Alma Mater Studiorum - University of Bologna

School of Engineering and Architecture

Department of Industrial Engineering
Second-cycle Degree in Mechanical Engineering

Master degree thesis

in
INTERNAL COMBUSTION AND HYBRID ENGINES M

Design of a user-friendly Plug-in HEV simulation platform for energy management strategies and e-Horizon functions performance evaluation

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Academic Year 2017-2018
Session II

Alma Mater Studiorum - Università di Bologna

Scuola di Ingegneria e Architettura

Dipartimento di Ingegneria Industriale
Corso di Laurea Magistrale in Ingegneria Meccanica

Tesi di laurea

in

Motori a Combustione Interna e Propulsori Ibridi - M

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Anno Accademico 2017-2018
Sessione II

To my parents and my sister

Per aspera ad astra

[Seneca]

Abstract

During the last decades the number of vehicles progressively rises together with the relative emissions of pollutants, such as CO_2 and other green-house gases, worsening air quality and traffic conditions especially in metropolitan areas. The OEM (Original Equipment Manufacturer) are investing a lot of money in alternative solutions, abandoning the Internal Combustion Energy which can no longer satisfy both the more and more stringent regulations as well as the market requests. The general tendency is to introduce an alternative source of energy flanking the conventional engine, allowing its downsizing and helping it during the less efficient operating points. Moreover, the new kind of sensor systems (named Advanced Driver-Assistance Systems) are starting to be implemented on-board. These analyse the surrounding environment and give the driver new kind of assistance functionality, like the *Lane Departure Warning*, *Adaptive Cruise Control* and *Parking Assistance*, avoiding dangerous or inefficient decisions. In parallel, these functions can recreate an electronic horizon, based on the path selected by the driver, supplying to the Control Unit a detailed preview. The natural tendency is to gradually limiting the driver control on the vehicle up to definitely excluding him from driving decisions. Nevertheless, the implementation of fully working and safe ADAS functions implies millions of kilometres of road test validations, to safely introduce them on the market. Thus, the OEM have to develop new methodologies to substitute the road tests with specific simulations, where tools (like *Model-in-the-Loop*, *Software-in-the-loop*, *Hardware-in-the-Loop*) are used to verify its reliability. This master thesis work wants to implement predictive ADAS functions for energy management, in a high performance parallel Plug-In Hybrid Electric Vehicle (PHEV) model (MiL), developed in Simulink environment. Firstly, torque management strategies have been implemented in the Control Unit in order to determine the optimal (*Discrete Dynamic Programming*)

or sub-optimal (*Equivalent Consumption Minimization Strategy*) torque split, as the solution of a cost function minimization problem. In this case, the cost function is the equivalent consumption of fuel (both chemical and electric). In parallel, three specific predictive functions have been implemented: the *City Events Finder*, the *Zero Emissions Area* and the *Predictive Thermal Management*. All the functions are based on the knowledge of the driving cycle at priori. In particular, they are focused on the urban zone where the usage of the conventional engine is forbidden, so the vehicle has to switch to full electric mode. Firstly, the City Events Finder detects if in the selected route there will be this kind of city. Then, the Zero Emissions Area function gives to the torque strategies a target to fulfil, in order to guarantee enough battery state of charge at the beginning of the event. When the City Event occurs, the Predictive Thermal Management decides if there is the possibility of managing the battery cooling circuit more efficiently and saving energy. In the end, the simulations results are made compliant with the newest regulations of the laboratory tests (Worldwide harmonized Light vehicle Test Cycle) and of the road tests (Real Driving Emissions).

The final step has been the creation of a Graphic User Interface with the aim of making the simulations faster and easier to run for inexperienced external operator. The thousands of line codes are hidden behind *drop-down* menu and *check-boxes*. The final post-process is written on Excel file and locally saved on PC, while the most representative results are printed on the GUI.

Abstract in lingua italiana

Negli ultimi decenni si è registrato un progressivo aumento dell'utilizzo di mezzi di trasporto individuali e delle relative emissioni di agenti inquinanti, come CO_2 e altri gas serra, peggiorando la qualità dell'aria e la viabilità, specialmente nelle aree metropolitane. Le case costruttrici stanno investendo molte risorse in soluzioni alternative, riconoscendo come i motori a combustione interna, per quanto efficienti questi possano essere, non riescano più a soddisfare le richieste di mercato e rispettare la legislazione sempre più stringente. L'obiettivo dichiarato è l'abbandono definitivo dei combustibili fossili in favore di una progressiva elettrificazione dei veicoli. L'implementazione di una fonte di energia alternativa, in particolare quella elettrica, permette una riduzione delle dimensioni del motore termico e un aiuto nei punti operativi meno efficienti ma richiede una nuova concezione della sua gestione a bordo. In più, i nuovi sistemi di sensoristica avanzata (in gergo Advanced Driver-Assistance Systems), analizzando l'ambiente circostante, consentono di introdurre nuove funzionalità di supporto al guidatore, come il *Lane Departure Warning*, *Adaptive Cruise Control* e *Parking Assistance*, per evitare che esso compia scelte pericolose o inefficienti. Parallelamente queste funzioni possono permettere la ricostruzione di un orizzonte elettronico, basato sul percorso deciso dal guidatore, fornendone alla centralina un'anteprima dettagliata. La conseguenza naturale sarà quella di limitare progressivamente il controllo del guidatore sul veicolo fino ad escluderlo definitivamente. Tuttavia, l'implementazione di funzionalità ADAS pienamente funzionanti e sicure prevedrebbe milioni di chilometri di test su strada, prima di introdurle sul mercato. Ciò obbliga i costruttori a sperimentare nuove tipologie di validazione per soddisfare questa esigenza sostituendo i test stradali con specifiche simulazioni, all'interno delle quali vengono utilizzati strumenti (Model-in-the-Loop, Software-in-the-loop, Hardware-in-the-Loop) per verificarne l'affidabilità.

Questo elaborato si pone l'obiettivo di implementare funzioni ADAS predittive per la gestione dell'energia, in un modello veicolo (MiL) di un Plug-In Hybrid Electric Vehicle parallelo ad alte prestazioni. Inizialmente sono state introdotte strategie per determinare lo split di coppia ottimale o sub-ottimale, come soluzione di un problema di minimizzazione della funzione costo, in questo caso individuata dal consumo equivalente di combustibile (chimico ed elettrico). In parallelo, sono state implementate tre funzioni predittive che sfruttando la conoscenza a priori del percorso da seguire forniscono soluzioni più efficienti di gestione dell'energia. La prima, denominata *City Event Finder*, riconosce le aree urbane ad emissioni zero dove quindi è possibile solo la guida in elettrico. Quest'ultima viene garantita dalla funzione predittiva *Zero-Emissions Area* che regola le strategie di gestione dello split di coppia in modo da arrivare all'inizio della città con un livello di batteria sufficientemente alto. Infine, durante l'evento città la funzione *Predictive Thermal Management* valuta la possibilità di gestire in maniera più efficiente il circuito di raffreddamento della batteria e risparmiare energia. I risultati delle simulazioni vengono poi corretti seguendo le più recenti normative di omologazione sia per test eseguiti in laboratorio (Worldwide harmonized Light vehicle Test Cycle) sia per test su strada (Real Driving Emissions). Infine, è stata creata un'interfaccia grafica per velocizzare le simulazioni e per permetterne l'utilizzo anche a operatori meno esperti del software di simulazione, evitandogli di intervenire direttamente sulle linee di codice limitandosi a selezionare le condizioni al contorno del test tramite *tool* grafici come *dropdown-menu* e *checkbox*. Il *post-process* verrà poi svolto su un foglio Excel e salvato in locale sul computer, mentre i risultati più rappresentativi saranno visualizzati direttamente sull'interfaccia.

Acknowledgments

My heartfelt thanks to Professor Nicolò Cavina, who has given me the opportunity to start this formative project and taught me how professionally approaching the problems. Another special thanks to Ing. Michele Caggiano for allowing me to be a part of a innovative and great company, for helping me with his precious advices and for his willingness. I want also to thanks all the FEV Emilia team, Lorenzo, Gabriele, Alessandro, Luca, Andrea, Enrico, for the constant support, help and the time spent together.

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Nomenclature

Acronyms

ADAS	Advanced Driver Assistance System
ADASIS	Advanced Driver Assistance System Interface Specifications
BEV	Battery Electric Vehicle
BMS	Battery Management System
BSG	Belt-driven Starter Generator
BTM	Battery Thermal Management
CEF	City Events Finder
CG	Center of Gravity
CPU	Central Processing Unit
DDP	Discrete Dynamic Programming
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimization Strategy
eHCU	electric Horizon Control Unit
eHS	electronic Horizon Strategy
EM	Electric Motor
EMS	Energy Management Strategy
ESS	Energy Storage System
EV	Electric Vehicle
GHG	Green-House Gas
HCU	Hybrid Control Unit
HEV	Hybrid Electric Vehicle
HiL	Hardware-in-the-Loop
HT	High Temperature

HV	Hybrid Vehicle; High-Voltage
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
ISG	Integrated Starter Generator
LIDAR	LIght Detection And Ranging
LT	Low Temperature
MHEV	Mild Hybrid Electric Vehicle
MiL	Model-in-the-Loop
MT	Middle Temperature
NEDC	New European Drive Cycle
ODE	Ordinary Differential Equation
OEM	Original Equipment Manufacturer
OVC	Off-Vehicle Charging
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PTM	Predictive Thermal Management
RADAR	RAdio Detection And Ranging
RBS	Rule-Based Strategy
RDE	Real-Driving Emissions (test)
REEC	Relative Electric Energy Change
REESS	REchargeable Energy Storage System
SAE	Society of Automotive Engineers
SiL	Software-in-the-Loop
SoC	State of Charge
TXV	Thermal eXpansion Valve
V2C	Vehicle-To-Cloud
V2I	Vehicle-To-Infrastructure
V2P	Vehicle-To-Pedestrian
V2V	Vehicle-To-Vehicle
V2X	Vehicle-To-Everything
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
ZEA	Zero Emissions Zone

Symbols

$b(\cdot)$	control bit of actuators activity [-]
Δ	change
$\Delta_{\%}$	percentage change
$C(\cdot)$	electric capacity [Ah]
$u(\cdot)$	control (output) signal
$\eta(\cdot)$	efficiency [-]
$F(\cdot)$	force [N]
g	gravitational acceleration [m/s^2]
J	moment of inertia [kg·m^2]
m, M	mass [kg]
$P(\cdot)$	power [W]
r	radius [m]
$R(\cdot)$	resistance [Ω]
$\alpha(\cdot)$	angle of slope [rad]
$\alpha_{\%}(\cdot)$	percentage road slope [%]
$\xi(\cdot)$	state of charge (of the high voltage battery) [-]
$\omega(\cdot)$	revolution speed [rad/s]
c_p	specific heat capacity at constant pressure [J/(kg·K)]
$n(\cdot)$	revolution speed [rpm]
$v(\cdot)$	longitudinal speed [km/h]
$\tau(\cdot)$, $T(\cdot)$	temperature [℃]
t	time [s]
$T(\cdot)$	torque [Nm]
$V(\cdot)$	voltage [V]

Subscripts

$_{act}$	actual
$_{amb}$	ambient
$_{aux}$	auxiliaries
$_{b}$	high voltage battery

$_{b,bat}$	battery
$_{cd}$	coast-down
$_{ch}$	charging
$_{cpr}$	compressor
$_{d,D}$	drag
$_{dh}$	discharging
$_{el}$	electric, electrical
$_{eq}$	equivalent
$_{ice}$	internal combustion engine
$_{f,fuel}$	fuel
$_{fin}$	final
$_{f}$	frontal
$_{0}$	initial value
$_{init}$	initial
$_{in}$	input; event start
$_{loss}$	loss, losses
$_{max}$	maximum
$_{mec}$	mechanical
$_{mot}$	motoring (force, torque)
$_{nb}$	not balanced
$_{oc}$	open circuit
$_{out}$	output; event end
$_{REF}$	reference
$_{req}$	requested
$_{res}$	resistant (force, torque)
$_{R}$	rolling
$_{r}$	rear
$_{S}$	auxiliary source
$_{tiCityIn}$	instant of city entrance
$_{tot}$	total
$_{tr}$	transmission
$_{t}$	target
$_{ul}$	upper limit

$_{v,veh}$	vehicle
$_{\mathrm{w}}$	wheel
$_{x}$	longitudinal direction
$_{z}$	vertical direction

Chapter 1

Introduction

1.1 Motivations, challenges and targets

Starting from the twentieth century, the population growth, together with the technological development, has lead the industrialization process to completely new scenarios: the birth of more and more factories and the consequent movement of the people from the countryside to the city centres, both with the final and only purpose of manufacturing. This period saw an exponential growth of production, giving the people technologies, once prohibitive for the price and now more accessible. As a natural consequence of the economic boom, in parallel with a general carelessness and incompetence about environment, the emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) rapidly increased over the year, becoming one of the most challenging issues of the present time. An important role is played by the automotive industries, in fact, cars are used throughout the world and they have become the most adopted solution for people transportation in many countries. Transportation was responsible for 24% of direct CO_2 emissions in 2017. The 77% of both global final energy demand and CO_2 emissions are accountable to the transport sector as a whole, comprehending cars, trucks, buses and two-wheelers. Car buyers continue to choose bigger, heavier vehicle and this has lead to a rise in the average new car CO_2 emissions in 2017 [1]. Therefore, the European Union has made substantial efforts tightening the CO_2 maximum limit on a New European Driving Cycle from 130 ${}^{g_{CO_2}}/_{km}$ of 2015 to 95 ${}^{g_{CO_2}}/_{km}$ by 2020 [2], aiming at the

fixed target of 68 $^{g_{CO_2}}/_{km}$ by 2025 [3].
Hence, automobile manufacturers and engineers have spent the last decade trying to develop innovative solutions with the double purpose of satisfying the market request and complying to the regulations, increasingly stringent. The result of these years of research is the decision to adopt other form of energy supporting the conventional engine. In the so-called Hybrid Vehicles the primary energy source is generally an internal combustion engine; depending on the nature of the secondary source, "Hybrid" can mean

- **Hydraulic Hybrid** that kind of vehicles have a hydraulic pump as secondary mover or generator, which stores the energy in an auxiliary hydraulic accumulator where oil is used as operator fluid. For their weight and their characteristics, this powertrain is particularly indicated for heavy-duty vehicles;

- **Kinetic Hybrid** kinetic hybrid powertrain means a driveline with a high-speed flywheel as auxiliary mover, with the possibility of storing kinetic energy, especially during regenerative braking; [4]

- **Compressed-air Hybrid** these vehicle are powered by motors which produce power with the compressed-air expansion in a similar way of the steam engine. As a non-flammable fluid, he compressed-air can stored in pressurized tank at $30MPa$;

- **Electric Hybrid** here, the auxiliary energy source is the electro-chemical energy provided by Electric Motors and the batteries are the storage system which can be recharged during breaking or with the ICE.

The more promising technology in term of CO_2 reduction is the Hybrid Electric Vehicle (HEVs). Focusing on them, the level of hybridization depends on the range of action of the electric motor which is indicated by the Hybridization Degree and described by the eq. (1.1).

$$HD = \frac{P_{S,max}}{P_{S,max} + P_{ICE,max}} \tag{1.1}$$

where $P_{S,max}$ is the maximum power of the secondary source of energy while $P_{ICE,max}$ is the maximum power deliverable by the IC engine.

On the based of what have been said so far, it's possible to distinguish the following typology of HEVs:

Micro Hybrid with a $HD \sim 5\%$, it's a vehicle equipped with an Electric Motor (EM) linked to the ICE and it can only have Start and Stop functionality. Most of the them have also some sort of Energy Management function, which optimizes the consumption of the low voltage (12 V) battery energy [5];

MHEV (Mild Hybrid EV) with a $HD \sim 15\%$, these types generally use a compact electric motor (usually $< 20kW$) to provide auto-stop/start features, extra power assist during the acceleration and to work as a generator on the deceleration phase (regenerative braking). The battery is a Low Voltage Battery of 48V, whose purpose is to actuate an Energy Management Strategy (EMS) and it allows a minimum range of full electric drive.[1]

FHEV (Full Hybrid Electric Vehicle) where the $HD \sim 35\%$, the Electric Machines and batteries are increased in size, allowing an extended full-electric drive. The recharging of the batteries can happen only with breaking recuperation and with the ICE, because it isn't possible to do from external sources;

PHEV (Plug-in HEV) is usually a general fuel-electric Off-Vehicle Charging (OVC) hybrid with increased energy storage capacity and a $HD \sim 50\%$. This allows the vehicle to drive on all-electric mode a distance that depends on the battery size and its mechanical layout (series or parallel). At the end of the journey, it may be connected to mains electricity supply through a socket to avoid recharging using the on-board internal combustion engine. This concept is attractive to those seeking to minimize on-road emissions by avoiding – or at least minimizing – the use of ICE during daily driving. As with pure electric vehicles, the total emissions saving, for example in CO_2 terms, is dependent upon the source of the energy produced by the provider company;

BEV (Battery EV) are vehicles where there isn't an IC engine and the traction is granted only by electric motors powered by batteries. Properly, they're not

[1]Exceptions of full-electric drive vehicle equipped with a 48V battery are the MEET model developed by MAHLE[6] or the one designed by Valeo[7]

hybrid vehicle, because the energy source is only one, but it will be the arrival point of the transaction where the hybrid vehicles are only intermediate step. At the moment, the main problem of BEV is the capacity of the battery cells, so how the energy is stored [5]. In Fig. 1.2, the fuel (gaseous and liquid) and batteries specific energy is represented in function of their volumetric density, there the problematics of the batteries compared to the other fuels are clearer. To make a more practical example, the same energy needed for a drive of about 500km is stocked in 46 litres ($\sim$ 43kg) of gasoline but in more than 700kg of batteries. Nevertheless, from the dawn of the batteries for automotive purpose, thanks to the improvement in technology their cost becomes cheaper and cheaper, while their energy density increases[8].

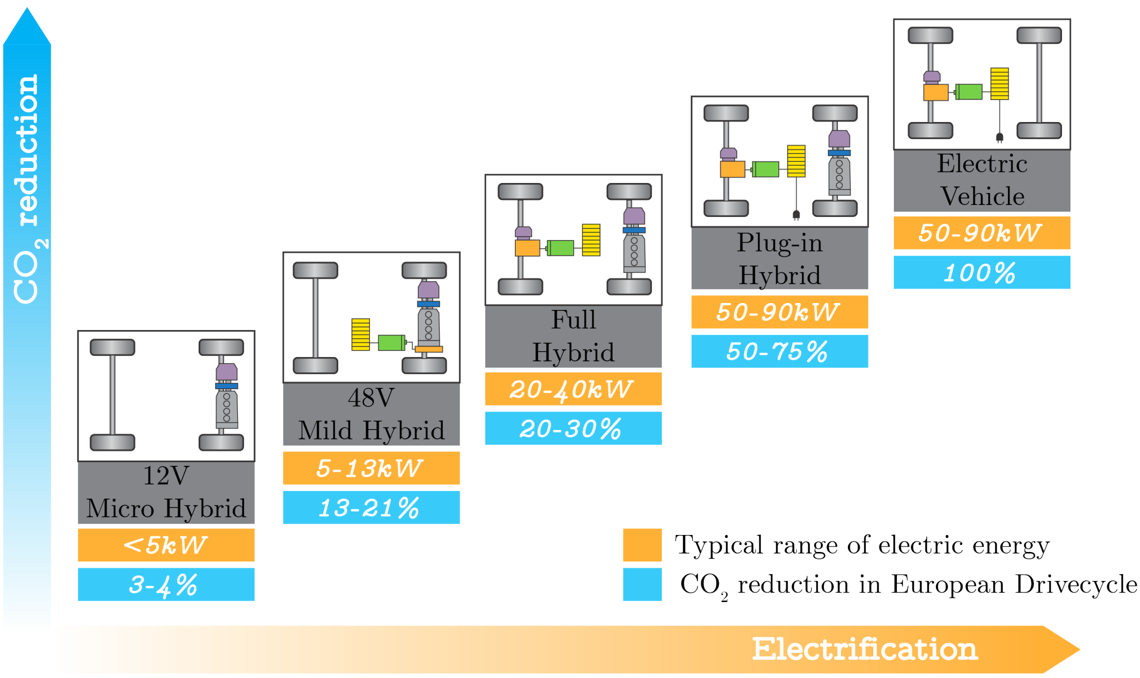

Figure 1.1: Overview of the Hybrid Electric Vehicle depending on Hybridization and CO_2 reduction

Once the typology has been defined, it is possible to describe how the energy flow is transferred from the energy storage (tank for ICE or battery for the EMs) to the wheels. Three paths are possible:

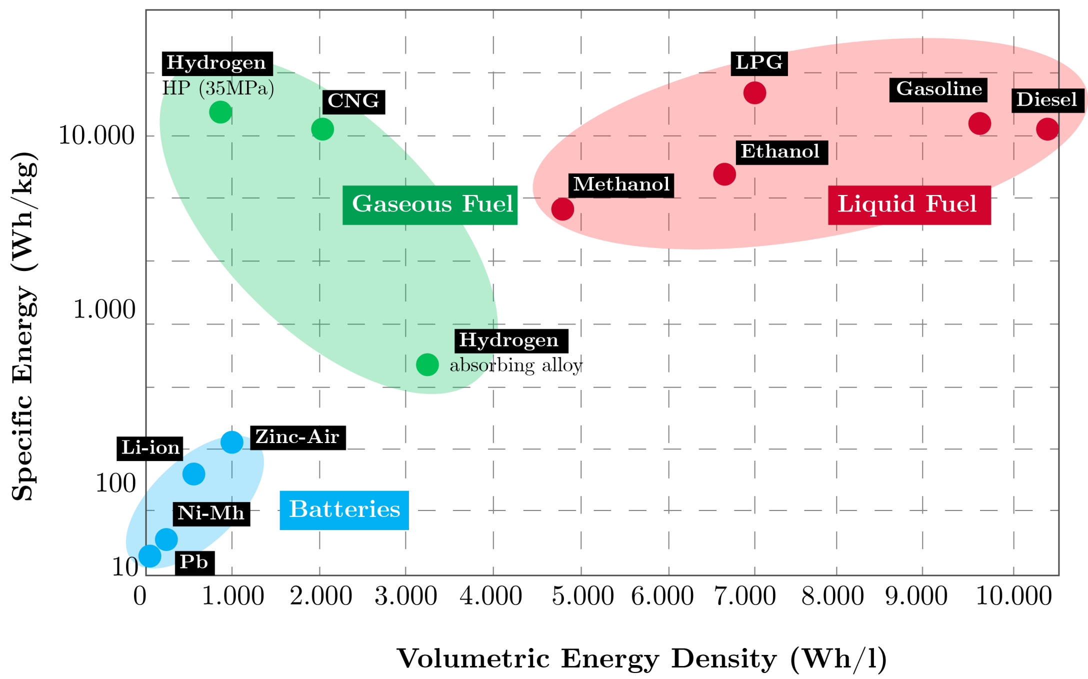

Figure 1.2: Fuel specific energy in function of their volumetric density

Parallel the engine is the main power source while the electric motor provides assistance as needed, delivering torque from zero rpm during standing starts and acceleration. This cooperation consent to avoid engine working points where the specific fuel consumption is high. The powertrain can be adapted simply by adding an electric motor and batteries to an existing vehicle, as in Fig. 1.3.

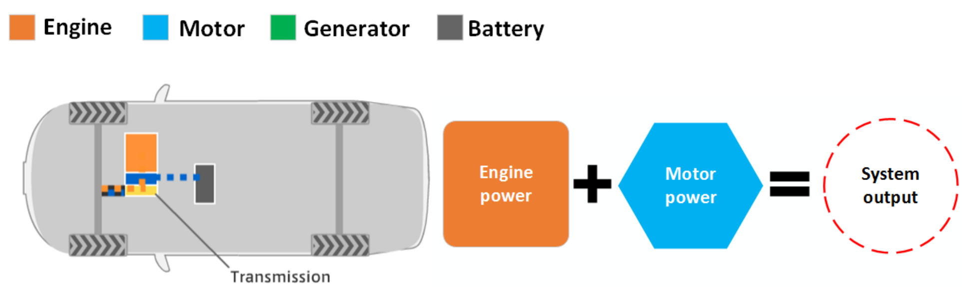

Figure 1.3: Parallel hybrid power characteristics

Series/parallel combined hybrid vehicles share characteristics of series and parallel layouts. In particular, the EM powers the vehicle from a standing start and at low speed whereas, as the speed increases, ICE and EM work together to efficiently provide the power required. As can be expected, the system is more complex featuring a *power split device* and a *generator*. An exemplification is shown in Fig. 1.4.

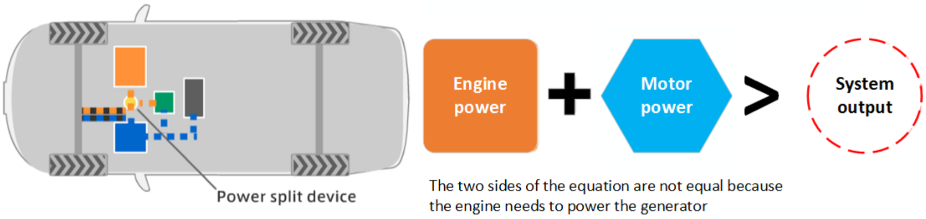

Figure 1.4: Series/Parallel hybrid power characteristics

Series the series layout provides torque solely by using electric motors, like electric vehicles, and the aim of ICE is to recharge the battery with the generator. The powertrain is equivalent to an EVs, but because the vehicle also includes an engine, it is considered a hybrid (Fig. 1.5) [9].

Figure 1.5: Series hybrid power characteristics

For what concern the HEVs parallel topology, several architectures are possible differing from each other for the position of the electric machines within the driveline. As shown in Fig. 1.6, they are as follow:

P0 the engine is coupled to the motor through a belt, so the electric machines is called Belt-driven Starter Generator (BSG);

P1 the EM is directly mounted on the crankshaft, upstream of the clutch, and it is named Integrated Starter Generator (ISG);

P2 the EM is separated from the engine by a clutch, that allows the pure electric drive;

P3 the EM is mounted on the secondary shaft out of the gearbox;

P4 the EM is connected to the front or rear wheels by means of a transmission ratio;

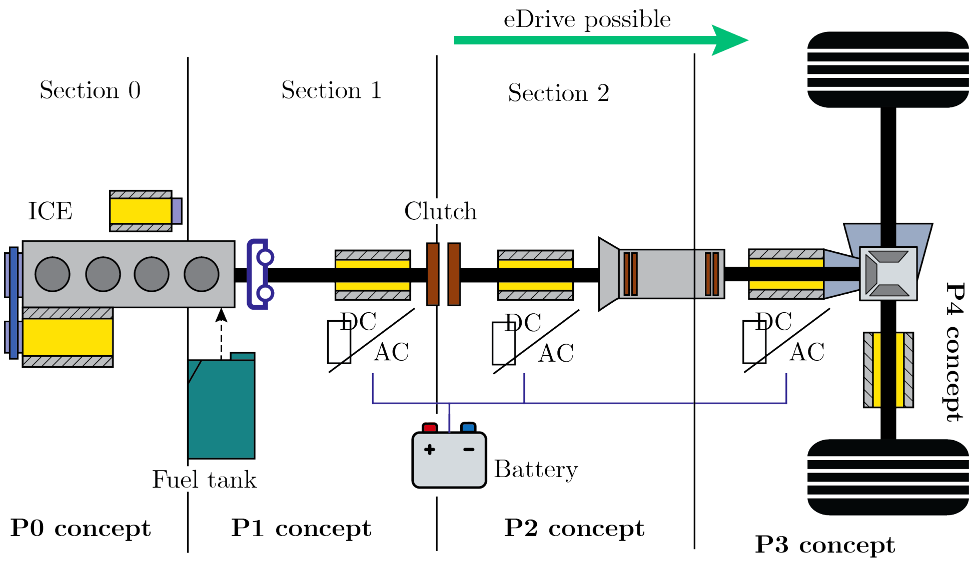

Figure 1.6: Parallel hybrid driveline architecture

Introducing a different type of energy flow (electrical energy) additional to the chemical one, engineers have to face new challenging problems. In fact, while the available space remains the same, the components rise in number: one or more electric motors, a bigger battery, a more powerful control unit and the inverters have to be rationally placed inside the vehicle. Adding new components doesn't imply only a different spacing configuration but it also means a more complex control at system level and also regarding the safety. On one hand, it's possible to achieve similar performance to standard vehicle with internal combustion engine while greatly improving fuel efficiency and tailpipe emission, recovering the energy from braking. On the other hand the torque split (so how the torque request is fulfilled) becomes the new control variable and it is complicated to handle. The challenge is to find the more efficient split that covers the torque request among the possible solutions.

As a matter of fact, the computational effort of the control unit becomes heavier. Finding the optimal or sub-optimal solution is a part of the so called Energy Management Strategy which tries to minimize a two-variables function, where the fuel consumption is no longer the only parameter to keep under observation, but it's flanked by a new one: the state of charge of the Battery Storage System, shortened SoC. The state of charge represents the actual capacity of the battery over its maximum capacity and it's expressed in percentage. To better understand its meaning, it could be compared to the physical level of the liquid fuel in the tank and, as the fuel, it has got its own value. So then, the OEMs have invested money and time to develop new energy optimization strategies with the purpose of minimizing the overall energy consumption.

1.2 ADAS and connectivity

The general tendency is moving toward a vehicle efficient and clean, but a non-negligible limit to that goal it will always be the driver, the less predictable variable in the system. The innovative Advance Driver-Assistance Systems (ADAS) come to help limiting the driver actions but they require a reliable detection of the vehicle and the surrounding environment. That virtual reconstruction permits the Hybrid Control Unit (HCU) to make more efficient choices both regarding the road safety as well the torque management. The new generation of on-board sensors and control strategies assist a common driver during acceleration and braking and they help him to avoid inefficient decisions such as during the gear shift, stop & start system, increasing the driving comfort and safety. A short explanation of that kind of equipment is given below, and it is shown in Fig. 1.7.

- LIDAR (LIght Detection And Ranging)
  remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) [10].

- RADAR (RAdio Detection And Ranging)
  detection system that uses radio waves to determine the range, angle, or velocity of objects. In particular it is distinguished in long range (LRR) for Adaptive

Cruise Control, medium range (MRR)for cross traffic alert and lane change assist, short-range (SRR) for parking aid, obstacle/pedestrian detection [11].

- CAMERAS
  a video sensor used to perceive the environment around the vehicle.

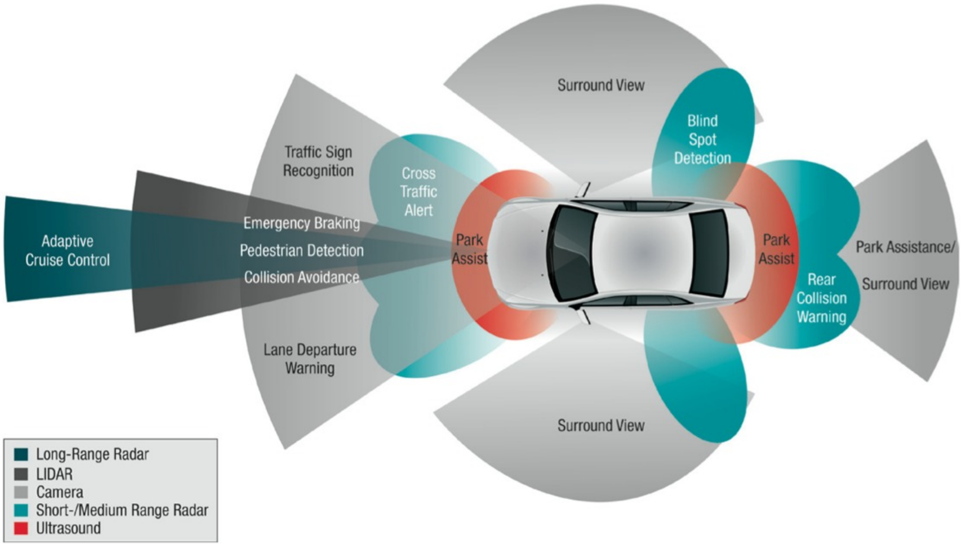

Figure 1.7: On-board sensing equipment

All these efforts are made with the aim of designing and producing an autonomous vehicle capable of driving safely and efficiently on the road. This, from one hand will erase or at least reduce mortal accidents, and on the other hand will gave to the people a less polluting way of transportation. Obviously, to reach that goal, some gradual steps have to be fulfiled. The Society of Automotive Engineers (SAE) has defined different automation levels, which span from Level 0, without automation systems, to Level 5, where the car is completely self-driving [12]. In Fig. 1.8 there is represented a schematic description of each level.

In the future, the ADAS will intervene in the driving process more intensively and autonomously, for example influencing braking and steering maneuvers (with traffic jam chaffeur or motorway autopilot functionalities) [13]. The progress in wireless communication technologies, sensor fusion, imaging technologies and Big Data (more decisional power means high computational effort) is the foundation of numerous applications like adaptive cruise control, lane departure warning systems,

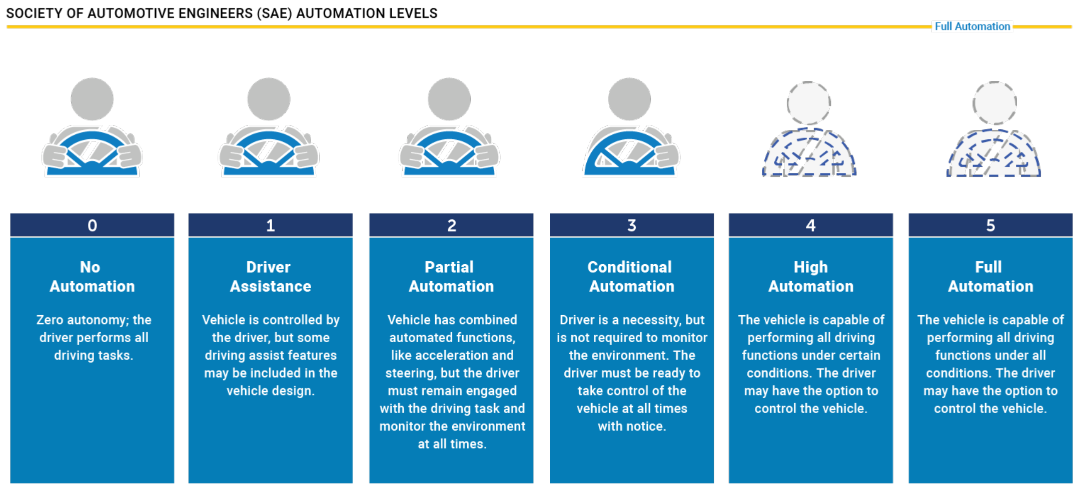

Figure 1.8: SAE automation levels for self-driving cars

and parking assistants.[2] The way toward the autonomous driving is strictly linked with the progresses made by the telecommunication industries, in a on-going development of the Vehicle-to-Everything connectivity technologies, with the aim of passing information from a vehicle to any entity that may affect the vehicle and vice versa:

- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Cloud (V2C)
- Vehicle-to-Pedestrian (V2P)

The amount of informations work together in order to achieve road safety, traffic efficiency and energy savings. Some of the functionality given by the connectivity could influence the vehicle as a warning (for forward collisions, lance change and blind spots) or directly acting on it. They are and will be at the base for a safety and effective autonomous driving.

[2] Achievable by the next generation of CPU developed by NVIDIA, able to guarantee 320 trillion of operations per second (TOPS)[14]

1.2.1 Predictive driving (eHorizon)

In term of efficiency, the optimal solution will be reached with the complete knowledge of the future, because it would permit to elaborate a strategy suitable for the specific route. In the following paragraph there is a very didactic example, but also very clear, of how the predictive drive will help: Fig. 1.9 shows a possible path of a commercial vehicle that approaches a climb. In normal conditions, climbing the hill, the internal combustion engine will provide the torque requested, but doing so it recharges, or doesn't discharge the battery. Once the car reaches the top of the climb, there is a downhill in front of it where it could perform regenerative breaking but the battery capacity could be already at the maximum limit. So the potential energy of the slope is useless. But if the presence of this difference in height were known, the control unit will allow the EMs to help the ICE during the climb, making it working at more efficient points, and at the top of the hill the battery could be recharged. This is only a little example of the enormous potential of a predictive

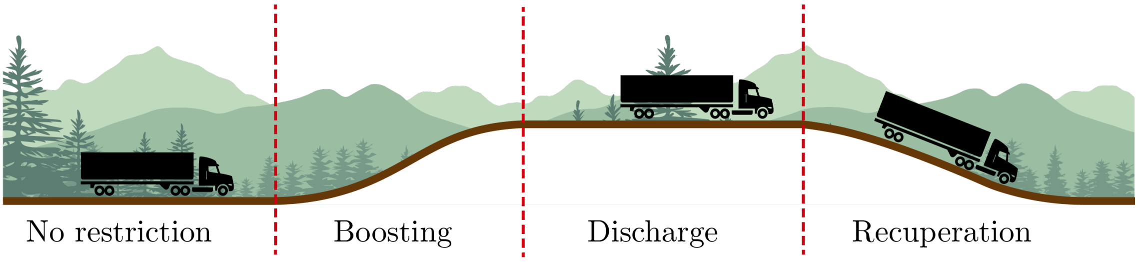

Figure 1.9: Ideal predictive strategy

strategy, in fact, it will be possible to avoid traffic congestions, accidents, dangerous situations and so on. In this essay, for example it will be analysed the effect on Energy Management by the knowledge of how the battery will heat and discharge during a city road where, for supposed local legislations, the emissions have to be zero.

Chapter 2

Simulink model

2.1 Simulation environment

The industries have to face a shortening of the vehicle *time-to-market* driven primarily by consumer demand, advances in technology, and expertise of suppliers and partners. A recent survey shows that the 68% of the automotive companies have now a product development and launch cycle under two years [15]. This collides with the old developing methodologies, one for all the consolidated - and reliable - road tests, because they don't meet anymore the limited amount of time dedicated to validation. In fact, the innovative functionalities are allowed to bypass some driver's decisions under determined situations during which the safety of the vehicle has to be guarantee, so the test scenarios rise in numbers and the time to complete them exceed the above-mentioned *time-to-market*. Today's state-of-the-art statistical validation methods for a standard ADAS function, which only have to concentrate on few components and use cases, add up to about 2 million kilometres of test mileage per vehicle platform. The validation of all ADAS series products for just one vehicle platform might reach real-world test coverage of 36 million kilometres. For validation of high automation systems this could explode to roughly 1 billion test kilometres in real traffic [16]. Since validation drives nowadays already are a practical and economical challenge, new concepts of validation apart from real-world tests have to be developed in order to take the kilometres on roads into simulations on the desk, which are cheaper and faster. Removing reliable road tests in favour of

computer simulations implies making sure that there aren't errors in the hardware. Two noteworthy methodologies are *L3Pilot* and *ENABLES3*, both supported by the European Union. The first one is focused on the last steps before the introduction of automated cars in daily traffic, undertaking large-scale testing and piloting of Level 3 Autonomous Driving exposed to different users including conventional vehicle drivers and Vulnerable Road Users (VRUs), in mixed traffic environments [17]. The second one, EnableS3, comprehends validation methodology with new approaches to generate test cases which are run in a reusable validation frameworks, supported by several development stages. Both the project have to withstand the international regulation *ISO 26262*, titled "Road vehicles – Functional safety".
Focusing on functions development, in order to detect and remove software faults as early as possible in the development process, reducing costs, some discrete steps in the design of model are suggested:

- Model-in-the-Loop (MiL), refers to the kind of testing done to verify the accuracy or the acceptability of a mathematical model or a control system. MiL testing means that the model and its environment are simulated in the modelling software without any physical hardware components.

- Software-in-the-Loop (SiL), which groups the testing of the software making it to interact directly with the simulated environment model in order to be able to stress it with operational conditions. This allows first checks when the software is ready, without waiting the physical prototypes.[18]

- Hardware-in-the-Loop (HiL), as stated by the name itself, this step provide more advanced tests on the control system, linked to benches that reproduce, in a more or less complete way, the physical signals of the environment.

As displayed in § 1.2, the more the manufacturing complexity increases, the more is the computational power requested to simulate all the possible test cases. This request is partially covered by the advances in the IT, which provide new simulation software, such as *Simulink*, developed by *MathWorks*. *Simulink* is a graphical programming environment for modelling, simulating and analysing dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of

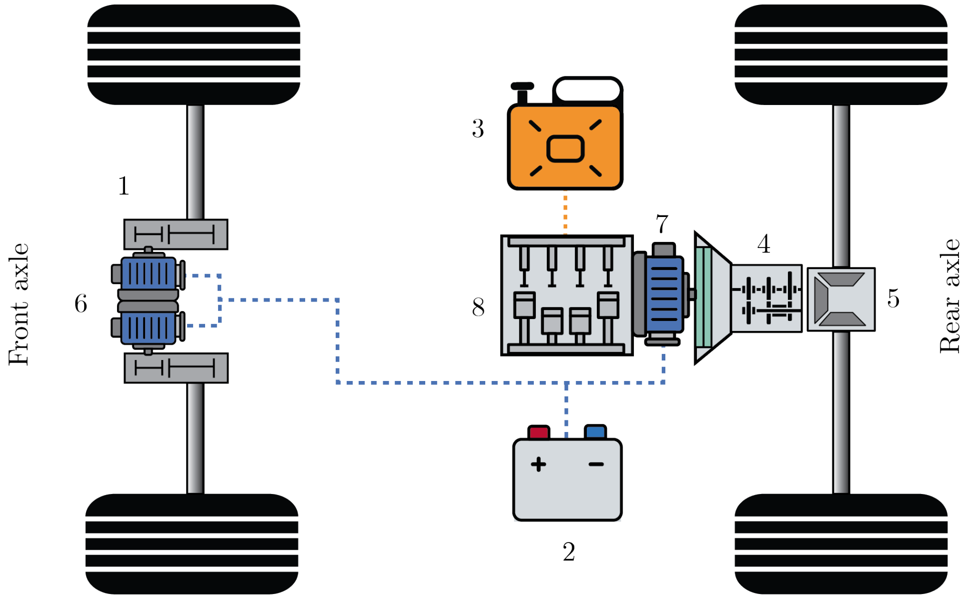

Figure 2.1: The P1P4 vehicle layout

Type	Number	Name
Components	1	Reduction gear
	2	HV Battery
	3	Fuel tank
	4	Gearbox and clutch
	5	Differential
Power supplier	6	EM (P4)
	7	ICE
	8	ISG (P1)

Figure 2.2: The P1P4 vehicle components

block libraries. It offers tight integration with the rest of the MATLAB environment and it can either drive MATLAB or be scripted from it.

2.2 Simulation model

For what concern this particular dissertation, it has been modelled a MiL representing high performance PHEV (for more details see § 1.1), which has a parallel layout, as depicted in Fig. 2.1. As widely explained in the previous chapter (§ 1), such vehicle is intrinsically complex, with multiple variables to keep under control. It's appropriate to mention the control of the torque split: as a double energy source configuration, the torque requested by the driver can be provided in several ways, even though nowadays the most advanced systems could interpose themselves between the pedal - the affective actuator - and the control of the torque performed by the HCU. It could be guaranteed by the pure electric mode, as well as in hybrid mode, with the P4s focusing on cover the less efficient operating points of the ICE. To better understand the possible operational modes the table 2.1 comes to help.

Table 2.1: Operational mode of a parallel hybrid vehicle

Thermal mode	The ICE is responsible for the entire demand of torque, typical of a heavy load condition, where the HCU makes up its choices giving up the efficiency but gaining in power.
Hybrid mode	The request is handled between the ICE and the two EMs mounted on the front axle. The way how the wheel torque is split is defined by the *split factor*, as output of the HCU.
Electric mode	The P4s take charge of the traction totally, allowing the ICE to switch off. This is a forced solutions in Zero Emissions Zones, like metropolis.

In this particular configuration, the ISG is directly linked to the crankshaft so the high voltage battery could be recharged, if the *load point shift* strategy provide for it. More in general the *load point shift* makes the ICE operating point shifted in the best specific fuel consumption area (following the ideal red line) thanks to electric motor, as it's displayed in Fig. 2.3.[1]

At the start of the master thesis work, the powertrain and the vehicle itself were

[1]The "load point shift" has a wide range of action: it may mean to turn off the engine in idle, turn off the ICE at lower torque request if SoC is sufficiently high, or on the other hand recharge the battery with ICE when SoC is low and the request is limited [8]

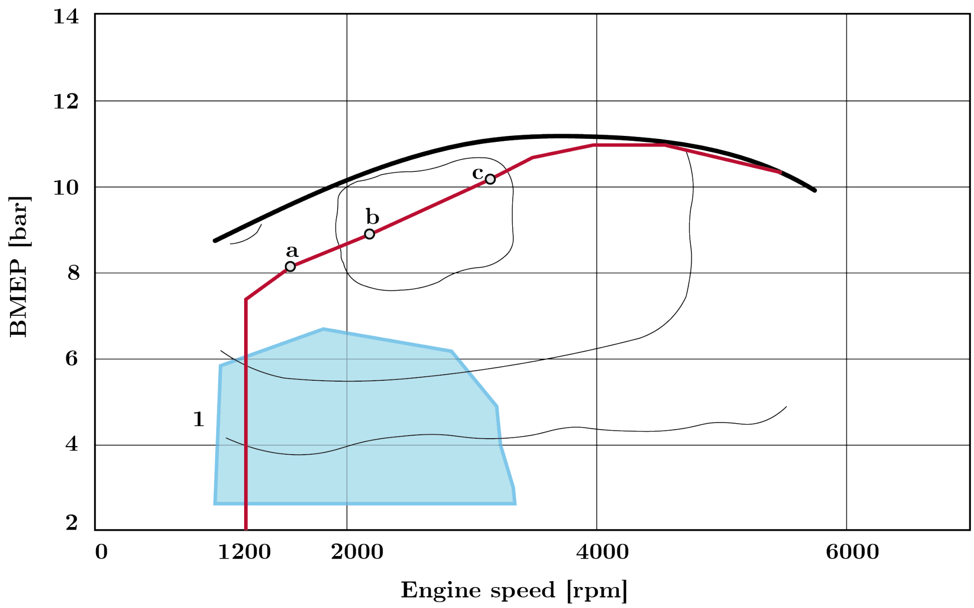

Figure 2.3: Efficiency of a ICE combined with EMs
a,*b*,*c*: Operationg points   1: Operating area ICE only
redline: Optimal line

modelled with Simscape, and this approach had permitted to simulate components as it were physically connected to each other. Validated elements can be used to model the complete powertrain, without expliciting torque and speed equations with Simulink blocks. Obviously, that warranted a high level of accuracy but on the other hand the model was penalized in computational effort and elapsed time. For this work, it isn't necessary to simulate such precise manoeuvres so it has been decided to head toward a faster model. In the following paragraphs the Simscape blocks are shortly explained to better understand how they could be removed.

2.2.1 Vehicle model

Simscape

Simscape block models a vehicle with two axles in longitudinal motion. The axles can have different number of wheels but with the condition that the vehicle wheels are assumed identical in size. The vehicle axles are parallel and form a plane: the longitudinal x direction lies in this plane and perpendicular to the axles. If the vehicle is travelling on an incline slope β, the normal z direction is not parallel to gravity but is always perpendicular to the axle-longitudinal plane, showed in 2.4

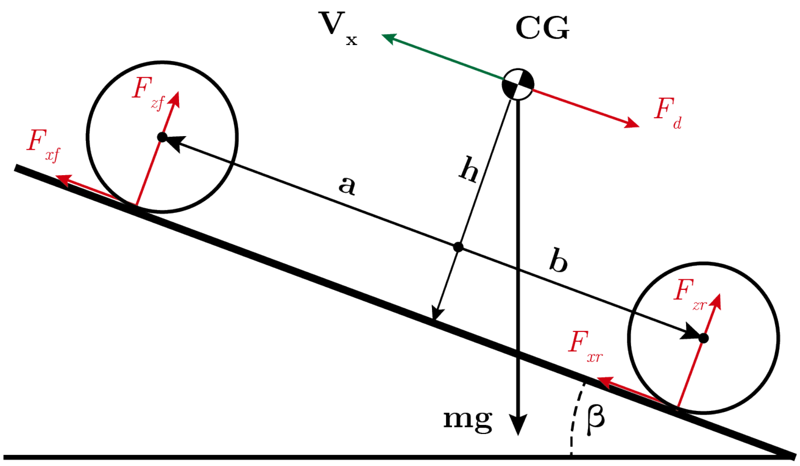

Figure 2.4: Vehicle body used in Simscape
$F_x f$,$F_x r$: Longitudinal forces $F_z f$,$F_z r$: Normal load forces
V_x: Longitudinal velocity a,b: Distances from axle to CG

The model used in this work is dynamic, so it has a driver modelled with PI (Proportional Integrated) controller and generates realistic pedal signals both for accelerator and brake depending on the driving mission it receives as external input from a look-up table, then the model calculates the dynamics of each component and the vehicle speed. For a representation of the driver model see Fig. 2.5

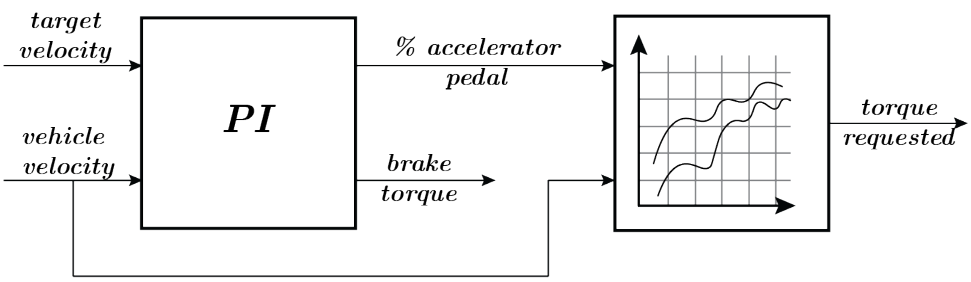

Figure 2.5: Schematic representation of the driver block

The vehicle motion is a result of the net effect of all the forces and torques acting on it:

- the longitudinal tire forces push the vehicle forward or backward;

- the weight mg of the vehicle acts through its center of gravity (CG). Depending on the angle of inclination, the weight pulls it either backward or forward;

- whether the vehicle travels forward or backward, aerodynamic drag slows it down. For simplicity, the drag is assumed to act through the CG.

The wheel normal forces satisfy:

$$\begin{aligned} m\dot{v_x} &= -mg \cdot \sin\beta \\ F_x &= n(F_{xf} + F_{xr}) \\ F_d &= \frac{1}{2} C_d \rho A (V_x + V_w)^2 \cdot sgn(V_x + V_w) \end{aligned} \tag{2.1}$$

where m is the vehicle mass in $[kg]$, v_x is the vehicle velocity in $[{}^{m}/_{s}]$, F_x is the longitudinal force in $[Nm]$, F_d is the aerodynamic drag force in $[Nm]$, g is the gravitational acceleration $[{}^{m}/_{s^2}]$, ρ is the density of the air in $[{}^{kg}/_{m^3}]$, and β is the slope in [°]. Zero normal acceleration and zero pitch torque determine the normal force on each front and rear wheel:

$$\begin{aligned} F_{zf} &= \frac{-h(F_d + mg\sin\beta + m\dot{V_x}) + b \cdot mg\cos\beta}{n(a+b)} \\ F_{zr} &= \frac{+h(F_d + mg\sin\beta + m\dot{V_x}) + a \cdot mg\cos\beta}{n(a+b)} \end{aligned} \tag{2.2}$$

Where F_z is the normal load force in $[N]$, h, a, b are the distances from CG, and n is the number of wheels per each axle.

The wheel normal forces satisfy:

$$F_{zf} + F_{zr} = \frac{mg\cos\beta}{n} \tag{2.3}$$

This model implies some limitations, in fact the Vehicle Body block models only longitudinal dynamics, parallel to the ground and oriented along the direction of motion. So, the equations assume that the wheels never lose contact and this constraint can result in negative normal forces.[19]

Simulink

The previous physical model has been substitute with analytical equations in order to achieve a consistent solution. The equations represent the effect of the resistance forces that act on the vehicle:

- **Air resistance:** the aerodynamic effect resulting from the movement of the vehicle onside a fluid, in this case the air:

$$\begin{aligned} F_D &= F_2 \cdot C_D \\ F_2 &= \frac{1}{2}\rho v^2 A \end{aligned} \tag{2.4}$$

  where A is vehicle frontal area in $[m^2]$ and C_D is the dimensionless drag coefficient.

- **Rolling resistance:** to simulate the result of the contact between the ground and the tyres:

$$F_R = F_0 + F_1 \cdot v \tag{2.5}$$

  where F_0 and F_1 are coefficient calculated from *coast down test* [2] and their dimensions are respectively $[N]$ and $[N^s/_m]$.

- **Ramp resistance:** if there is a slope, the gravity forces influences on the dynamics of the vehicle, and it could be whether positive or negative:

$$F_G = m \cdot g \sin\beta \tag{2.6}$$

As output the vehicle model gives the acceleration, and so the velocity and the travelled space as the respective integral. The equation is:

$$a_{veh} = \frac{C_{whl,fr} + C_{whl,re} - C_{res}}{\frac{J_{veh}}{r_{whl,fr}} + \frac{J_{veh}}{r_{whl,re}}} \tag{2.7}$$

[2]Coast down test consists in vehicle launch on a tarmac track from a certain speed with the engine ungeared, simultaneously recording the speed and travelled distance until vehicle stops with the aim of evaluate the resistant forces acting on the vehicle, so that to have the possibility to reproduce them analytically.[20]

where $C_{whl,fr}$ and $C_{whl,re}$ are the torques applied to the wheels of the front and rear axle in $[Nm]$, $r_{whl,fr}$ and $r_{whl,re}$ the radius of the front and rear wheels in $[m]$, J_{veh} the vehicle inertia in $[{}^{kg}/_{m^2}]$.

2.2.2 Engine and motors models

Simscape

Both the ICE and the P4 are modelled in Simscape as a mechanical energy source that generates torque, supposed to be ideal so that it's powerful enough to guarantee the specified request of power, regardless the angular velocity [19]. At the complementation of the modelling process, Ideal Motor Sensor and Inertia block from Simscape library are added. This way of proceed shall be call *black-box approach*, because the model gives an output without the knowledge of how this component work internally, for instance the behaviour of combustion of ICE is unknown but its effect - a torque on the crankshaft - yes.

Simulink

As it stands few lines above, the engine block has to provide only the signals for torque and angular velocity, considering anyway the effect of the inertia, in particular when the engine during cranking. Even the transmission (clutch and gearbox) was modelled with Simscape so during the transaction between Simscape to Simulink library it has to be recreated how the clutch and the gearbox effect on the components. It has been done with a fictitious signal which represent the clutch [3] and with the information of the state of the engine:

State	Description
0	the ICE is switched off
1	the ICE is starting
2	the ICE is running

Table 2.2: The three possible states of the ICE

[3] starting from the knowledge of the shifting request, if the clutch is open the model doesn't consider the rotative inertia of the engine

Going deeper, the torque is calculated from the following equation and controlled by the clutch signal:

$$C_{eng,act} = C_{eng,req} - J_{ICE} \cdot \dot{\omega} \tag{2.8}$$

where $\dot{\omega}$ is the angular acceleration in ${}^{rad}/_{s^2}$ For what concerns the calculation of the velocity, the process was a bit more complicated, in fact the actual rotational speed depends on the state of the engine, but explained this in details is not the purpose of this essay. In general, the problem has been solved thanks to the combination of:

- the velocity calculated from the longitudinal velocity of the vehicle, as follows: $\omega = \frac{v_{veh} \cdot \tau_{tot}}{r_{wheel}}$
  where ω is the angular velocity in $[\frac{rad}{s}]$, v_{veh} the actual speed of the vehicle, τ_{tot} the transmission ratio reduced to the wheels;
- The velocity in idle condition, set to $n_{idle} = 788\frac{rad}{s}$ from experimental value;
- The velocity during the start of the engine.

2.3 Thermal model

A fluid-dynamic model is particularly complicated to be recreated properly in Simulink, so what it needs is a simulation software like *LMS Imagine.Lab AMESim*, which is a commercial software for the modelling and analysis of multi-domain engineering systems and its name stands for *Advanced Modeling Environment for performing SIMulations of engineering systems*. The software package is a suite of tools used to model, analyse and predict the performance of a system. It offers plant modelling capabilities and the possibility to integrate controls, helping user assess and validate control strategies. Models are described using non-linear time-dependent analytical equations that represent the system's hydraulic, pneumatic, thermal, electric or mechanical behaviour [21]. An example is given by Fig. 2.6

Now, the model was completed by the implementation of a more realistic cooling (and heater) circuit of the more stressed components, and depending on temperature level they are classified in § 2.3.

All the cooling circuits described were already modelled in AMESim environment, calibrated and validated during a previous activity [21], whereas in this essay

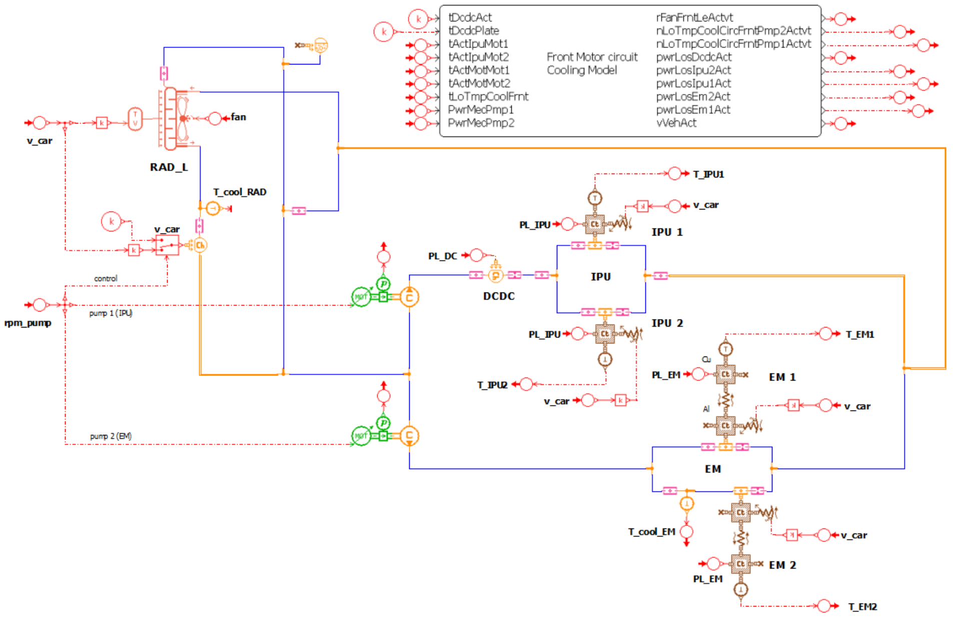

Figure 2.6: Example of hydraulic circuit modelled with AMESim

Name	Description
LT	Low Temperature: the battery A/C cooling system
MT	Middle Temperature: front-axle cooling circuit and ISG cooling circuit
HT	High Temperature: ICE cooling circuit

Table 2.3: Cooling circuits distinguished for temperature

the complete thermal model has been implemented in the current and updated vehicle model. Since the architecture of the MiL is such as to keep separated vehicle controls (comprehending all the control algorithms related to each modelled vehicle parts) from physical components (analytical and physical models are here implemented, including the thermal management control-oriented models). Unlike the models created with Simscape libraries (the engine and the electric motors, whose tendency has to be defined hypothetically in continuous), the cooling circuits simulates slower transients (such as the temperature of a mechanical components), so the simulation time-step has set to 1s. As a consequence, the implementation of AMESim doesn't reduce the speed of calculation and it doesn't create any problems. In the next paragraphs, it will be give examples of the cooling circuits physical representation. Fig. 2.7, Fig. 2.8 and Fig. 2.9.

2.3.1 Battery-AC integrated cooling circuit

The battery-AC integrated cooling circuit consists of the following

- battery indirect cooling circuit
  the coolant absorbs heat power from the HV battery flowing through cooling plates and it is then cooled down by the refrigerant in gaseous state by means of a chiller, a vapour-liquid heat exchanger. A thermal expansion valve (TXV) controls the refrigerant mass flow rate through the chiller;

- air-conditioning circuit
  the in-coming air from the external environment is cooled down in the evaporator, a vapour-liquid heat exchanger, by the refrigerant. A TXV with the same purpose is present, as well.[21]

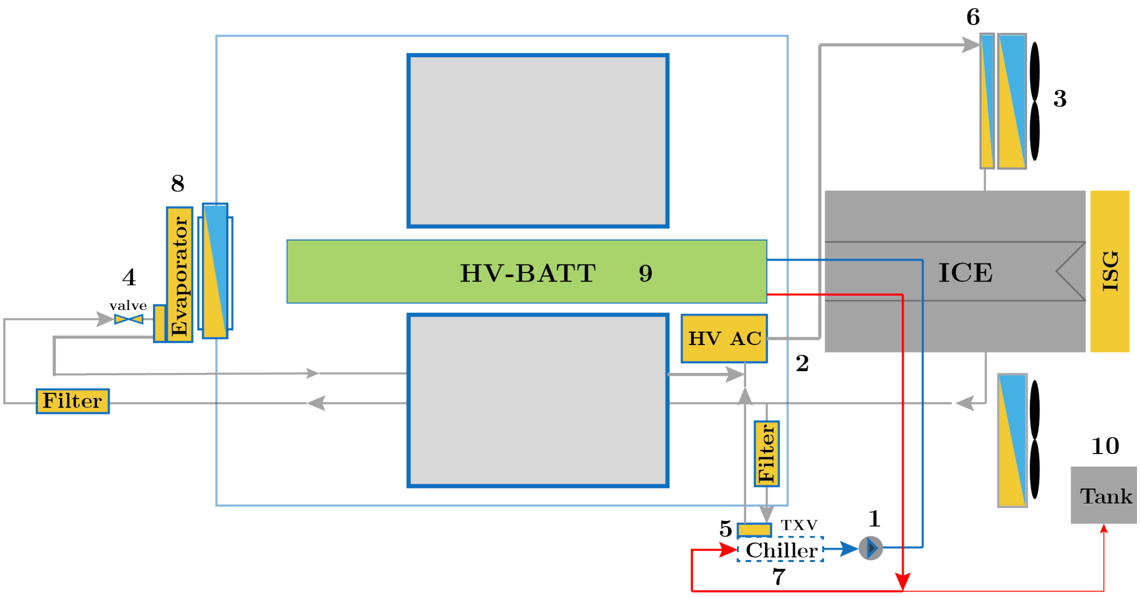

Figure 2.7: High-voltage battery and air-conditioning cooling circuit layout

Type	Number	Name
Actuators	1	Electric Pump
	2	High-voltage compressor
	3	Fan
	4	TXV (cabin loop)
	5	TXV (battery loop)
Components	6	Condenser
	7	Chiller
	8	Evaporator
	9	High-voltage battery
	10	Expansion tank

Table 2.4: Components of the HV A/C cooling circuit

2.3.2 ISG cooling circuit

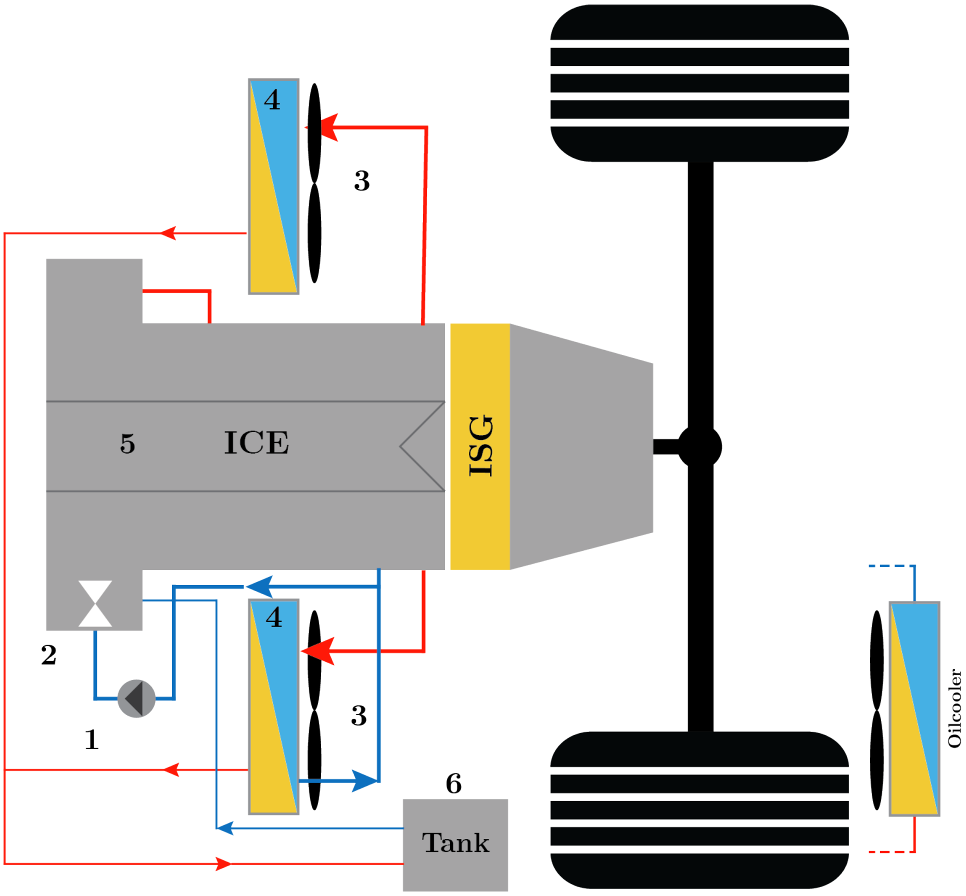

Figure 2.8: ISG cooling circuit layout

Type	Number	Name
Actuators	1	Electric Pump
	2	Fan
Components	3	Radiator
	4	ISG (P1)
	5	Inverters
	6	Expansion tank

Table 2.5: Components of the ISG cooling circuit

2.3.3 EM cooling circuit

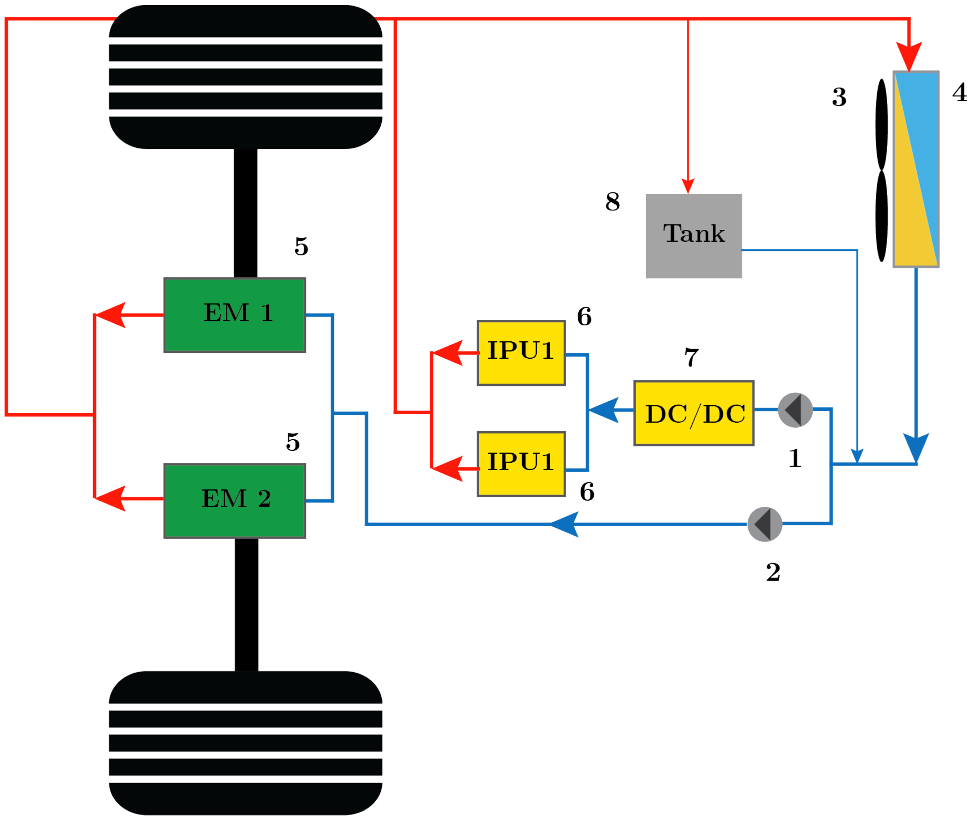

Figure 2.9: EM cooling circuit layout

Type	Number	Name
Actuators	1	Electric Pump (inverters loop)
	2	High-voltage compressor (motors loop)
	3	Fan
Components	4	Radiator
	5	Motors (P4)
	6	Inverters
	7	DCDC
	8	Expansion tank

Table 2.6: Components of the EMs cooling circuit

2.4 Validation

The transaction from a physical-approach Simscape model to an analytic-approach Simulink model was everything but linear, all the steps and modifications had to been evaluated, compared and analysed against the value obtained with the original MiL, under all circumstances. The purpose is to reach the same level of reliability of the physical components, to do so, some reference signals have been chosen among the physical quantities in output of the models, to make a better characterization of it. In other words, if the signals selected are the same of the original MiL, then the new model can be considered effective and representative.

The signals in exam are listed in 2.7.

Table 2.7: Reference signals useful for validation

Type	Name	Unit	Description
Driver	Vehicle speed	$\frac{km}{h}$	If the vehicle is following the input path
	Acceleration pedal	%	
Battery	State of Charge	%	If the battery is delivering the same power
	Power Absorbed	W	
	Current	A	
ICE and EMs	Power to P4	W	If the engine and motors are delivering the same power
	ICE torque	Nm	
	ICE angular velocity	$\frac{rad}{s}$	
	ISG torque	Nm	
	ISG angular velocity	$\frac{rad}{s}$	

The validation has been performed over multiple cycle speed profile, in order to erase causalities, starting from different states of charge, forcing the eDrive condition[4], and spacing from the simplest regulation driving cycle (such as NEDC) to the

[4]eDrive means that the requested power is provided only by the EMs, and it will be better explained in § 3

more complex WLTP ending with the newest RDE. For a matter of visualization, only the results of WLTP validation are displayed in Fig. 2.10 and in Fig. 2.11, because the NEDC was considered too soft for a good comparison while the RDE too long for a useful visualization. This proceeding has been accomplished without the AMESim physical blocks, because in the original MiL they weren't implemented and the final results could be altered, and even because their validation has been given for guaranteed. Doing so, a strong assumption is made, in fact it's supposed to consider reliable the combination of two separated and validated models.

The Fig. 2.10 and Fig. 2.11 show how the new model simulates the same manoeuvres as the original MiL, where they derived from physical blocks. Since the purpose of the present analysis will be focused on energy evaluation along a complete cycle, even if the new model loses a bit of accuracy, it is acceptable.

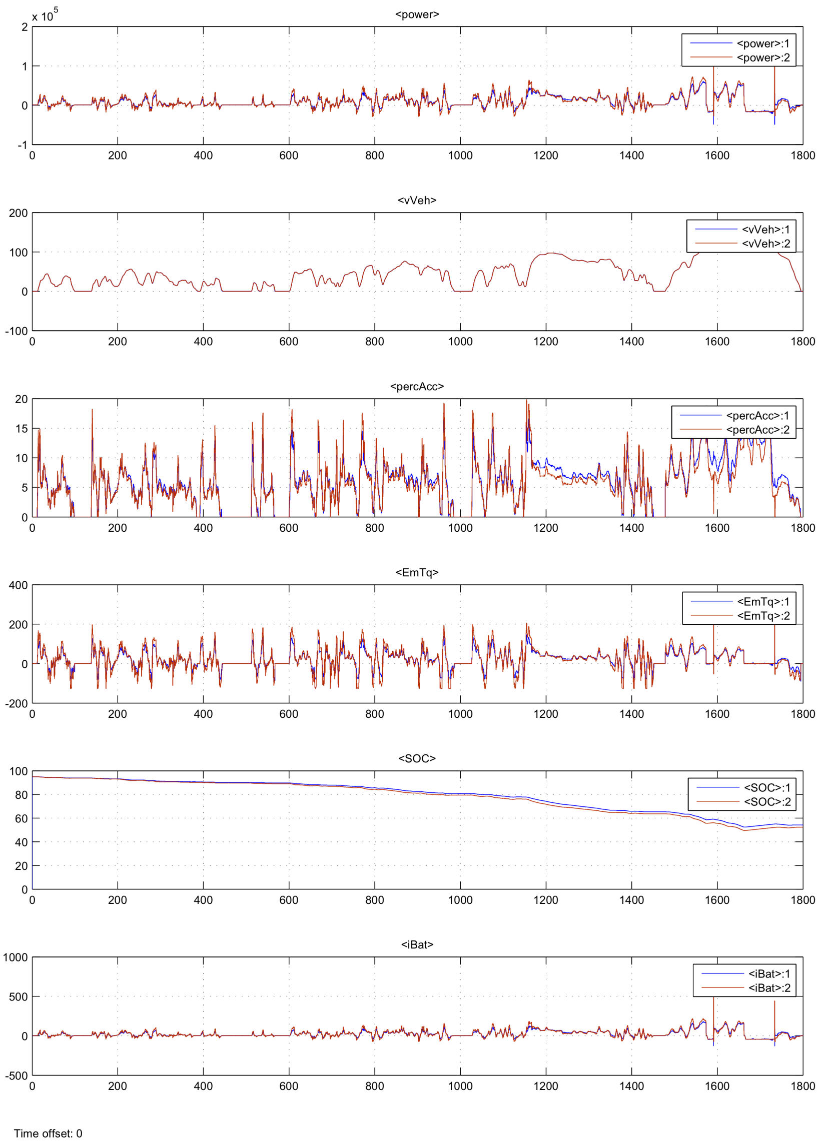

Figure 2.10: Validation of the model during a WLTP

Blue line	Original MiL
Red line	New MiL

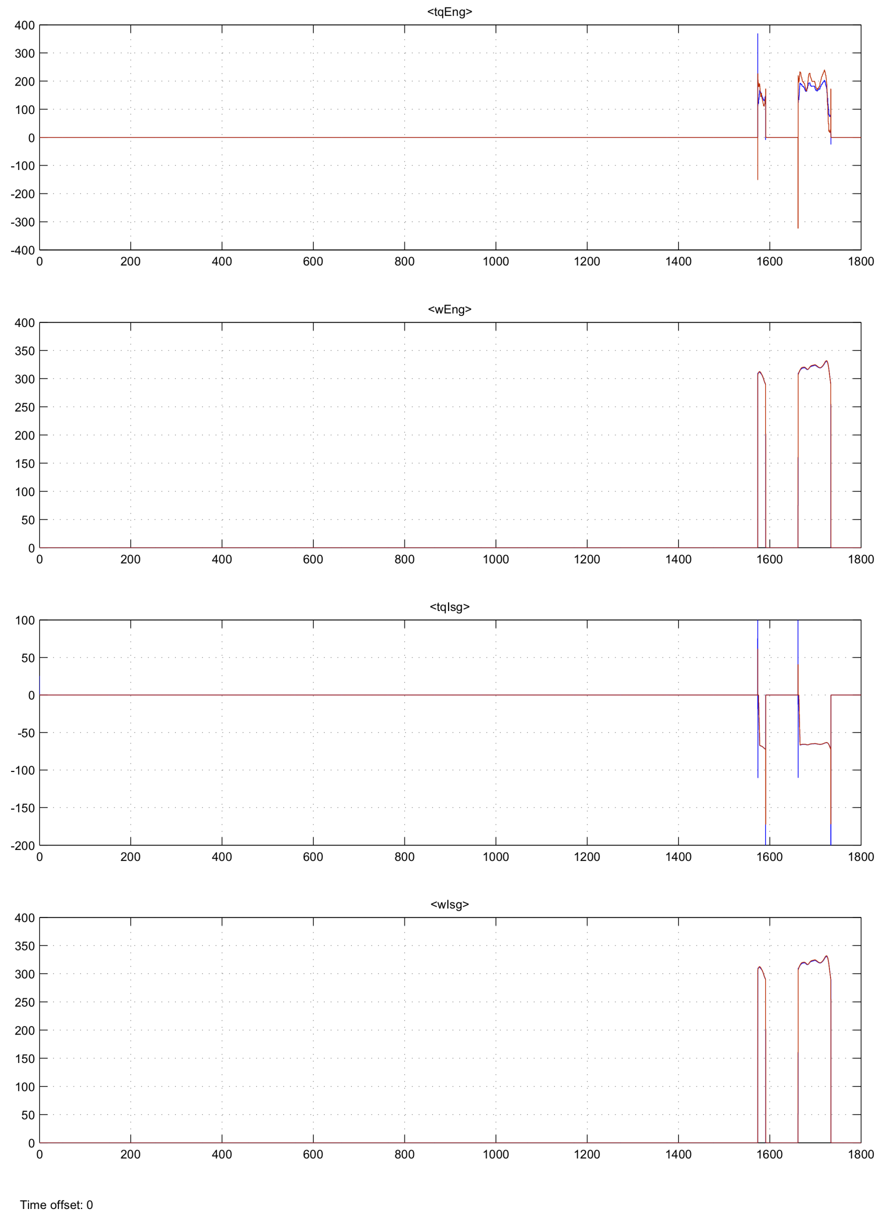

Figure 2.11: Validation of the model during a WLTP

Blue line	Original MiL
Red line	New MiL

Chapter 3

PHEV supervisory controls

The purpose of this chapter is to focus on both torque split strategies for fuel consumption minimization and eHorizon predictive strategies for a better usage of the energy on-board. For the purpose, the fuel consumption at the end of the driving cycle is used as comparison between different strategies.

3.1 Torque Manager Strategies

The focus of this first section is the torque split selection, starting from the original heuristic controller implemented in the vehicle model and moving toward more complex strategies and how they have been implemented. The driver block generates a realistic wheels torque request based on the driving path defined by the user. This request can be satisfied in several ways, so the solution is no more singular like it was for a common fossil-fuel vehicle. The problem is: what could be the best torque split to fulfil both the power requested and the efficiency target?

3.1.1 Rule-Based

These rules are calibrated to reach good efficiencies in specific driving conditions. Since the values are generally fixed, they do not have flexibility, so they cannot provide a high efficiency level in all the possible driving paths. First things, the Rule-Based Strategy (RBS) decides if it's possible to switch to full electric driving depending on the conditions. The limits represent a hysteresis so when the input is one, it remains so until the input drops below the lower value while when the input is zero, it remains zero until the input exceeds the upper value.

If the eDrive conditions are fulfilled at the same time, the requested torque to the wheels is handled only by the electric motors on the front axle, allowing the ICE to switch off. This particular situation is recommended in zones where only electric vehicles are allowed or when the driver request is not demanding and so the high performance engine is not necessary.

In all the other cases, when the power of the ICE is requested, the HCU determines how to split that request between the engine and the electric motors. In the following equations, it is possible to see the steps that lead to the torque at ICE, ISG and EMs. It's appropriate to specify that the torque of the ISG and the EMs could be either positive or negative. In the second, case the motors are performing regenerative braking (with the P4s) and/or *load point shift* (with the ISG).

As an output from the driver block, the requested torque at the wheels $C_{req,whl}$ arrives at the HCU, where it is split between the machines as following:

$$\begin{gathered} C_{ICE} = \frac{C_{req,whl}}{\tau_{tot}} - C_{ISG}(v_{veh}, SoC, \omega_{ICE}) \\ C_{ICE} \in [lim^{-}_{ICE}, lim^{+}_{ICE}] \end{gathered} \tag{3.1}$$

where τ_{tot} is the total reduction gear of the transmission, v_{veh} is the actual vehicle speed in ${}^{km}/_{h}$, and ω_{ICE} is the angular velocity of the engine in ${}^{rad}/_{s}$. While the boundaries of deliverable torque are:

- lim^{-}_{ICE} - is the lower limit and represents the internal frictions of the engine derived from a map function of rotational velocity;
- lim^{+}_{ICE} - is the upper limit and it is derived from the engine power curve.

$$C_{P4} = [C_{req,whl} - (C_{ICE} + C_{ISG}) \cdot \tau_{TOT}] \cdot \tau_{P4} \tag{3.2}$$

where τ_{P4} is the reduction gear between the P4s and the wheels. While the boundaries of deliverable torque are:

- lim^{-}_{P4} - is the lower limit and it sets constant by the host company;

- lim^{+}_{P4} - is the upper limit and it sets constant by the host company.

In conclusion, the range of action of the Rule-Based is only driven by the request of hybrid or eDrive mode, so it doesn't matter if the defined split is not recommended for fuel consumption, it will always follow the rules.

3.1.2 Equivalent Consumption Minimization Strategy

Switch to completely different approaches, there are the optimal and sub-optimal strategies, solving resepctively an optimal or sub-optimal control problem. In particular, Equivalent Consumption Minimization Strategy is a local-optimal solution which, instant by instant, minimize a cost function, which is a function that represents some "cost" associated with the event. In the case in exam, the ECMS cost function is the equivalent fuel consumption defined as the sum of the actual fuel consumption and the virtual fuel consumption associated to the use of electric energy [22] described by the following equation:

$$\dot{m}_{eq}(t) = \dot{m}_f(t) + \dot{m}_{bat}(t) = \dot{m}_f(t) + \frac{s}{Q_{LHV}} \cdot P_{bat}(t) \tag{3.3}$$

where $\dot{m}_f$ is the engine instantaneous consumption of fuel in ${}^{kg}/_{s}$, $\dot{m}_{bat}$ is the equivalent consumption of fuel due to battery usage in ${}^{kg}/_{s}$, P_{bat} is the electrical power requested at the battery in a instant of time, expressed in W, Q_{LHV} is the lower heating value of the fuel in ${}^{KJ}/_{kg}$, while s is the so called *equivalent factor*, in other words a coefficient to convert the electric power delivered by the battery in equivalent fuel consumption, as it was consumed by the engine. It has to be specified that, unlike the engine fuel consumption which is always positive, the equivalent one could be either positive or negative depending on the power requested by the battery.

More in detail, the ECMS is based on the Pontryagin's Minimum Principle, which is used in optimal control theory to find the best way possible for taking a dynamical system from one state to another, especially in the presence of constraints for the state or input controls [23]. The principle states, simplifying, that the cost function, in this case an *Hamiltonian*, must take an extreme value over controls in the set of all allowable controls. Whether the extreme value is maximum or minimum depends both on the problem and on the sign convention used for defining the Hamiltonian.

Applied to the ECMS, the Hamiltonian to be minimized becomes:

$$H(\xi,u,\lambda,t) = -\lambda(t) \cdot f(\xi,u,t) + \dot{m}_f(u,t) \tag{3.4}$$

where λ is the co-state variable, so the solution of:

$$\dot{\lambda}(t) = -\lambda \frac{\partial f(\xi,u,t)}{\partial \xi} \tag{3.5}$$

Physically, the co-state can represent the marginal cost if the constraints are being violated. The aforementioned *equivalent factor* $s(t)$ helps to define that co-state variable:

$$s(t) = -\lambda(t) \cdot \frac{Q_{LHV}}{P_{bat}(t)} \tag{3.6}$$

In light of this, the Hamiltonian becomes:

$$H(\xi,u,\lambda,t) = \dot{m}_{eq}(\xi,u,s,t) = s(t) \cdot \frac{P_{bat}}{Q_{LHV}} \cdot f(\xi,u,t) + \dot{m}_f(u,t) \tag{3.7}$$

The instantaneously optimal control $u*$ is the one that minimize the (3.7) and it will represent the optimal torque split factor. This approach is intrinsically more complex than the RBS: while the RBS, after deciding what is the driving mode (eDrive or Hybrid), splits the torque mathematically within physical limits, the ECMS uses the result of the minimization problem $u(t)$ [1] to decide the repartition of torque as showed by the table 3.1.

Table 3.1: Driving mode function of $u(t)$

Mode	**Split factor**	**ICE**	**ISG**	**EM**
eDrive	$u(t) = 1$	OFF	OFF	ON
Regenerative Braking	$u(t) = 1$	OFF	OFF	ON
ICE only	$u(t) = 0$	ON	OFF	OFF
Boosting	$0 < u(t) < 1$	ON	OFF	ON
Battery Recharging	$0 < u(t)$	ON	ON	OFF

Since this point, the ECMS optimization is a mathematical problem so, even if it

[1]which is unique but it can be reached in several ways due to the presence of multiple electric motors

has some constraints, it's not suitable for a driving vehicle, which has to withstand to boundaries both physical and mechanical. Implementing the strategy as it is will make the vehicle undriveable because the optimal split factor could change the state of the vehicle in less than a half-second. It is obviously unacceptable. Part of the work consists, in fact, of updating the routine with at least the following physical constraints:

- once started, the IC engine has to running at least for $10s$ because otherwise the spark plugs could break;
- the electric machine has to be switched on for at least $2s$ to prevent damages to the components.

The problem has been solved with the StateFlow[2] depicted in Fig. 3.1.

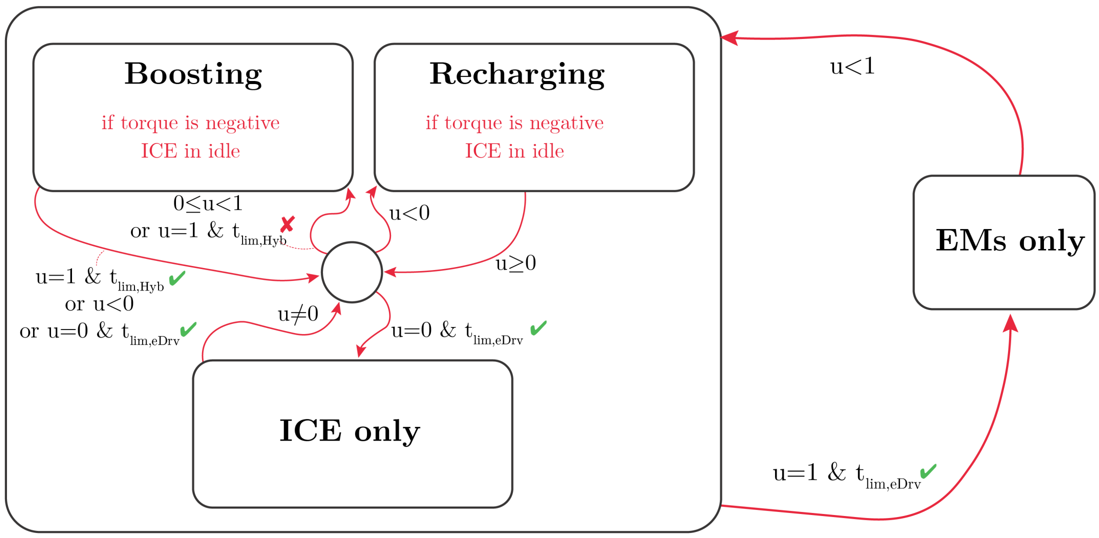

Figure 3.1: The flow chart ruled by the split factor

Where $u(t)$ is the split factor calculated by the ECMS routine, $t_{lim,eDrv}$ is the time EM spends running while $t_{lim,Hyb}$ is the time ICE spends running.

[2]StateFlow is a tool of MATLAB environment for modelling and simulating combinatorial and sequential decision logic based on state machines and flow charts.

Results

As it's possible to imagine, when some limitations are added to the ECMS original routine, the strategy looses in efficiency and the solutions chosen don't correspond any more with the local optimum. However, the behaviour of the powertrain (ICE and EMs) is more realistic and, more importantly, it could be implemented on a real vehicle. In Fig. 3.2 and in table 3.2 the obtained values are showed, comparing the CO_2 emissions between the original strategy and the limited one, normalized with respect to this letter. In particular, the simulations have been carried out on different driving cycle.

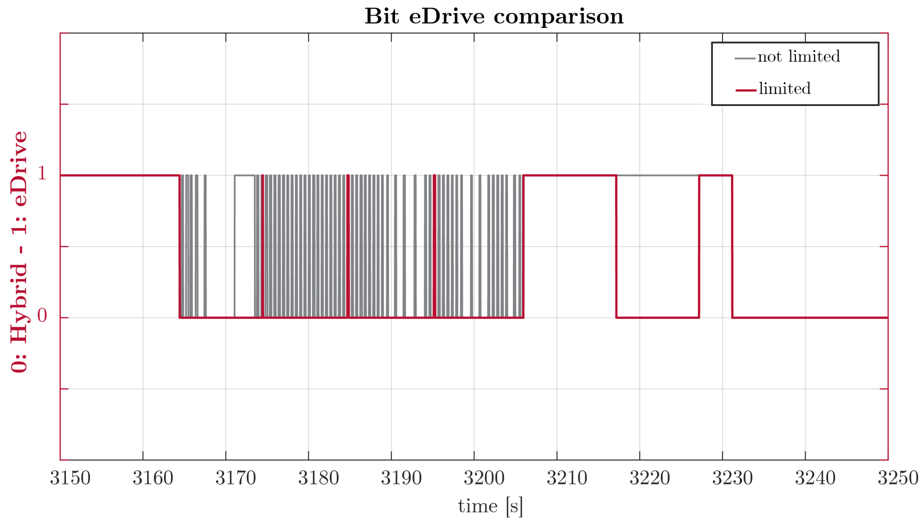

Figure 3.2: Comparison between the original strategy and the limited one
1: eDrive 0: Hybrid mode

	Original [%]	**Limited** [%]	**Gain** %
WLTC	96,487	100,000	+3,64%
RDE Aachen	95,291	100,000	+4,49%
RDE Cherasco Inv	92.122	100,000	+8,55%

Table 3.2: CO_2 emissions when ECMS is limited

3.1.3 Discrete Dynamic Programming

With the full information of the future driving path (including road map data, altitude, traffic information, and so on) the power demand from the powertrain can be computed and it can be assumed to be known at each instant of time [24]. This information allows, proceeding backward, to find the global optimal strategy. The theory of Dynamic Programming is based on the *Principle of Optimality* which states that, regardless of the initial conditions, the following choices make up the optimal policy with regard to the starting point [25]. This approach works only backward, choosing the target final value of the state variable, every possible previous decisions are analysed and for each decision the function cost is calculated. At the end, the path with the lower overall function cost is chosen among all the possibilities, given the initial state. The procedure path is shown in Fig. 3.3. However, the knowledge of the future makes this strategy unsuitable for real time applications but, carrying it out off-line, it provides useful benchmark data.

For what concern the application of this strategy on Hybrid Vehicle, it could be used to determine the sequence of optimum power split between the ICE and the EM at every instant of time to minimize the fuel consumption over a given trip or driving cycle. In order to achieve that result, the problem variables are defined as:

- **Disturbances:** the vehicle speed and slope derived from the driving trip;
- **State variables:** the state of charge of the battery and the gear engaged;
- **Control variables:** the split factor and the *load point shift*;
- **Cost function:** the sum of the instantaneous fuel consumption and the cost related to the state of charge of the battery which has to be recharged at the end of the trip.

In light of this, the strategy has been implemented in the study case model (which is a PHEV) firstly calculating off-line the optimal strategy maps moving backward from the final state, and then running the simulation forward and interpolating the maps to obtain a global sub-optimal solution. It has to be specified that the strategy implemented is a variation of the original one, it's called Discrete Dynamic Programming because, beside the time, even the state variables are discrete.

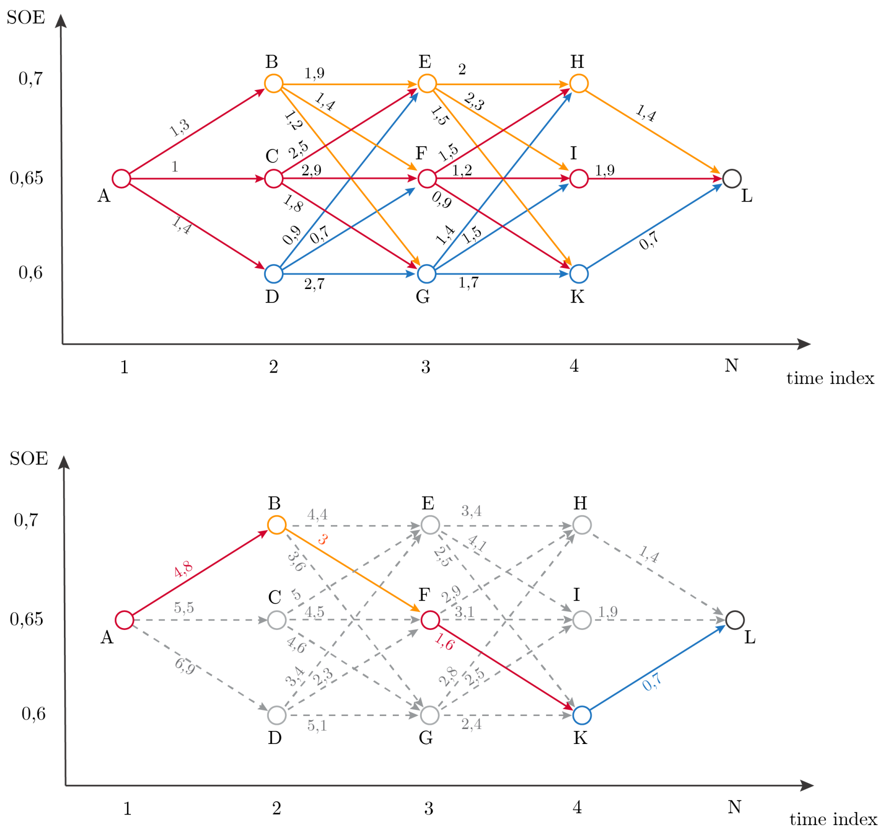

Figure 3.3: Dynamic Programming routine
A,B,..: States   1,3: Function cost between the stages

In addition, due to the mathematical nature of the DDP, the same physical constraints as the ECMS ($t_{Hyb,min} = 10s$ and $t_{EDrv,min} = 2s$) are needed in the model.

	Original [%]	**Limited** [%]	**Gain** %
WLTC	94,626	100,000	+5,41%
RDE	97,418	100,000	+2,58%
RDE Aachen	96,591	100,000	+3,53%

Table 3.3: CO_2 emissions when DDP is limited

3.2 Battery Management Strategies

3.2.1 Charge Sustaining

The vehicle doesn't rely on the actual battery state of charge to perform the driving operations, even if there were enough energy storage. Thus, the level of the SoC oscillates but it will remain inside boundaries defined by the developer, in a sequence of discharging and charging phases. The charge-sustaining strategy is generally implemented on HEVs.

The RBS sets a lower limit and a upper limit: when the SoC reaches the lower one, the strategy switches on the ICE to recharge the battery. At this point the battery is allowed to discharge until to the lower limit is overcame again. The typical trend of this strategy is clarified in Fig. 3.4

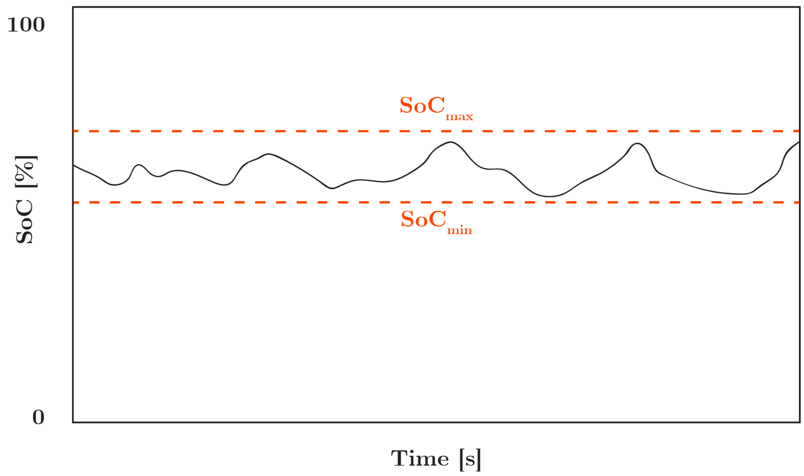

Figure 3.4: Exemple of charge-sustaining strategy

3.2.2 Charge Depleting

As already stated, the BMS depends also on the kind of vehicle, in fact, the CD strategy assume partially different meaning if it is applied on EVs or on PHEVs:

- **EV:** due to the absence of the IC engine, which otherwise could recharge the battery pack at will, the trend of the SoC is decreasing. Obviously, the trend is slowed down when regenerative braking take place. See Fig. 3.5;

- **PHEV:** firstly, the controller allows the discharging until a SoC target and then it sustains the state of charge around it. Usually the plug-in hybrid vehicles tend to arrive at the end of the driving event discharged, because can be plugged to the grid. See Fig. 3.6.

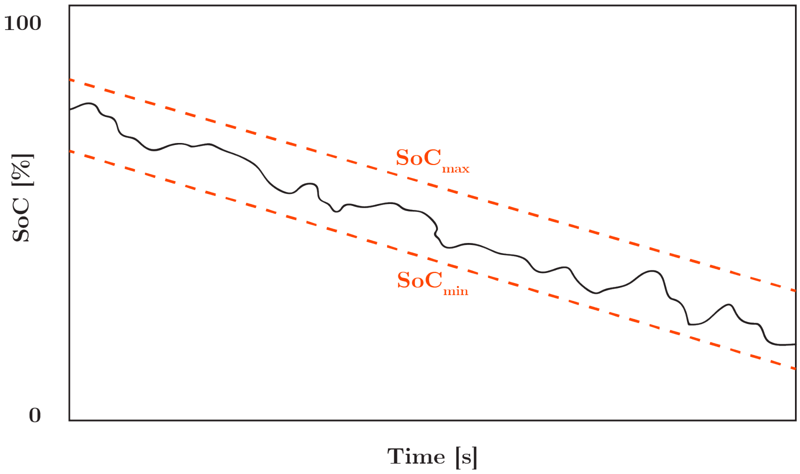

Figure 3.5: Example of charge-depleting strategy

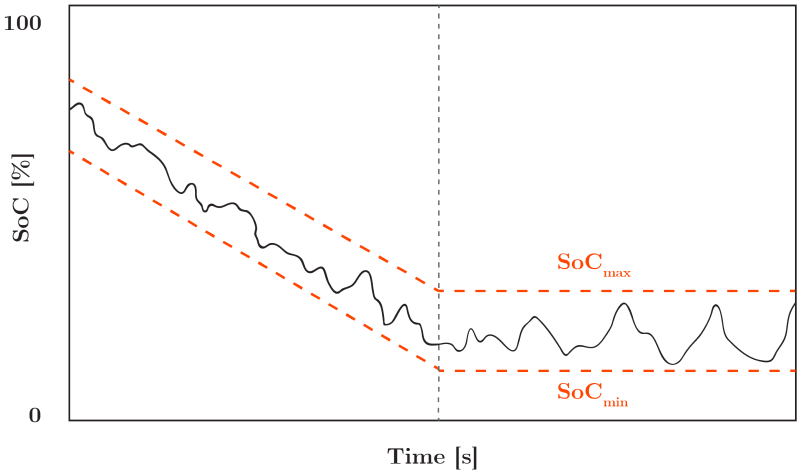

Figure 3.6: Example of charge-deleting and charge-sustaining strategy

3.3 eHorizon Control Strategies

Starting now, it is made the assumption that the future path is known. That permits to create the so-called eHorizon functions, whose purpose is to make more efficient decisions depending on what the vehicle has got in front of it. As stated in § 1, the vehicles will be allowed to access into metropolitan cities only in pure electric mode, due to the growth of pollutions. The developed strategies are based on the presence of a *City Event*, where the electric drive is mandatory, and in this work it will have the same meaning of *Zero Emissions Area*.

3.3.1 City Events Finder

First of all, the eHorizon Control Unit (eHCU) has to recognize if, in the given driving route, there is a City Event. Hypothetically, if the driver has set the path on a GPS navigator, the boundaries of the urban city are easily defined in function of the space (e.g. starting from a point A the city event occurs at point B in correspondence of the 35th kilometre), but in that model, obviously, the role of the navigator must be simulated. An other way to identify the physical boundaries of the city center is the speed limits, clearly, supposing the vehicle will respect them (with some flexibility). The limit is set to the legal speed limit (in other words, the road signs) plus an offset if the driver overcomes the limit for a short period.

Table 3.4: Speed limit and offset

	Speed limit [km/h]
City limit	50
Offset	9
Applied limit	59

The algorithm receives the driving path and returns a bit (1 if the speed is under the set limit, 0 otherwise). Then the output signal has to be filtered because the vehicle could travel under the City Limit even in extra urban roads. To identify when the vehicle is slow because is on a urban road and not because external disturbances like traffic or accidents, the city event is supposed to have a minimum duration of

1000 seconds (about 15 minutes). As it will be appear clearer in the next paragraphs, determining the spacial position of the city events isn't an end in itself, but it will be necessary for the other eHorizon functions, which, to be effective, shouldn't be applied over a short urban area.

The City Event Finder works properly independently on the chosen driving cycle (such as RDE or inverted RDE with the urban section at the end) and on the number of cities the car has to pass through. On the other hands, it is focused only to individuate the Urban Center (the only section really useful for the functions) and it forgets about the other possible road typologies (Rural and Motorway, typical of the RDE driving cycle used for the simulations).

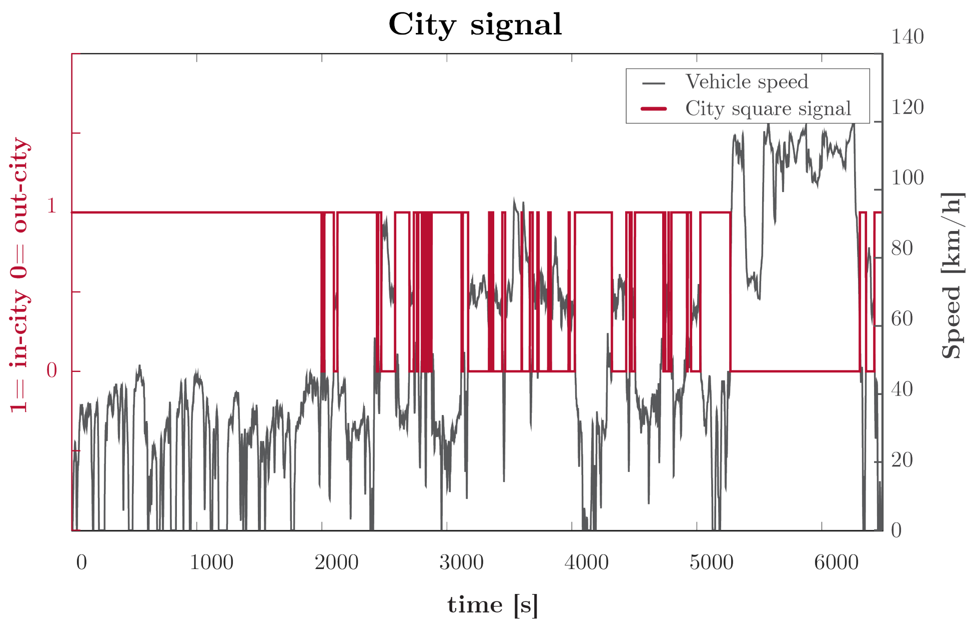

Figure 3.7: City square signal not filtered

3.3.2 Predictive Thermal Management

Assuming that a Urban City Center coincides with a Zero Emissions Zone, and so is mandatory the electric drive (available for the PHEV), it stands to reason that the continuous usage of the battery induces on it a rise in temperature. Originally, the battery temperature control was handled by a rule-based strategy, which activated the pump and compressor when the temperature level overcame the upper limit of

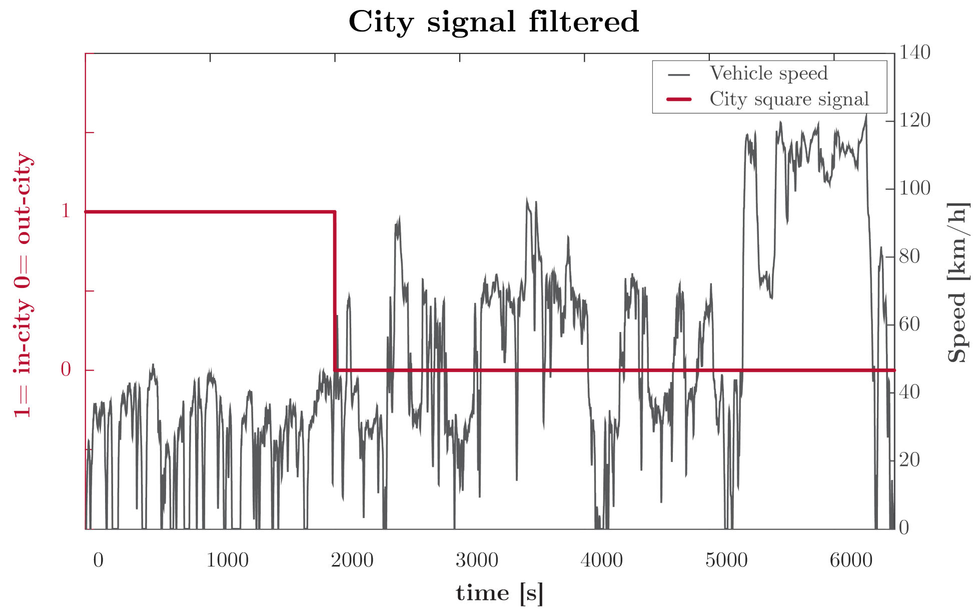

Figure 3.8: City square signal filtered

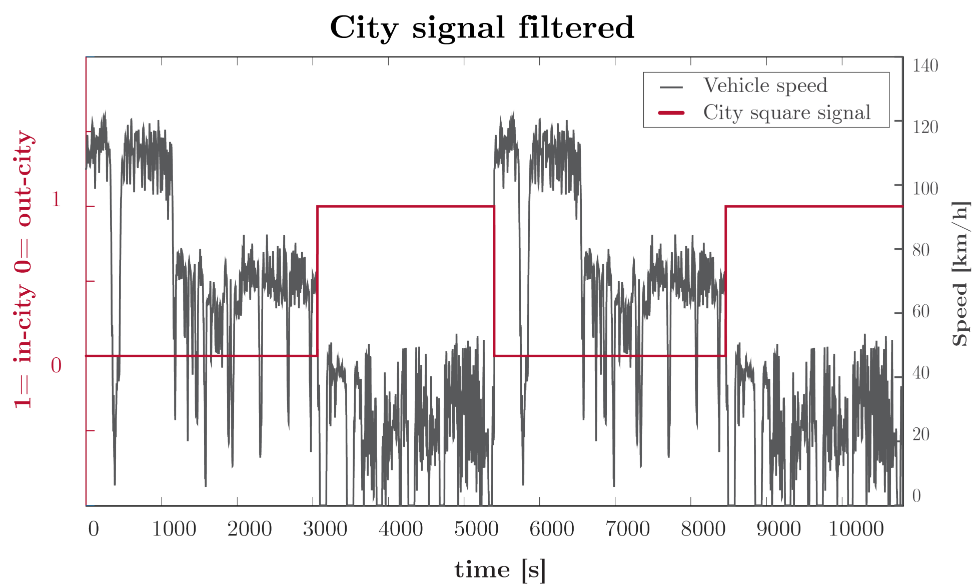

Figure 3.9: Example of CEF applied on multiple city events

$30°C$ and it turned them off when the temperature reach the lower limit of $28°C$. The eHorizon thermal management proposes to handle in a cleverer way the energy flow from or toward the battery, predicting its temperature behaviour. The process is carried out by a function, developed in a previous master thesis work [21], which simulate analytically the vehicle driving inside the urban area defined by the CEF. The function, enabled by a trigger signal at the start of the event, can only simulate the requested power to the battery and so its heating, due to the Joule effect, $P_{loss} = R \cdot I^2$. This because the function can't calculate the instantaneous torque split. Thus, it is turned on only during the full-electric drive events where the whole requested torque is provided by P4s. The ambient temperature is set by the external user and remains constant for the entire simulation and the initial battery temperature coincides with it, if the city event is at the beginning of the driving trip. Some physical constraints has to be defined, in addition to the maximum torque deliverable by the machines, even the temperature upper limit. Considering the ageing and the de-rating of the battery, the available power changes when heated or cooled (Fig. 3.10 [21]), so the $T_{b,ul}$ is set to $40°C$.

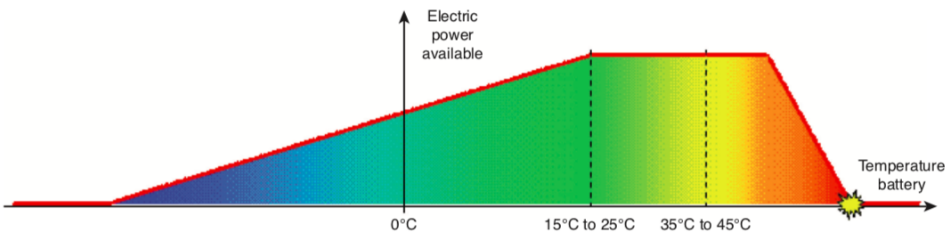

Figure 3.10: Battery power supply as a function of its temperature

At this point, the prediction can present two different case, depending on the maximum temperature (indicated as $T_{b,max}$) reached by the predictive function:

- $\boldsymbol{T_{b,max} < T_{b,ul}}$
  so the battery temperature will remain under the upper limit for the entire event. It can result by the combination of cold ambient conditions and short driving cycle. When this situation occurs, the Predictive Thermal Management function overwrites the Rule Based and it keeps off the pump and the compressor of the cooling circuit, saving energy. However, after exiting the urban section this approach load the IC engine which, commanded by the RBS,

has to cooling the battery until its temperature falls within the limits. That case is depicted in Fig. 3.12.

- $\boldsymbol{T_{b,max} > T_{b,ul}}$
  On the contrary, when the temperature of the environment is particularly high and the event long, the battery temperature will reached the upper limit before the end of the city. To avoid that, the PTM activates the pump and the compressor in advance, and performs a recalculation of predicted trend until that prediction will be under the $T_{b,ul}$. The Fig. 3.14 this eventualities.

Practically, the upper limit is set to $38°C$ because the temperature transitory is particularly slow, so initially the temperature will continue to rise and it is not recommend to overcome $40°C$.

3.3.3 Zero Emissions Area

The Zero Emission Area is the result of a previous thesis project [26], which proceeded in parallel with the development of PTM, and like this one the ZEA is built on a MATLAB function, directly implemented in Simulink. The master core is the analytic model used even in the PTM to simulate the behaviour of the powertrain, including the high-voltage battery model, which calculates the minimum requirement of energy to carry out the urban zone in pure electric mode. The value of electric energy required at the batteries is converted in a target state of charge, ξ_{target}, as main output of the function.

As for PTM, the model can recreate the heating process of the battery but not how it cools. The problem is not easy to solve, the best solution would be a mathematical conversion of the cooling circuits but it would falls outside the purpose of this work. An alternative is to suppose that as long as the battery temperature is below the $T_{b,ul}$ (see § 3.3.2) the auxiliary electric power request to the actuators is null (only the constant value of $P_{aux} = 750W$ for infotainment, lights, and so on), but when the limit is reached a fixed quantities is added to the valuation of the power demand. After some considerations, in order to avoid underrating value of the *SoC target*, the fixed value for compressor and pump is $1000W$.

Once the target has been computed, three scenarios has possible:

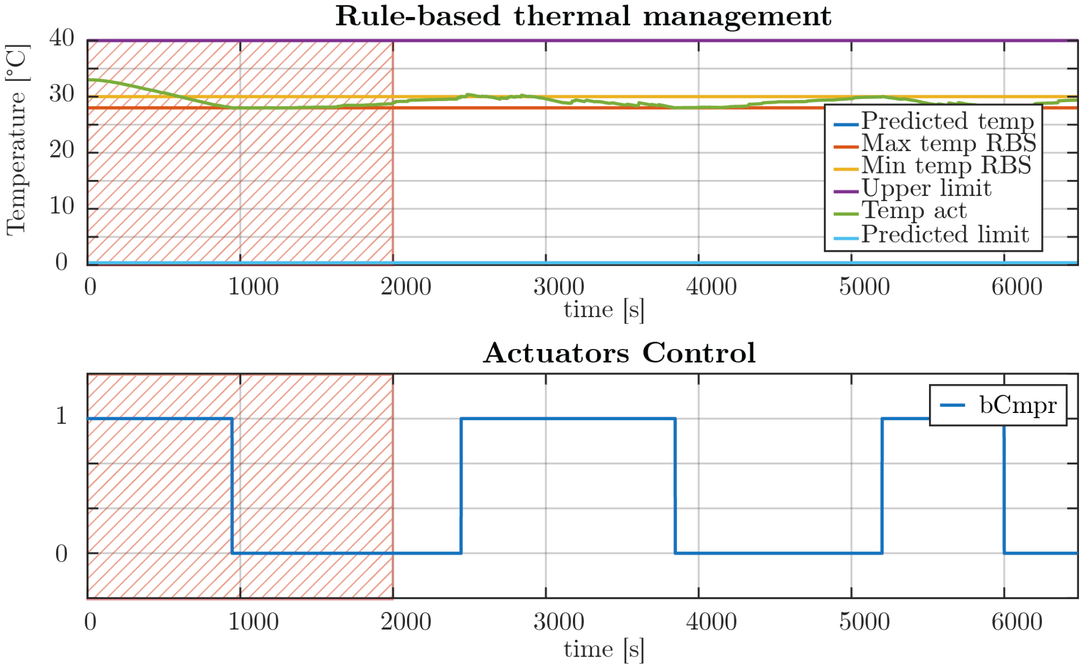

Figure 3.11: Temperature trend with RBS activate and $T_{init} = 30°C$

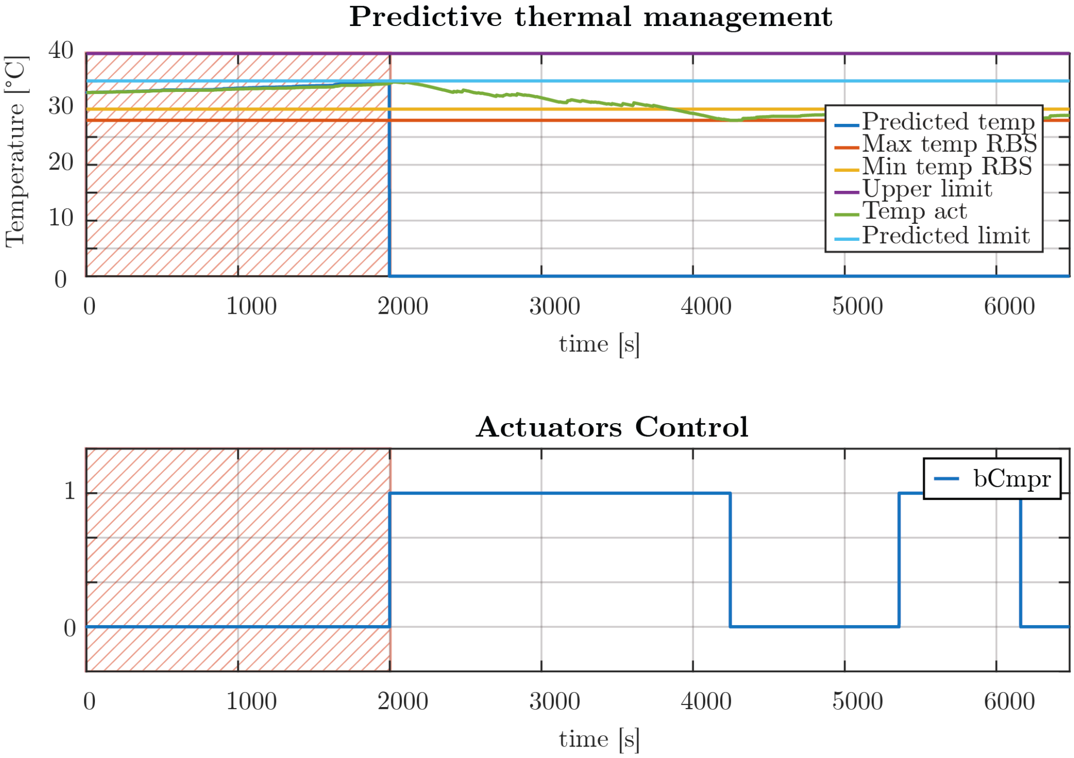

Figure 3.12: Temperature trend with PTM activate and $T_{init} = 30°C$

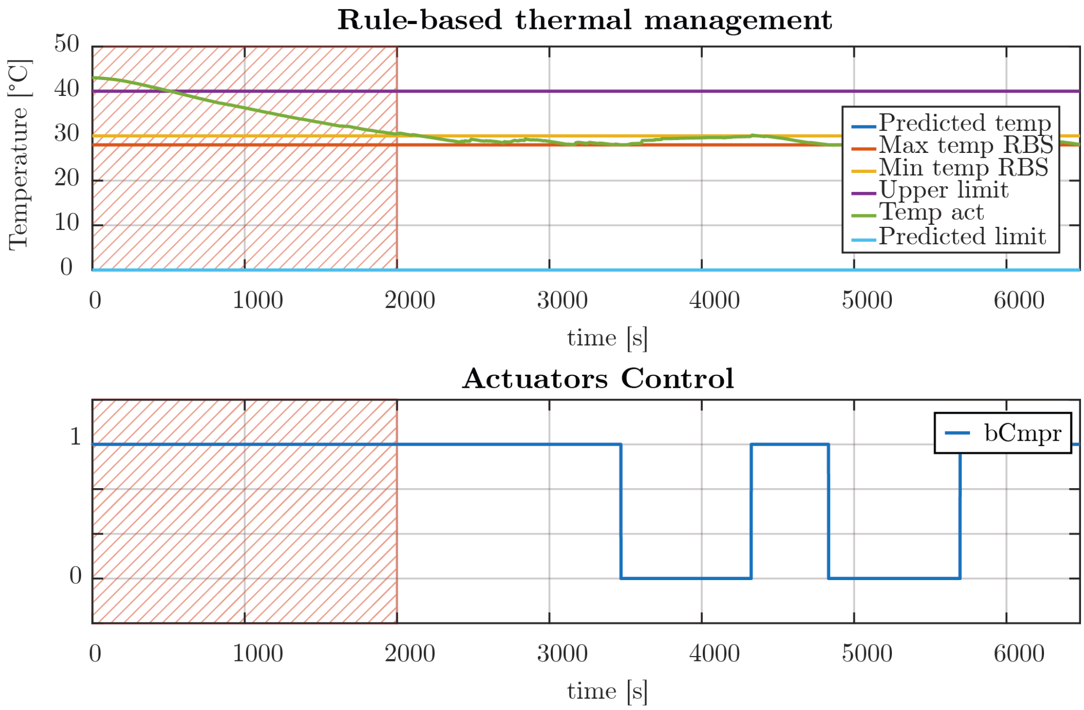

Figure 3.13: Temperature trend with RBS activate and $T_{init} = 40°C$

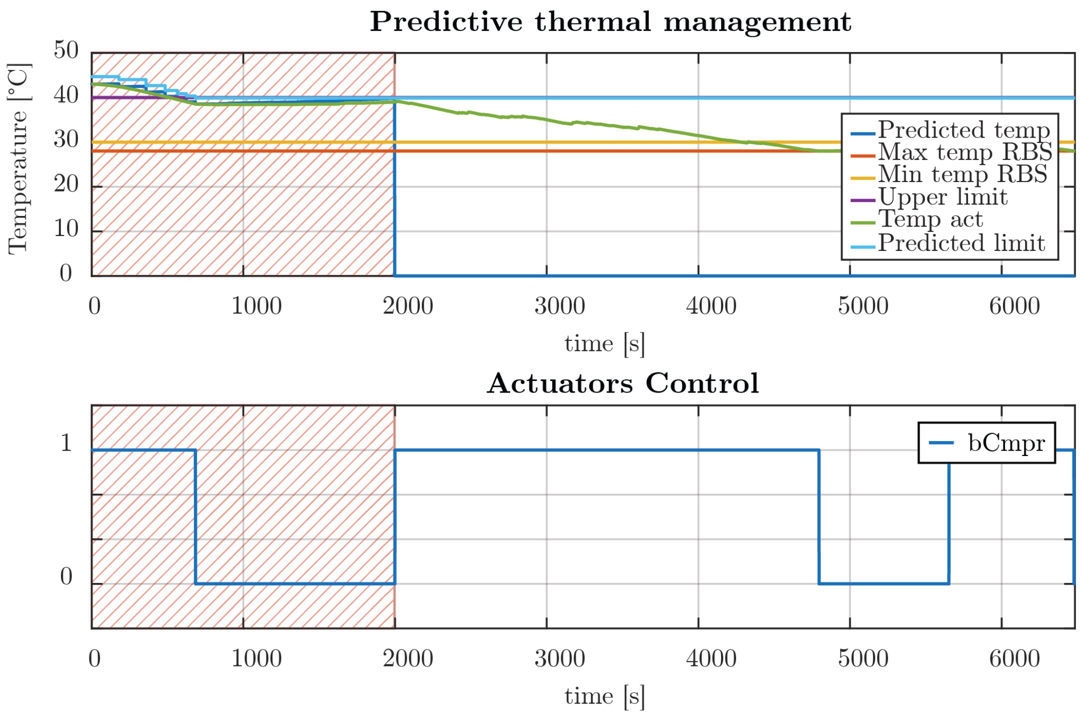

Figure 3.14: Temperature trend with PTM activate and $T_{init} = 40°C$

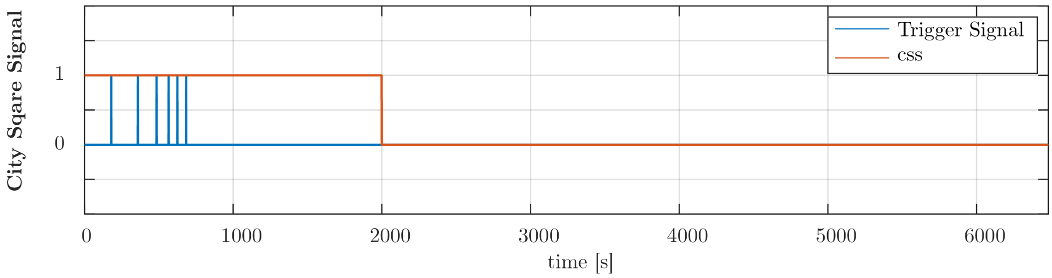

Figure 3.15: PTM function trigger

$\boldsymbol{\xi_{init} > \xi_t}$ even if it depends on the torque management strategy, in general the eHorizon supervisor will select a charge depleting mode until the battery state of charge overcomes the ξ_t threshold; the RBS has fixed boundaries for the SoC in charge sustaining mode, the ECMS restricts that limits as the vehicle approaches to city event, and the DDP will perform the best decisions to end the extra-urban zone with exactly that target;

$\boldsymbol{\xi_{init} < \xi_t}$ the engine recharges the battery and then the BMS switched to charge sustaining mode, and how the SoC follows the target is based on the TMS selected as before;

$\boldsymbol{\xi_{init} \sim \xi_t}$ the control operates charge-sustaining mode during all the extra-urban path before the city event.

With the CEF algorithm and the implementation of the ZEA function, a city event during the cycle can't be neglected any more. After some simulations analysis, it comes out that, when fully operational, the temperature is always between $28°C$ and $30°C$ as defined in the battery control. For safety reasons, the temperature prediction will start at the upper limit.

The effect of ZEA function over an RDE cycle (see Fig. 3.18) is the advance of sustaining strategy to guarantee the all City Event in electric driving. If the torque split were ruled by the RBS, the operation would be everything but efficient because there is no need to maintain the level of the battery at the ξ_{target} over the entire cycle but only to reach it with a margin of error at the beginning of the city. One of the benefits of sub-optimal and optimal strategy is the flexibility they have before the City Event. In the figure, in fact, the upper and lower limit, set by the ECMS,

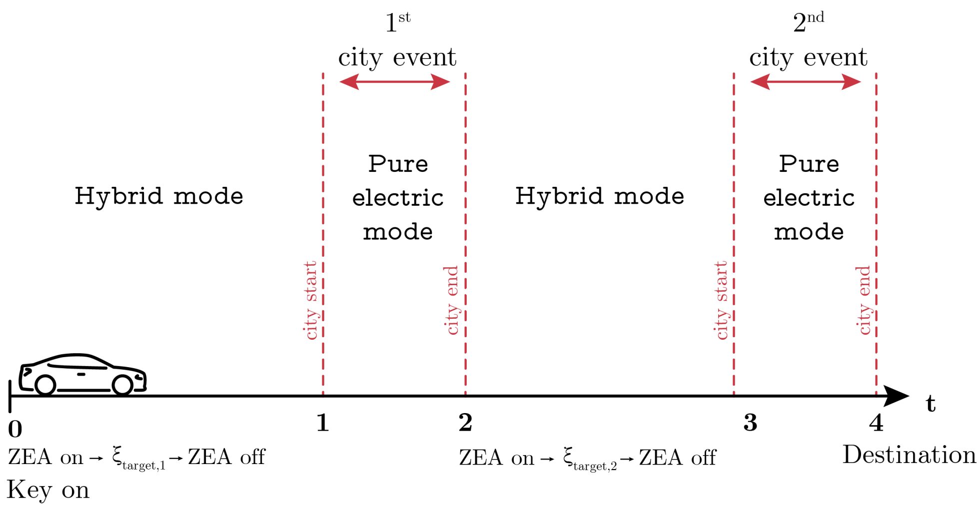

Figure 3.16: Working procedure for the ZEA function

became more and more strict approaching the urban zone.

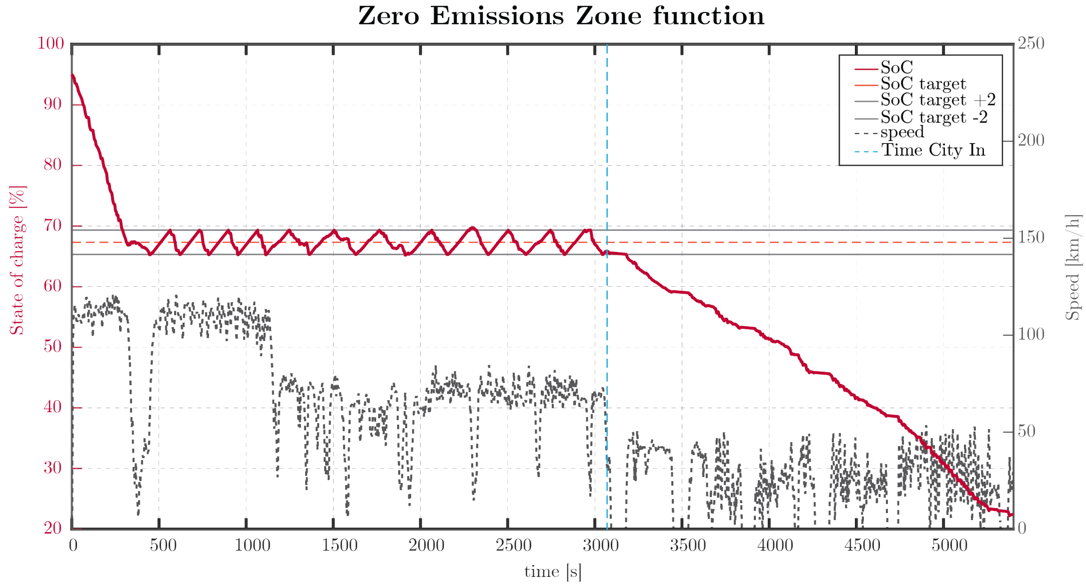

Figure 3.17: ZEA function working on a RDE cycle with RBS

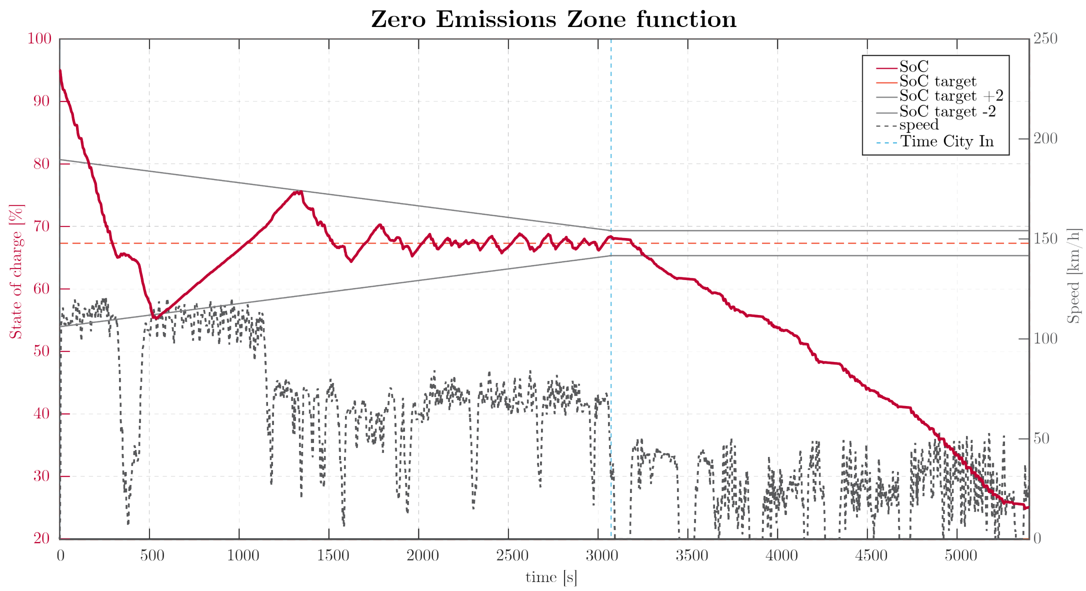

Figure 3.18: ZEA function working on a RDE cycle with ECMS

Chapter 4

Regulations and Simulations

As mentioned in the previous chapters, regulations are influencing hardly the automotive sector. In particular, this work is focusing on the CO_2 emissions, which are used as a basis for the new implemented strategies comparison (both TMS and eHS). Since the vehicles are propelled using two power sources, delivered by chemical and electric energy, the performance comparison needs to be evaluated considering the overall energy consumption. As a consequence, the electric energy usage has to be expressed in term of fuel consumption and the way it's done depends on the applied regulation. The regulation for evaluating the vehicle performance is, in Europe, the well-known WLTP (Worldwide harmonized Light vehicles Test Procedure) which is ruled by the R1151 EU regulation. In parallel, it was introduced a new test-procedure called RDE (Real Driving Emissions) in order to measure the pollutants, such as NOx, emitted by cars while driven on the roads. RDE does not replace the WLTP laboratory test, but complements it proving that cars deliver low emissions under on-road conditions.

Moreover, back to the simulations, in the considered vehicle model there isn't a calculation of the pollutant emissions nor for CO_2, but only for the instantaneous fuel consumption expressed in kg/h. To obtain the value of the emissions the experimental equation for the fuel consumption has been inverted in eq. (4.1)

$$FC = (\frac{0{,}1206}{\rho_{fuel}}) \cdot [(0{,}829 \cdot HC) + (0{,}429 \cdot CO) + (0{,}273 \cdot CO_2)] \tag{4.1}$$

where FC is the fuel consumption in $^{l}/_{100km}$, HC represent the emissions of hydro-carbons in $g/_{km}$, CO stand for the emissions of carbon monoxide in $g/_{km}$ and in the end ρ is the fuel density in $kg/_{l}$. Setting the HC and CO to their regulation limit and inverting the eq. (4.1), it's possible to calculate the conversion factor.

Table 4.1: Calculation of the FC to CO_2 conversion factor

Name	Value	Unit
HC	0.01	$g/_{km}$
CO	1	$g/_{km}$

After these considerations, it's possible to analyse individually the different test cases.

4.1 WLTC

The old reference cycle, known as NEDC has become outdated due to its poor representation of real-driving condition and it has been substituted since 2017 by the WLTC. This latter was developed using real-driving data, gathered from around the world to better representing everyday driving profiles. The WLTP driving cycle is divided into four parts with different average speeds: *low*, *medium*, *high* and *extra high*, whose details are listed in table 4.2. Each part is characterized by a variety of driving phases, stops, acceleration and braking manoeuvres. In conclusion, the WLTP was born with the aim of being used as a global test cycle across different regions, so pollutant and CO_2 emissions as well as fuel consumption would be comparable worldwide.

Table 4.2: WLTC test section specifications for class 3 vehicle [27]

	Units	Low	Medium	High	Extra high	Total
Duration	s	589	433	455	323	1800
Distance	m	3095	4756	7162	8254	23266
Maximum speed	$km/_{h}$	56.5	76.6	97.4	131.3	-

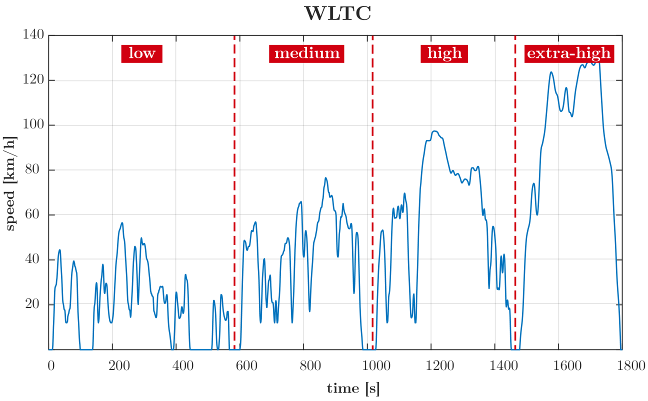

Figure 4.1: The WLTC test cycle and its phases

4.1.1 R1151

The regulation is thought for laboratory test so it defines a lot of conditions that must be satisfied (e.g. between each cycle there is a soak period of a maximum of 30 minutes where the key switch shall be in the "off" position). In order to obtain an affordable and unique value, which will be used for comparison, it has been converted the usage of electric energy into equivalent fuel consumption. To do so, as in the previous R101 regulation, two different kind of tests have to be performed:

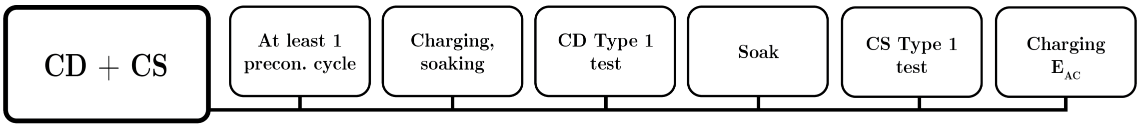

Figure 4.2: CD + CS test procedure

CD Type 1 test with the battery fully charged, it must be run consecutive WLTCs until the break-off criterion eq. (4.2) is reached[1].

$$REEC_i = \frac{|\Delta E_{REESS,i}|}{E_{cycle} \cdot \frac{1}{3600}} = \frac{\sum_{j=1}^{n}(\int_{t_0}^{t_{end}} U_{REESS,j,k} \cdot I_{j,k} dt)}{\sum_{t_{start}}^{t_{end}} F \cdot d} < 4\% \tag{4.2}$$

where:

[1]In more practical words, during the *n + 1-th* cycle the usage of battery has to be under the 4% of the storage maximum capacity

- $REEC_i$ is the Relative Electric Energy Change for the $i-th$ cycle of the CD test;
- $\Delta E_{REESS,i}$ is the change of electric energy of all REESS[2] during $i-th$ cycle in Wh;
- E_{cycle} energy demand for the complete cycle of the test vehicle positive loads in Ws;
- $I_{j,i}$ is the electric current of $j-th$ REESS during period i in A;
- $U_{REESS,j,i}$ represents the voltage of $j-th$ REESS during period i in V.

For what concern the nomenclature, the cycle which fulfils this criterion is considered to be the $n+1-th$ cycle, while the previous one is the $n-th$ cycle and it's called *transient* cycle.

CS Type 1 test the test provides for a set of n CS Type 1 cycles, where the first one is called *Reference Cycle* and it has the SoC ending value of the CD test as initial condition. The other $n-1$ cycles have to contain at least one measurement with a negative and one measurement with a positive charging balance $E_{REESS,i}$. After that, it's possible to determine the corrective factor, named K_{CO_2}, analytically defined by eq. (4.3).

$$K_{CO_2} = \frac{\sum_{n=1}^{n_{CS}}((EC_{DC,CS,n} - EC_{DC,CS,avg}) \cdot (M_{CO_2,CS,nb,n} - M_{CO_2,CS,nb,avg}))}{\sum_{n=1}^{n_{CS}}(EC_{DC,CS,n} - EC_{DC,CS,avg})^2} \tag{4.3}$$

- $EC_{DC,CS,n}$ is the energy consumption associated with the $n-th$ CS cycle, in $^{kW}/_{km}$;
- $EC_{DC,CS,avg}$ is the average energy consumption over the n CS cycles, in $^{kW}/_{km}$;
- $M_{CO_2,CS,nb,n}$ is the net CO_2 emissions during the $n-th$ CS test, in $^{g_{CO_2}}/_{km}$;
- $M_{CO_2,CS,nb,avg}$ is the average emissions of the n CS test, in $^{g_{CO_2}}/_{km}$.

[2]REESS = REchargable Energy Storage System

After that, the mass of CO_2 is weighted on the distance of each phases and then summed as in eq. (4.4). The same can be done for the CD test emissions.

$$M_{CO_2,CS,weighted} = \frac{\sum_{i=1}^{i=4}(M_{CO_2,CS,nb,n} \cdot d_i)}{d_{tot}} \tag{4.4}$$

where d_i is the spacial duration of the $i-th$ phase in km.

Furthermore, the regulation introduces the Utility Factors, which are ratios based on driving statistics functon of the range achieved in charge-depleting condition. They are used to weight the charge-depleting and charge-sustaining exhaust emission compounds, CO_2 emissions and fuel consumption for OVC-HEVs. Their values derive from eq. (4.5) and showed in Fig. 4.3 [27].

$$UF_i(d_i) = 1 - exp(-(\sum_{j=1}^{k} C_j \cdot (\frac{d_i}{d_n})^j)) - \sum_{i=1}^{i-1} UF_i \tag{4.5}$$

where C_j is the $j-th$ coefficient of the table in [27] in the fifth appendix of R1151, $\sum_{l=1}^{i-1} UF_i$ is the sum of calculated utility factors up to phase $i-1$ and d_n is the normalized distance, set to $800km$. The output curve is represented in Fig. 4.3.

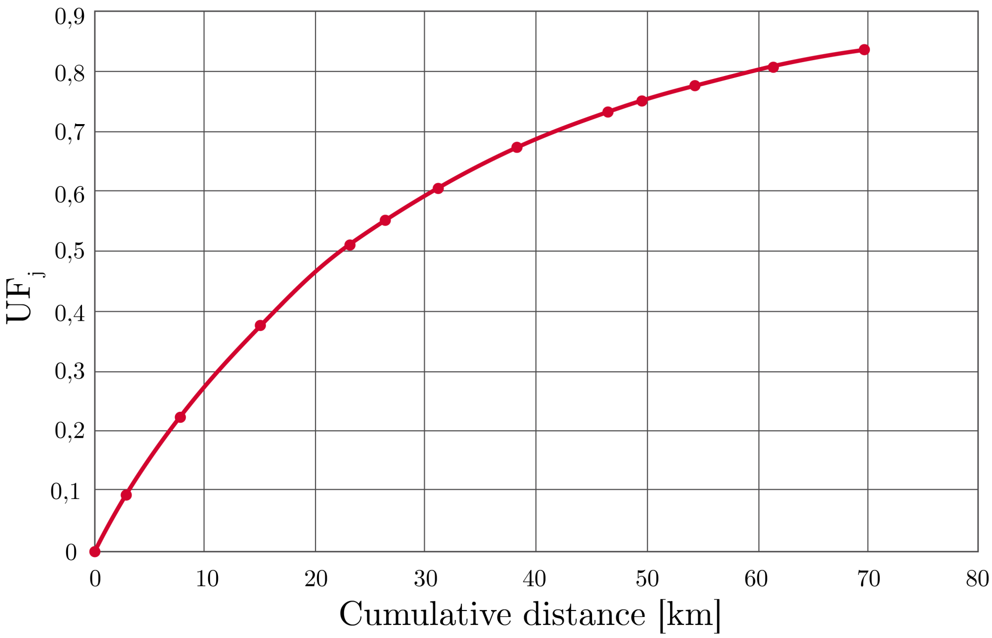

Figure 4.3: Utility factor depending on distance

As described in eq. (4.6), the combination of the charge-depleting and charge-sustaining test is weighted with the Utility Factors calculated above.

$$M_{CO_2,weighted} = \sum_{j=1}^{k}(UF_j \cdot M_{CO_2,CD,j}) + (1 - \sum_{j=1}^{k}(UF_j) \cdot M_{CO_2,CS,weighted} \tag{4.6}$$

The value of the conversion factor K_{CO_2} remains fixed if the vehicle and the control strategies don't change, in particular considering strategies that act on the state of charge and fuel consumption. So, it shouldn't be calculated every time.

This method has been implemented in the MiL with a post-process approach: after all the necessary tests are simulated, a MATLAB script saves the workspace variables locally and writes the results in an Excel pre-compiled template where the effective calculation is done. In the same Excel file it's computed even the Effective All-Electric Range (EAER) which is the portion of the total charge-depleting actual range (R_{CDA}) attributable to the use of electricity from the REESS over the charge-depleting range test, as in eq. (4.7).

$$EAER = (\frac{M_{CO_2,CS} - M_{CO_2,CD,avg}}{M_{CO_2,CS}}) \cdot R_{CDC} \tag{4.7}$$

where the $EAER$ is in km and R_{CDC} means the charge-depleting cycle range according to the R1151 [27] in km.

In conclusion, the R1151 permits to calculate the effective gaseous pollutant emissions only for laboratory tests which are easily reproducible by definition, like the WLTC, and the output is reliable and solid. In fig. 4.4 the results of the regulations are shown. However, since in this content the eHorizon functions are applied on City Events (not defined in WLTC), the reference cycles considered are all compliant with RDE regulation.

						%			%
WLTC	[%]	Normative	**100.000**	Normative	**91.737**	**8.26**	Normative	**90.179**	**9.82**

Figure 4.4: R1151 results for all the three TM strategies

4.2 RDE

The Real Driving Emissions (RDE) test measures the gaseous emissions, such as NOx, emitted during a road driving test and it requires a vehicle equipped with an on-board detection system named PEMS (Portable Emissions Measurement System) to collect and analyse them.

During a RDE cycle, a car is driven on public roads over a wide range of different conditions, so it's easy to understand how it differs from a laboratory test. The vehicle must follow a speed profile that has to satisfy a series of requisites defined by the R1151 regulation, Annex IIIA. These are related to maximum/minimum accelerations, average speeds (for all the phases), time share, altitude and three different zones:

- **Urban roads:** to simulate a vehicle driving at low speed with stop and start events. This part of the cycle is the one detected by the CEF described in § 3.3.1;
- **Rural roads:** with medium speed manoeuvres;
- **Motorways:** for the high velocity roads.

Without the emissions modelling, which gives a value of gaseous pollutants, the actual regulation for RDE cycles can't be applied on the study cases. Thus, other paths have to be taken. In particular, this essay focuses on two approaches: one starts from the regulation and readapts it for the RDE while the other one takes into account the energy balance. The latter, in fact, the requested power at the wheels has to be the same both if delivered by ICE or by EMs.

4.2.1 Derivation from R1151

The aim of this approach is to calculate a corrective CO_2 factor to convert the battery energy usage to dioxide carbon emissions, with a similar approach to the R1151. The procedure to calculate the K_{CO_2} term is the same as the regulation. Then the results is used in eq. (4.8).

$$m_{CO_2,CS} = m_{CO_2,CS,nb} - K_{CO_2} \cdot EC_{DC,CS} \tag{4.8}$$

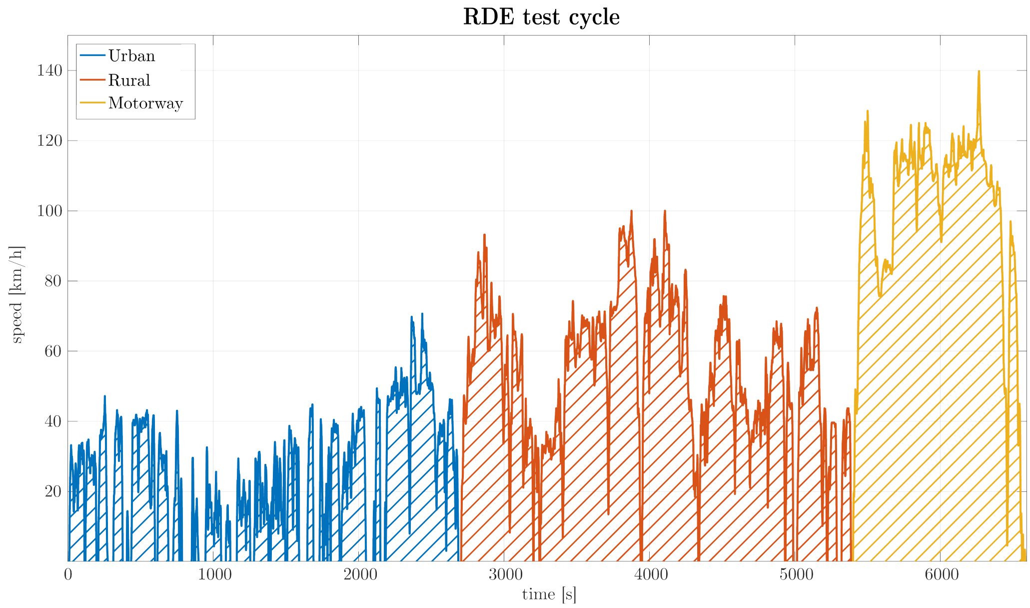

Figure 4.5: Example of a RDE cycle

The first difference with the R1151 is that the CD Type 1 test is more complex to carry out due to the long duration of the RDE [3] where, moreover, specific and fixed phases are not defined. So that, it's difficult to identify the cycle which fulfils the break-off criterion eq. (4.2), and consequently the ending of the test. Anyway, the RDE is intrinsically not particularly different from the behaviour of the original CD Type 1 test and it could be used analogously. In conclusion, only the three simulations must be performed, without the *EAER* and *reference* tests, while the value SoC_{REF} represents the value around which the sustaining is performed.

The three simulations are necessary in order to evaluate the K_{CO_2} factor, then the analysed simulation is performed and corrected with the factor just calculated.

As the R1151, the value of K_{CO_2} doesn't change if the vehicle and the strategy remain the same, and, in addition, its regulation basis can guarantee a certain level of reliability. On the other hand, the computational effort is something that can't be overlooked. Furthermore, this way of proceeding is referred to charge-sustaining strategy without analysing its behaviour under charge-depleting conditions, so the results could be not so representative.

[3]In general, a RDE test procedure lasts about 90 minutes in order to satisfy all the conformity factors

4.2.2 Energy balance

Basically, the request of energy at the wheels can be delivered both by the IC engine and by the EMs so two different situations come up if the energy balance at the end of the cycle is positive or negative. In the first case, it's supposed that the difference of the electric energy is covered by the engine with an additional request of torque. Thus, it's possible to calculate the fuel consumption needed to complete the manoeuvre, with the average efficiency of ICE and ISG, as showed in eq. (4.9).

$$\Delta m_{fuel} \cdot LHV_{fuel} \cdot \eta_{ICE} = \frac{\Delta EC}{\eta_{ISG}} \tag{4.9}$$

where ΔEC is the energy consumption of the battery in KJ, LHV_{fuel} is the lower heating value of the fuel equal to $42500^{KJ}/_{Kg}$ and η_{ICE} and η_{ISG} are the average efficiencies respectively for the engine and for the ISG calculated directly in Simulink.

The other situation, with negative energy balance, considers the difference as a further request of torque addressed to the P4s in order to discharge the REESS. Analogously to the other case, the balance is defined by eq. (4.10).

$$\Delta m_{fuel} \cdot LHV_{fuel} \cdot \eta_{ICE} = \Delta EC \cdot \eta_{P4} \tag{4.10}$$

where η_{P4} is the average efficiency of the P4s.

At this point, two other paths, both based on the energy balance, can be followed to complete the simplified correction procedure.

Relative comparison

Given that the uncertainty takes place if the final states of charge for the two simulations differs from each other, it is possible to apply the energy balance relatively only to a single strategy and the other is taken as reference, forcing charging or discharging to reach the same final SoC (in that case usually the RBS is the reference as the starting point of this work). This approach doesn't consider the real consumption of the vehicle, in fact, the energy is not balance over the entire test. Anyway, it has got some advantages, because generally the physical considerations made above use the average efficiencies calculated during specific operations and it would be applied on others, in all likelihood, different from them. But with this solution the approximation is minimal.

$$\Delta SoC = SoC_{fin,Sim1} - SoC_{fin,Sim2} \tag{4.11}$$

where $SoC_{fin,Sim1}$ is the reference value and $SoC_{fin,Sim2}$ the value to be balanced. If the difference is negative (so the analysed strategy uses less electric energy), it has to be discharged addressing it to the P4s, while if it is positive (the strategy requests more to the battery) the recharging phase is accounted to the ISG.

Absolute conversion

To achieve the energy balance, the same procedure can be applied to the entire driving cycle, and the result is absolute and not relative to another strategy. In this case, using the average efficiencies of the machine to balance the energy over the entire cycle, the approximation level is higher than in the relative conversion.

$$\Delta SoC = SoC_{init} - SoC_{fin} \tag{4.12}$$

In both the corrections it has been performed only two simulations, saving computational time, but without any correlation with the regulation and so the results could be weaker. The post-process is made in a Excel file where a script save the output quantities, it recognizes which simulation is done with the RBS, so the reference one, and if the balance is negative or positive. A simulation for each strategy is always mandatory, and because one approach doesn't preclude the other, they are both implemented in the same post-process.

4.2.3 Results

As it is possible to see, only for the WLTC the results are sustained by a complete regulation procedure, and there isn't one approach substantially better then an other, so two different RDE cycles has been carried out (one performed in the urban area of Aachen, in Germany, and one is a generic RDE) and for every driving test all the three correction post-processes are executed. The chosen strategies to compared are the RBS and ECMS but the same comparison could be performed between others. The results has been normalized with respect to the R1151 corrected fuel consumption value.

Table 4.3: CO_2 emissions corrections for a generic RDE cycle

RDE generic cycle	Unit	RBS	ECMS	Gain
$m_{CO_2,nb}$	%	80,886	73,835	-
SoC_{end}	%	24,10	27,94	-
$m_{CO_2,R1151}$	%	100,000	85,701	**+14,3%**
$m_{CO_2,rel}$	%	80,886	72,618	**+10,2%**
$m_{CO_2,abs}$	%	91,354	82,448	**+9,7%**

Table 4.4: CO_2 emissions corrections for a RDE in Aachen

RDE Aachen cycle	Unit	RBS	ECMS	Gain
$m_{CO_2,nb}$	%	82,794	76,198	-
SoC_{end}	%	25,90	27,24	-
$m_{CO_2,R1151}$	%	100,000	92,199	**+8,5%**
$m_{CO_2,rel}$	%	82,794	75,725	**+8,1%**
$m_{CO_2,abs}$	%	93,702	86,136	**+7,8%**

With these kind of results, it isn't possible to chose the most precautionary solution either because, for example, the R1151-based correction for RDE Aachen is the most conservative, while for the generic RDE it is not. So, from this point forward, the absolute energy balance correction will be adopted because to fulfil the aim of this work the strategy often changes and the R1151-based solution is everything but fast or flexible.

4.3 Simulations

Briefly, at the moment the Simulink model is without Simscape, so the computation is considerable faster then the original MiL, then in the HCU new kind of Torque Split strategies have been implemented and finally the model is enriched with the innovative eHorizon CU for predictive strategies. The next step will be using this model to compare the strategies analysing the fuel consumption for every situations, in order to confirm that the gain obtained is higher if optimal, sub-optimal (so DDP and ECMS respectively) and predictive strategies (as CEF,ZEA and PTM) are added.

4.3.1 Test Cases

The simulations are performed in different conditions, on different driving cycles and with different combinations of the active strategies. The expected result is a consistent improvement in fuel consumption both changing the TMS and the eHCU, even considering the physical limitations inserted in the optimal and sub-optimal controls.

The cycles chosen for the simulations and the torque split strategies are listed in table 4.5 and in table 4.6.

Table 4.5: Cycles for the simulations

Cycle —	WLTC	RDE	RDE Aachen	RDE Cherasco

Table 4.6: TMS for the simulations

Torque Split Strategies —	RBS	ECMS	DDP

For what concern the eHCU functions, they are switched on one at the time to see the individual effects of each strategy on the fuel consumption.

Table 4.7: Different test cases with several combinations of strategies

Strategy	**CEF**	**PTM**	**ZEA**
1^{st} simulation	OFF	OFF	OFF
2^{nd} simulation	ON	OFF	OFF
3^{rd} simulation	ON	ON	OFF
4^{th} simulation	ON	ON	ON

4.3.2 Results

In the representation of the results, it will be referred to Excel tables and graphs where the fuel consumption and the state of charge are the quantities chosen as a basis for comparison. The post-process R1151 correction is used only for WLTC, whereas the energy balance corrections are adopted for the RDE cycles. The name of values showed are described in the following legend:

- **SoC end** means the value of the battery state of charge at the end of the driving cycle;
- **fc** stands for the $^{g_{CO2}}/_{km}$ emitted during the procedure;
- **corr. Rel** is the result of the relative energy balance, illustrated in § 4.2.2;
- **corr. Ass** is the result of the absolute energy balance, which is used to calculate the gain and it's described in § 4.2.2;
- **RDE Cherasco Inv** was originally a RDE performed in the city of Cherasco, and then inverted in a way to obtain the City Events at the end of the cycle;
- $\boldsymbol{SoC_{tiCityIn}}$ corresponds with the state of charge at the beginning of the city.

The ECMS and DDP results deserve a particular observation. Both the strategies are characterized by a consistent numbers of IC engine ignitions which penalize the emissions. This penalization can't be seen directly in the fuel consumption, but since the cranking phase is addressed on the ISG, which brings the ICE up to $800rpm$ where it starts to injects the fuel, the more are the ignitions and the higher is the usage of electric energy. In the present dissertation, all the results are normalized with respect to the RBS balanced fuel consumption value.

4.3.3 CEF OFF + PTM OFF + ZEA OFF

The first simulation shows the comparison between the three torque split strategies (RBS § 3.1.1, ECMS § 3.1.2 and DDP § 3.1.3) and it's possible to see immediately the advantages brought by their implementation. However, some considerations have to be done.

Firstly, as it was possible to imagine, the optimal strategy provides for lower emissions than the sub-optimal, which is itself considerably better than the RBS, with the exception of the generic RDE simulation, where the results of the ECMS and DDP are particularly near to each other. This is due to a better efficiency of the ECMS and not a malfunction of the DDP, in fact generally the gain of the ECMS is around $5-7\%$ while in this case it reaches the 9%. However, the general tendency is confirmed by the other simulations.

Then, others results catch the eye. In the Inverted Cherasco RDE both the fuel consumption and the percentage gain substantially rise because performing the Motorway section of the RDE with the battery fully charged is less efficient than performing a Urban event in the same conditions, and the RBS doesn't work properly. Thus, the new strategies, which adopted better solutions, produce a consistent gain.

		1st SIM 95% 25°C: CEF OFF + PTM OFF + ZEA OFF								
		RBS		ECMS		Gain	DDP		Gain
RDE	[%]	SoC end	25.00	SoC end	28.01		SoC end	27.27	
	[%]	fc	73.326	fc	66.940		fc	64.511	
	[%]	corr. Rel	73.326	corr. Rel	65.864	%	corr. Rel	63.658	%
	[%]	corr. Abs	100.000	corr. Abs	90.979	**9.02**	corr. Abs	90.038	**9.96**
RDE Aachen	[%]	SoC end	25.86	SoC end	27.50		SoC end	26.97	
	[%]	fc	71.432	fc	67.159		fc	63.839	
	[%]	corr. Rel	71.432	corr. Rel	66.507	%	corr. Rel	63.396	%
	[%]	corr. Abs	100.000	corr. Abs	94.154	**5.85**	corr. Abs	91.268	**8.73**
RDE Cherasco Inverted	[%]	SoC end	25.16	SoC end	26.92		SoC end	27.07	
	[%]	fc	72.234	fc	61.773		fc	54.306	
	[%]	corr. Rel	72.234	corr. Rel	61.136	%	corr. Rel	53.602	%
	[%]	corr. Abs	100.000	corr. Abs	86.612	**13.39**	corr. Abs	79.221	**20.78**
						%			%
WLTC	[%]	Normative	**100.000**	Normative	**91.737**	**8.26**	Normative	**90.179**	**9.82**

Table 4.8: Simulation with all the eHCU strategies switched off

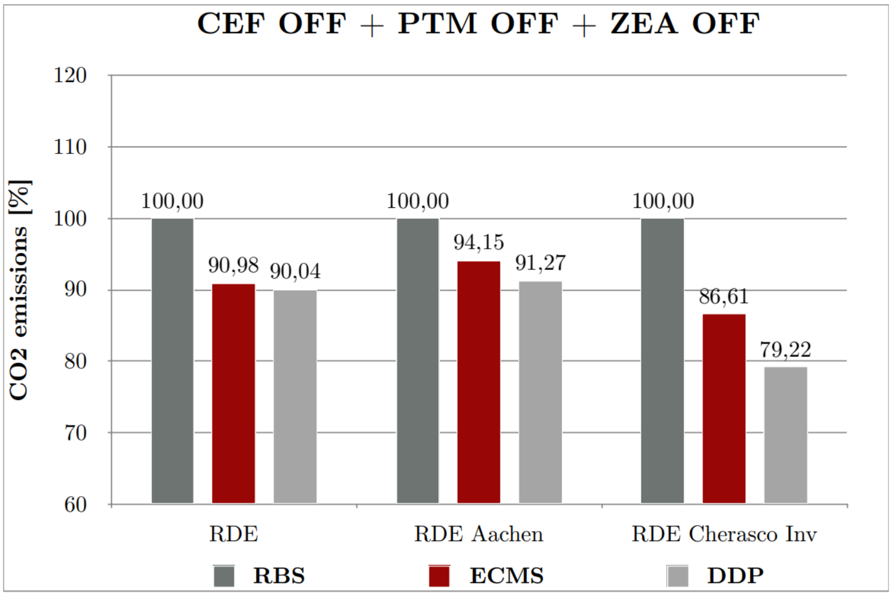

Figure 4.6: Histogram with fuel consumption of the 1^{st} set of simulations

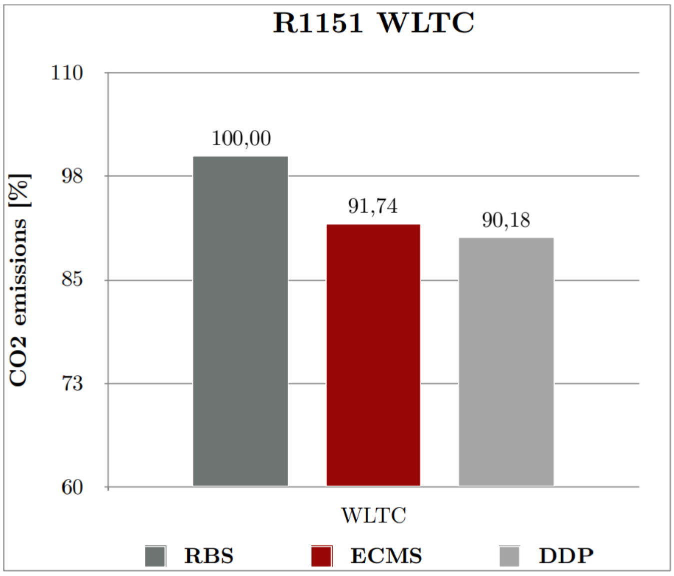

Figure 4.7: Histogram with fuel consumption of the WLTC simulations

4.3.4 CEF ON + PTM OFF + ZEA OFF

In this set of simulations it has been activated the City Event Finder and that means the eDrive mode is mandatory within the city. On one hand, this condition implicitly avoid unnecessary cranking during the city event, where strong accelerations occur, on the other hand the new constraint limits the ECMS and DDP range of action. That condition translates into a slightly worsening of the fuel consumption and of the respective percentage gains.

		2nd SIM 95% 25°C: CEF ON + PTM OFF + ZEA OFF							
		RBS		ECMS		Gain	DDP		Gain
RDE	[%]	SoC end	25.00	SoC end	26.85		SoC end	27.37	
	[%]	fc	73.251	fc	68.484		fc	64.527	
	[%]	corr. Rel	73.251	corr. Rel	67.813	%	corr. Rel	63.659	%
	[%]	corr. Abs	100.000	corr. Abs	93.365	**6.63**	corr. Abs	89.335	**10.67**
RDE Aachen	[%]	SoC end	25.87	SoC end	27.63		SoC end	27.13	
	[%]	fc	71.569	fc	68.163		fc	63.485	
	[%]	corr. Rel	71.569	corr. Rel	67.460	%	corr. Rel	62.986	%
	[%]	corr. Abs	100.000	corr. Abs	95.113	**4.89**	corr. Abs	90.460	**9.54**

Table 4.9: Simulation with the CEF active

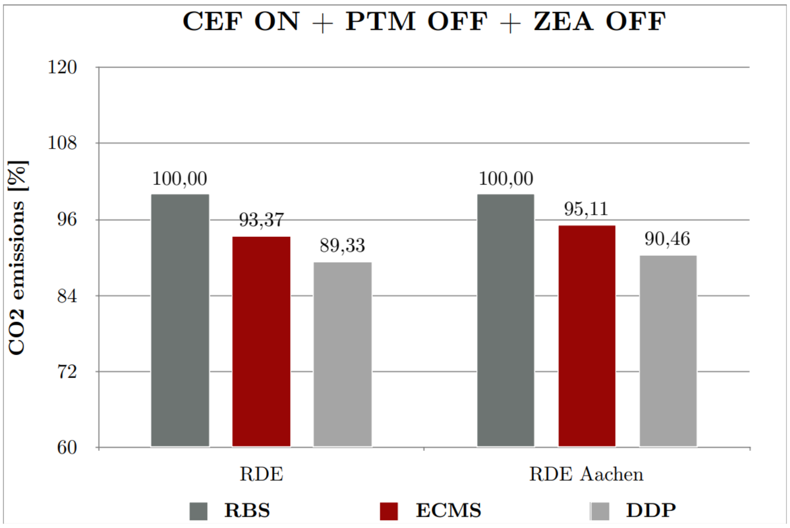

Figure 4.8: Histogram with fuel consumption of the 2^{nd} set of simulations

4.3.5 CEF ON + PTM ON + ZEA OFF

Once the City Event is recognized, the eHCU strategies can be introduced one at the time. Firstly, the Predictive Thermal Management simulates the behaviour of the battery temperature along the Urban zone. If it doesn't overcome the upper limit the actuators will remain off, and this bring an advantages on the usage of electric storage as in Fig. 4.10. For what concern the emissions, there isn't a significant improvement because, after exiting the city, the strategy is overwrite by the thermal management rule-based strategy, which uses all the deliverable power of the compressor and the pump to cool down the battery. In the future, the problem will be solved using the informations given by the CEF. In particular, if there won't be a thermal stressed event (like a City Event or a highway) the battery will be allowed to cool slower, without addressing all the power request to the compressor but taking advantage of the air convection.

		3rd SIM 95% 25°C: CEF ON + PTM ON + ZEA OFF								
		RBS		ECMS		Gain	DDP		Gain
RDE	[%]	SoC end	25.00	SoC end	27.84		SoC end	27.37	
	[%]	fc	73.249	fc	69.044		fc	64.520	
	[%]	corr. Rel	73.249	corr. Rel	67.506	%	corr. Rel	63.654	%
	[%]	corr. Abs	100.000	corr. Abs	93.013	**6.99**	corr. Abs	89.338	**10.66**
RDE Aachen	[%]	SoC end	25.87	SoC end	27.63		SoC end	27.13	
	[%]	fc	71.572	fc	68.165		fc	63.488	
	[%]	corr. Rel	71.572	corr. Rel	67.462	%	corr. Rel	62.988	%
	[%]	corr. Abs	100.000	corr. Abs	95.116	**4.88**	corr. Abs	90.463	**9.54**

Table 4.10: Simulation with CEF and PTM active

With an ambient temperature of $T_{amb} = 25°C$, the RBS of the thermal management upper limit ($T_{RBS,TM,lim} = 30°C$) won't be reached during the city event and so the effectiveness of the PTM function isn't so clear, but to maintain a sort of homogeneity in the simulation the results will be left. In order to appreciate the eHorizon function in action, a new set of simulations has been performed, but this time starting from a $T_{amb} = 35°C$. In the table table 4.12 and in fig. 4.10, the advantages of the SoC is illustrated.

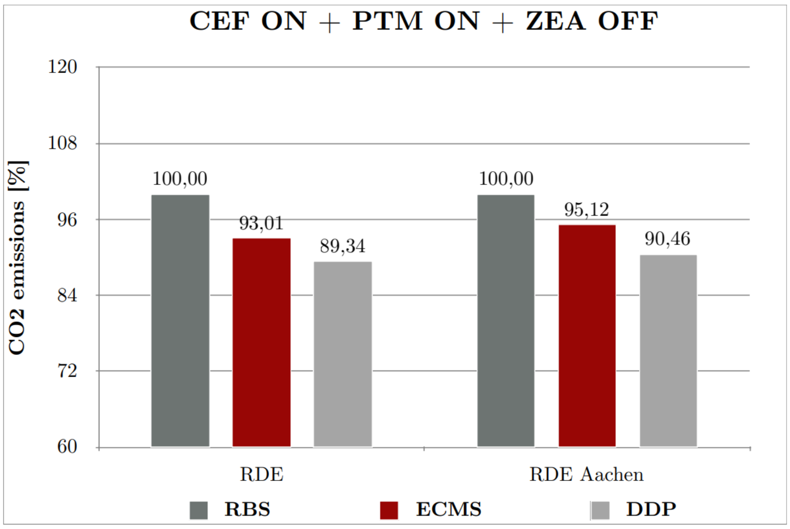

Figure 4.9: Histogram with fuel consumption of the 3^{rd} set of simulations

		3rd SIM 95% 35°C: CEF ON + PTM OFF + ZEA OFF							
		RBS		ECMS		Gain	DDP		Gain
RDE	[%]	SoC $_{cityend}$	**58.10**	SoC $_{cityend}$	**58.10**		SoC $_{cityend}$	**58.10**	
	[%]	SoC end	24.37	SoC end	27.35		SoC end	26.95	
	[%]	fc	72.972	fc	68.413		fc	65.527	
	[%]	corr. Rel	72.972	corr. Rel	67.339	%	corr. Rel	64.584	%
	[%]	corr. Abs	100.000	corr. Abs	92.986	**7.01**	corr. Abs	90.594	**9.41**
RDE Aachen	[%]	SoC $_{cityend}$	**62.22**	SoC $_{cityend}$	**62.22**		SoC $_{cityend}$	**62.22**	
	[%]	SoC end	25.88	SoC end	27.45		SoC end	27.11	
	[%]	fc	71.669	fc	68.132		fc	63.711	
	[%]	corr. Rel	71.669	corr. Rel	67.514	%	corr. Rel	63.228	%
	[%]	corr. Abs	100.000	corr. Abs	94.866	**5.13**	corr. Abs	90.457	**9.54**

Table 4.11: Comparison of the State of Charge at the end of city event and PTM OFF

		3rd SIM 95% 35°C: CEF ON + PTM ON + ZEA OFF							
		RBS		ECMS		Gain	DDP		Gain
RDE	[%]	SoC $_{cityend}$	**58.80**	SoC $_{cityend}$	**58.80**		SoC $_{cityend}$	**58.80**	
	[%]	SoC end	24.38	SoC end	29.63		SoC end	26.92	
	[%]	fc	72.865	fc	69.386		fc	65.233	
	[%]	corr. Rel	72.865	corr. Rel	67.465	%	corr. Rel	64.299	%
	[%]	corr. Abs	100.000	corr. Abs	93.329	**6.67**	corr. Abs	90.309	**9.69**
RDE Aachen	[%]	SoC $_{cityend}$	**62.91**	SoC $_{cityend}$	**62.91**		SoC $_{cityend}$	**62.91**	
	[%]	SoC end	25.87	SoC end	27.66		SoC end	27.08	
	[%]	fc	71.550	fc	68.988		fc	63.943	
	[%]	corr. Rel	71.550	corr. Rel	68.273	%	corr. Rel	63.463	%
	[%]	corr. Abs	100.000	corr. Abs	96.063	**3.94**	corr. Abs	90.879	**9.12**

Table 4.12: Comparison of the State of Charge at the end of city event and PTM ON

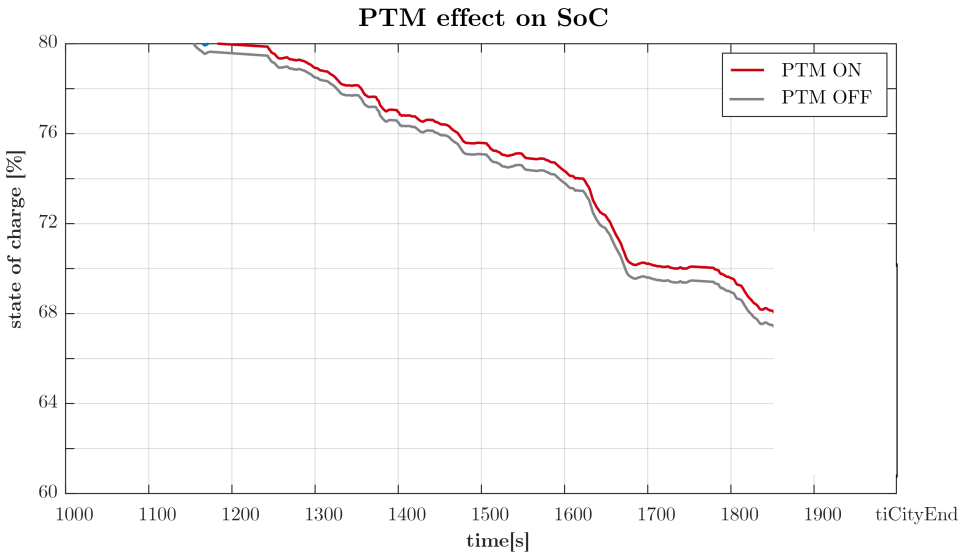

Figure 4.10: Effect of the PTM function on the state of charge

4.3.6 CEF ON + PTM ON + ZEA ON

In order to appreciate the effects of the Zero-Emissions Area function, there should be a City Event after the beginning of the simulation, giving the battery time to recharge if needed. Thus, only the Inverted Cherasco RDE is analysed. For this kind of strategy, the efficiency is no more the target to reach, because the ZEA has only to guarantee the full electric drive during the urban stretch, so the CO_2 emissions are inevitably higher. One other necessary consideration is about the final value of the battery state of charge. Since the Urban Area is the same for every simulation, the same ending SoC would expected. The discrepancies born from the different ways to reach the ξ_{target} of every strategies, however the ΔSoC addressed to the City Event is the equal in all the situations.

		4th SIM 95% 25°C: CEF ON + PTM ON + ZEA ON							
		RBS		ECMS		Gain	DDP		Gain
RDE Cherasco Inverso	[%]	SoC end	22.77	SoC end	25.44		SoC end	29.16	
	[%]	fc	69.885	fc	64.666		fc	61.722	
	[%]	corr. Rel	69.885	corr. Rel	63.607	%	corr. Rel	59.225	%
	[%]	corr. Abs	100.000	corr. Abs	92.201	7.80	corr. Abs	87.419	12.58
		$SoC_{tiCityIn}$	ΔSoC	$SoC_{tiCityIn}$	ΔSoC		$SoC_{tiCityIn}$	ΔSoC	target
		65.80	43.04	68.30	42.86		71.66	42.50	69.18

Table 4.13: Simulation with CEF, PTM and ZEA actives

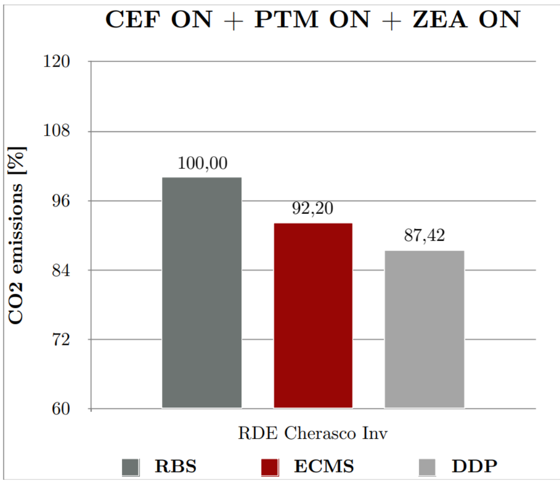

Figure 4.11: Histogram with fuel consumption of the 4^{th} set of simulations

In conclusion, the simulations show that the DDP gain is generally constant

about 9-10% regardless the activated eHorizon functions, while the ECMS gains are more variable, highlighting its dependency on boundary conditions. However, the DDP is always better than the ECMS, which, in turn, is better than the RBS.
In parallel, the vehicle now detects the city events and their electric consumption in term of battery state of charge. With this knowledge, during such events it guarantees the full-electric mode and saves energy with a more efficient thermal management.

Chapter 5

User-friendly Interface

In order to correctly load and run a single set of simulations, some technical and engineering skills are required to the external user. In fact, the operator must:

1. load the external variables which defines the simulated vehicle. This operation could be simplified by collecting the variables in MATLAB structures (family of values under the same name) and then in a $*.mat$ file to group them all. In addition, also the temperature and state of charge initial conditions have to be declared;

2. select the specific cycle that he want to use in the simulation, running the respective MATLAB function located in a folder (with all the cycles functions) in the working directory;

3. choose the desired Torque Management Strategy in the HCU model. The selection of the TMS depends on the value of a variable called $SIM.chosen\_strategy$ and goes from 0 to 2, so the user must know the value corresponding to each strategies;

4. switch on the desired eHorizon strategies. It is responsibility of the user to understand if they are suitable for the selected cycle; analogously to the HCU strategies, the control in the Simulink model is executed by a specific variable for each functions;

5. indicate the post-process script suitable for the simulation.

Evidently, the necessary steps are many and complicated even for an expert user. A first simplification comes writing MATLAB script where some dialogue boxes help the user during the selection of the strategies and the setting of environment initial conditions. But it's still a bit intricate and it's easy to overlook some wrong initialisations within the script. To overcome this obstacle, the solution is a graphical interface which hides the thousand of code lines from the user, limiting his rage of action to few multiple choices. MATLAB itself gives several tools to create the interface: GUIDE and App Designer. For a matter of usage simplicity, in this work it has been chosen App Designer.

5.1 App-designer environment

App Designer is a rich development environment that provides layout and code views, a fully integrated version of the MATLAB editor and a large set of interactive components. App Designer integrates the two primary tasks of app building: laying out the visual components of a Graphical User Interface (GUI) and programming app behaviour. In the editor showed on the left in Fig. 5.1, it's possible to create the canvas by simply dragging and dropping visual components to the workspace and use alignment hints to get a precise layout. The difference with GUIDE is that App Designer automatically generates object-oriented code that specifies app's layout and design, as represented in the right side of Fig. 5.1 [28].

5.2 Procedures

For this particular application, the layout has been designed with three macro selectable panel tables where the specific procedure commands relative to the simulation are grouped. Outside of them, there are three *push* buttons, which execution is necessary to load the working path, to open the Simulink model and the *LMS Amesym server* for the co-simulation. To underline them there are three virtual red lamps that become green if the respective command has been carried out. In the next paragraphs, every sections will be analysed in detail.

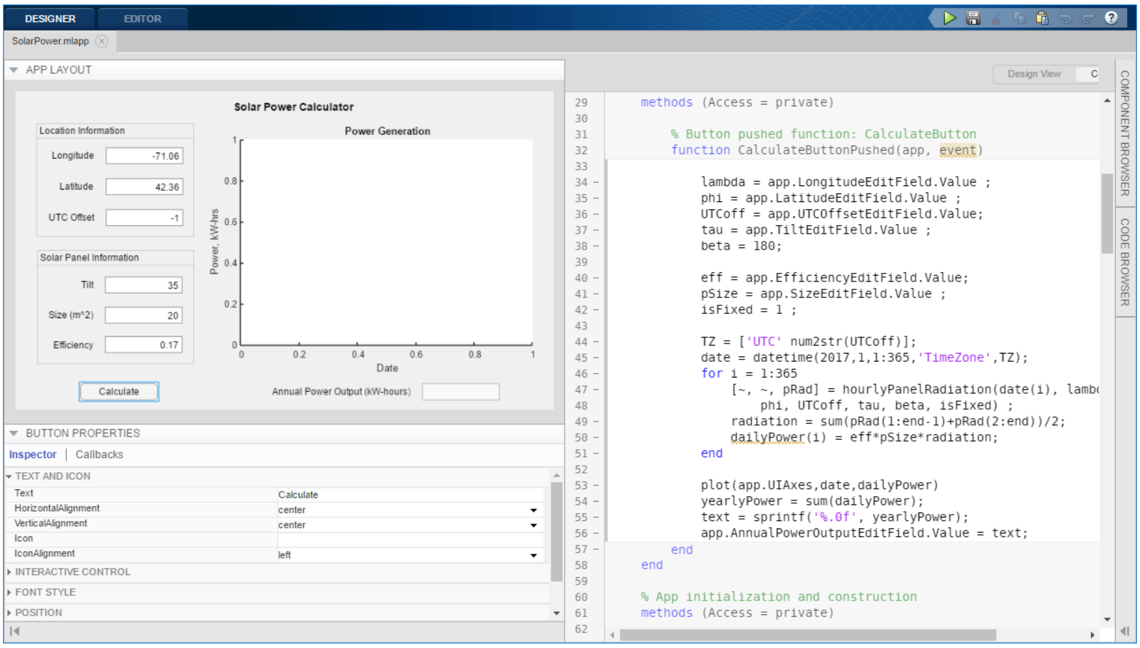

Figure 5.1: Example of App Designer working environment

5.2.1 Single simulation mode

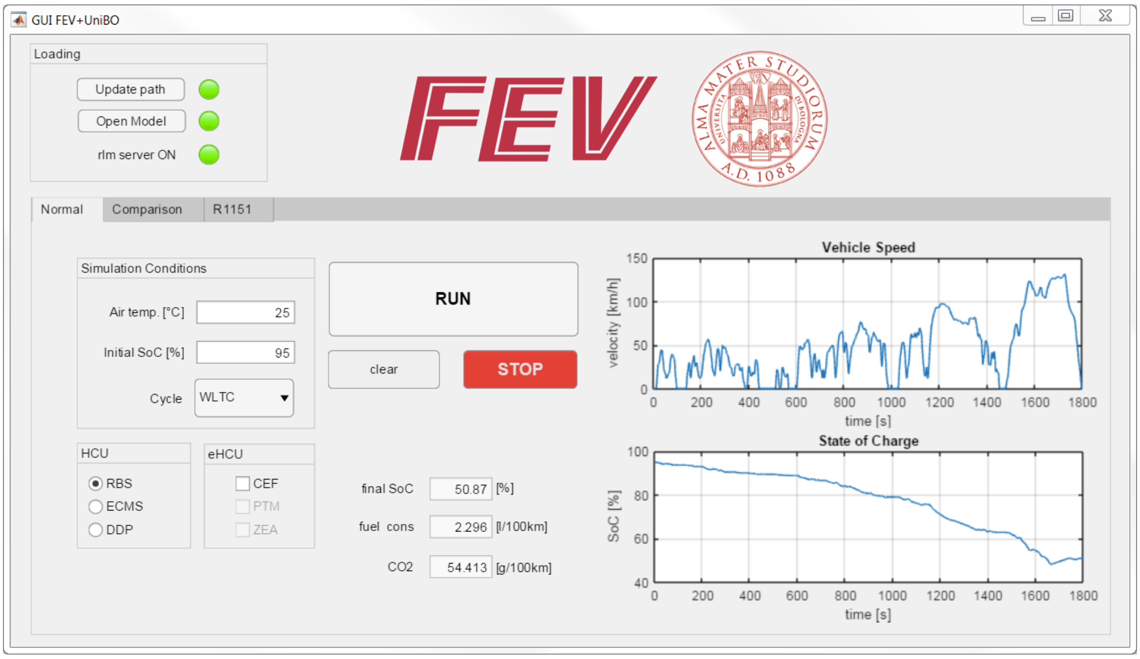

Figure 5.2: The tab of the GUI dedicated to a Single simulation mode

The first panel is focused on the initialisation of a single simulation, so no correction or comparison are made. The user can modify the environment conditions as the ambient temperature, the initial battery state of charge and select the desired driving cycle from a drop down menu. Once the procedure is defined, the app will load all the variables needed for all the strategies and it plots the speed profile on the interface, so the user can see what kind of test he's going to run. Then, he can select the preferred strategies both for the torque split and the eHorizon functions. The PTM and ZEA check boxes are enable only if the CEF is active and the cycle isn't a WLTC. Now that the boundary conditions have been set, the *"RUN"* push button becomes enabled and, if pressed, it will start the simulation in background. Nevertheless, Simulink doesn't show the progression bar if the simulation command arrived from the MATLAB command window, as in this case. So, in order to help the user understanding the actual state of the simulation, a message box appears with a progression bar displayed on it. When the process is over, the GUI shows the value of the state of charge, the fuel consumption expressed in $^{l}/_{100km}$ and the CO_2

emissions in $^{g}/_{km}$. During the simulation, the operator can even stop it any time thanks to the *"STOP"* bottom and clear the workspace with the *"clear"* bottom.

5.2.2 Comparison simulation mode

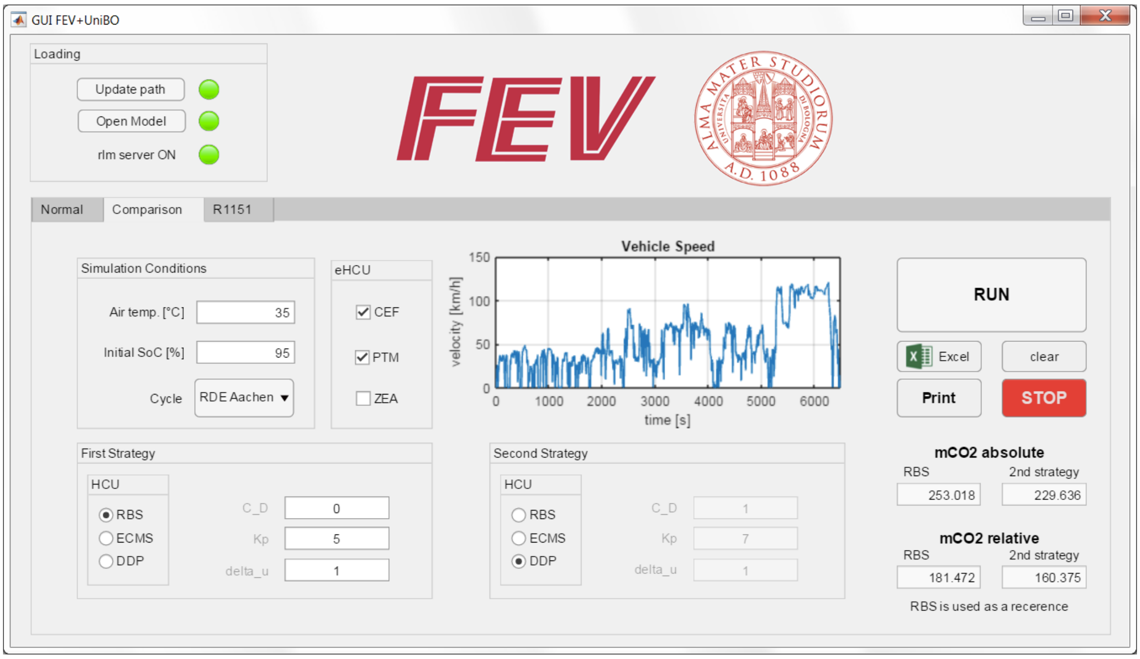

Figure 5.3: The tab of the GUI used to compare two strategies with the energy balance approach

From this point forward, the panels regard the comparison and correction post-process. Here, the user can chose to compare two different strategies and their emissions corrected with the *energy balance* approach. Regarding the boundary conditions, their selection is analogue to the previous panel, while for the strategy there are few differences. In particular, the first selected strategy usually is the rule-based because, as explained in 4.2.2, is used as reference (it could be even the second, but at least one RBS is mandatory for the post-process Excel).

Then it's possible to select the strategy to compare. If the ECMS button is selected, the user is allowed to modify some calibration parameters and this is the only technical request to the user that doesn't change from the script. These parameters have been already calibrated when they was implemented in the Simulink model. In particular, if the operator want to perform the simulation in charge-depleting mode has to use the parameters in the left column of the table table 5.1, otherwise the value in the right column. Thus, the GUI will give the external user some tips on which are the possible values when he's trying to give a wrong input in the text boxes, like in Fig. 5.4.

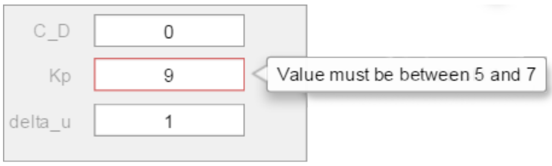

Figure 5.4: The message displayed when the user exceed the range

Table 5.1: Calibrated parameters for simulations ruled by the ECMS

	CD	CD/CS
C_D	0	1
Kp	5	7
Δu	1	1

During the simulations, the progress waitbar appears on the screen showing which strategy is being simulated, and it is shown in Fig. 5.5.

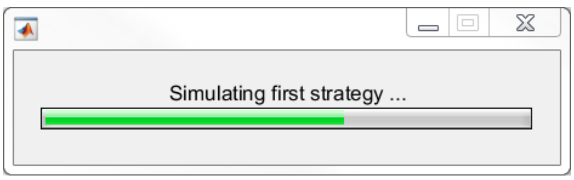

Figure 5.5: Progression of the waitbar implemented in the GUI

In addition to the *"RUN"*, *"STOP"* and *"clear"*, that have the same purpose of the *Single simulation panel*, there are other two buttons. The *"Excel"* button which open the Excel file with the post-process results and a more detailed procedure and the *"print"* buttons which loads the final results in the app interface.

5.2.3 Regulation mode

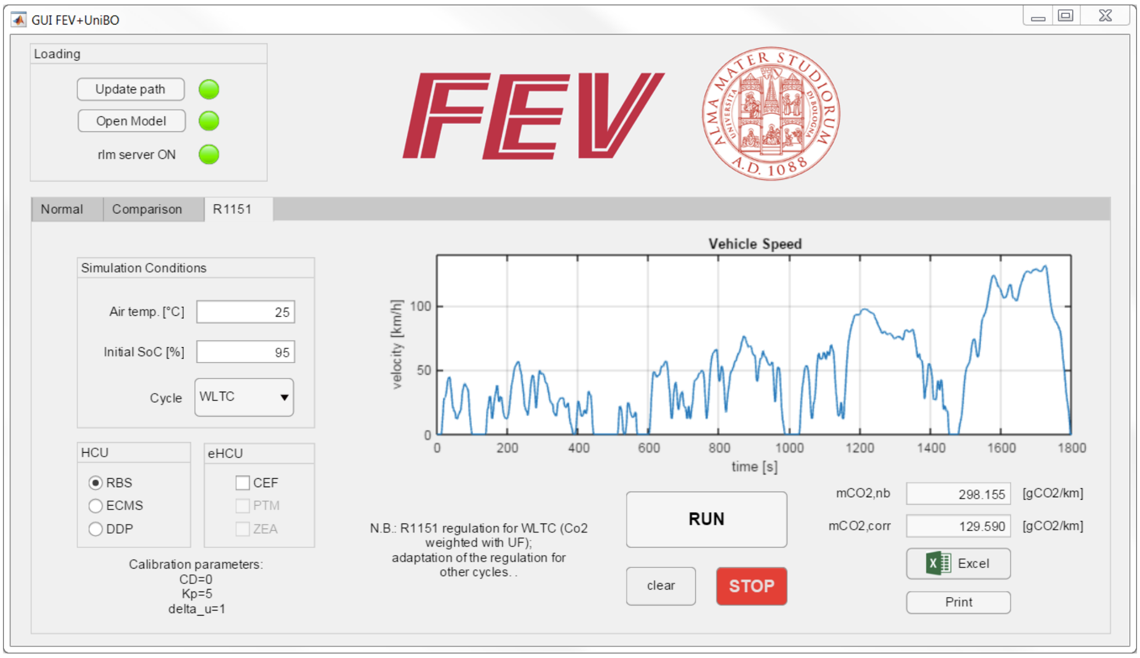

Figure 5.6: The tab of the GUI dedicated to regulation procedure

The last panel is dedicated to the R1151 regulation, both for the WLTC (§ 4.1.1) and for RDE cycles (§ 4.2.1). The procedure to set the desired boundary conditions is the same as for the previous panels, with the only difference that for the ECMS the calibration parameters are fixed for CD/CS strategy, necessary for the correction. The choice of the script isn't under the responsibility of the user, because the app already performs the corrected one, depending on the selected cycle. The waitbars show the degree of progress of the regulation procedure thanks to label printed in the dialogue box. When the simulations are completed, the results can be both printed and displayed in the Excel file with the respective buttons.

Chapter 6

Conclusions and future works

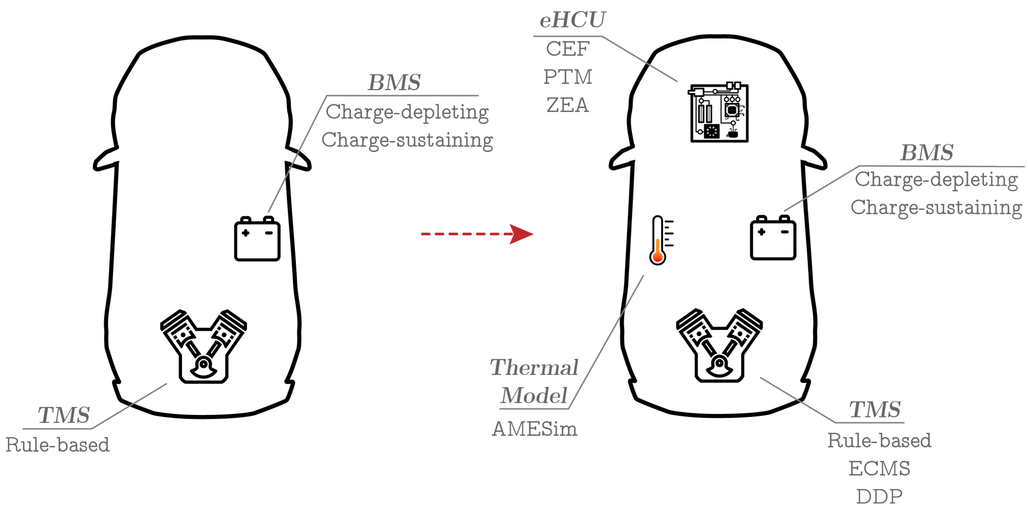

Figure 6.1: From starting model to the final version

Initially, the vehicle was modelled in Simulink with the addition of Simscape library blocks, with the fixed-size step of $2ms$, handled by a rule-based strategy implemented in the HCU, there wasn't a thermal modelling of the cooling circuit and it was initialised by a single $*.mat$ file, with all the variables inside of it. Now, the model can count on faster components modelled only in Simulink environment (the time step becomes of $20ms$, so the simulations are Real Time) and on validated thermal circuits (co-simulated with AMESim). Focusing on the Control Units, the sub-optimal (ECMS) and optimal (DDP) strategies are implemented in the Hybrid

CU, while the new kind of eHorizon CU introduces the first predictive strategies which permit to recognize the presence of a City Event, guarantee its completion in full electric driving and save electric energy meanwhile. The final results display a more efficient vehicle with a smarter energy management. Even for what concern the MATLAB command window, the improvement is consistent because all the variables are now grouped in structures which are loaded by a $*.m$ file from MATLAB so it'll be easier modify some components parameters.

The next steps towards a more realistic model will be:

- the creation of an analytical thermal model to be inserted into the MATLAB functions in order to obtain a more solid prediction of modelling;
- the implementation of pollutant gaseous emissions (NOx, PM, HC and CO) modelling to overwrite the actual simplify fuel consumption block, because the R1151 regulation already provides for limiting these kind of emissions for RDE cycles;
- a smarter management of the PTM depending on what there is after the City Event. In the 3.3.2 it is mentioned the intrinsic issue of the function, in fact, at the end of the city, the RBS comes in control again and it finds a high temperature of the battery, as consequence of the strategy rigid rules, the RBS cools down the battery in the shortest possible time. It will be used the information from the CEF to see if there will be a thermally stressed event (like a ZEA or a motorway), but otherwise the battery cooling will be slower;
- the calibration of experimental maps for simulate the additional fuel consumption due to the cold starts and catalyst heating;
- introducing the possibility to select the DDP backward script to create the maps used in the Real-Time simulation in the GUI;
- converting the codes in the real Control Unit in order to prepare the model for the future Hardware-in-the-Loop and on road tests, so it will be possible to measure the effectiveness of the eHorizon strategies.

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