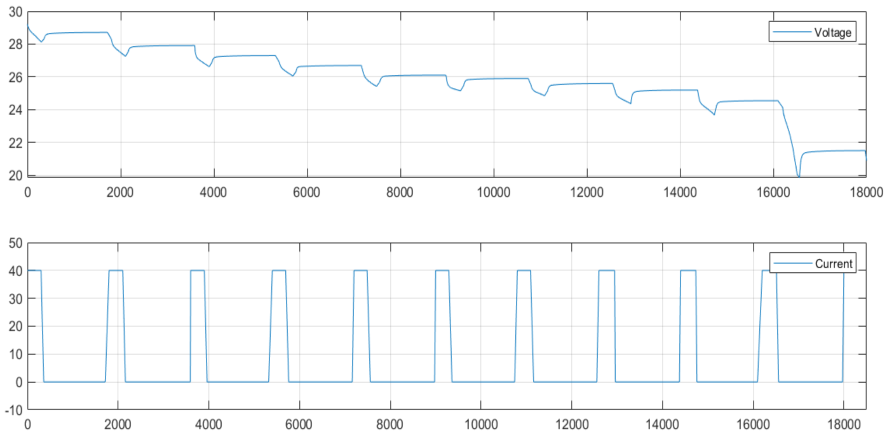

Figure 4.9: Battery model validation: discharge test

Chapter 5

Control strategies

All the potentialities of the hybrid electric vehicle are fully exploited only if they are properly controlled. The interaction between components belonging to different domains requires efficient synchronization, mainly for the control of power conversions on the powertrain. This is the major challenge in hybrid electric vehicles and control strategies are under continuous improvements to be optimized.

Therefore, the vehicle control system is more complicated than in a conventional vehicle, in which certainly lower tasks are involved. For this reason, a hierarchical structure is used to implement the hybrid vehicle control system [13] (Figure 5.1). The modular approach used makes the control system highly reliable and robust. The supervisory Control Systems interact with all the subsystems, by sending commands to a specific Electronic Control Unit (ECU) depending on the requested task. The HEV control strategy is implemented at the supervisory control system level. Various controls can be introduced depending on the type of hybridization, so the highest level of the control system is strictly related to the hybrid powertrain structure.

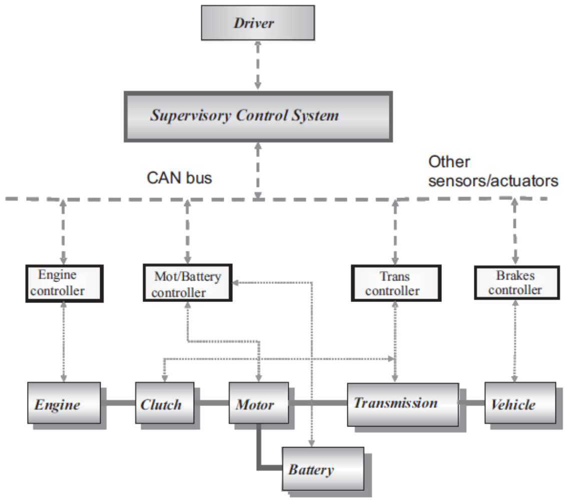

Figure 5.1: HEV hierarchical control system [13]

5.1 Control strategies classification

A control strategy is focused on the identification of the best operating mode accordingly to the driving conditions. It inputs the requested power by the driver, as well as information related to the speed or accelerations, and outputs decisions related to how to propel the vehicle, to the activation/deactivation of a certain component, or the variation of its operating region into a more efficient one. From these decisions, it is expected a reduction of emissions or improvement in terms of fuel consumption, by ensuring at the same time good drivability. Indeed, various operating modes are enabled by the control strategies. For instance, in the conventional vehicle, all the mechanical energy from braking is lost, while in hybrid electric vehicles it is used in the regenerative braking mode to recharge the battery. However, this is not the only way to handle the energy flowing in the powertrain, but there are various actions related to the different modalities. Depending on the used approach, power management strategies are usually divided into rule-based and optimization-based controls strategies, as reported in Figure 5.2.

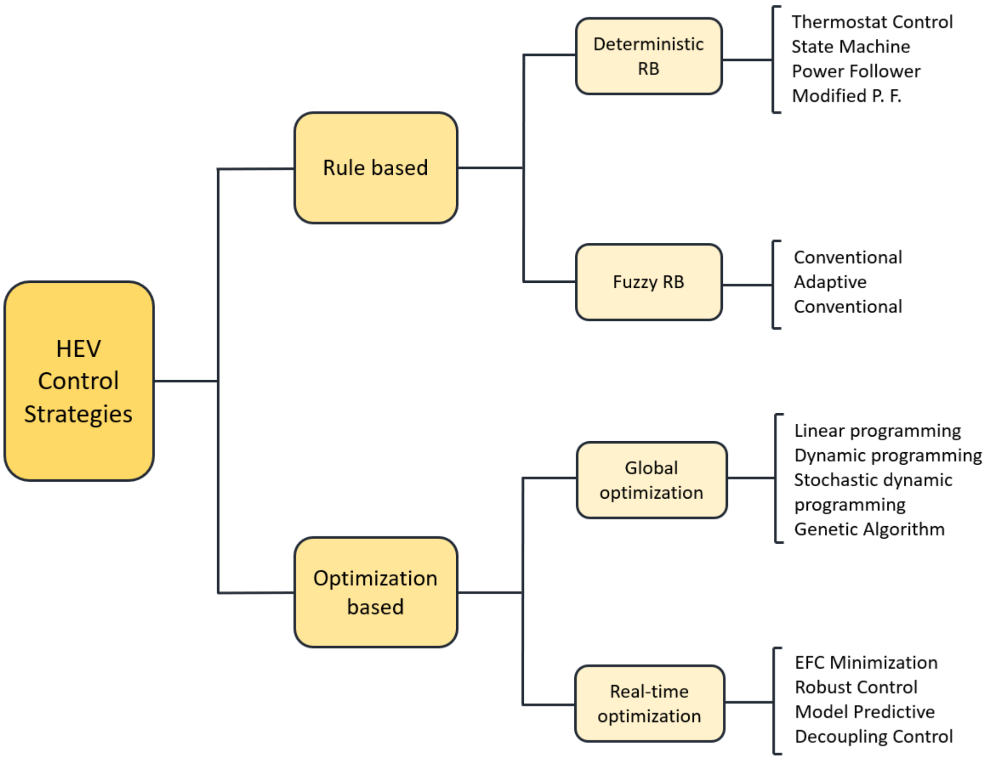

Figure 5.2: HEV Power Management Strategies classification

5.1.1 Rule-based control strategies

Rule-based control strategies are designed based on engineer intuition, experimental results, analysis of power flow in the powertrain, but are not based on a predefined driving cycle. This means that are intended for online control of the power flow in a hybrid powertrain. The relations presented in this kind of control strategy usually are based on the concept of 'load-levelling' [14]. The main idea is to move the engine operation into high efficiency regions, by fully exploiting, at the same time, the cooperation between ICE and electric machine.

However, this kind of strategies does not introduce always a global optimum control, meaning that usually improvements concern only one factor rather than others. Rule-based control strategies are divided into:

- Deterministic rule-based control strategies.
- Fuzzy rule-based control strategies.

Both the methods present decisions for the split of the power flow over the powertrain. However, the deterministic approach, although requires low computational effort, is not adaptive. Hence, the control strategies based on fuzzy logic can be considered an extension of the deterministic rule-based ones. They introduce robustness and flexibility to the control, implementing decisions that compensate for inexact measurements, at the expense of higher computational complexity.

These online power management strategies can suitably respond to sudden variations in driving condition and even if seem too rough are one of the most used in the market. The only drawback of these techniques is that not always present a global optimization, but, as it will see, can be improved from some offline refinements.

5.1.2 Optimization-based control strategies

The optimization-based control strategies define a non-causal solution since they are applied with a priori knowledge of the driving cycles. Due to the non-causality, it is possible to find a global optimum solution, even if can not be implemented in real-time. The optimization, indeed, is achieved over a time horizon so, in the transient, it is collected an accurate solution at the cost of high computational complexity. For this reason, the results of optimization-based control strategies are usually employed for the evaluation of the online controls, or to determine some improved rules for the rule-based control strategies. However, optimization-based control strategies are divided into:

- Global optimization-based control strategies.
- Real-time optimization-based control strategies.

The two approaches are both based on the minimization of a cost function, usually related to the fuel consumption, but the second one is intended for the optimization of an instantaneous cost function. In that case, as stated in [15] “in addition to a measure for fuel consumption, variations of the stored electrical energy should also be taken into account to guarantee electrical self-sustainability”. So, global optimization-based controls are employed to define a feasible real-time optimization control strategy.

One of the most used offline optimization methods is the Dynamic Programming. This approach determines a global optimum solution for power-split in HEV, over a pre-fixed driving cycle; nevertheless, its high complexity is a critical aspect, thereby it is usually employed for the definition of advanced deterministic rules in the rule-based control strategies, as proposed in [16].

5.2 Definition of a rule-based control strategy

As mentioned before, a rule-based control strategy allows to efficiently control the power flow in the powertrain, although without introducing a global optimization. However, as will be demonstrated, this approach already introduces a good improvement in terms of fuel consumption. The proposed strategy manages optimally the power flow at any time, by switching from the available operating modes based on the driver’s requested power. Particularly, four operating modes are defined: pure electric mode, engine-only mode, hybrid mode and regenerative braking mode. The flowchart in Figure 5.3 summarizes the working operational modes of the logic. Interpreting the throttle pedal position, the driver’s power demand is computed. Based on this parameter and the state of charge of the battery, continuously monitored by the controller, the whole control logic is developed.

A first decision is taken based on the sign of the requested power by the driver. If the power is negative, braking control is activated. Then, depending on the SoC of the battery the mechanical energy from the brakes is used for mechanically stop the vehicle or recharge the battery:

- If the battery SoC is lower than the maximum and the requested power is lower than the maximum available from the generator, the regenerative braking is activated, and the battery is charged.
- If the battery SoC is lower than the maximum and the requested power is higher than the maximum available from the generator, a part of the power is used for the regenerative braking and the rest is lost in mechanical braking.
- If the battery SoC is higher than the maximum the mechanical braking is activated.

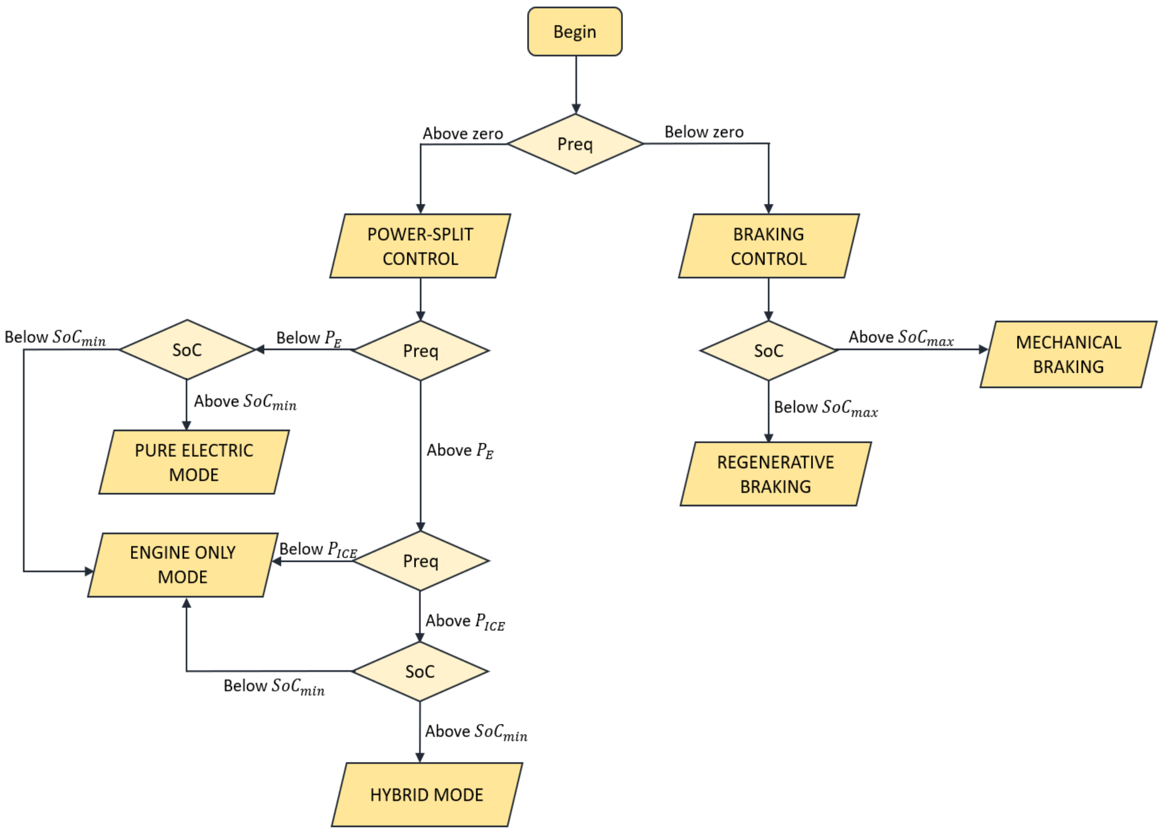

Figure 5.3: Flowchart of the rule-based Power Management Strategy

Furthermore, if the requested power is positive, the power for the traction must be provided at the wheels. Thus, three modes are available: full electric, full engine and hybrid. Pure electric mode is the prior one and is employed always in the starting phase, then one mode is preferred to the other according to the following rules:

- If the battery SoC is higher than the minimum, and the battery can deliver the requested power to the electric motor, then the vehicle moves in purely electric mode.
- If the required power is greater than a threshold corresponding to the high efficient area of the engine, the pure engine mode is used.
- If the battery SoC is higher than the minimum and the required power is such that the engine can not operates in the efficient area, both the electric motor and the ICE provide the power at the wheels.
- If the battery SoC is lower than the minimum, regardless of the requested power, the engine alone supplies the vehicle.

As can be seen, in this power management strategy the engine does not provide power to the battery directly. Usually, this is done by delivering an amount of energy higher than that required at the wheels. In that context, there are various approaches, or the battery is recharged when the engine for a certain range works in the high efficiency area (usually at cruise speed and in Plug-in hybrid vehicles), or some logics are implemented for maintaining the state of charge within a predefined range.

Therefore, an extension of the previous strategy is implemented too. It provides the charge sustaining mode, which allows keeping the battery within a range of SoC defined a priori. This type of approach is implemented in hybrid electric vehicles to ensure that, with the support of an auxiliary control system, called Battery Management System (BMS), the battery works always in good efficiency areas preventing it from being damaged or fully discharged. Depending on the battery, within the selected SoC bounds, a range of 5-10% for the charge sustaining is usually chosen (65-60% SoC commonly).

This feature is added to the previous power management strategy (Figure 5.4). At each iteration of the logic, if the requested power is positive, it is verified that the SoC is greater than the minimum, before implementing one of the traction modes. If the SoC is lower of that threshold, the charging control is executed and, in addition to the required power, the ICE provides an extra power to recharge the battery.

As will be shown in the results, obviously this approach allows to track the battery SoC avoiding battery depleting but does not ensure the same reduction of fuel consumption as the original power management strategy.

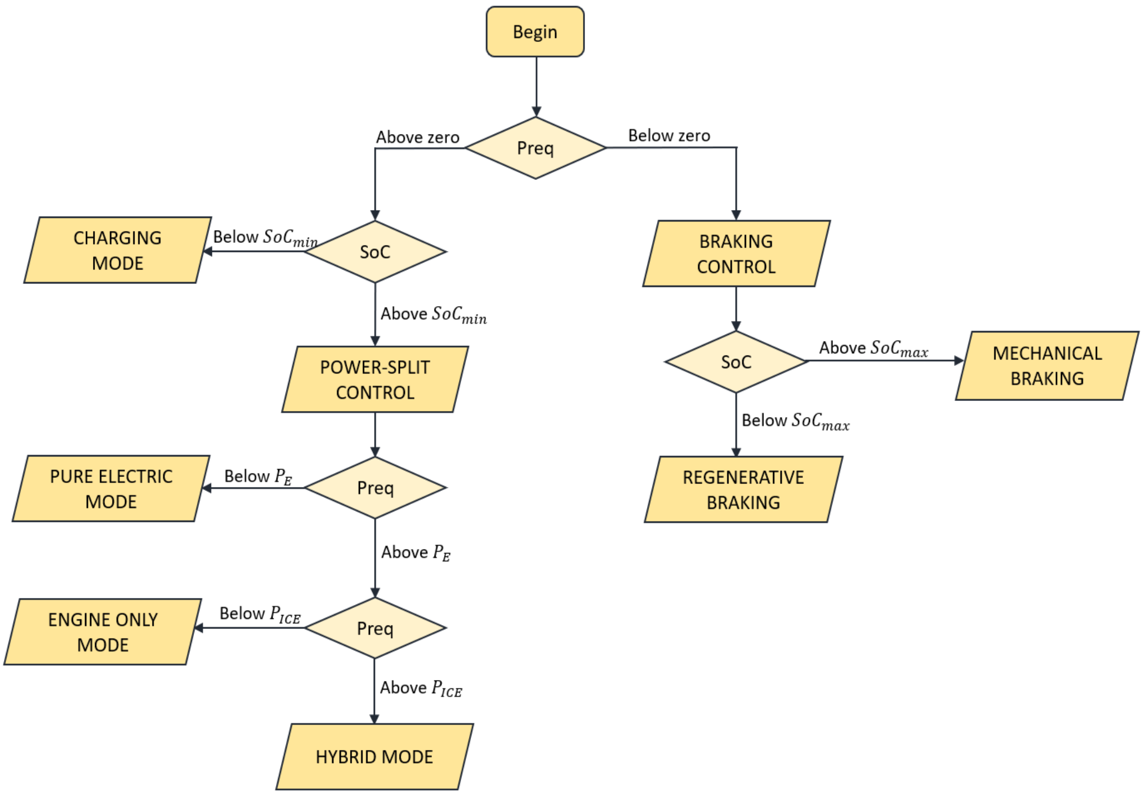

Figure 5.4: Flowchart of the rule-based Power Management Strategy with charge sustaining

In both approaches, the operating modes are defined according to Table 5.1, where α is a coefficient related to the hybridization factor used for the torque distribution. This is because a big assumption is introduced in the proposed model; it is not considered a mechanical coupler that can take into account the different contributions of the ICE and the electric motor in hybrid mode. However, through the clutch and the motor command, it is possible to disengage, respectively, the engine and the motor, depending on the operating mode.

In the presented control strategy, the power flow sign convention used is under what is defined in Chapter 4, about the charging or discharging of the battery. Furthermore, the SoC bounds are selected to avoid internal current and voltage values that could seriously damage the battery, trying to reproduce the real behaviour of the battery in which current and voltage limitations are expected.

Table 5.1: HEV operating modes description

Operating mode	P_{EM}	P_{ICE}	SoC
Electric mode	P_{dem}	0	$SoC > SoC_{min}$
Engine mode	0	P_{dem}	$n.a.$
Power assist mode	$\alpha\ P_{dem}$	$(1-\alpha)\ P_{dem}$	$SoC > SoC_{min}$
Regenerative braking mode	P_{dem}	0	$SoC < SoC_{max}$
Charging mode	P_{ch}	$P_{dem} + P_{ch}$	$SoC < SoC_{min}$

Chapter 6

Experimental evaluations

In this Chapter are reported all the performed analyses. Besides the validation for the single model components reported in the previous sections, the whole system is validated. Simulations about vehicle driving performances and stability are made over several missions thanks to the predefined test cases provided by TruckSim. Procedures like driving on a straight road or brake in a turn are executed; after verified the reliability and the structural coexistence of the vehicle, the main evaluation of the developed vehicle model is performed with reference to official data provided by the OEM of the reference vehicle. In this context, the main parameter analysed is the fuel consumption and consequently the CO_2 emissions, since for the reference vehicle there are official results issued in the type-approval phase. This kind of analysis is collected by subjecting the vehicle to some defined driving cycles.

6.1 Driving cycles

A driving cycle usually represents a set of vehicle speed points versus time. It is used to evaluate in a normalized way pollutant emissions and fuel consumption of a vehicle, comparing different vehicles or defining if a vehicle is compliant with the in-force regulations. However, a driving cycle sometimes is implemented in vehicle simulation too, to predict powertrain performances. In that case, driving cycles could be also non-legislative, but only intended to assess the behaviour of components, in terms of both single component and whole integrated system efficiency.

There are different kinds of driving cycles, depending on the path to be reproduced or on the country which produced them. They are collected in urban driving cycles, characterized by low speed, low engine load and short distance, or extra-urban driving cycles, with higher speed and distance. These kinds of cycles are too restrictive to a specific driving scenario, so generally, a driving cycle with both urban and extra-urban velocity profiles is used to evaluate vehicle performances. A typical driving cycles is the New European Driving Cycle (NEDC). It is made of an urban part, that is repeated four times, and an extra-urban part, in which more aggressive driving modalities are introduced reaching a maximum speed equal to 120 km/h (Figure 1). It lasts 1180 s for a total distance of 11.02 km. However, the NEDC is very far from the real driving pattern since there are a lot of constant speed cruises and too soft accelerations. It was used as a reference cycle for homologating vehicles until 2017 in Europe and some other countries. Then, more realistic reproduction of the modern driving style was necessary to improve the consistency of the vehicle tests. The NEDC is so gradually replaced by another driving cycle and from September 2019 onwards all the new vehicles must be approved for it. It is the Worldwide Harmonized Light vehicles Test Procedures (WLTP) and is intended to equalize test procedures on an international level.

The WLTP considers all the quick accelerations followed by short brakes that can occur in the daily route and so defines a more accurate estimation of the effective pollutants and emissions. The test procedure is divided into 3 cycles depending on the power-to-mass ratio (PMR) of the under-test vehicle. This parameter is defined as the ratio of the rated power, expressed in W, and the curb mass, in kg. According to PMR value, the WLTCs are divided as follow:

- PMR ≥ 34, class 3 cycle.
- 22 ≤ PMR ≤ 34, class 2 cycle.
- PMR ≤ 22, class 1 cycle.

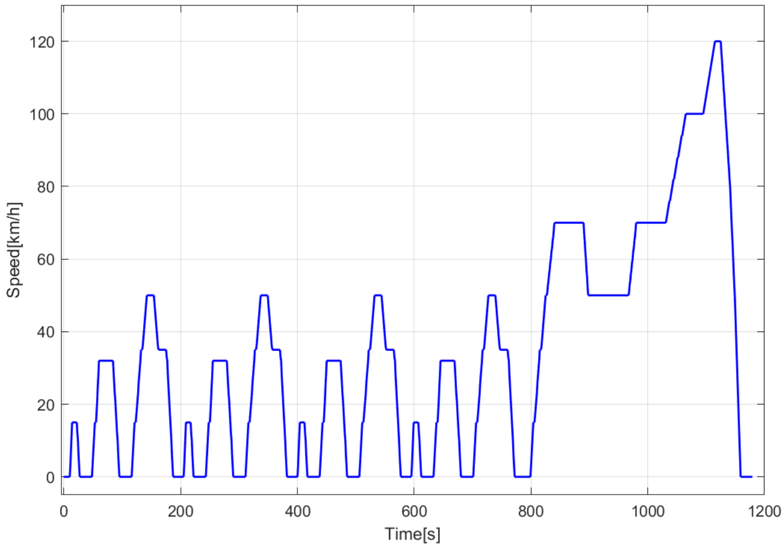

Figure 6.1: New European Driving Cycle (NEDC)

The WLTC class 3 cycle (Figure 6.2.a.) is referred to the high-power vehicles and is divided into four parts reaching a maximum speed equal to 131.3 km/h, while WLTC Class 2 (Figure 6.2.b) and Class 1 (Figure 6.2.c) cycle are intended, respectively, for medium and low-power vehicles.

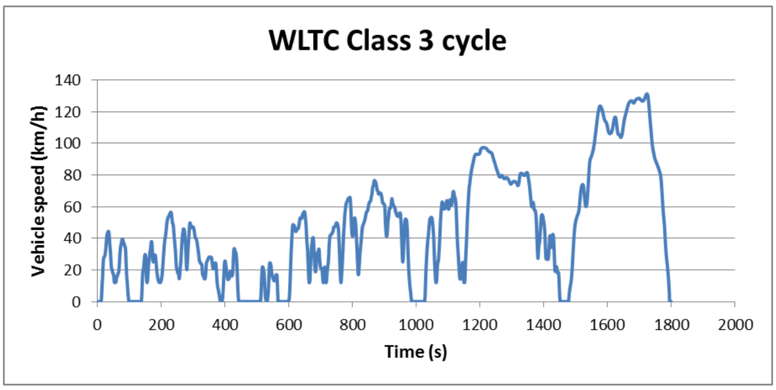

Figure 6.2.a: WLTP: class cycle 3

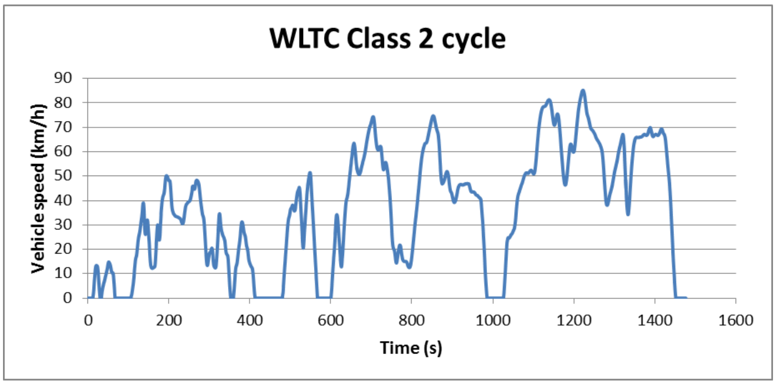

Figure 6.2.b: WLTP: class cycle 2

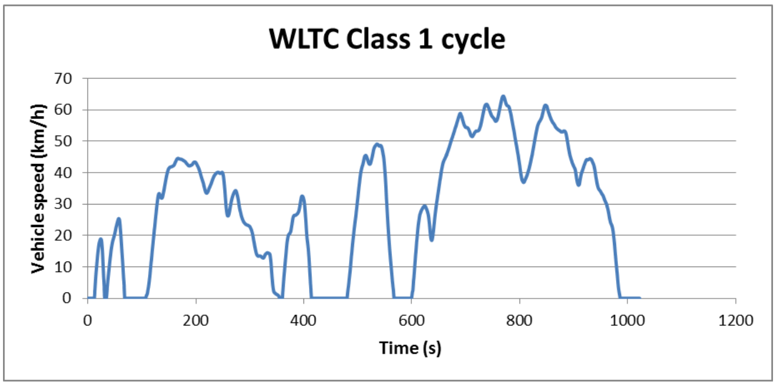

Figure 6.2.c: WLTP: class cycle 1

6.2 Model simulations

The math models defined in TruckSim are intended to provide a realistic simulation of the physical vehicle. To validate the implemented models, both the conventional and the hybrid ones are tested over the driving cycles. The speed profiles defined in TruckSim are used as input by a driver model, which outputs a power command for the drivetrain based on the accelerations from the target speed of the vehicle. The driver model is defined as a closed-loop speed controller that adjusts throttle and braking according to the variation in vehicle speed. It is defined as a controller that, given a target speed, computes the requested acceleration with the following equation:

$$Ac_{req} = K_p\, V_{err} + K_i\, V_{ierr} + K_{p^3} V_{err}^3 \tag{6.1}$$

where $V_{err} = V_{target} - V_{xz_{fwd}}$ and $V_{ierr} = \int V_{err}\; dt$, while K_p , K_i , K_{p^3} are respectively the proportional, integral and cubic control gain.

The environmental conditions considered are under what is declared in the regulations of the cycles, hence a test on a straight road without elevation and unitary friction road coefficient.

6.2.1 Reference vehicle model simulation

The conventional vehicle model is validated over the NEDC, since the issued consumptions provided by the OEM refer to it and a better comparison with the literature is achievable. The obtained results, as will be shown, are close to the expected ones, hence the conventional vehicle is simulated over the WLTP too. In this way it is possible to have feedback on its performance for a currently in force and modern driving cycle.

The vehicle speed over the NEDC, as reported in the Appendix, is followed quite well, demonstrating the reliability of the results obtained. However, as will be shown in the next paragraph, a small error in terms of fuel consumption is introduced by the vehicle model.

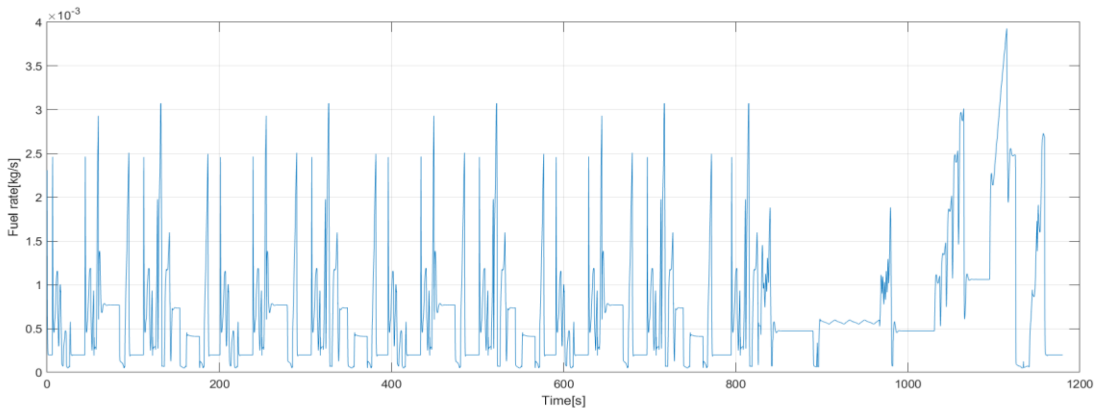

Figure 6.3: Conventional model: fuel rate over NEDC

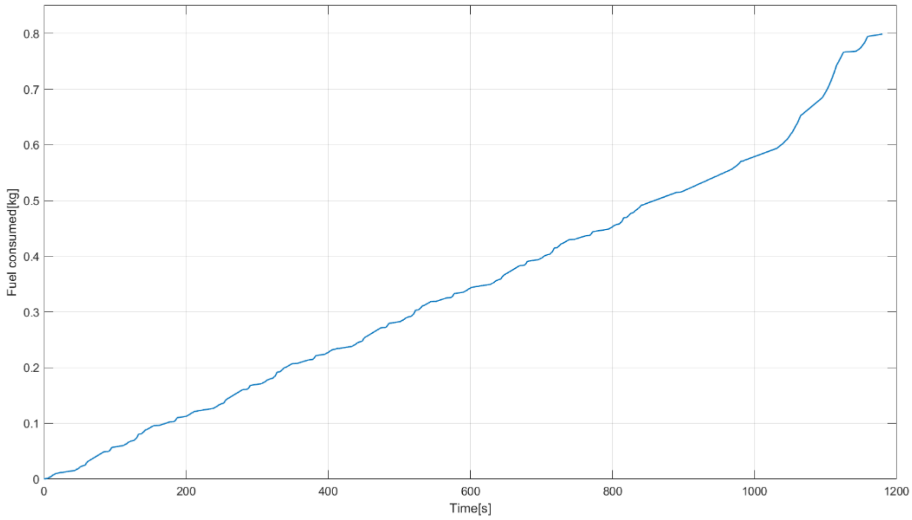

Figure 6.4: Conventional model: equivalent fuel consumed over NEDC

Figure 6.3 depicts the amount of fuel rate produced by the vehicle during the NEDC test, while in Figure 6.4 is reported the equivalent fuel consumption, expressed in kg.

The same test is repeated subjecting the conventional vehicle model to the WLTP. According to the WLTC cycles classification, the reference vehicle has an RPM equal to 36, therefore is tested using the WLTC class 3 cycle. The results achieved in that case cannot be rigorously discussed due to the lack of real simulations under the WLTP. However, they seem acceptable since the WLTP is a more restrictive procedure that introduces higher values of emissions.

Figure 6.5 and Figure 6.6 show the fuel rate and the equivalent fuel consumed by the reference vehicle over the WLTP.

6.2.2 Hybrid vehicle model simulation

From the simulation results of the conventional vehicle, a comparison with the hybrid model is performed. Two kinds of analysis are considered based on the charge sustaining mode is enabled or not. In both cases, the battery is not considered fully charged to reproduce the common approach used in HEV

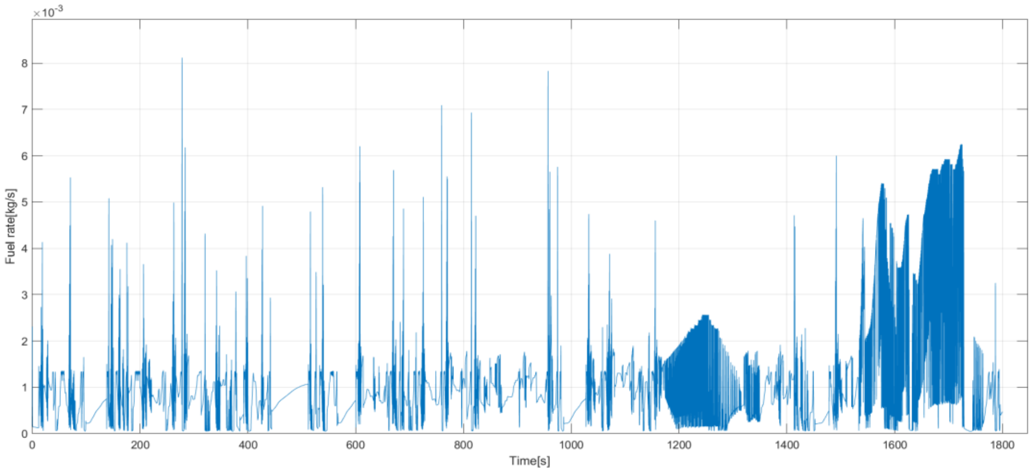

Figure 6.5: Conventional model: fuel rate over WLTP

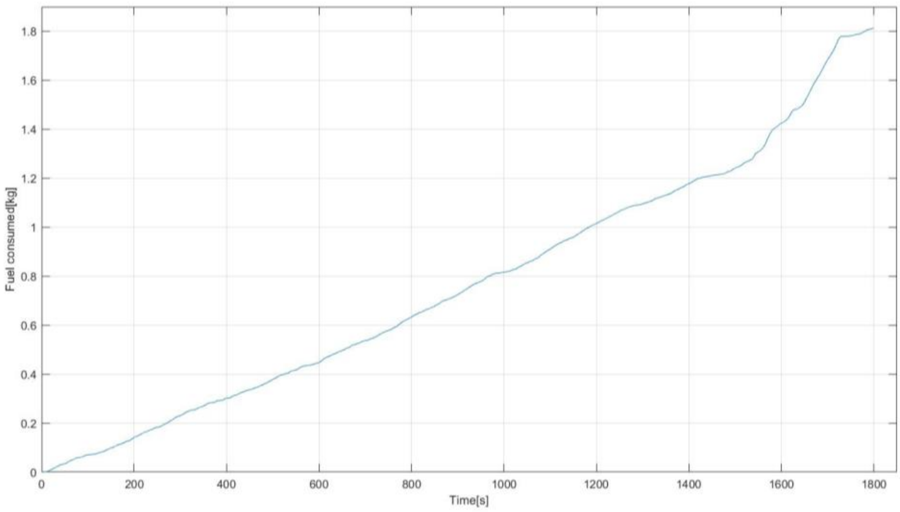

Figure 6.6: Conventional model: equivalent fuel consumed over WLTP

which avoids battery damaging, and good improvements are achieved in terms of fuel consumption. However, some important considerations on the obtained results will be pointed out in the next paragraph.

About the NEDC, the fuel consumption decreases compared to the conventional vehicle while the battery SoC maintains goods efficiency values (Figure 6.7).

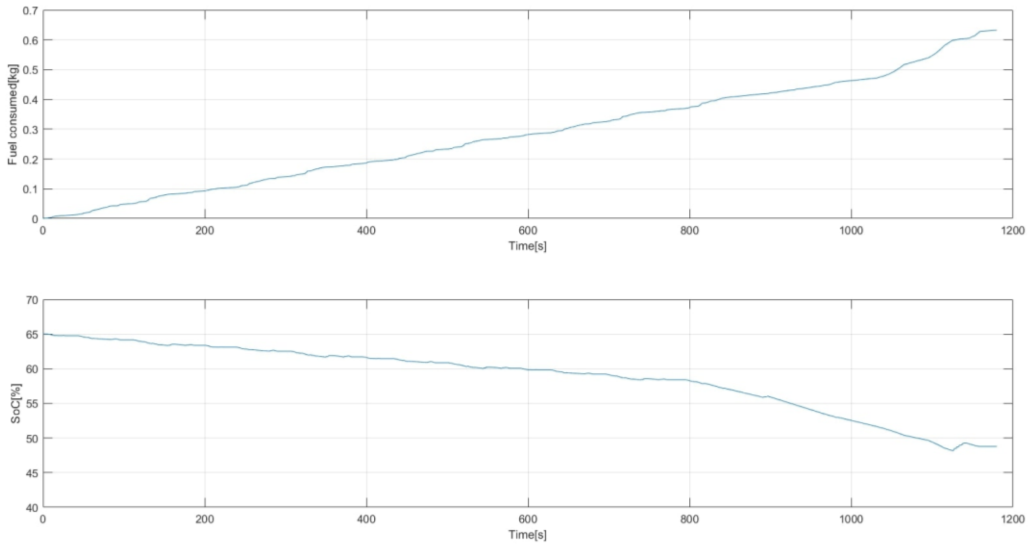

Figure 6.7: Hybrid model: results over NEDC

The previous plots refer to the first power management strategy proposed. On the other hand, for the charge sustaining power management strategy, the results are similar but, as expected, introduce a higher fuel consumption, with the advantage of maintaining the battery SoC between the fixed range in a way to extend the battery autonomy (Figure 6.8).

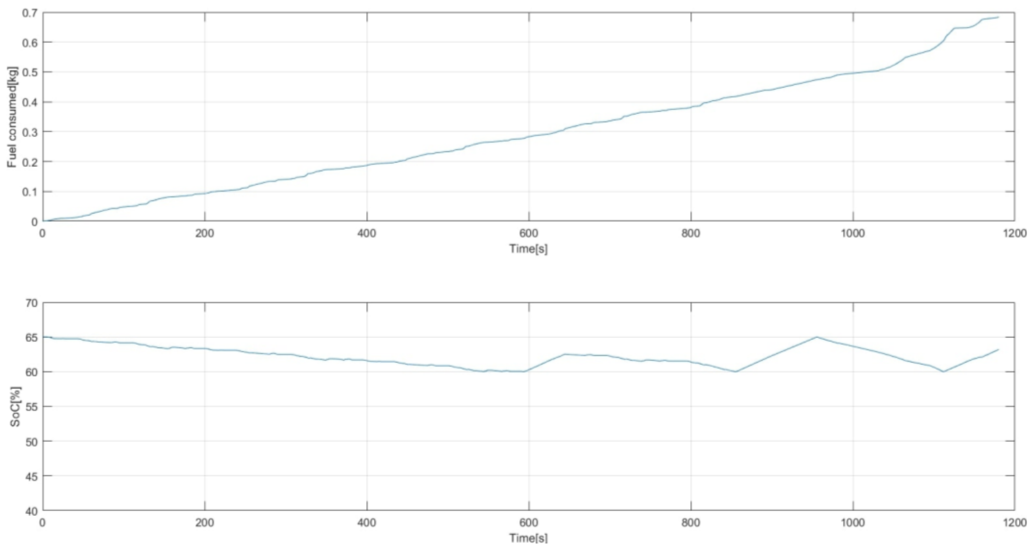

Figure 6.8: Hybrid model: results over NEDC with charge sustaining pms

The same simulations are performed for the WLTP. Again, the fuel consumption is proportionally higher than the one obtained over the NEDC procedure. However, in the first power management strategy the battery depletes quickly due to the higher power requested by the driver for the hybrid traction mode (Figure 6.9).

On the other hand, in the control strategy with the charge sustaining mode, the battery SoC remains in the prefixed range at the cost of higher fuel consumption (Figure 6.10).

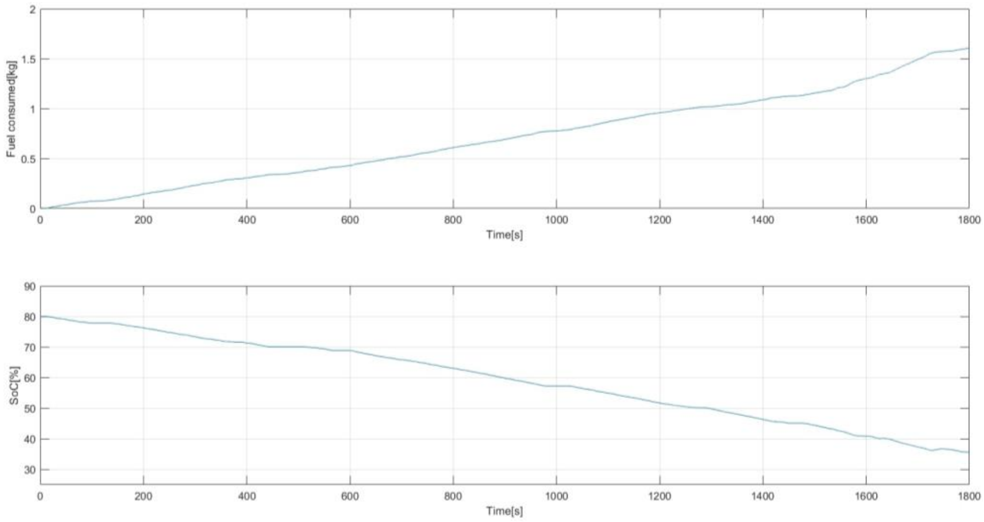

Figure 6.9: Hybrid model: results over WLTP

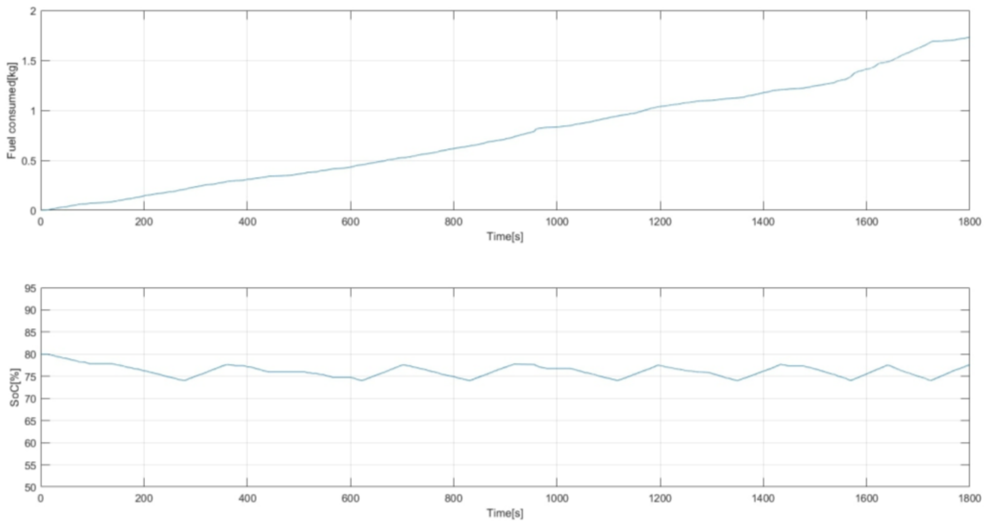

Figure 6.10: Hybrid model: results over WLTP with charge sustaining pms

6.3 Results

The model of the conventional vehicle is validated from the type-approval data issued by the OEM. Compared to the reference vehicle, the model implemented in TruckSim introduces an error of 3% about CO_2 emissions, over the NEDC driving cycle. This value is considered acceptable and the efficiency analyses of the implemented hybrid electric vehicle are reported to it.

Therefore, the two implemented rule-based power management strategies are evaluated first for the NEDC. Table 6.1 collects the results divided by the type of power management strategy adopted.

Table 6.1: Results over NEDC

Control strategy	Fuel consumed (kg)	CO_2 (g/km)	Improvement (%)
Rule-based	0,63	181,7	18,8
CS Rule-based	0,68	196,2	12,4

The obtained improvements are consistent but strictly affected by the driving cycle used. Indeed, from the implemented control strategy, since the NEDC is a driving cycle characterized mostly by low speeds, the purely electric mode prevails, leading to a high reduction in fuel consumption compared to the conventional vehicle.

To test the robustness of the employed control strategy, the vehicle is simulated over the WLTP too, obtaining the following results collected in Table 6.2. It can be noted that, compared to the previous test, the percentage of improvement is reduced due to the higher power required by the driver, meaning that the vehicle, according to the implemented power management strategy, runs mostly in the hybrid mode requiring significant power to the internal combustion engine.

Table 6.2: Results over WLTP

Control strategy	Fuel consumed (kg)	CO_2 (g/km)	Improvement (%)
Rule-based	1,6	220,37	11,85
CS Rule-based	1,73	237,8	4,9

Globally, the obtained results are consistent with the structure of the hybrid powertrain and the sizes used. However, in both types of analysis, are introduced some approximations which could generate a mismatch in real conditions. The power losses of the electrical machine are not considered, neither all the thermodynamic aspects that impact, for instance, the battery efficiency.

Chapter 7
Conclusion and future work

This thesis is produced to analyse the structure of the hybrid powertrains, their relative control strategies, and propose a hybrid electric model for a lightweight commercial vehicle, assessing its performance and discussing the obtained results in terms of reduction of fuel consumption and emissions. Therefore, it is proposed a parallel P2 hybrid electric vehicle, controlled by a rule-based power management strategy.

The conventional vehicle is rigorously defined in TruckSim at first, in which, starting from the vehicle dynamic theory, the sizes and weights of the truck are parametrized as well as the powertrain components. Particular attention is reserved to the internal combustion engine model, defining it starting from its efficiencies map and maximum torque profile. The validation of the conventional model developed in TruckSim has described a fuel consumption close to the declared one by the OEM, with an error of 3%.

Then, the electric components of the hybrid electric model are modelled in Simulink using a model-based approach. A brushless electrical machine and a Thevenin equivalent circuit of the battery are used. The controller for the power management is implemented in Stateflow, presenting two variations: a rule-based control with only pure electric mode, engine only mode, hybrid mode and regenerative braking mode, and another rule-based control that ads a charge sustaining mode at the previous operational modalities. By employing this control in the hybrid model, compared to the conventional vehicle, improvements in terms of fuel consumption are introduced, but the obtained results show that the efficiency of the proposed system depends on the nature of the driving cycles. Among all the simulations performed, the best result leads to a reduction of the fuel consumption equal to 18,8% for the NEDC and 11,85% for the WLTP.

The obtained results are consistent with the kind of hybridization used; however, it is necessary to underline some limitations of the implemented system which can be considered for future developments. Some models of the used components, can be described in more detail, such as for the electric machine would be interesting to reproduce its whole dynamic and to characterize it in the presence of the power losses too, which impact the control of the power flow in the powertrain. At the same time, the control strategy could be improved by introducing coordinating control of gear shifting to optimize the engine working points. Finally, all the thermodynamic effects are not considered while can be interesting to evaluate the efficiency of the components over the temperature too. In that sense, an air conditioning system is what allows maintaining the optimal operating temperature of the components in the vehicle. It is crucial but impacts the battery performance, so could be interesting to implement it evaluating the battery efficiency and characterizing more accurately the obtained results.

Appendix

Vehicle Parameters

The parameters used to define the reference vehicle model are described in the following section. Then, starting from the values in Table A.1, the parameters obtained from the vehicle dynamics theory are presented too.

Table A.1: Vehicle parameters

Parameter	Value
Wheelbase	3520 mm
Max. length	6109 mm
Max. height (unloaded vehicle)	2940 mm
Max. width	2010 mm
Front overhang	1048 mm
Rear overhang	1541 mm
Front track	1724 mm
Rear track	1542 mm
Total mass loaded	3500 kg
Curb mass	2491 kg
Max font axle load	2100 kg
Max rear axle load	2600 kg

Aerodynamic cross-section

The aerodynamic cross-section used in the vehicle model is the following one:

$$S = 4{,}56\ m^2$$

It is computed using Equation 3.2, by using $\psi = 0{,}90$ as a constant value, $t = 1724\ mm$ as the front track, and $h = 2940\ mm$ as the overall height of the vehicle.

Tire parameters

The tire structure of the reference model is defined by the following index:

$$195/75 \quad R\,16 \quad 110/108 \quad R$$

From these data and according to Equation 3.3 the tire parameters used in the model are computed:

Figure A.1: Tire geometry

$$Sidewall = \frac{195\ \times 75}{100} = 146{,}25\ mm$$

$$Unloaded\ diameter = 2 \times Sidewall + Rim\ diameter = 698{,}9\ mm$$

$$R_e = \frac{Rim\ diameter\ \times 98}{100} = 342{,}46\ mm$$

$$R_l = \frac{Rim\ diameter\ \times 92}{100} = 160{,}74\ mm$$

The load index for the single wheel is equal to 108, that corresponds to 2205 lbs (1100 kg); while for the dual wheels it is equal to 110, that corresponds to 2337 lbs (1060 kg).

Internal Combustion Engine characteristic

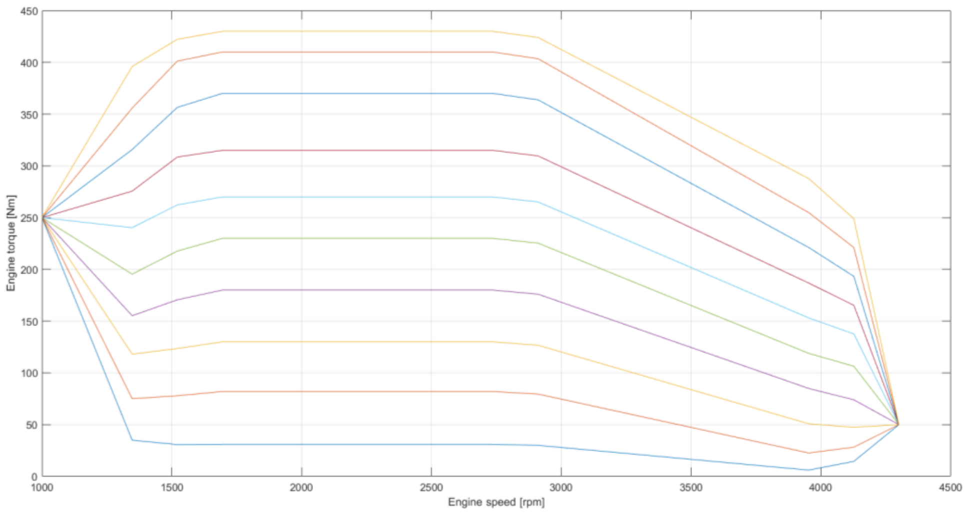

Figure A.2: ICE torque characteristic

The ICE is characterized by the torque profile, defined as a function of the throttle position and the engine speed (Figure A.2). The different throttle settings are reported as the different curves in the figure and the torque is expressed as:

$$T_e = f(throttle, w_e)$$

In the presented model is defined the rate of fuel consumption for the ICE too. By using the BSFC map and Equation 3.6, the fuel rate is computed and collected into a LUT.

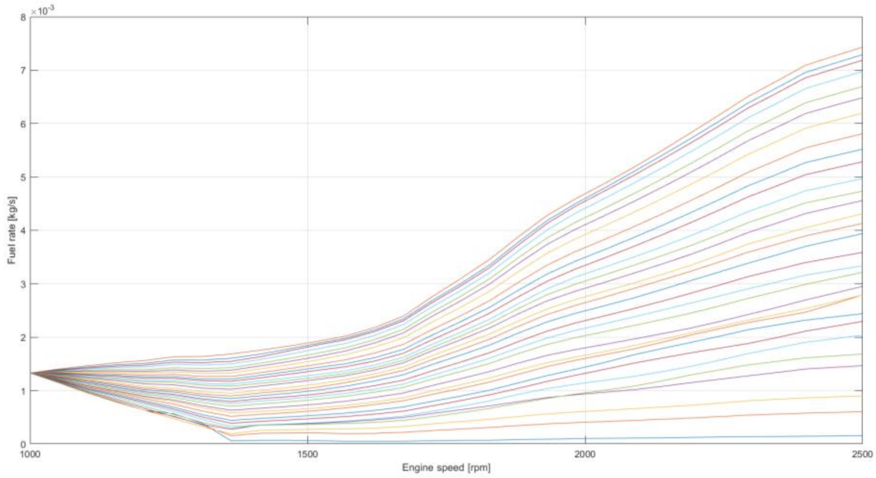

Figure A.3: ICE fuel rate

Battery parameters

The parameters used for defining the equivalent circuit model are presented here. They are all expressed in function of the battery SoC and, for each component, two datasets are used depending on the sign of the current. In this way are identified the charge or discharge modes of the battery.

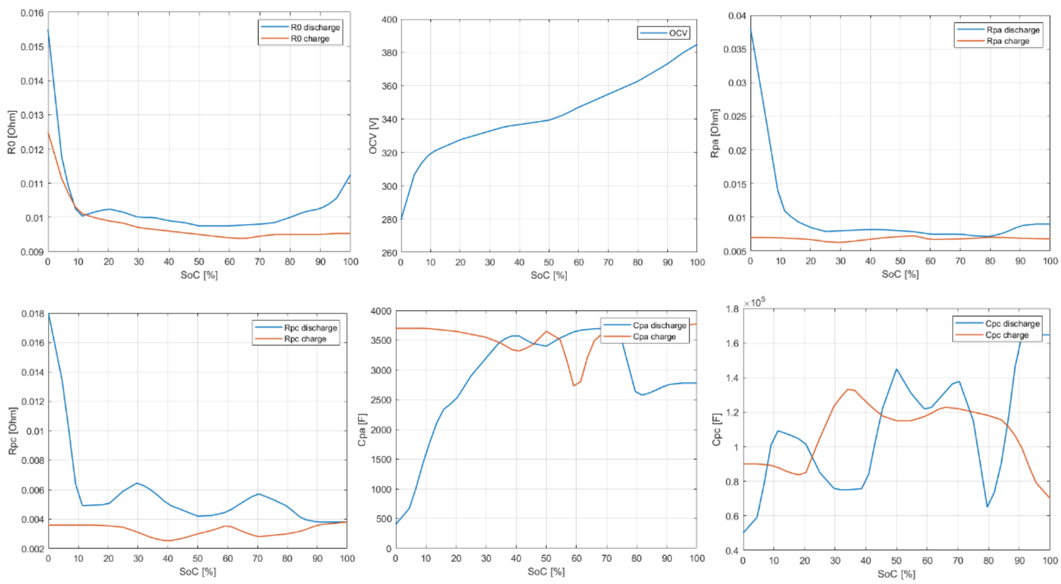

Figure A.4: Battery parameters

Driving cycles

The speed profile of the vehicle with respect the different driving cycles are reported here. The accuracy of the speed achieved during the simulations is strictly related to the reliability of the fuel consumption and CO_2 emissions results. As stated in Chapter 6, the speed profile is accurate enough for both the conventional vehicle model and the hybrid one. The speed profiles over the NEDC and WLTP of the conventional vehicle model are:

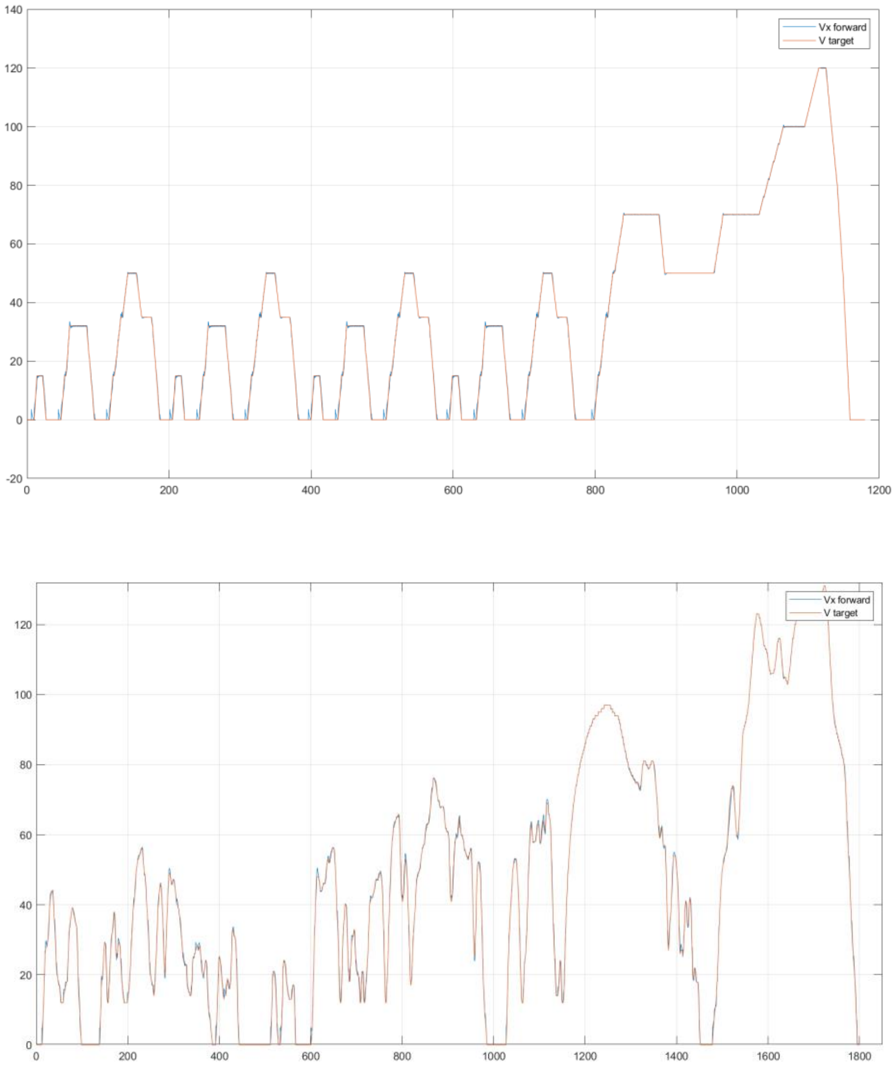

Figure A.5: Conventional vehicle model speed profiles

While for the hybrid electric vehicle model the speed profiles are:

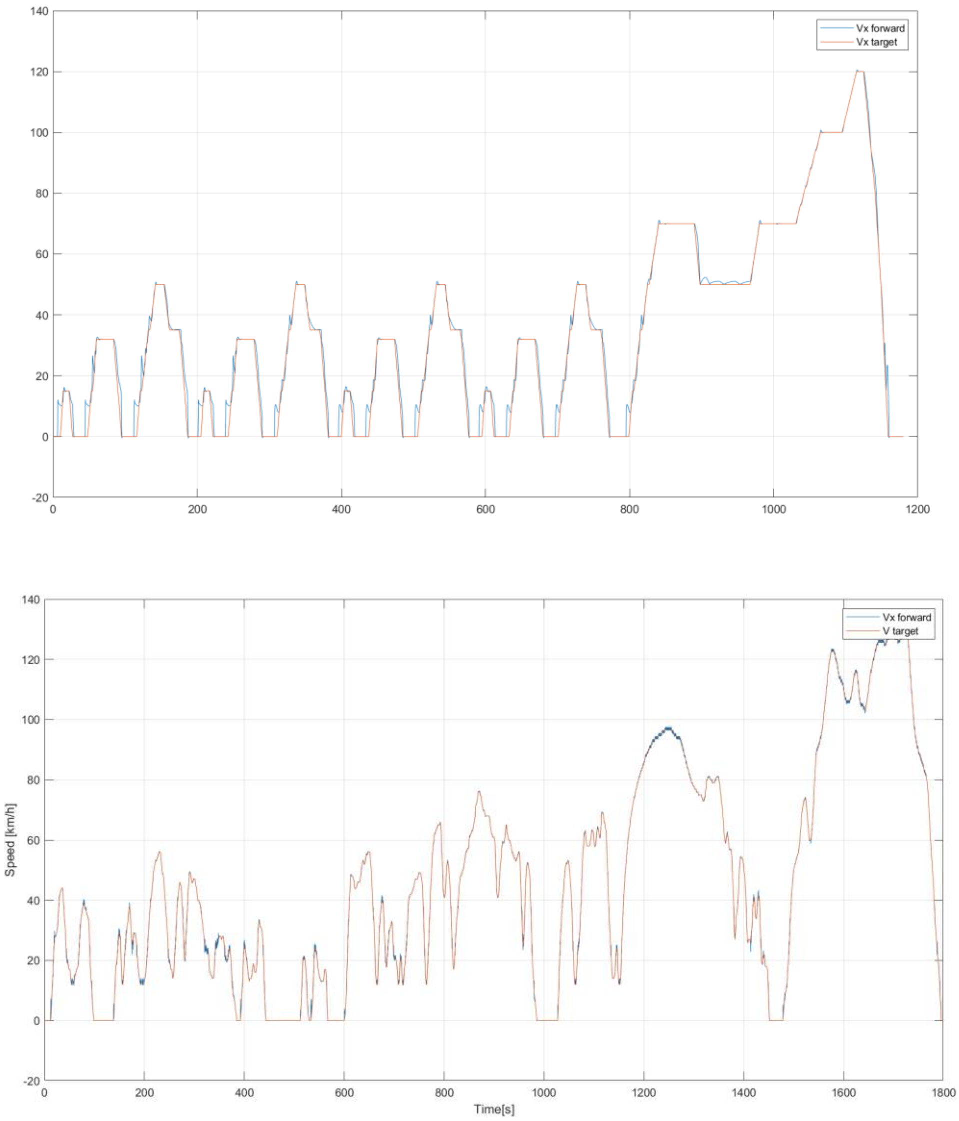

Figure A.6: Hybrid electric vehicle model speed profiles

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