POLITECNICO DI TORINO

Mechanical Engineering

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Numerical Investigation of an Optimal Thermal Management Strategy for a Plug-In Hybrid Electric Vehicle

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Summary

Recent UE legislation requires that CO_2 emissions of newly registered passenger cars should reduce by 55% in 2030. The widespread adoption of electrification powertrains will be needed to achieve these targets. Moreover, the thermal management of the vehicle will play a fundamental role to guarantee that the powertrain will operate with high efficiency.
The object of this thesis, made in collaboration with POWERTECH Engineering S.r.l., is therefore the development of a control strategy aimed to optimize both the thermal management and the fuel efficiency of a Plug-in Hybrid Electric Vehicle (PHEV).
First, a physical vehicle model, representative of a C-SUV passenger car, is built on the commercial software GT-SUITE. This vehicle model is composed by different subsystems: the drive-line and the powertrain (electric motor, battery pack and the engine), the thermal circuits for the thermal management and the vehicle controllers. The drive line contains all the hybrid powertrain components, for example engine, electric motor, clutches, battery, and the controllers linked to these components. The thermal subsystem includes the cooling circuit with radiators, heat exchangers, oil circuit, among the others. The controller overseeing the Energy Management Strategy of the entire powertrain is developed in Simulink.
As a starting point, an online Equivalent Consumption Minimization Strategy (ECMS) is used. Then, the ECMS controller is updated in order to account for the engine thermal state. In this way the controller at each time interval receives different powertrain inputs, such as the driver power demand and the engine temperature and computes the

optimal split between engine and electric motor power. The vehicle model featuring the ECMS accounting for the engine thermal state is tested in charge sustaining operation along two different driving cycles: the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). Moreover, two different environment temperatures have been considered: -10 °C and 20 °C.
The controller showed an improved fuel consumption for both the starting temperatures, demonstrating that the integration and knowledge of the thermal state of the powertrain by the ECMS controller allows to improve the energy management strategy of hybrid vehicles.

Acknowledgements

First of all, I would like to thank my professor, Federico Millo, for transmitting to me his passion for this subject, and for his support throughout the thesis. I also would like to thank POWERTECH Engineering S.r.l. for welcoming me, especially Alessandro and Antonio. Last but not least I would like to thank my family for allowing me to get to where I am now.

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Acronyms

AECMS
: adaptive equivalent consumption minimization strategy

CD
: charge depleting

CS
: charge sustaining

ECMS
: equivalent consumption minimization strategy

ECU
: engine control unit

EM
: electric motor

EV
: exhaust valve

GCU
: generator control unit

GDI
: gasoline direct injection

HEV
: hybrid electric vehicle

HT
: high temperature

ICE
: internal combustion engine

IV
: intake valve

LT
: low temperature

NEDC
: new european driving cycle

PHEV
: plug-in hybrid electric vehicle

PID
: proportional integral derivative

SOC
: state of charge

WLTC
: worldwide harmonized light vehicles test cycles

Chapter 1

Introduction

Global warming is a fundamental aspect that became crucial in the last decade, because 18% of it is produced by ground vehicles emissions [1]. This led to the birth of new European and global regulations on CO_2 emissions. To comply with these requests car makers are increasing the production of Hybrid Electric Vehicles especially during the last years. HEV are a good solution to increase efficiency, respect the new regulations for CO_2 emissions and preserve the planet, that's why they are currently spreading worldwide.

1.1 Hybrid Architectures

Hybrid Vehicles exploit two different sources of power that can provide propulsion. The simplest case is with an ICE and an EM, but there can also be more complex cases. The second will have the role of converting the electric energy into mechanical (and vice versa) while the electric energy is usually stored in a battery.

Another important big distinction that has to be made before proceeding is related to the type of hybrid vehicle. We know that HEV exploits both mechanical and electrical energy, but we have to make a distinction between classic HEV and Plug-in HEV. The battery of the first one can be charged only thanks to the engine, so the SOC at

the end of the trip will be the same of the initial one. The second type, instead, can be charged also when the vehicle is turned off, thanks to an external current generator.
So depending on the trip, with a Plug-in HEV at the end of the cycle we can have a SOC which is lower than than starting one (charge depleting).

The first distinction that has to be made, regards where the EM is placed along the powertrain. For this reason it is possible to understand where it is thanks to an abbreviation made by the letter P followed by a number. Here all the possible cases are described .

- P0: the electric machine is connected with the internal combustion engine through a belt, on the front end accessory drive (FEAD)
- P1: the electric machine is connected directly with the crankshaft of the internal combustion engine
- P2: the electric machine is side-attached (through a belt) or integrated between the internal combustion engine and the transmission; the electric machine is decoupled from the ICE and it has the same speed of the ICE (or multiple of it)
- P3: the electric machine is connected through a gear mesh with the transmission; the electric machine is decoupled from the ICE and it's speed is a multiple of the wheel speed
- P4: the electric machine is connected through a gear mesh on the rear axle of the vehicle; the electric machine is decoupled form the ICE and it's located in the rear axle drive or in the wheels hub

The second distinction regards the type of path followed by the energy inside the vehicle from the energy sources to the wheels, for this reason there are three categories of HEV:

- Series: The link between engine and EM is only electric, so only the EM is linked to the wheels, while the engine is linked to a

second electric motor that works as generator. In this way there are two different energy flows:the EM linked to the wheels can be powered directly by the battery or by the second electric motor moved by the ICE. The biggest advantage of this architecture is that the engine is always disconnected to the wheels, in this way it is possible to choose not only its torque but also its speed, keeping it in its maximum efficiency range.
On the other side, one of the disadvantages is that there are lots of energy conversions among the path that lead to a big power loss. Today series architectures are used only as Range Extender, usually in the extraurban trip the engine turns on.

- Parallel: in this case the link between ICE and EM is mechanical. There are always two energy sources: electrochemical battery and fuel tank, but in this case there are both ICE and EM linked to the transmission, so there are two parallel energy flows. The advantage is that ICE s directly linked to the wheels, in this way it is possible to have a smaller EM, but the disadvantage is that there is one less degree of freedom on the engine speed so efficiency is not always the optimal. The most used parallel architecture is the Single shaft which consists in a mechanical connection of the motors thanks to a shaft and a clutch (or belt). The single shaft structure can be coaxial or non coaxial, depending on the positioning of the connections.

- Complex: it is a mix of the previous two. There are both mechanical and electrical connection between ICE and EM, so depending on which clutch is connected it is possible to decide if create a series or a parallel connection. Some of them are even more complex and are based on an epicycloidal system that links motors and wheels.

There are also other different kinds of features related to the electric powertrain that can help in reducing the fuel consumption:

- Idle-Off: the ability to turn off the engine when the vehicle stops (usually called start/stop function in non hybrid vehicles)

- Regenerative Braking: exploiting the reversible behavior of the EM, during braking it is possible to convert some kinetic energy into electric energy, generating a current that will charge the battery
- Electric Only Drive: the ability of turning off the engine and proceed only with electric energy. This is usually done during the start and at low speed, for higher speeds the engine turn on.

1.2 Problem Formulation

Using a PHEV allows the user to have a large variety of powersplits between ICE and EM to satisfy the driver request. The formulation of the problem will be based on a cost function that it is necessary to minimize. This cost function is represented by the total equivalent fuel consumption, which is the sum of the real fuel consumption of the ICE and the equivalent consumption of the EM, which is calculated multiplying the power battery with a constant called equivalence factor. At each time step there is a power request by the driver, and this request can be satisfied splitting the power between ICE and EM in different ways. The controller will choose the split that minimize the total equivalent fuel consumption explained before.
This is called Static Optimization Strategy [2], which is based on the fact that the control is doing an instantaneous optimization of a predefined cost function with no a priori knowledge. Doing so, a reduction in fuel consumption at the end of the cycle can be seen, improving also emissions.

A brief description of the three possible algorithms for the fuel consumption optimization is reported.

- Dynamic programming: is a numerical method for multistage decisions problems. It is the only one able to optimize problems of any complexity (computational effort permitting) but it is non casual, so the entire driving cycle has to be known in advance, so it can be applied only in simulations environment. It is based on

Bellman's principle which states that the optimal path from any of its intermediate steps to the end corresponds to the terminal part of the entire optimal solution.

- Equivalent consumption minimization strategy: introduced by Paganelli, it reduces the global optimization to an instantaneous minimization problem, to be solved at each time instant. In this way no information about the future are needed.

- Rule-based control strategies: the most common way for implementing supervisory controls. The control introduces a set of rules that decide the power split. These rules are based on engineering intuitions, do not come from formal Ordinary Differential Equation (ODE).

The one chosen for this case study is the Equivalent consumption minimization strategy, which will be described in detail in Paragraph 1.3

Only after all these passages the development of the new control can start. The new controller has to be created to take into account also the engine temperature and calculate the new total equivalent fuel consumption. With the new results it is possible to make a comparison with the starting ones and appreciate the reduction in fuel consumption on the same cycle.

1.3 Starter controller: ECMS strategy

The starting controller of this study is based on the ECMS which is, as mentioned in the Paragraph 1.2, an instantaneous minimization strategy that considers each time step and try to minimize the cost function computed, without information on the future. If CS constraint must be satisfied, this means that the variation between starting and final SOC is negligible, so basically the electrical energy storage can be considered as a buffer. In this way during the cycle the battery will charge and discharge but at the end its energy stored will be similar to the initial one. So when the SOC will be lower than the starting

one, a bigger fuel consumption will be needed in order to recharge the battery, instead when the SOC is higher it is possible to use an amount of electric energy to reduce the engine load and decrease a bit the SOC value to the initial one.
Depending on the sign of P_{batt} the electric equivalent fuel consumption can be positive or negative, so the total equivalent fuel consumption can be higher or lower than the real fuel consumption. To implement the control P_{batt} and m_f (engine fuel consumption) have to be expressed as a function of the load (driver power demand), so it is necessary a deep knowledge of the powertrain, that will be illustrated later in the model overview.

The instantaneous minimization strategy is computationally less demanding and applicable in real-world situations because it is not necessary to have information about the future driving conditions. [3] [4]

A more detailed explanation needs to be done for the equivalence factor, which is a fundamental parameter that affects the total equivalent fuel consumption and also the energy management strategy. In fact, if it is too high an excessive cost is attributed to the use of electrical energy, so battery will spend less energy and so at the end of the cycle the value of the SOC will be higher than the initial one (battery charged). On the other side if it is too low, electric energy will be used more than necessary, so at the end SOC will be lower. In both cases CS is not respected, so before running any simulation is important to find by iteration optimization the correct value of the equivalence factor that guarantees the charge sustaining, and then it is possible to carry on all the studies. Its value will depend on the vehicle characteristics and of course on the driving cycle, so even if it is an instantaneous minimization procedure, the cycle has to be known first to find the best value for the equivalence factor. [5] [6]

An evolution of the standard ECMS controller is the Adaptive ECMS (AECMS), a controller able to vary the value of the equivalence factor

k along the cycle. This because with a standard ECMS the system is very rigid and needs a previous tuning of the k factor in order to satisfy the SOC boundary conditions. With an adaptive controller, instead, the SOC value is always kept within the boundary conditions zone, and decides the instant value of the equivalence factor depending also on the driving conditions. The AECMS regulates the battery state of charge (SOC) based on linear or nonlinear control algorithms, such as the typical proportional-integral-differential (PID) controller. It can reduce correlation between the equivalence factor and driving condition, and only needs to calculate the difference between the current SOC and expected value. In this manner, dynamic adjustment of the equivalence factor can be tackled according to feedback of the SOC difference. Furthermore, this method takes the SOC error into account, and neglects influences induced by the battery capacity variation. Another of the advantages obtained is that the controller is more stable and insensitive to the k value, because it is not decided a priori but is implemented in real time.
Standard ECMS gives a suboptimal solution while AECMS is also affected by suboptimality, but the degradation of fuel economy is so slight that it is absolutely acceptable, giving an outcome that is very close to the Dynamic programming, that's why it is worth insisting in this direction because it is the only controller completely real time based and that can be implemented in every driving situation.[2]

1.4 Aim of the Work

This thesis aims to develop a new controller able to take into account the thermal state of the engine, which is a fundamental parameter when computing the fuel consumption. Furthermore, the ECMS is a local control, so it is near the optimum and at the same time it does not require too much computational effort, that's why it can be a valid alternative to the existing controllers already present on hybrid cars.

In Chapter 2 there will be a detailed description of the physical models used, in Chapter 3 the two driving cycles will be described and also the procedure for the controller implementation, in Chapter 4, there will be all the plots related to the fuel consumption improvement and some comments on the results obtained, and in Chapter 5 there will be the conclusions and possible future developments.

Chapter 2

Physical models

In this section the physical model used to run the simulations will be described. The model is divided into two subdomain: vehicle and thermal. The vehicle part has the role to compute all the inputs for the thermal one in order to study at the same time the thermal behavior of all components.

The software used for building and running the physic model is GT-SUITE, a tool developed by Gamma Technology, while the energy management controller will be implemented on Matlab and Simulink making these two software interact. A brief introduction on the type of approach used for this study is reported.

2.1 Quasi Static Approach

The quasi static approach has been chosen for this case study. For this type of simulation, where the cycle is pre-defined and only fuel consumption has to be evaluated, quasi static approach is the best choice in terms of accuracy and numerical effort.
It is made by a PID controller that compares the target vehicle speed profile with the actual speed and generates a power demand in order to follow the target, solving longitudinal vehicle dynamics equations. Once determined torque and speed it is possible to compute the fuel consumption interpolating engine maps, which can be made dependent

on the engine temperature. All the physic features of the model will produce the input information for the Simulink controller, which is the main part of this study and if well calibrated will be the responsible of the fuel consumption reduction.

All the powertrain components have been modeled using steady-state efficiency maps and all the blocks are connected each other thanks to speed and torque information.

2.2 Vehicle Model

The vehicle model reproduces the powertrain (from the energy source to the wheels) based on a parallel hybridization, some controls, monitors and the driver that generates through a PID controller the power request.

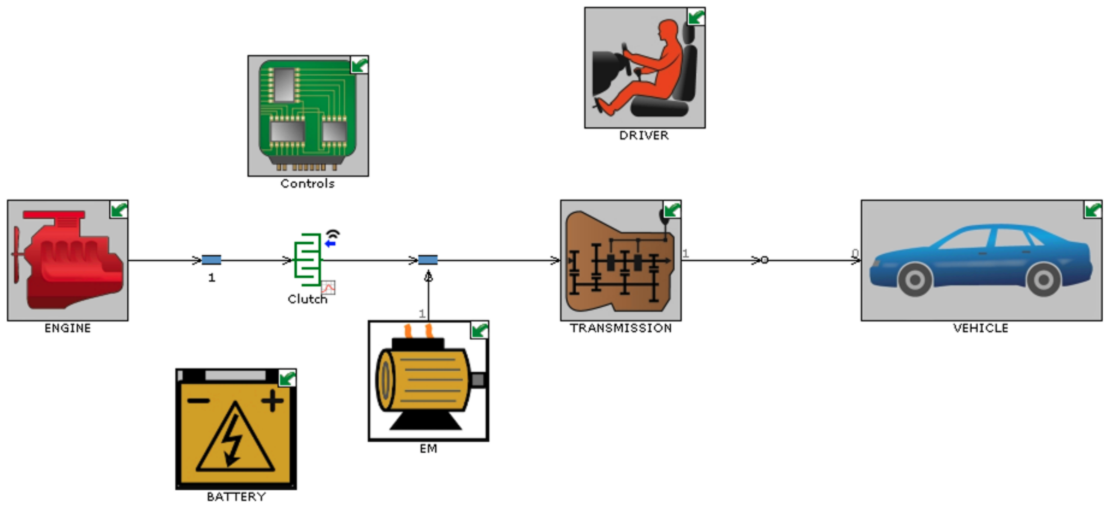

Figure 2.1: Vehicle model

As shown in Figure 2.1 vehicle model is composed of different physic components:

- Engine
- ICE-shaft and Clutch-ICE

- Electric Motor in P2 configuration
- Battery
- Clutch Transmission, Transmission and Driveshaft
- Vehicle (axes, brakes, wheels)
- Driver (PID control)

and a control block that includes:

- Engine Control Unit
- Generator Control Unit
- Clutch 1 and Clutch 2 Control
- Battery Control Unit
- Regenerative Braking, Start-Stop and Hybrid Controls

and finally there are some monitors to keep trace of fuel consumption and emissions. Principal blocks and controls will be singularly described in a more detailed way.

2.2.1 Engine

The engine is a Gasoline Direct Injection with four cylinders and a Variable Geometry Turbine turbocharger and heavy Miller cycle. More detailed information can be found in Table 2.1:

Different engine maps will be used, such as consumption rate, friction, exhaust flow rate, exhaust temperature and all the pollutant emissions, and they are all interpolated based on load, speed and engine temperature. The oil and water pump are linked to the engine model as accessory load. Coolant circuit will be better explained in Paragraph 2.3.3. In Figure 2.2 it is possible to see the full load performance engine curve used for these simulations in terms of speed and load.

Volume	1500 cm^3
Bore	74.5 mm
Stroke	85.9 mm
Rod	143 mm
IV Diameter	26.1 mm
EV Diameter	22.3 mm
Compression Ratio	12.5

Table 2.1: Engine specifications

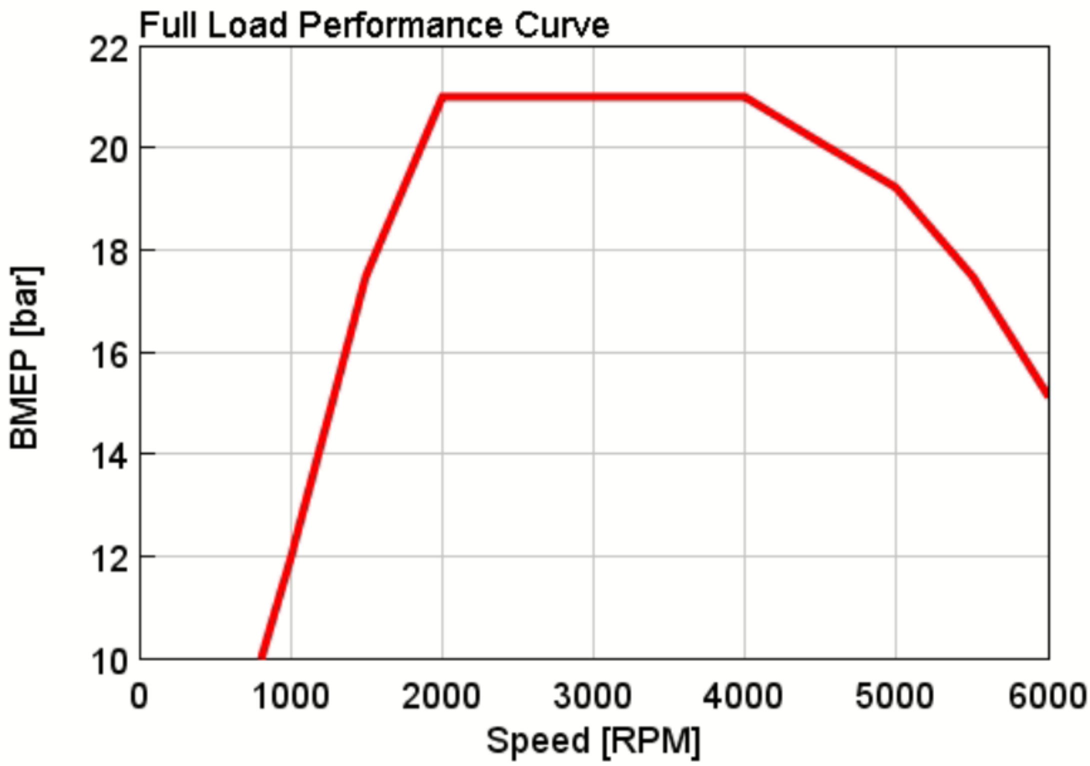

Figure 2.2: Full load performance engine curve

2.2.2 Battery

Also the battery is modeled through electro-chemical maps. It is made by Li-ion cells and more information can be found in Table 2.2

Cell capacity	37.5 Ah
Cell OCV	400 V
Cell internal resistance	83.4 $m\Omega$
Coulombic efficiency	0.98
Max discharge current	250 A
Max charge current	250 A
Max discharge voltage	270 V
Max charge voltage	450 V
Wiring length	1 m
Wiring cross section	1 mm^2
Resistivity	0.016 $\Omega\ mm^2/m$

Table 2.2: Battery specifications

2.2.3 Electric Motor

The EM model is controlled through a brake torque. All the efficiencies are inserted in a map in function of speed and load and they include also the inverter for a more precise calculation. The EM is controlled in such a way as to consider the limits of the battery, that is, the maximum charge and discharge power. Then it is linked to the E-Motor shaft to give it the output torque

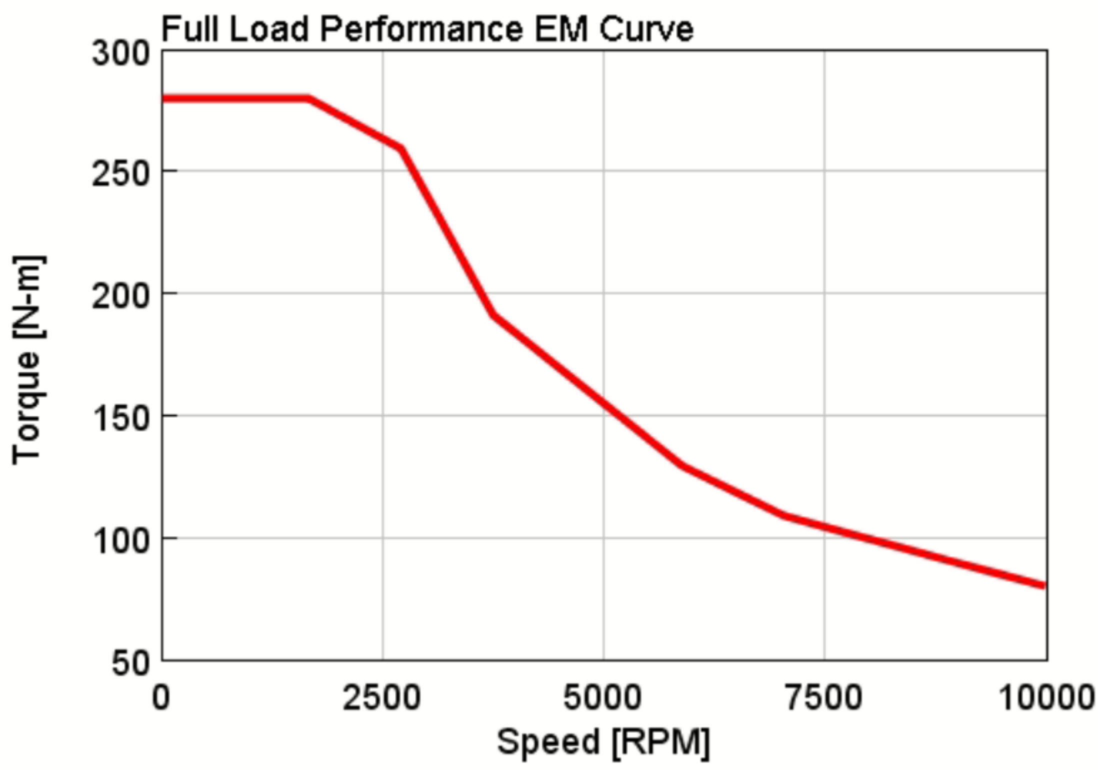

Figure 2.3: Full load performance EM curve

2.2.4 Vehicle

Vehicle resistance can be described as a sum of three terms: rolling resistance, drive-line losses and aerodynamic drag. The first is a constant, the second is linearly dependent to the vehicle speed and the third has a quadratic dependence on the vehicle speed. In Figure 2.4 there is a detailed view of the vehicle components.

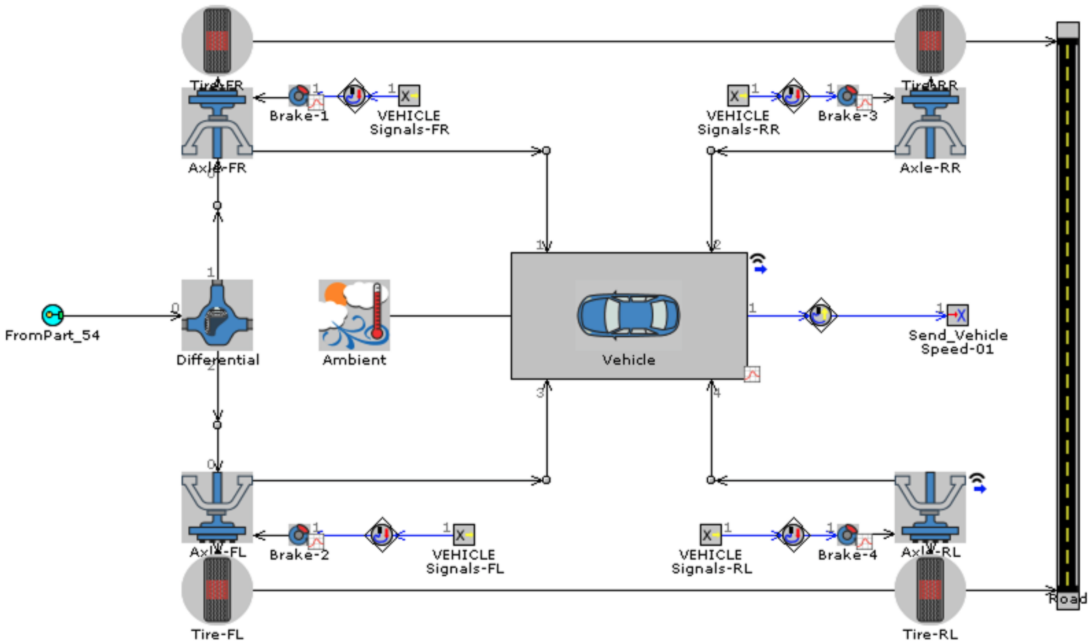

Figure 2.4: Vehicle setup

In Tab 2.3 and Tab 2.4, the vehicle specifications are reported.

Vehicle Mass	1475 kg
EM, Battery and Inverter Mass	250 kg
Brake repartition (front to total)	0.75
Drag coefficient	0.37
Frontal area	2.54 m^2

Table 2.3: Vehicle specifications

Final Drive	1st	2nd	3rd	4th	5th	6th	7th
1	15.53	10.085	6.793	4.978	3.795	3.069	2.565

Table 2.4: Manual Transmission gear ratios

2.3 Thermal Model

In this section, the thermal model is presented. This one is strictly linked to the vehicle because all vehicle outputs are used as inputs for the thermal model in order to compute all the thermal losses of the car components. As shown in Figure 2.5 it is divided in four main parts. Three of them are directly linked, while the control works separately.

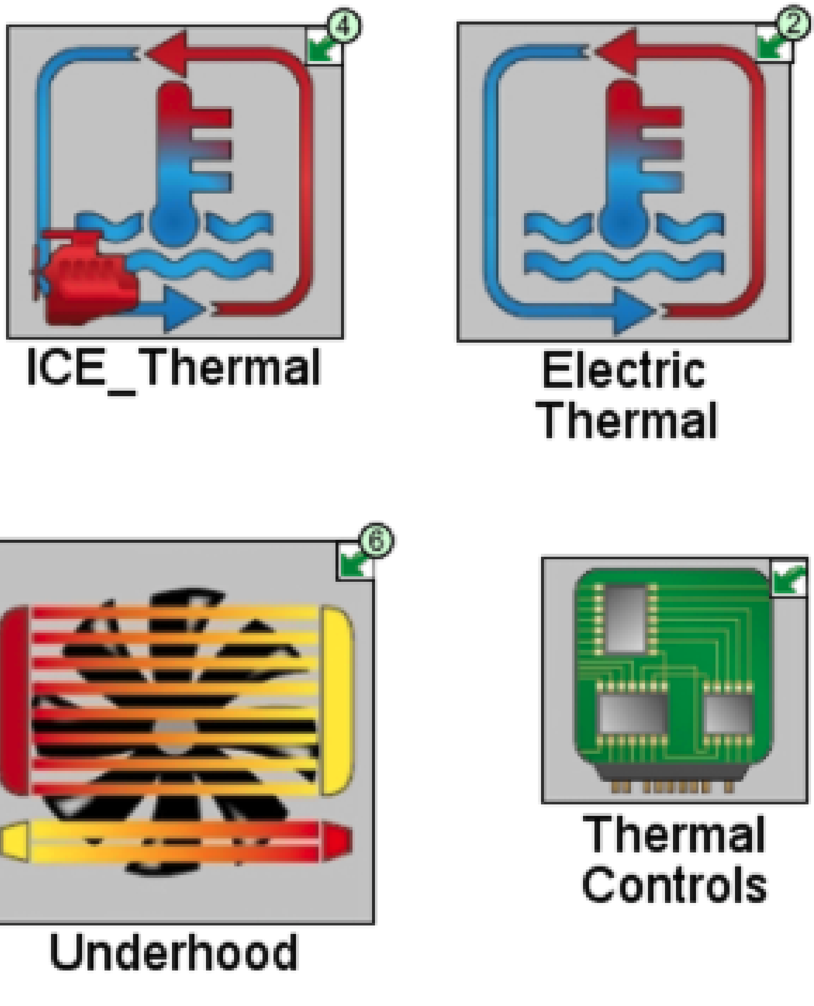

Figure 2.5: Thermal model

The two most important parts are Electric Thermal and ICE Thermal, a more detailed description will follow.

2.3.1 Electric Thermal

The Figure 2.6 represents the cooling circuit of all the electrical components of the hybrid system. The Low Temperature (LT) circuit has the responsibility of decreasing the temperature of EM and Inverter if it gets too high.
On the left here is a radiator that works as heat exchanger while on the right there is a tank for the liquid and a pump. Coolant fluid used for this circuit is egl-5050 with a density of 1071.11 kg/m^3.

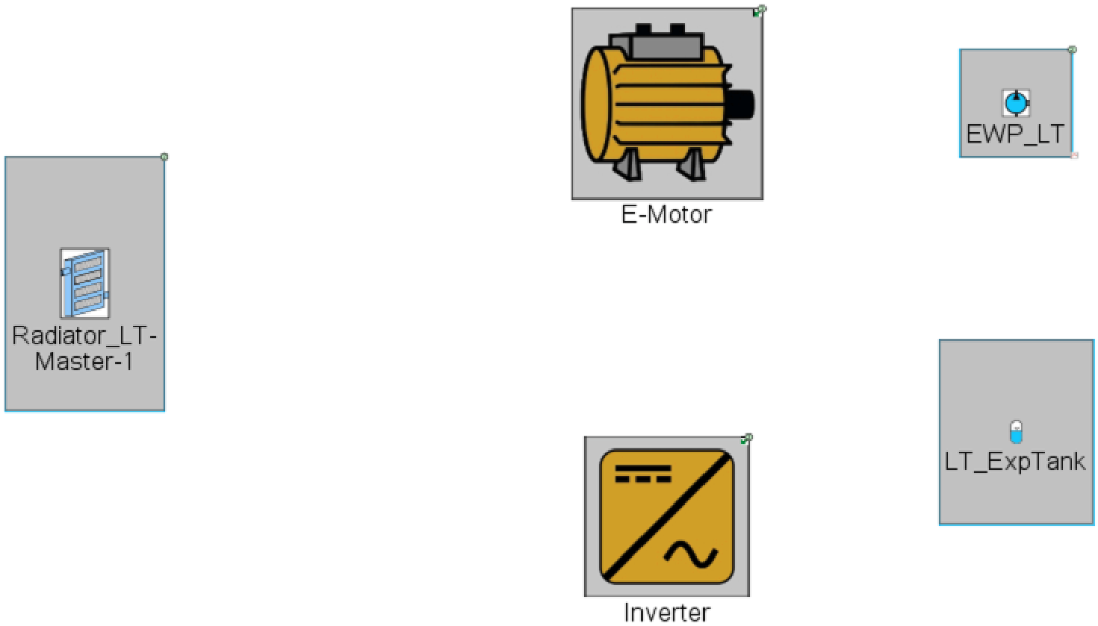

Figure 2.6: Electric thermal

2.3.2 ICE Thermal

ICE Thermal is for sure the main part of the thermal model, because on its ability to compute the thermal losses depends all the implementation of the power split controller. First of all it is necessary to make another subdivision inside the ICE Thermal, as shown in figure 2.7.

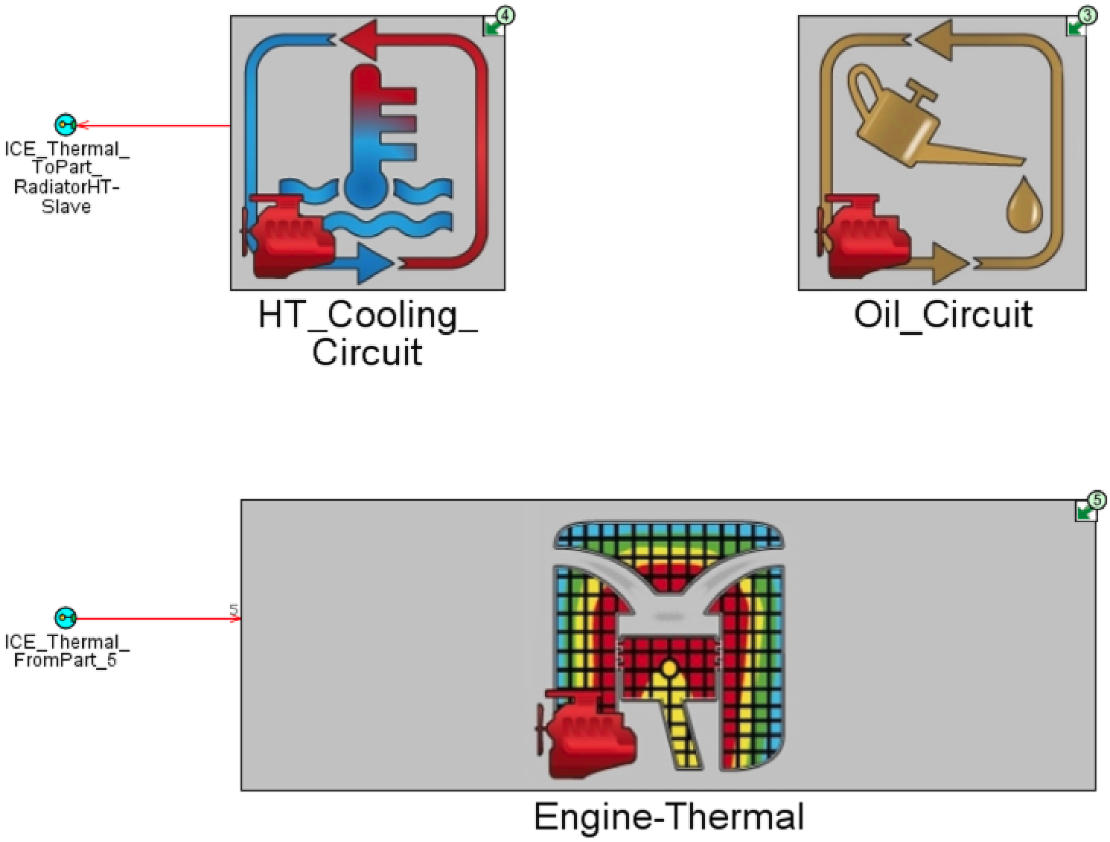

Figure 2.7: ICE thermal

HT Cooling circuit is fundamental for this kind of study, so it is necessary an in-depth description.

2.3.3 HT cooling circuit

The High Temperature circuit has been modeled as showed in Figure 2.8. There is the radiator which is the main heat exchanger, the link with the oil circuit, the cabin-heater, the water pump (gear ratio 1.3) linked to a thermostat and in the center there is the Engine out part that communicate with the ICE. In that point there is also a signal generator that takes the outlet coolant temperature that will be used in the Thermal ECMS to take into account also for the engine thermal state.

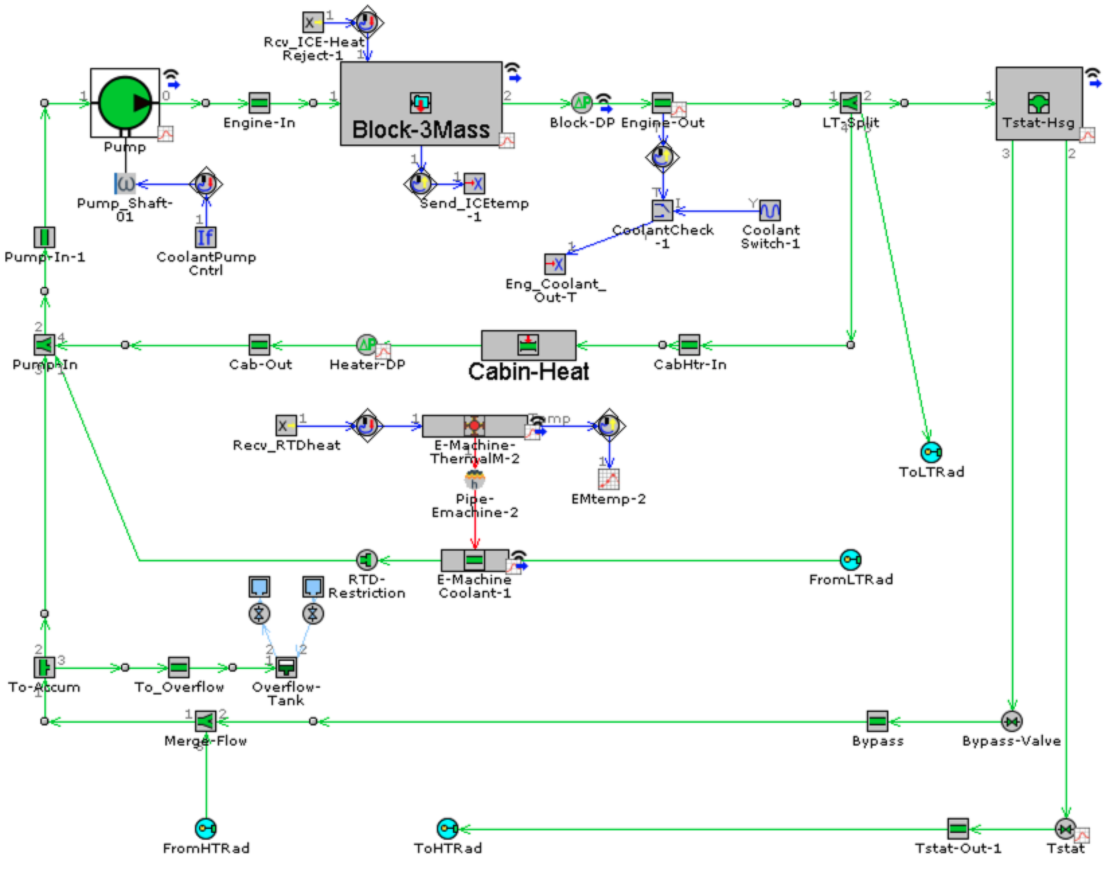

Figure 2.8: HT circuit

The thermostat is set to follow the two curves in Figure 2.9 for opening and closing positions:

The physical models have been described, focusing on the main components that will be needed for implementing the Thermal ECMS, so in the next Chapter there will be an explanation on how to build this controller.

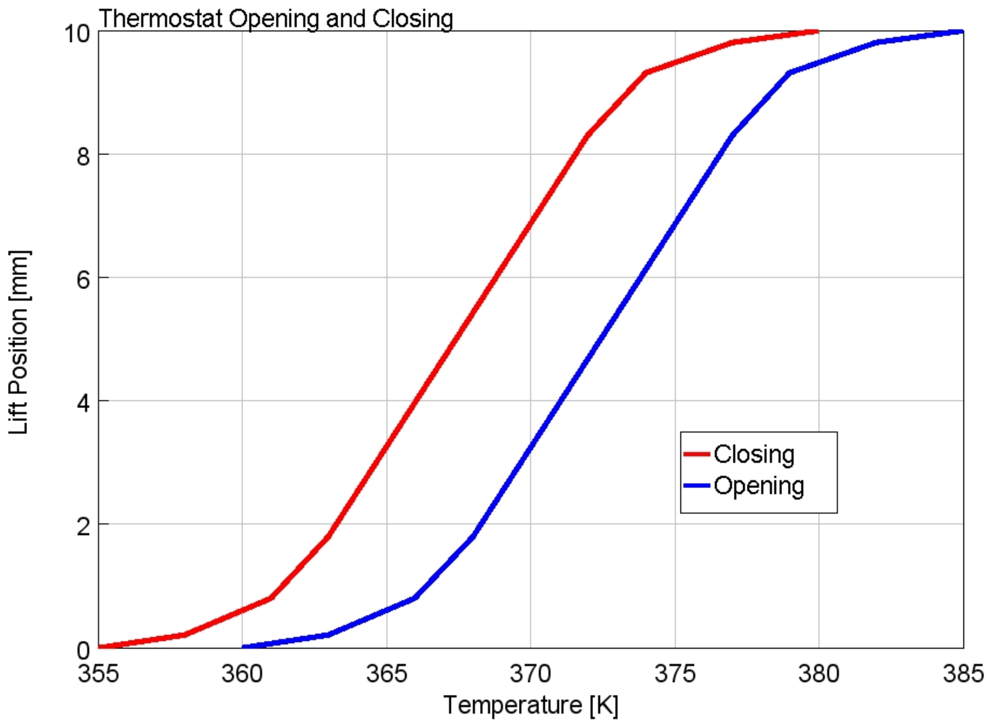

Figure 2.9: Thermostat Opening and Closing

Chapter 3

Case study and controller implementation

In the following steps the methodology adopted for this case study will be introduced. As outlined in the paragraphs before, the aim of this study is to optimize the fuel consumption of a PHEV exploiting the thermal state of the engine. The new controller created will be a Thermal ECMS, so a control able to split the driver power request between ICE and EM taking into account not only speed and load but also the engine temperature, which is a relevant parameter when considering the fuel consumption, especially when the engine is not warmed yet. This new controller will be created starting from a classic ECMS explained in Paragraph 1.3.

3.1 Driving cycles

Both NEDC and WLTC test cycles will be described, emphasizing the differences in terms of duration and speed reached. [7]

3.1.1 NEDC Cycle

In order to have a better view of how the new thermal control works, NEDC cycle has been considered for this case study. The New European Driving Cycle was last updated in 1997 and in the last decade has been substituted by the WLTC. This kind of cycle is supposed to represent the typical usage of a car in Europe, however it has been criticised different times because shows fuel consumption that are difficult to achieve in reality. The cycle should be performed on a flat road and in absence of wind, however in order to have repeatability it is usually performed on a roller test bench. A lookup table will give the aerodynamic drag as a function of the speed, and so a reverse torque will be applied to the wheels.

As anticipated before, one criticism is the difference with the real driving conditions, because there are low accelerations and constant speed cruises, however in this case emissions measurements are not needed, but the objective is only to see how the new control is able to reduce the fuel consumption on the same path followed by the car.

The cycle is represented in Figure 3.1 and in Table 3.1 its main characteristics are reported.

Duration	1200 s
Distance	11 km
Mean Velocity	33 km/h
Max Velocity	120 km/h

Table 3.1: NEDC specifications

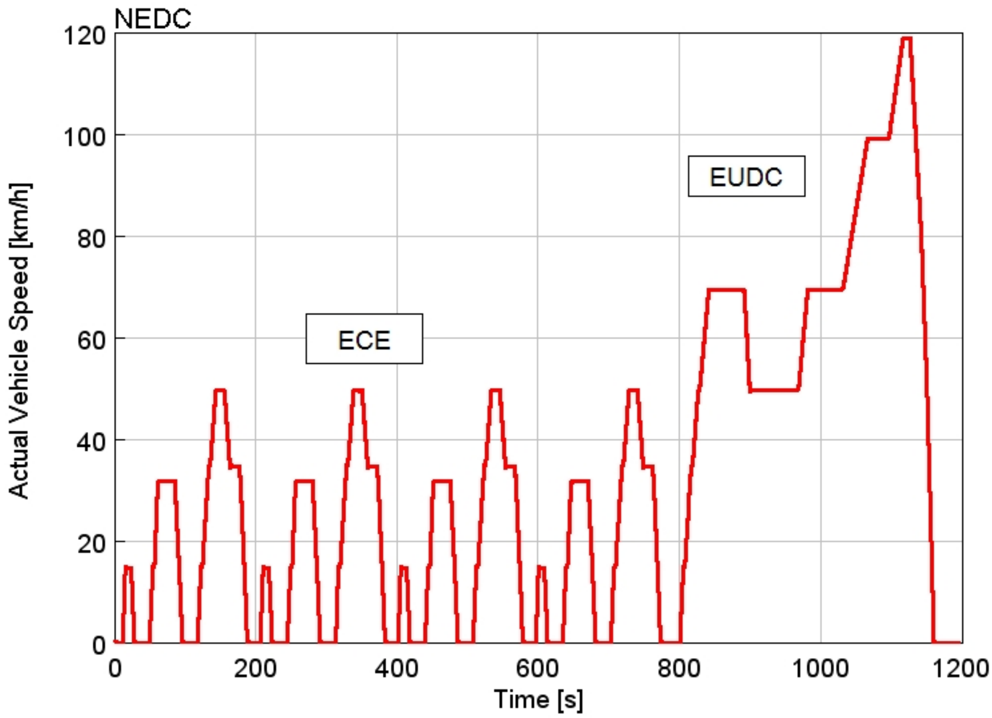

Figure 3.1: NEDC Speed

3.1.2 WLTC Cycle

In this section the test cycle is reported. It is called Worldwide harmonized Light vehicles Test Cycles and it is an approval driving cycle, imposed for homologation regulation by EU legislation. It is a chassis dynamo-meter test for the determination of emissions and fuel consumption from light-duty vehicles. This test has been developed by the UN ECE GRPE (Working Party On Pollution and Energy) group.

The WLTC replaces the European NEDC based procedure for type approval testing from 2017 and it is applicable to vehicle categories of different power-mass ratio. In Figure 3.2 it is possible to see the vehicle speed imposed during the cycle, while in Table 3.2 its main characteristics.

Duration	1800 s
Distance	23.27 km
Mean Velocity	46.5 km/h
Max Velocity	131.3 km/h
Max Acceleration	1.67 m/s^2
Min Acceleration	-1.5 m/s^2
Mean Pos. Acc.	0.41 m/s^2
Mean Neg. Acc.	-0.45 m/s^2

Table 3.2: WLTC specifications

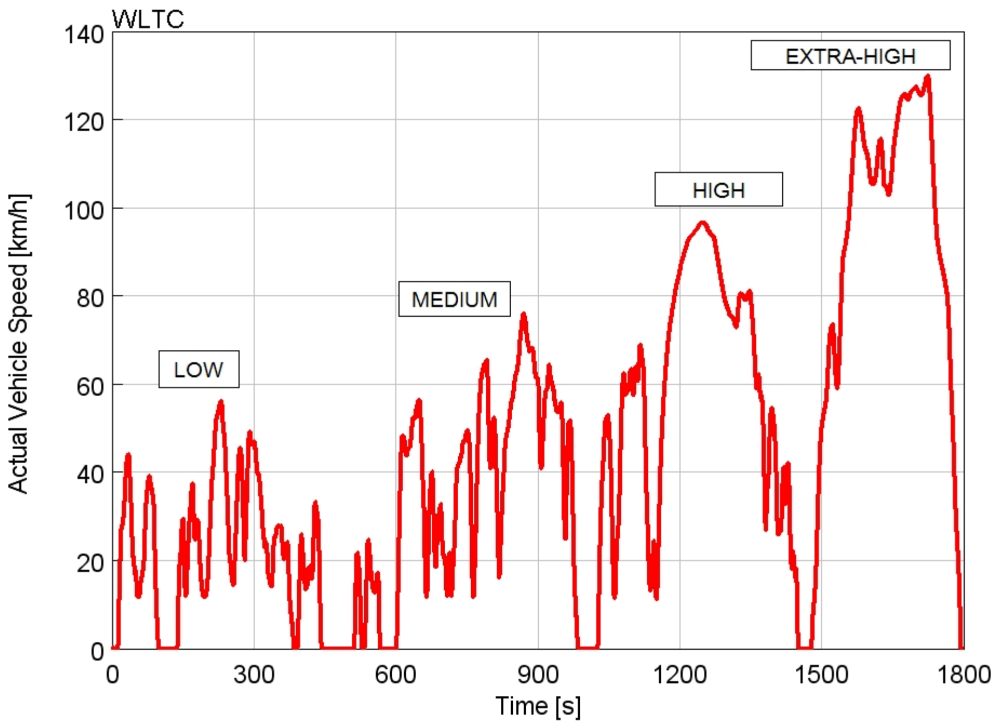

Figure 3.2: WLTC Speed

3.2 Cost function computation

As mentioned in Paragraph 1.3, the standard ECMS is the starting point for the development of the new control. The equation of the cost function to minimize (J) for the standard ECMS is the equivalent fuel consumption which is calculated as the sum of the ICE instantaneous consumption (m_f) and the product between the battery power and the equivalence factor k:

$$J = m_f + k \cdot P_{\text{batt}} \tag{3.1}$$

At each time step (0.05 s) 10000 different power split will be computed and the control will choose the one with the lowest J value. Of course P_{batt} can be either positive (charging) or negative (discharging), so there can be moments in which the equivalent fuel consumption is lower than the real one, but this is not important, because we just have to consider the equivalent fuel consumption as an indicator of the best split between ICE power and EM power.

In this section the starting controller will be modified in order to create a new one able to take into account also the engine temperature, in order to have a lower fuel consumption especially when the engine is not warmed yet. To do this, it is necessary to modify the cost function, adding a new equivalent consumption term that is the product between the thermal power exchanged by the engine $P_{thermal}$ and a thermal equivalence factor p:

$$J = m_f + k \cdot P_{\text{batt}} + p(t) \cdot P_{\text{thermal}} + m_p \tag{3.2}$$

The fourth term m_p considers load variations, and its order of magnitude is lower than the other three.

As well as the ICE fuel consumption, also the thermal power will be interpolated through 3-D maps receiving as inputs speed, load and engine temperature.
Before going on with the computation, it is fundamental to do a clarification: while the equivalence factor k is constant during the simulation (its value is found by iteration with the aim of obtaining the charge sustaining), the thermal equivalence factor p depends on time, so its value will change at each time step. $p(t)$ will be directly obtained through the following equation:

$$p(t) = p_0 \cdot e^{\frac{t}{MC} \cdot \frac{\partial P_{th}}{\partial \theta}} - \frac{\frac{\partial m_f}{\partial \theta}}{\frac{\partial P_{th}}{\partial \theta}} \tag{3.3}$$

MC is a thermal capacitance expressed in J/K and its value depends directly on the amount of water present in that moment in the HT radiator. In this case study it was decided to calculate an average value

of it, considering the water volume in the HT circuit and in the piston block. Its value is constant and equal to 8770 J/K.
Both the derivatives are computed through interpolation in 3-D maps while t is the time of the simulation expressed in seconds. The last parameter that needs to be defined is p_0, and it is possible to get its value only by iteration, so imposing a value that at the end of the cycle will make the function $p(t)$ expressed in the equation 5.3 almost zero (it is a decreasing exponential function). After finding the right value of p_0, it is necessary to find a k that guarantees the charge sustaining for this new type of control. The equivalence factors k and p_0 will be different for each cycle and each starting temperature, so this iteration process will be repeated different times.

The starting SOC will always be 0.5 and in order to guarantee the charge sustaining, its value has to be almost the same at the end of the cycle.
At each time step the controller will calculate a large variety of possible power split, and the best one will be chosen considering the equivalent fuel consumption. This parameter is obtained summing four different contributes:

- Engine fuel consumption
- Battery equivalent fuel consumption
- Load equivalent fuel consumption
- Thermal equivalent fuel consumption

The fourth parameter is the one that was not present in the starting controller (standard ECMS) and is the only one that takes into account the thermal behavior of the engine. A description of the four parameters will follow.

3.2.1 Engine fuel consumption

The m_f is the real fuel consumption of the engine, expressed as a function of load and speed in the starting controller, but in the new controller implemented it will be a function of a 3D map, considering also the engine temperature. It is important to underline that at each time instant the controller will choose the power split with the lowest equivalent fuel consumption, so the engine fuel consumption will not necessarily be the lowest among the different power split strategies proposed.
Through the fuel consumption obtained by the engine fuel map in the physical model, thanks to an integration during the whole cycle, it will be possible to compute the total fuel consumption and make a comparison between the two controllers.

3.2.2 Battery equivalent fuel consumption

It is the equivalent fuel consumption that takes into account the power delivered by the battery. It is of the same order of the real engine fuel consumption, so has a significant impact on the choice of the power split. It is computed multiplying at each time instant the battery power with the equivalence factor k. This factor will be constant during the entire cycle, but in order to satisfy the charge sustaining constraint some iterations are needed, because the final SOC is directly proportional to the k value. It is measured in g/kWh and its value will also depend on the starting environment temperature, because the lower the starting temperature the higher the engine fuel consumption, so the controller will tend to use more the electric energy in order to reduce the fuel consumption, but in this way the risk is to have SOC too low at the end of the cycle. To avoid this situation, it is necessary to give a higher weight to the battery equivalent fuel consumption, increasing k. Just to have an idea of its order of magnitude, its value is between 200 and 300.

Unlike the engine fuel consumption, the electric one can be both positive or negative, depending on the battery status (charging or discharging), in fact when the battery is charging its power will be positive and so also the battery equivalent fuel consumption will be higher than zero.

3.2.3 Penalty equivalent fuel consumption

This parameter is always bigger than zero, but it's an order of magnitude lower, so has a lower impact on the power split choice. It is just a penalty function for the load oscillations, in fact thanks to this parameter there should be fewer power swings. It is computed through a gain of the order of 10^{-6} and its value is proportional to the sum of the square of the difference between the current power and the vector of possible powers of the engine and EM.

3.2.4 Thermal equivalent fuel consumption

Last but not least this parameter is the principal difference between the starting controller and the new one. As said before this parameter takes into account the thermal behavior of the engine, improving the power split choice because the final fuel consumption will strongly depend on how the engine warms up.
Its value is computed multiplying the instant thermal power dissipated by the engine with an equivalence factor called p. The Formula 5.3 explained previously shows how to compute p during the cycle, so one of the first main difference is that while for the electric equivalent fuel consumption the equivalence factor k was constant during the whole cycle, in this case there is a variable thermal equivalence factor that tends to zero when the coolant temperature reaches the steady state value of about 95°.

The thermal equivalent fuel consumption can be both positive or negative, depending on the thermal power sign, however in these simulations the engine warms up during the cycle, so the thermal equivalent fuel consumption is negative because the thermal capacity is "charged".

3.3 Controller

This section will show the procedure for creating the new controller. The software environment used is Simulink. Everything starts with the 3D maps generation on Matlab. These maps express the ICE fuel consumption as a function of load, sped and engine temperature. In this way at each time instant the instantaneous fuel consumption will be computed. The calculation of the electric equivalent fuel consumption is also quite easy. The equivalence factor k, which is constant during the whole simulation, is multiplied at each time instant with the battery power. Both values are given as input by the physic plant built on GT-SUITE. Regarding the penalty equivalent fuel consumption, it will have a gain of $6 \cdot 10^{-6}$. Finally it is possible to compute the thermal equivalent fuel consumption. First of all it is necessary to compute the factor p, which will change at each time instant.

An explanation on how to compute each term of Formula 3.3 is reported. p_0 and MC are the only two parameter that are constant during the whole simulation and are given as input by the physic plant, chosen by the user in order to obtain the best calibration, with low oscillations and in a such way that the p function, being an exponential function, will ideally reach 0 when the engine becomes warm. While MC is a thermal capacitance related to the engine and will be the same for all the cycles and simulations, p_0 will be different, depending on the driving condition and on the environment temperature, and its best value will be found by iteration.
As well as for the fuel consumption, these maps are generated on Matlab and then inserted in the Simulink model. The maps are in function of load, speed and engine temperature, so at each time instant they will change.
To obtain the equivalent thermal fuel consumption at each time instant p has to be multiplied with the thermal power calculated, as a function of temperature.

The mechanical characteristics of ICE and EM are discretized with a discretization factor of 100, generating 10000 possible powersplits. For each of the 10000 possibilities the controller computes the equivalent fuel consumption as a sum of the four terms explained before. The power split that will show the lowest value of equivalent fuel consumption will be chosen. This procedure repeats at each time instant that in these simulation is equal to 0.05 s. Once the best powersplit is selected, the controller will automatically choose the powersplit with minimum fuel consumption, compute the power requested to the ICE and the power requested to the EM, and will give these two values as input for the physic plant. The latter will compute all the thermal losses and then will give back to the controller a new value of power demand associated to the new time instant. The cycle repeats until the end of the simulation. [8] [9] [10] [11]

Chapter 4

Results

In this Chapter it is finally possible to appreciate the differences in term of fuel consumption thanks to the new controller. In the following paragraphs each cycle and each starting environment temperature will be singularly analyzed, containing also the plots of the integrator of the fuel consumption during the cycle and also the engine temperature trend. Three different case studies are reported: the first one is the reference case, with a starting temperature of 95 °C (warm engine) and with standard ECMS, the second one is the standard ECMS with cold starting temperature and the third one is the new Thermal ECMS with cold starting temperature.

In this way it will be possible to understand not only the differences between old and new controller (with the same starting temperature), but it will be also possible to see how far they are from the warm case. In the final paragraph, moreover, there will be an analysis on the Thermal ECMS in comparison with the AECMS controller explained in Paragraph 1.3.
In all the cases that will be discussed next, the three types of simulation have always the same color: green for the warm engine simulation with the reference ECMS, red for the cold start with the reference ECMS, and blue for the cold start with the new controller (Thermal ECMS). The blue one will be always higher than the green one but lower than the red one in terms of fuel consumption, demonstrating

that the improvement has been achieved.

4.1 NEDC starting at -10 °C

This is the case where the new controller showed the best improvement. As shown in the diagrams a difference bigger than 2% of fuel consumption is obtained with the Thermal-ECMS.

In the next graph are plotted the engine temperatures along the cycle. It is possible to see that with the new controller the engine at the beginning tends to work less, in order to optimize consumption, and then its temperature starts to increase more quickly because CS requires that the final SOC will be the same so it is not possible to work too much with the EM otherwise it is not possible to recharge completely the battery till the value of 50%, which is the final SOC value set for all the simulations.
It is also possible to see that with the new controller the fuel consumption is closer to the ideal case plotted, that corresponds to a starting temperature of 95 °C, so engine completely warm. Considering also that the difference between the old controller and the warm engine fuel consumption is quite large, the Thermal-ECMS shows a remarkable improvement.
Only for this specific case more plots will be included, showing the equivalent fuel consumption trend and also the exponential function of the thermal equivalence factor p.

The last graph for each section is an histogram showing how the new controller reduces the fuel consumption, with the percentages values taking as a reference the warm case (green), when the starting temperature of the engine is 95 °C.

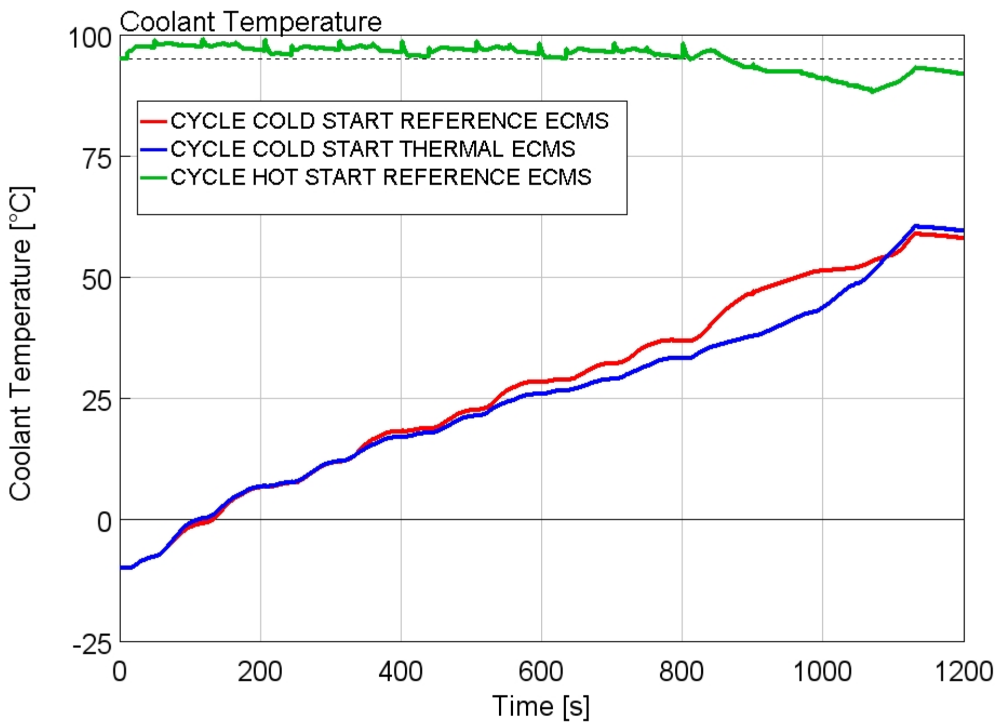

Figure 4.1: NEDC T-10 °C Engine Temperature

It is possible to appreciate a reduction in the fuel consumption higher than 2%. The histogram in Figure 4.9 has been obtained thanks to the monitoring of the fuel consumption cumulative along the cycle, described in Figure 4.3.

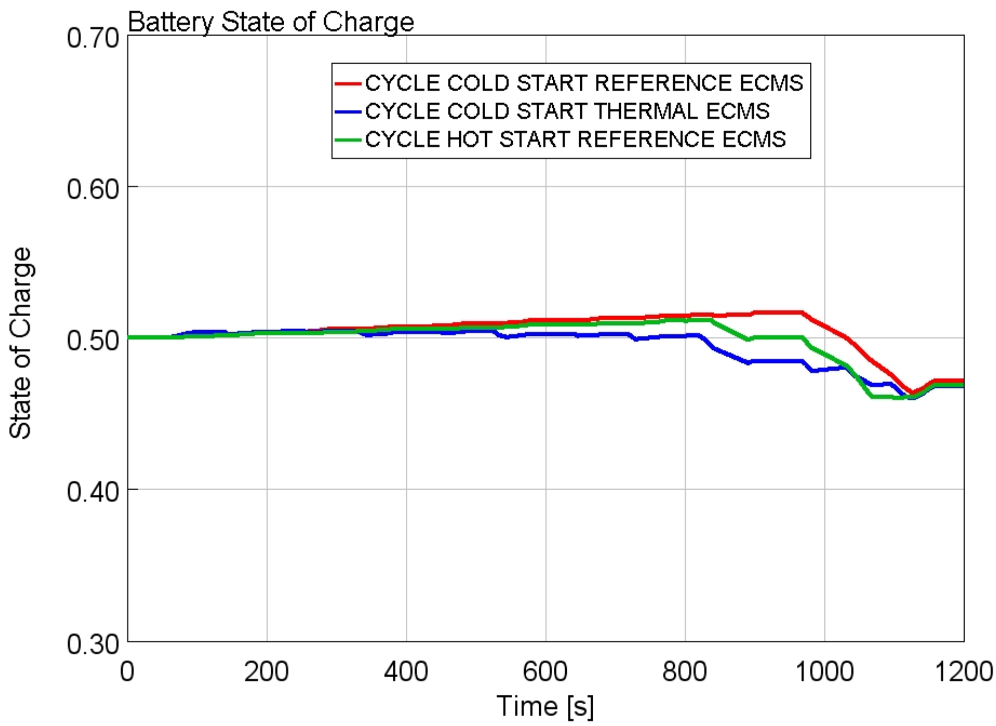

Figure 4.2: NEDC T-10 °C SOC

In Figure 4.2 is shown the Battery SOC. It is important to remember that all the simulations must satisfy the charge sustaining constraint, which means that the final SOC must be equal to the initial one, which is 0.5. It's easy to see that in the final part the behavior is very different between the two controllers, while the warm engine simulation, always with the reference controller, is in the middle.

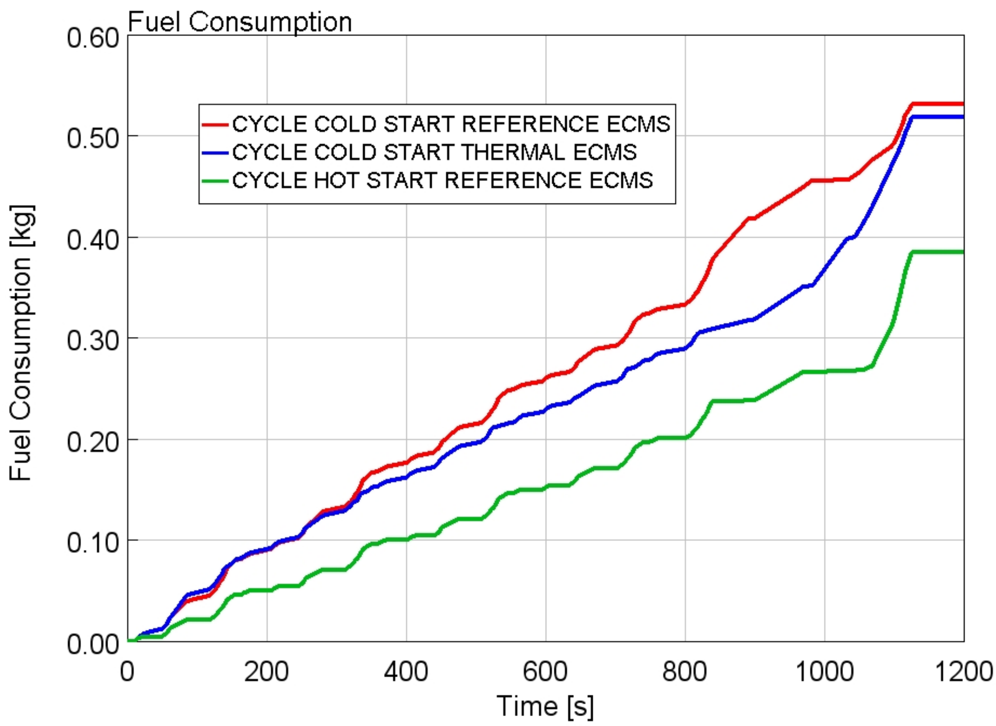

Figure 4.3: NEDC T-10 °C Fuel Consumption

In Figure 4.1, instead, is plotted the engine temperature along the cycle, taking as a reference the coolant temperature present in the HT circuit. The dashed line indicates the temperature of 95 °C, that corresponds to the warm engine. Thermal ECMS tends to get hot slower, this because at the beginning electric power is exploited more in order to avoid the high engine fuel consumption rate when the temperature is too low.

As anticipated before, only for the NEDC T-10 °C case there will be also the plots of the various equivalent fuels and the exponential function p, in order to understand better how the new controller works. The following figures represent all the fuels parameters explained in Chapter 3.

- Engine real fuel consumption
- Battery equivalent fuel consumption
- Penalty equivalent fuel consumption
- Thermal equivalent fuel consumption (present only in the new controller)

It is possible to see that the penalty equivalent fuel consumption is one order of magnitude lower, so its influence in the power split is very small, just to avoid excessive power oscillations. Engine fuel and battery equivalent fuel consumption, instead are of the same order, so they are comparable. Especially in the Figure 4.5 it is clear that the new controller presents an higher value along the cycle. This is related to the fact that the new controller, in order to respect the CS constraint, requires a value of k much higher than the reference controller, so the battery equivalent fuel consumption, being directly dependent to this variable is higher.

Finally it is very important to focus on Figure 4.7 with the thermal equivalent fuel consumption. This is the main aspect that distinguishes the reference controller from the thermal one. This variable has a sort of exponential function that starts from a negative value and then tend to zero. This because at the beginning there is more thermal power exchanged, so it has a big impact on the fuel consumption and on the power split. Going on during the cycle, the engine temperature rises, so the thermal equivalent fuel consumption will start to have less important until reach values close to zero when the engine is warm (of course with some oscillations as shown in the plot).
In the last graph, thermal equivalence factor p is plotted in Figure 4.8. It is clear that its behaviour is exponential like the thermal equivalent fuel consumption, but on the positive side of the y axes. Also here, neglecting some oscillations, its value approaches almost zero at the end of the cycle, because the thermal state has no more influence when the engine is not cold any more.

It is possible to see that in p and m_{th} plots there are some spikes. This is mainly related to the fact that in some time instant the value of the derivatives in the p formula may have a value much bigger than the exponential one, so the function rapidly decreases because the derivative are predominant. In this way, also m_{th} will oscillate widely because, as explained before, it is obtained multiplying the thermal power with p.

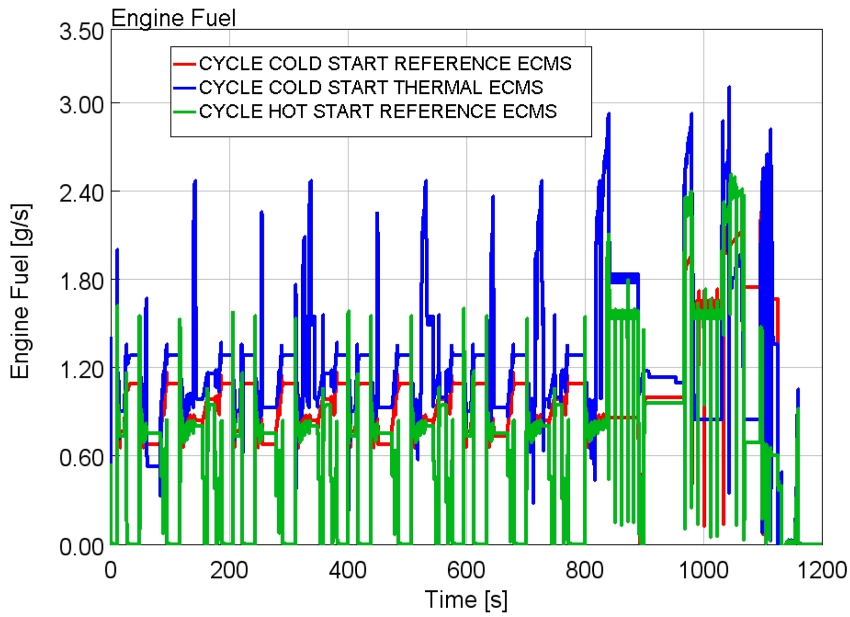

Figure 4.4: NEDC T-10 °C Engine Fuel

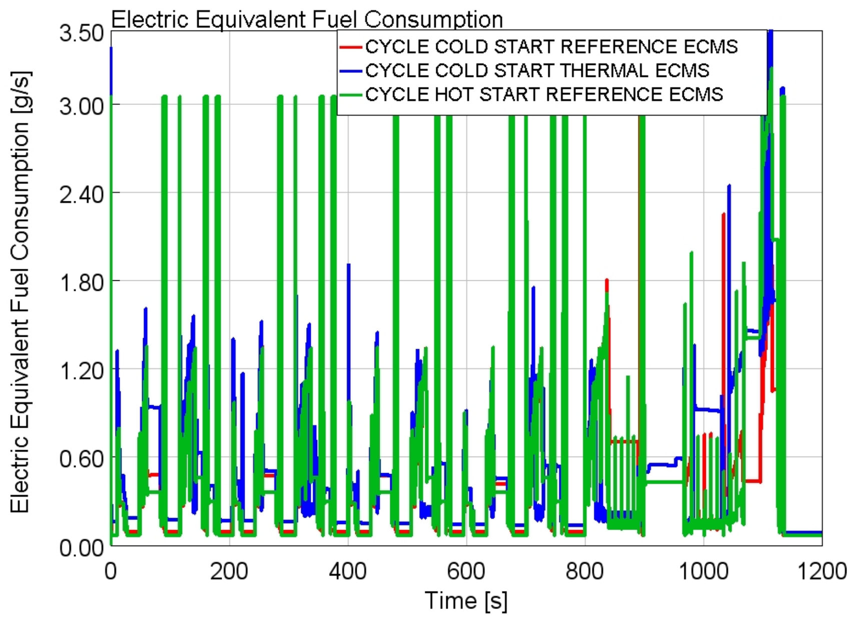

Figure 4.5: NEDC T-10 °C Battery equivalent fuel consumption

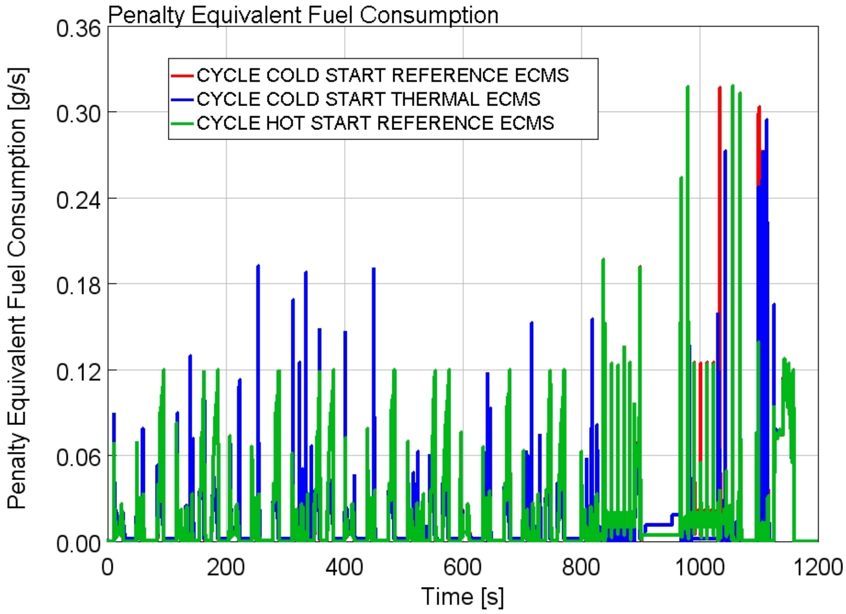

Figure 4.6: NEDC T-10 °C Penalty equivalent fuel consumption

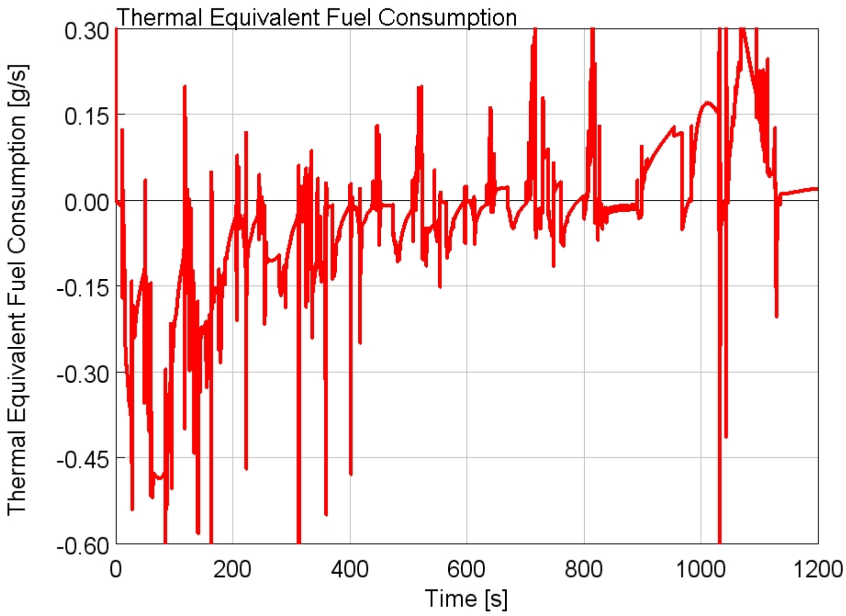

Figure 4.7: NEDC T-10 °C Thermal equivalent fuel consumption

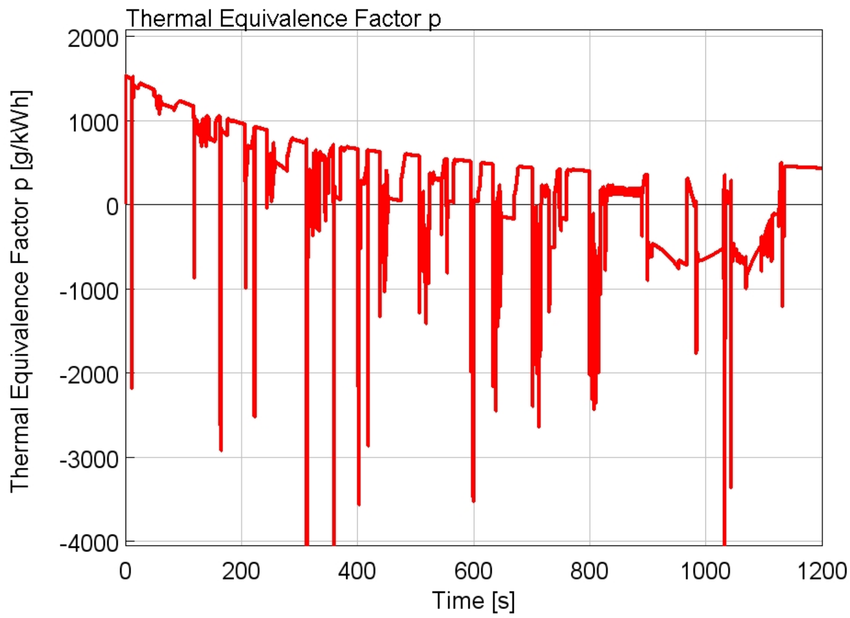

Figure 4.8: NEDC T-10 °C Thermal equivalence factor p

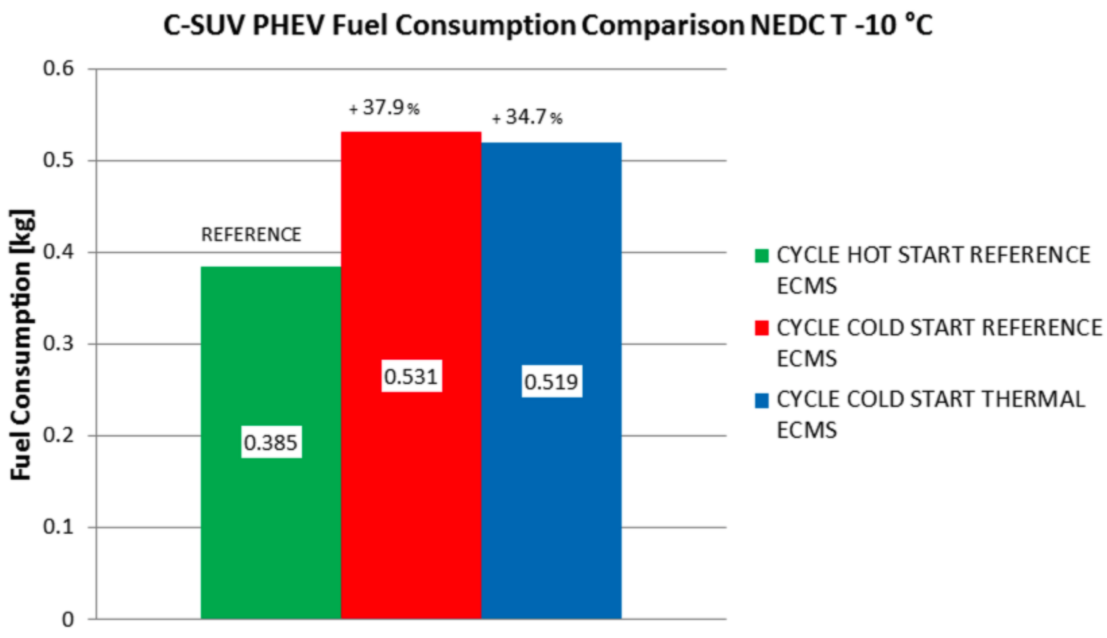

Figure 4.9: NEDC T-10 °C Fuel Consumption

4.2 NEDC starting at 20 °C

Starting from a higher temperature than the previous case of course reduces the effectiveness of the new controller, however there are still good improvements as shown in the Figure 4.13.

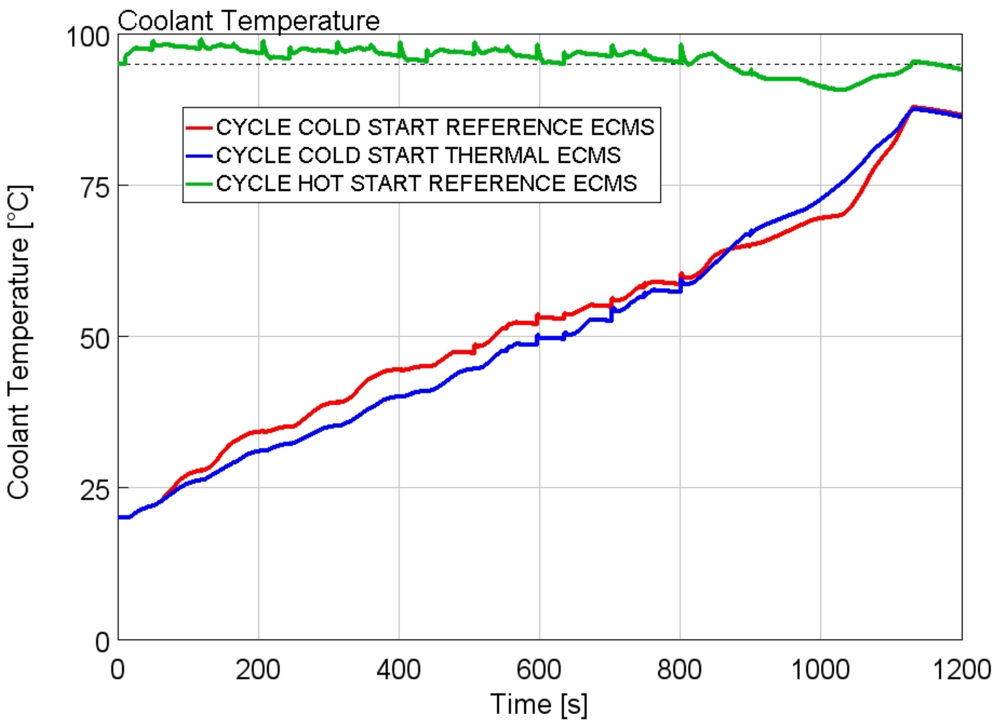

Figure 4.10: NEDC T 20 °C Engine Temperature

There is still an improvement higher than 2% which demonstrates the power of the Thermal ECMS implemented. Only cumulative fuel consumption, SOC and engine temperature will be shown.

Also in this case it is possible to appreciate the different behavior in terms of engine warming. The Thermal ECMS tends to warm the engine in a slower way and then in the final part it accelerates the warming.

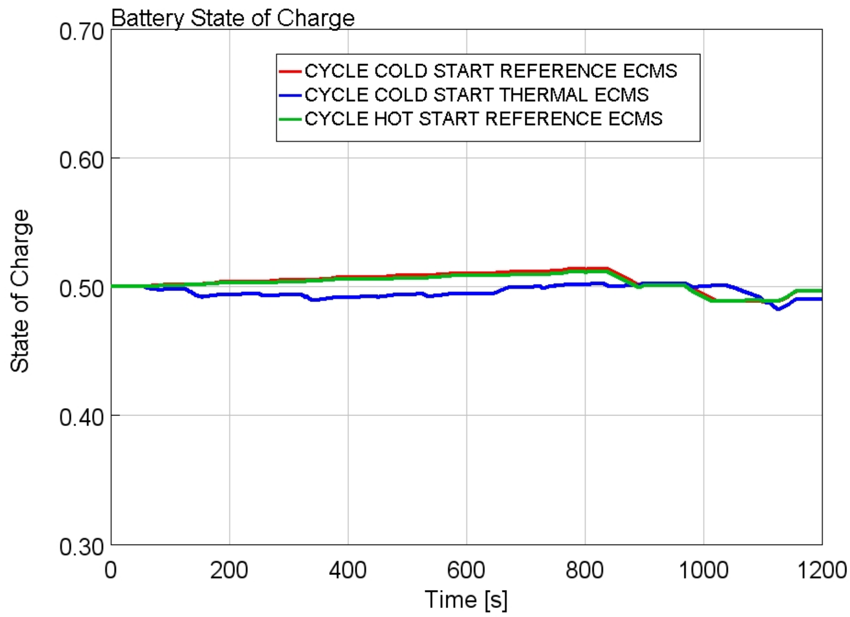

Figure 4.11: NEDC T 20 °C SOC

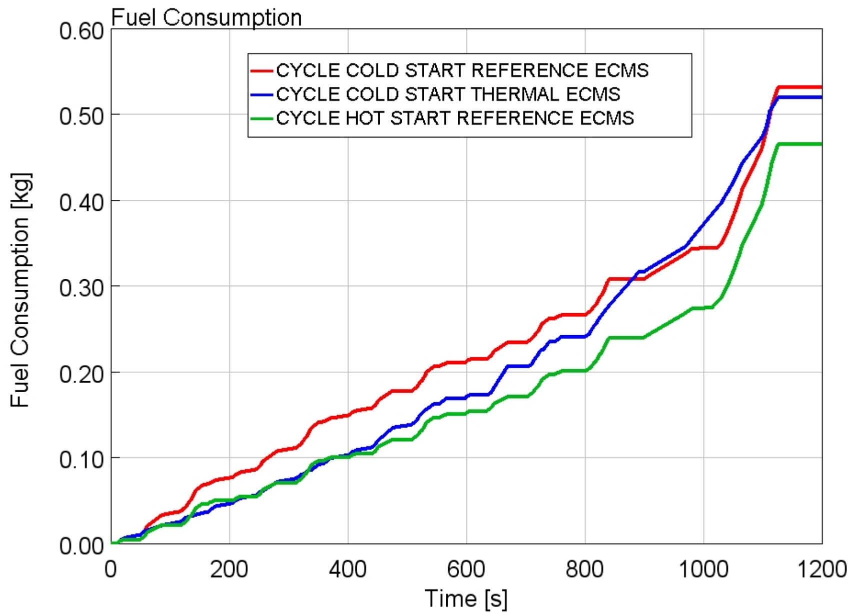

Figure 4.12: NEDC T 20 °C Fuel Consumption

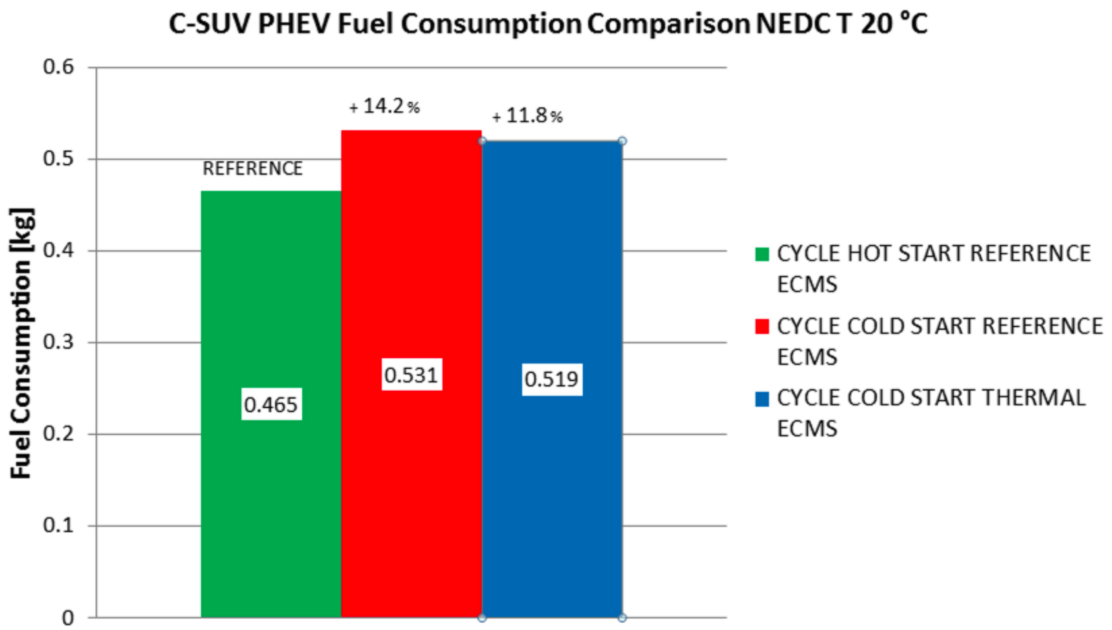

Figure 4.13: NEDC T 20 °C Fuel Consumption

4.3 WLTC starting at -10 °C

In this section a different cycle will be analyzed, more aggressive in terms of power and fuel consumption, so the benefits of the new controller will be less conspicuous, as shown in Figure 4.17.

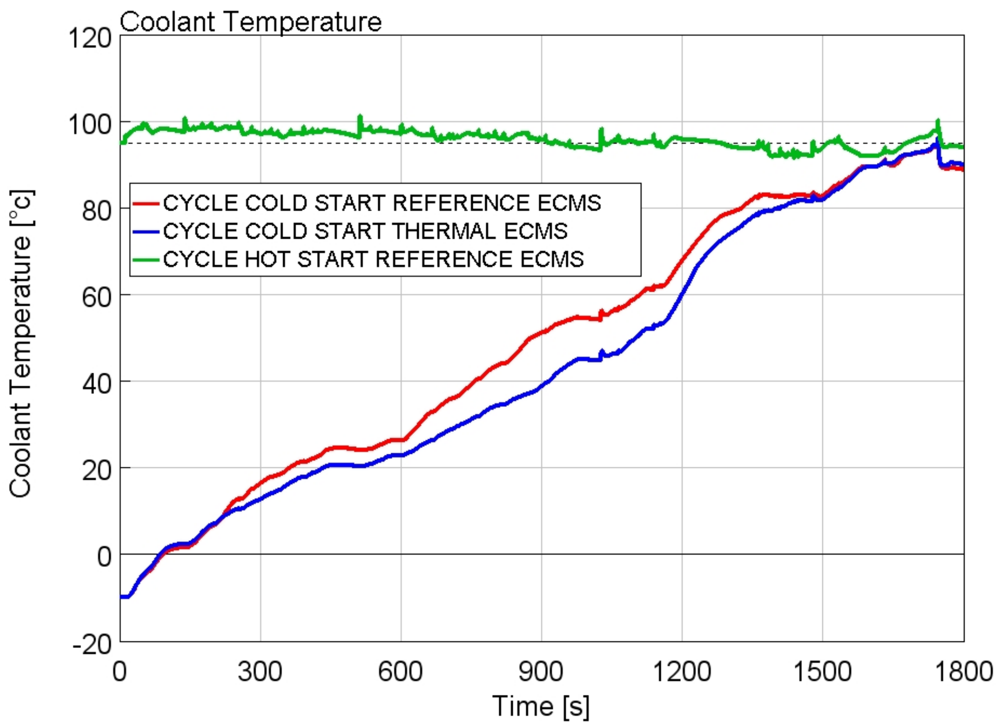

Figure 4.14: WLTC T -10 °C Engine Temperature

In this case the difference in terms of fuel consumption is lower, only a little more than 1%, while in NEDC cycle it was double. Cumulative fuel consumption, engine temperature and SOC plots are reported.

The behavior of the new controller is the same highlighted in the NEDC cycle. Concerning the engine temperature, it keeps it lower respect to the reference ECMS and in the final part of the cycle it increases more quickly. Also the SOC plot shows the same trend: the new controller uses more the electric power at the beginning (SOC

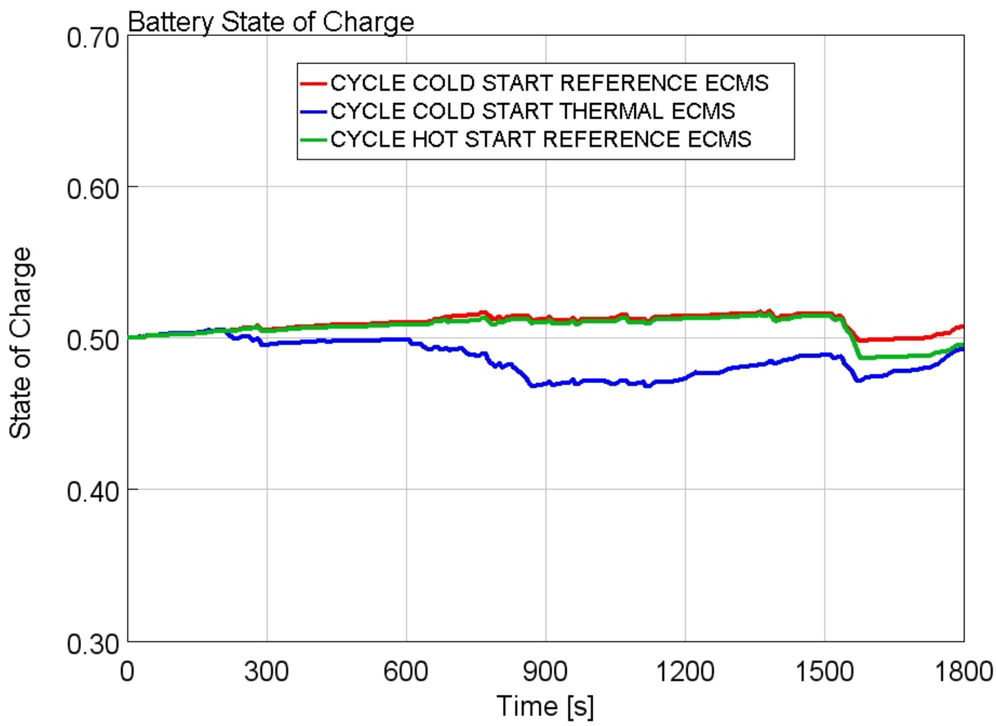

Figure 4.15: WLTC T -10 °C SOC

decreases more respect to the reference), while in the final part, when the engine is warm, it charges the battery.

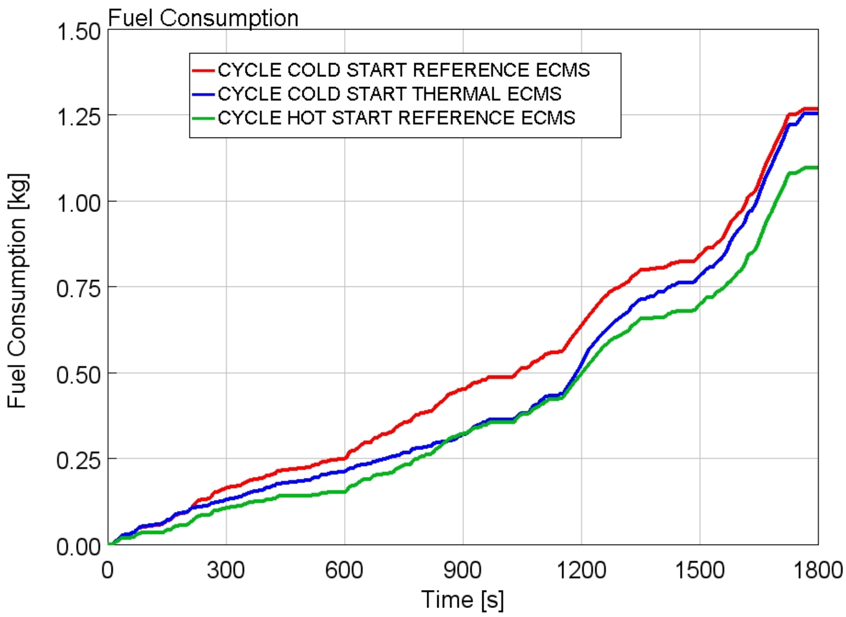

Figure 4.16: WLTC T -10 °C Fuel Consumption

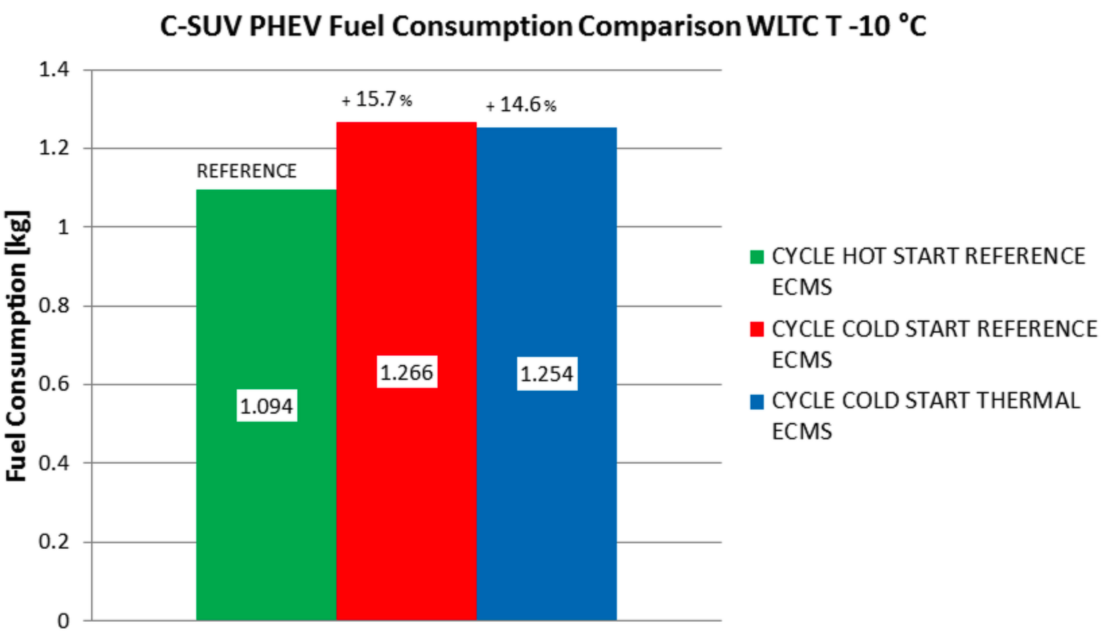

Figure 4.17: WLTC T -10 °C Fuel Consumption

4.4 WLTC starting at 20 °C

The last case analyzed is the WLTC cycle starting from 20 °C. Although the starting temperature is higher than the previous case, the improving obtained with the new controller is larger, as shown in Figure 4.21, more than 1.5%.

Also SOC and Engine Temperature behave in a way similar to the previous case along the cycle.

In Figure 4.22 there is a summary of the fuel improvement obtained along the two cycles for both temperatures. The reference is the case with warm engine, it is clear that the new controller Thermal ECMS shows a lower percentage of fuel required in addition to the reference value, so the new controller requires less fuel than the standard one. However, the Figure 4.23 shows that the final SOC in the cases analyzed is not perfectly the same, especially in the WLTC simulations. This means that for sure a contribution to the fuel consumption improvement is given also by the difference in SOC.

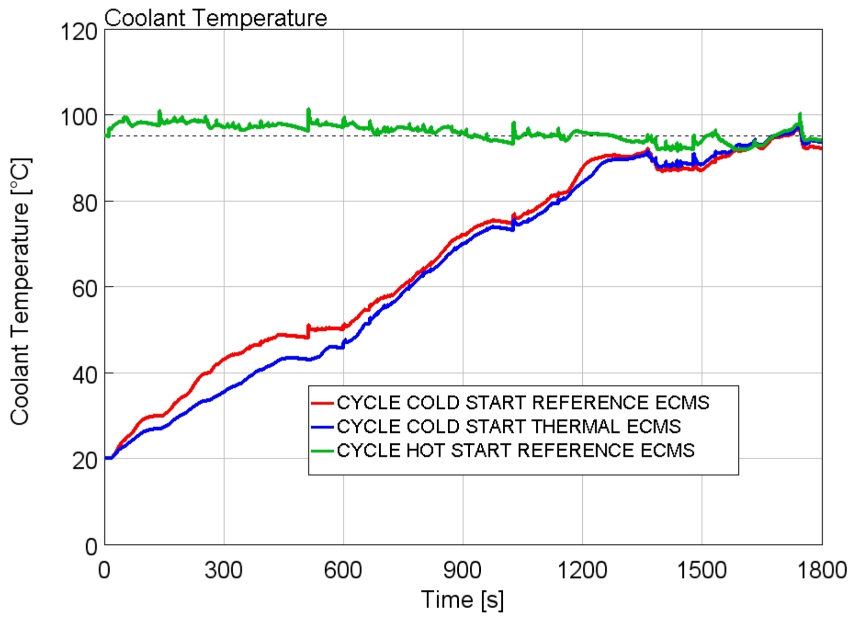

Figure 4.18: WLTC T -10 °C Engine Temperature

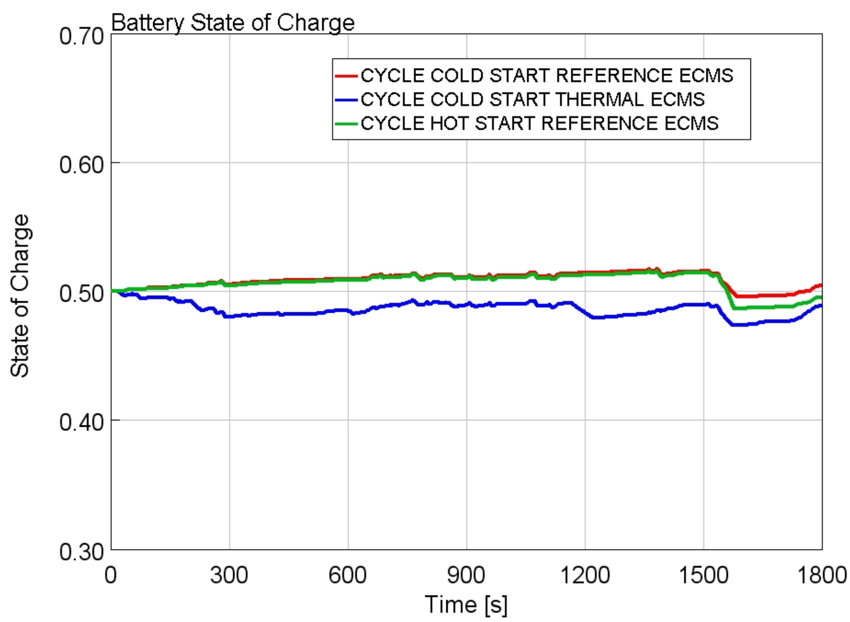

Figure 4.19: WLTC T 20 °C SOC

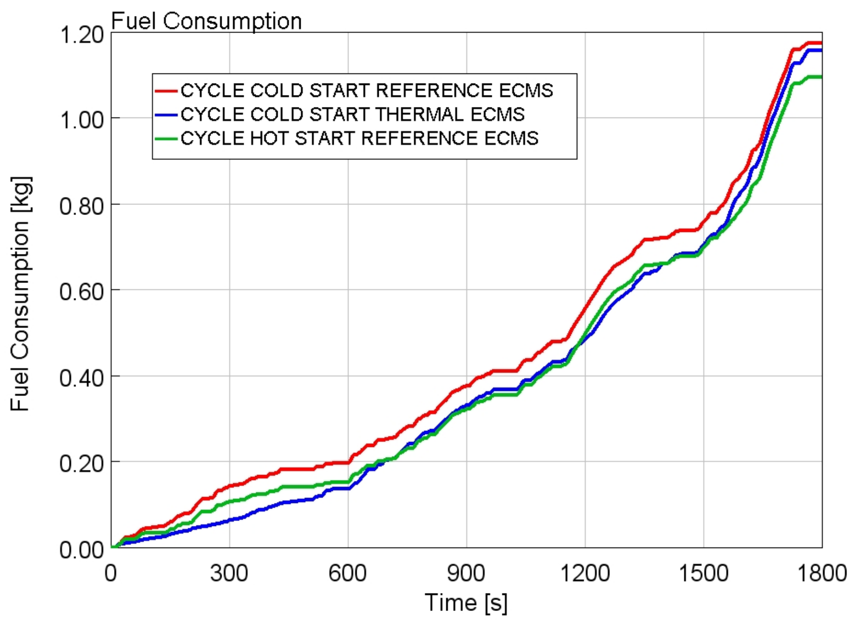

Figure 4.20: WLTC T 20 °C Fuel Consumption

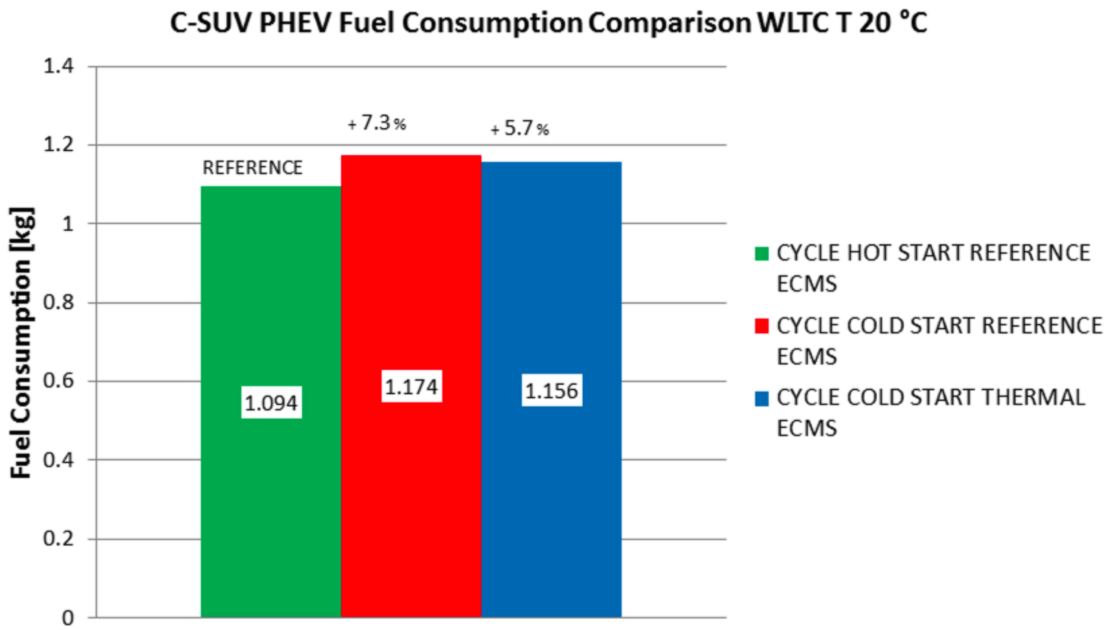

Figure 4.21: WLTC T 20 °C Fuel Consumption

Fuel Consumption		Warm engine	Standard ECMS	Thermal ECMS
NEDC	T -10 °C	Reference	37,90%	34,70%
	T 20 °C		14,20%	11,80%
WLTC	T -10 °C		15,70%	14,60%
	T 20 °C		7,30%	5,70%

Figure 4.22: Fuel Consumption Improvement Summary

Final SOC		Warm engine	Standard ECMS	Thermal ECMS
NEDC	T -10 °C	46,8%	47,1%	46,8%
	T 20 °C	49,7%	49,6%	49,0%
WLTC	T -10 °C	49,5%	50,6%	49,2%
	T 20 °C	49,5%	50,3%	49,0%

Figure 4.23: Final SOC Summary

4.5 NEDC in combination with AECMS

In this Paragraph a variant of the ECMS will be considered, the AECMS. The birth of this new control is mainly due to the fact that the standard ECMS (with a constant k factor) is not so efficient when the driving condition is highly mixed with different road types. In fact, in this cases, it is very difficult to choose in advance a constant k factor that will be the same for the whole driving cycle. Furthermore, as explained in Paragraph 1.3, this type of controller is completely real time based, so it is implementable in every driving situation and at the same times gives results very close to the optimality. This adaptive control automatically changes the value of the battery equivalence factor k, in order to reduce the fuel consumption with the same final SOC, while in the previous simulations the value of k set at the beginning of the cycle was held constant.

Only NEDC cycle has been considered for this study, both with -10 °C and 20 °C as starting temperatures. The results shows that the AECMS reference controller, without the thermal computation, equals the benefit obtained using the Thermal AECMS. In Figure 4.26 is plotted the cumulative fuel consumption using AECMS with and without thermal equivalent fuel consumption.

It is clear that the fuel consumption is quite the same, also the SOC and engine temperature plot show a similar trend between the two controllers.

An important evaluation, instead, can be done in the case at 20 °C. In Figure 4.27 is plotted the battery equivalence factor for both the controllers. This graph emphasize the real nature of the AECMS strategy, which is based on a continuously changing of the k factor.
The big difference is that while in the reference AECMS the value of k oscillates widely only at the end of the simulation, using the thermal AECMS it starts to oscillate widely from the beginning of the cycle, as shown in Figure 4.27.

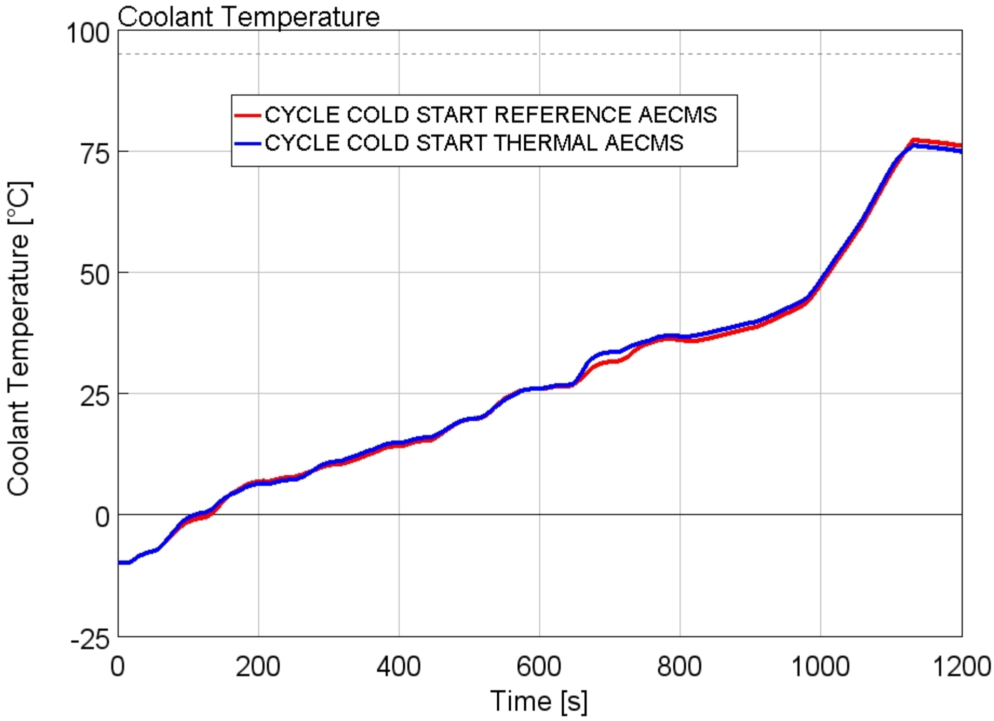

Figure 4.24: NEDC T -10 °C Engine Temperature

Paragraph 4.5 is just an addition to the case study presented at the beginning of the thesis, but can be taken as an input for future analysis on the power split optimization, maybe considering both k and p_0 as adaptive values that change during the cycle and that could optimize even more the fuel consumption.

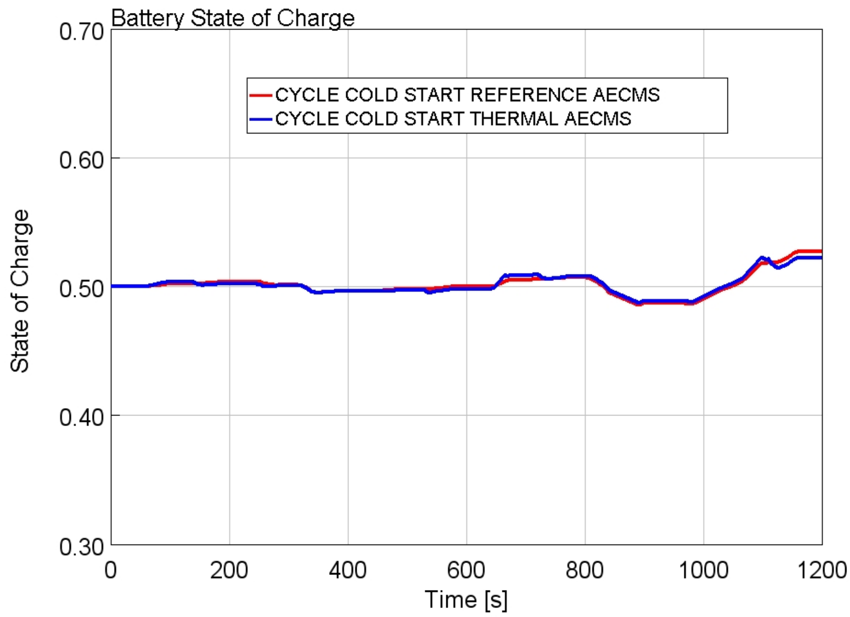

Figure 4.25: NEDC T -10 °C SOC

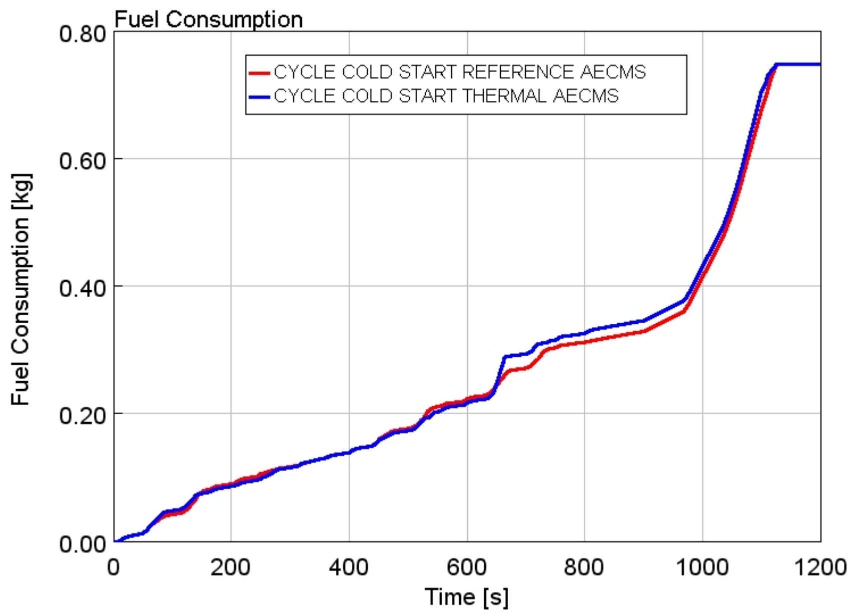

Figure 4.26: NEDC T -10 °C Fuel Consumption

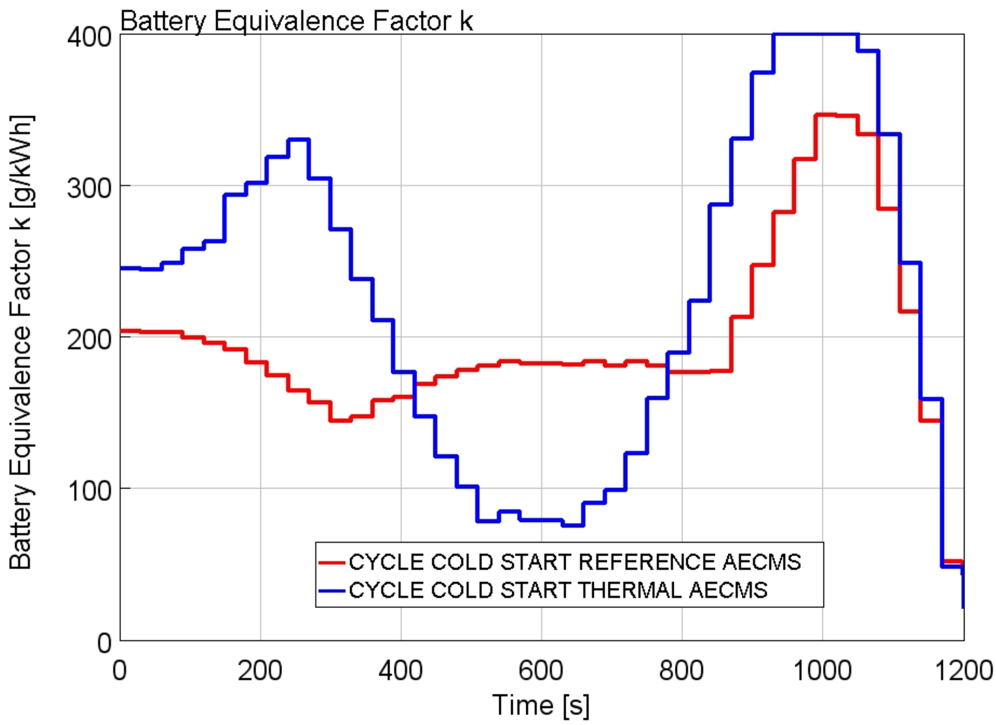

Figure 4.27: NEDC T 20 °C Battery Equivalence Factor

Chapter 5

Conclusions

Different steps have been followed in order to reach the results showed in Chapter 4. Firstly, a vehicle model was built, in order to reproduce all its powertrain components. Then this model has been integrated with a detailed 1D thermal model, able to compute the heat losses and heat exchanges. After some calibration with the aim of obtaining a model as close as possible to the reality, the implementation of the controller began.
Starting from a reference ECMS, the thermal state of the engine has been added to the controller, modifying its procedure of optimizing the powersplit. The new controller, called Thermal ECMS, showed an improvement of 2.5% and 1.5% along NEDC and WLTC cycles respectively. These improvements are smaller in the WLTC due to the aggressiveness of the driving conditions.

Considering that PHEV and HEV will be fundamental in the near future, this is an important step forward also for the environmental impact and to meet the needs for the next years in terms of pollution.

There is still more that can be discovered and implemented on PHEV and HEV, because it is a new generation of means of transport that is still far from the optimal configuration, especially in terms of power management strategy, because the majority of vehicle still uses heuristic methods that do not minimize in the best way the fuel consumption.

Regarding possible future developments, there are still other powertrain variables that can be taken into account in order to find the best way to use energy in a hybrid vehicle, such as catalyst temperature, battery aging and thermal power requested by the cabin.

Bibliography

[1] Sarah Keller. *A WORLD OF THOUGHTS ON PHASE 2 - last access March 22, 2022*. Available on line. 2016. URL: https://theicct.org/a-world-of-thoughts-on-phase-2/ (cit. on p. 1).

[2] Yonggang Liu, Jie Li, Zhenzhen Lei, Wenzhi Li, Datong Qin, and Zheng Chen. «An Adaptive Equivalent Consumption Minimization Strategy for Plug-In Hybrid Electric Vehicles Based on Energy Balance Principle». In: *IEEE Access* 7 (2019), pp. 67589–67601. DOI: 10.1109/ACCESS.2019.2918277 (cit. on pp. 4, 7).

[3] Jérémy Malaizé and Paolino Tona. «Optimization-based control design for hybrid energy storage systems in electric vehicles». In: *2011 IEEE Vehicle Power and Propulsion Conference*. 2011, pp. 1–7. DOI: 10.1109/VPPC.2011.6043117 (cit. on p. 6).

[4] Qi Jiang, Florence Ossart, and Claude Marchand. «Comparative Study of Real-Time HEV Energy Management Strategies». In: *IEEE Transactions on Vehicular Technology* 66.12 (2017), pp. 10875–10888. DOI: 10.1109/TVT.2017.2727069 (cit. on p. 6).

[5] Hsiu-Ying Hwang. «Developing Equivalent Consumption Minimization Strategy for Advanced Hybrid System-II Electric Vehicles». In: *Energies* 13.8 (2020). ISSN: 1996-1073. DOI: 10.3390/en13082033. URL: https://www.mdpi.com/1996-1073/13/8/2033 (cit. on p. 6).

[6] Li Tang, Giorgio Rizzoni, and Simona Onori. «Energy Management Strategy for HEVs Including Battery Life Optimization». In: *IEEE*

Transactions on Transportation Electrification 1.3 (2015), pp. 211–222. DOI: 10.1109/TTE.2015.2471180 (cit. on p. 6).

[7] *WLTP sostituisce NEDC - last access March 22, 2022.* Available on line. URL: https://www.eurococ.eu/it/blog/wltp-sostituisce-nedc/ (cit. on p. 22).

[8] Merz, F., Sciarretta, A., Dabadie, J.-C., and Serrao, L. «On the Optimal Thermal Management of Hybrid-Electric Vehicles with Heat Recovery Systems». In: *Oil Gas Sci. Technol. - Rev. IFP Energies nouvelles* 67.4 (2012), pp. 601–612. DOI: 10.2516/ogst/2012017. URL: https://doi.org/10.2516/ogst/2012017 (cit. on p. 32).

[9] Julien Lescot, Antonio Sciarretta, Yann Chamaillard, and Alain Charlet. «On the integration of optimal energy management and thermal management of hybrid electric vehicles». In: *2010 IEEE Vehicle Power and Propulsion Conference*. 2010, pp. 1–6. DOI: 10.1109/VPPC.2010.5729158 (cit. on p. 32).

[10] Xun Gong, Hao Wang, Mohammad Reza Amini, Ilya Kolmanovsky, and Jing Sun. «Integrated optimization of Power Split, Engine Thermal Management, and Cabin Heating for Hybrid Electric Vehicles». In: *2019 IEEE Conference on Control Technology and Applications (CCTA)*. 2019, pp. 567–572. DOI: 10.1109/CCTA.2019.8920605 (cit. on p. 32).

[11] Jay Anderson, Eric Rask, Henning Lohse-Busch, and Scott Miers. «A Comparison of Cold-Start Behavior and its Impact on Fuel Economy for Advanced Technology Vehicles». In: *SAE International Journal of Fuels and Lubricants* 7.2 (2014), pp. 427–435. ISSN: 19463952, 19463960. URL: http://www.jstor.org/stable/26273034 (cit. on p. 32).