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APPLICATION OF ECMS FOR HYBRID POWERTRAIN CONTROL

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ABSTRACT

The increasing attention about environment protection and climate change, that are main topics discussed by public opinion and governments in this historical period, inevitably produces pressure on car marker in order to reduce emissions, produced by road transportation, in particular the Carbon Dioxide (CO_2) that significantly contributes to the greenhouse effect. OEMs are constantly looking for new and innovative solutions to achieve the target imposed by governments for the type approval of new vehicles. One possible solution is to move towards hybrids powertrains: vehicle in which the conventional thermal engine is assisted by an electrical part in order to achieve a global optimization of the powertrain allowing for a significant reduction of emissions.

In particular the aim of this thesis is to study and implement a real time controller for a commercial vehicle, equipped with a diesel engine and an electric motor in a parallel hybrid configuration, with the target of optimizing the CO_2 emissions and Fuel Consumption.

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OVERVIEW ABOUT CO_2 STATUS AND THESIS MOTIVATION

As introduction to the master thesis job, a short overview about the CO_2 emission caused by road transport in order to clarify what is CO_2, which impacts has road transportation, what is doing the government to reduce it and the importance of hybrid powertrain to reach the common target of Carbon Dioxide Reduction.

Carbon Dioxide is commonly produced by combustion reactions in which carbon fuel, the combustible, reacting with oxygen, the oxidizing, gives as results CO_2 plus water; CO_2 is also produced by industrial and agricultural processes, other than human breathing: a study of professor Alberto Minetti, published on Physiology News, shows how a man running emits 25 g/km of CO_2 : this to underline how many are possible CO_2 sources all over the world.

Regarding vehicle emissions, CO_2 is not considered a primary pollutant since it does not primary harms humans but it is very dangerous from the time when it contributes to the greenhouse effect; Solar radiations that hit the Hearth are reflected in the atmosphere, the presence of pollutant such as Carbon Dioxide is creating a shield, a sort of greenhouse, that avoid the passage of reflected solar radiation. The effect is a second reflection towards Hearts, with the consequence of increasing the global Heath temperature.

Consequences of this phenomenon could be critical: the warming of climate will cause melting of glacial ice blocks with the effect of raising sea levels, changes in agricultural patterns, and increase severe weather phenomena, such as hurricanes and floods.

In the last years the CO_2 in Europe emitted by transportation is increased with respect to 1990; below is reported a study coming from European commission that compares the evolution of CO_2 emitted by various sources in 1990 and in 2016:

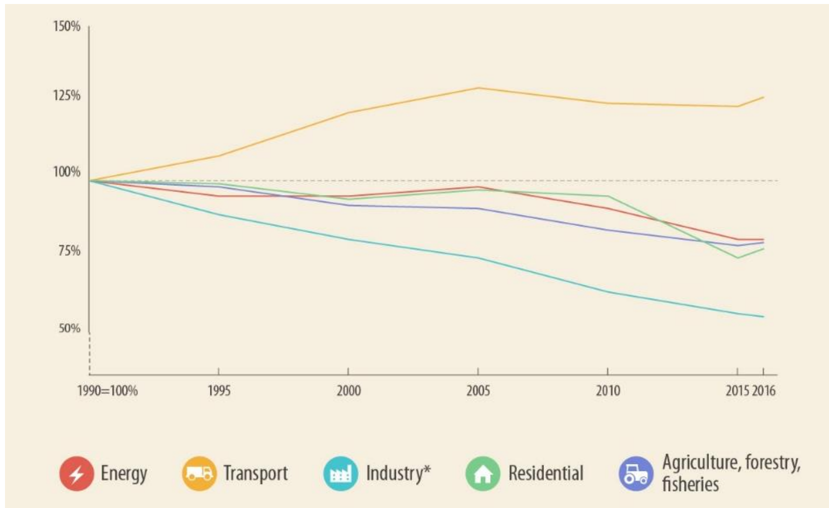

Figure 1: Evolution of CO2 Emissions by sector (1990-2016)

The source of our interest is the transport one: it is responsible for about 30% of CO_2 emission emitted in Europe, of which the 72% comes from road transportation, as explained in details in the figure below.

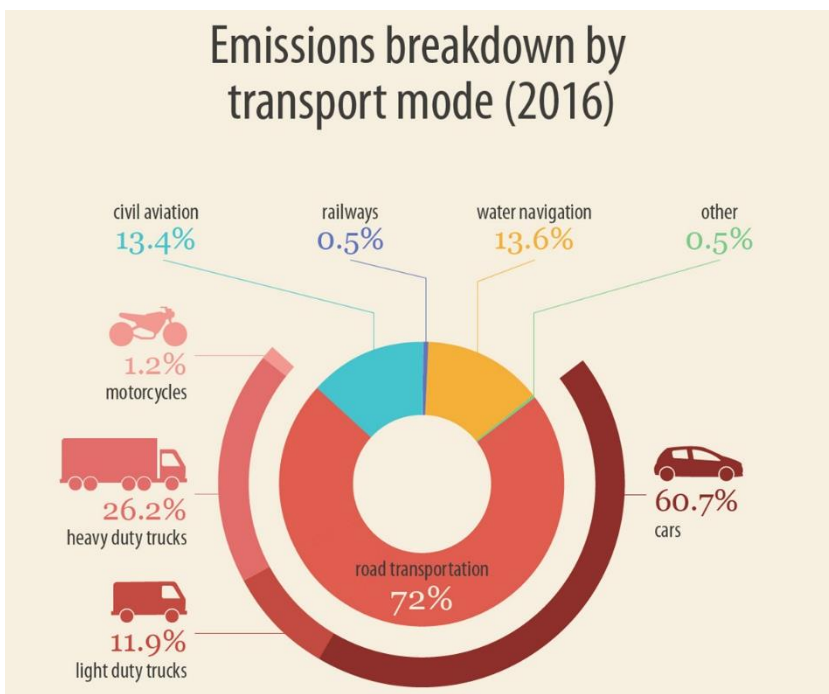

Figure 2:Emission Breakdown by transport mode (2016)

The European commission's position is quite strong on this theme: the target is to reduce drastically CO_2 emissions by means of penalties on new vehicle on flat basis. In the graph below, taken directly from the European Commission site, is sum up the effort of European commission into the carbon dioxide reduction.

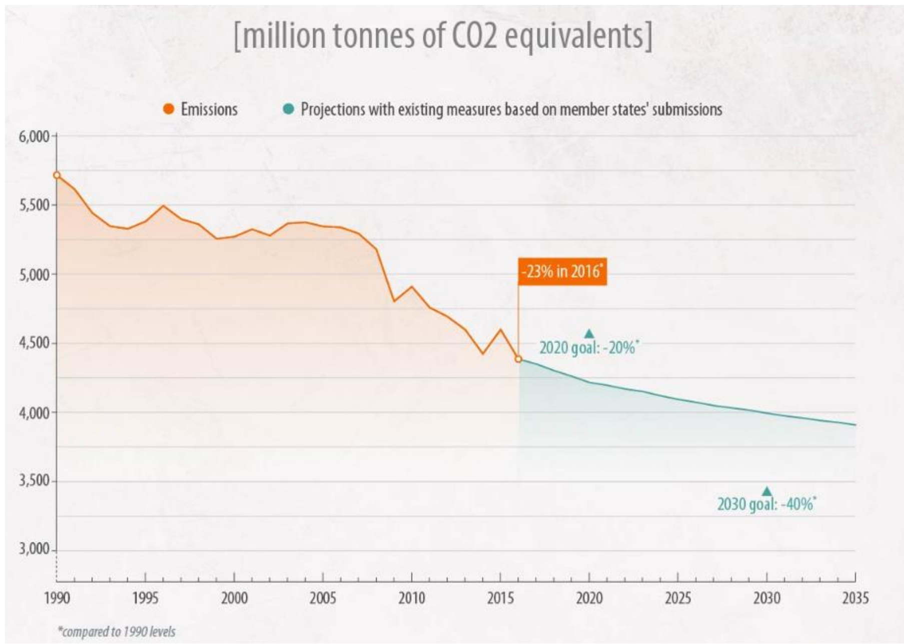

Figure 3:Greenhouse Emission Target and prediction for Europe

First logical option could be to move green, boosting the OEM's production plans towards Pure Electric Vehicle solutions. There is an important aspect to be considered in order to discuss about CO_2 emitted by vehicle: the distinction between emission Tank To Wheel (TTW) and emission Well To Wheel (WTW).

Tank to Wheel emission: this approach considers only the pollutant emitted by the vehicle on the Road, ignoring all the rest: just measure the tailpipe emission of a vehicle. Taking as reference this approach the emission of Electric Vehicle are zero: it does not make sense to compare conventional vehicle with Pure Electric vehicle following this method; reason why there is the need of introducing a second methodology.

Well To Wheel emission: This second approach takes into account all the emission occurring during the lifecycle of a vehicle: from the production and disposal to the fuel production and the tailpipe emission; considering the whole automotive process is possible to have a reasonable comparison between conventional and electric vehicles.

Once clarified the difference between the Tank to Wheel and the Well to Wheel approach, it is interesting to analyse the European commission study showing that, even though electric vehicles are more efficient than conventional one, depending on how the electric energy is produced, Well to Wheel emission could be higher than expected.

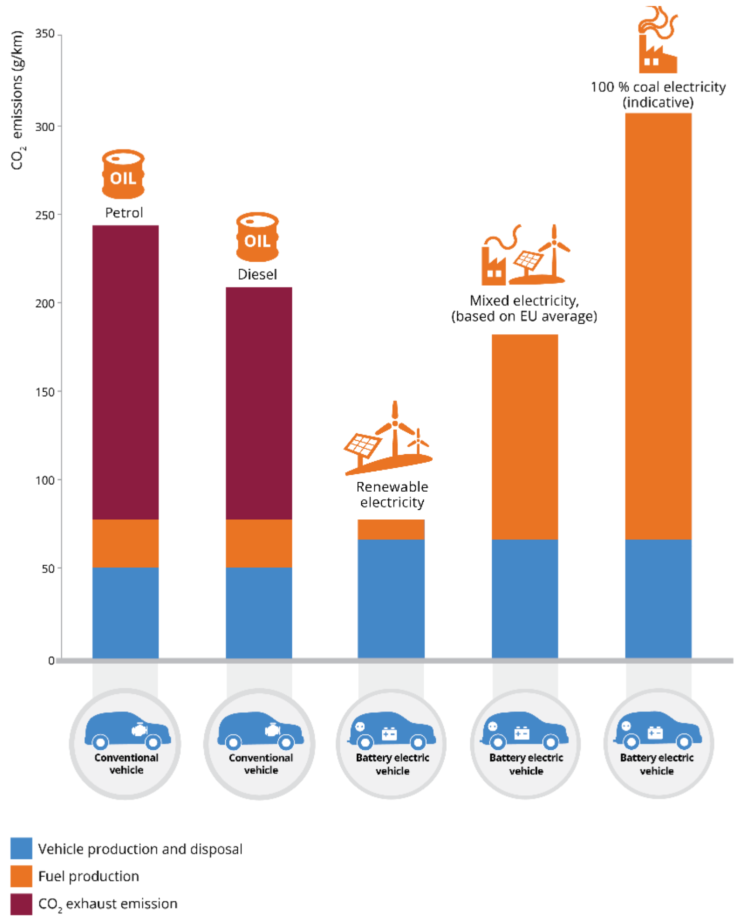

Figure 4: Range of life-cycle CO2 emissions for different vehicle (2015 TNO)

The introduction of hybrid electric vehicle is explained in this graph: by now the production of electricity for the purpose of propulsion of Pure Electric Vehicle is actually releasing about the same CO_2 amount than conventional vehicle does. Moreover, the actual performance of production batteries are not competitive in terms of range and time to recharge with respect to conventional vehicles that, with a refuelling event of 5 minutes allow about 600-1000 km range; so the mid-term most quoted solution is to electrify vehicle: building hybrid powertrains with conventional engines supported by electric motors in order to increase the overall powertrain efficiency to limit the pollutant emissions, in particular the Carbon Dioxide.

1. INTRODUCION ABOUT HYBRID CONFIGURATION USED

1.1 Vehicle parameters

The vehicle analysed is a prototype of a possible configuration of a commercial vehicle realized in a parallel hybrid arrangement with a diesel Internal Combustion Engine (ICE), typical of this kind of vehicle, supported by an electric motor in order to increase the global powertrain efficiency reducing emissions and fuel consumption.

Hereafter is reported a table with all the relevant parameters regarding vehicle main features and components.

PARAMETER	Value	Unit
Vehicle curb weight	5600	kg
Frontal Area	6.5	m^2
Cx	0.7030	-
ICE displacement	2.7	l
ICE peak power	230	kW
EM peak power	120	kW
Battery Capacity	4870	Ah
Battery nominal voltage	300	V
Gear number	6	-

Table 1: Vehicle main parameters

At first glance it is possible to notice that the commercial vehicle is quite big, with a frontal area of 6.5 square meters, and in Europe it is classified as N2: a commercial truck for goods transportation since its mass is above 3.5 and below 12 tons.

As regard gearbox it is chosen to keep a manual gearbox with 6 gear number, even though it is not fully exploiting the potentiality of a parallel hybrid powertrain, it is cheap for both purchasing ad installing since it is a consolidated best practise.

Concerning the architecture, which will be fully detailed in the next chapters, it is possible to have an idea about how much the powertrain is electrified by defining the Hybridization ratio; For parallel hybrids it is defined as the ratio between the power of the Internal combustion engine and the total power of the vehicle:

$$R_{par} = \frac{P_{ICE}}{(P_{ICE} + P_{el})}$$

Equation 1: Hybridization ratio definition

Applying this simple equation to the vehicle data of the Table 1, it comes out that the hybridization ratio is about 65%.

1.2 Vehicle basic layout

The vehicle is a parallel hybrid, in particular it is a P2 configuration, depicted in the figure 5. Being a P2 configuration means that the electric motor is coupled to transmission independently respect to the ICE by means of a clutch: this layout allows the total decoupling of the thermal part with respect to the electric one.

Being ICE and EM independent each other is a big advantage from the optimization point of view since it gives the chance to set a variety of working mode, reported and described in the next subchapter, that allow the controller to reach an high degree of optimization.

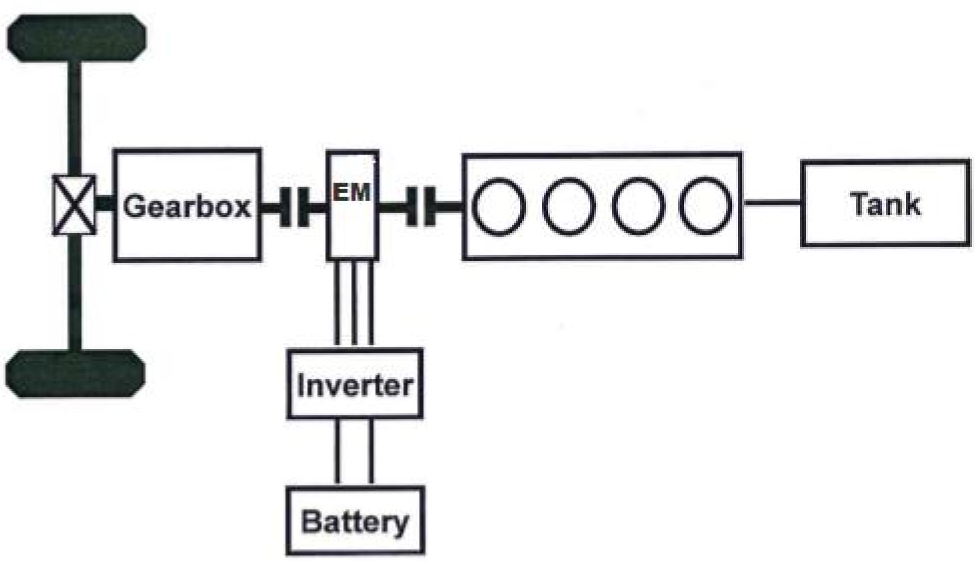

Figure 5: P2 powertrain basic scheme

1.3 Powertrain possible working modes

The following energy path (modes) are then possible:

- Pure Electric: the energy stored in the primary battery is the source of energy used for traction; all the effort for propulsion is on charge of the electrical part: the ICE can be switched off, allowing zero fuel consumption and pollutant emission. In this specific case it is possible to notice that the clutch linked to the electric motor is engaged, while, on the contrary, the second clutch connecting the ICE is open; the reason is to avoid unnecessary piston movement dissipating power. Being the system parallel hybrid, the battery is not sized to withstand prolonged runs in this Pure Electric mode, so it is necessary to properly set the ECU controller in order not to deplete the battery too fast. Typical Pure electric events are short manoeuvres like in a traffic jam or in parking, where the required power is limited and it is better to use electric motor, also because internal combustion engine displays a very low efficiency at low power usage.

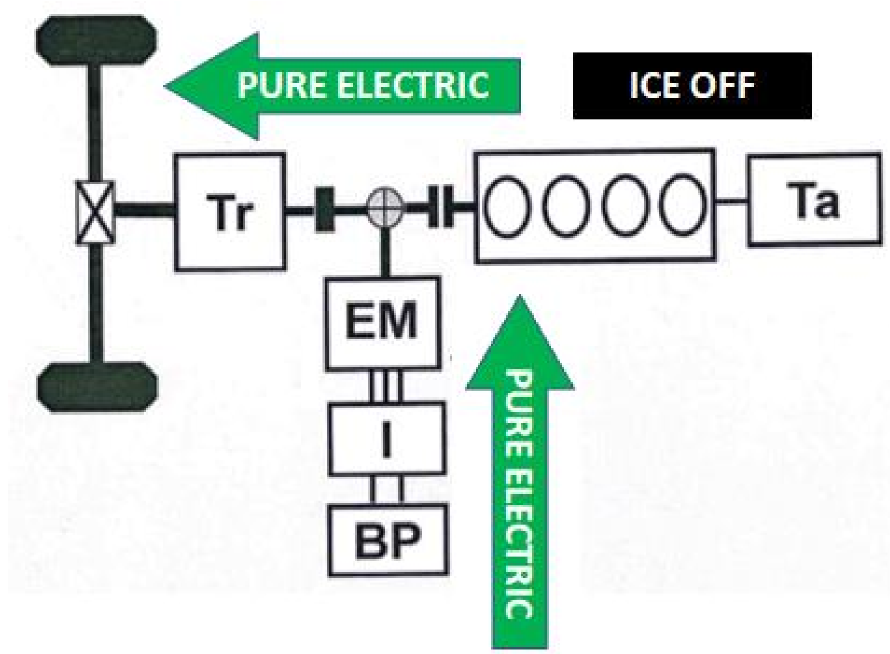

Figure 6: Pure Electric Power flow

- <u>Pure Thermal</u>: The traction power is provided only by the Internal Combustion Engine and so the energy comes totally from the fuel stored in the tank. The clutch of the electric motor is open to allow no losses due to friction, while the clutch connected to the Internal combustion engine is fully engaged to provide traction to the wheels. This working mode is preferable in all the situations in which is required high power and high speeds, for example the typical condition encountered in highway driving, where the battery would be depleted too fast due to the intrinsic batteries characteristics when high power for prolonged time are required.
  On the other end, conditions in which are required high speeds and high loads are the best in terms of efficiency for conventional engine.

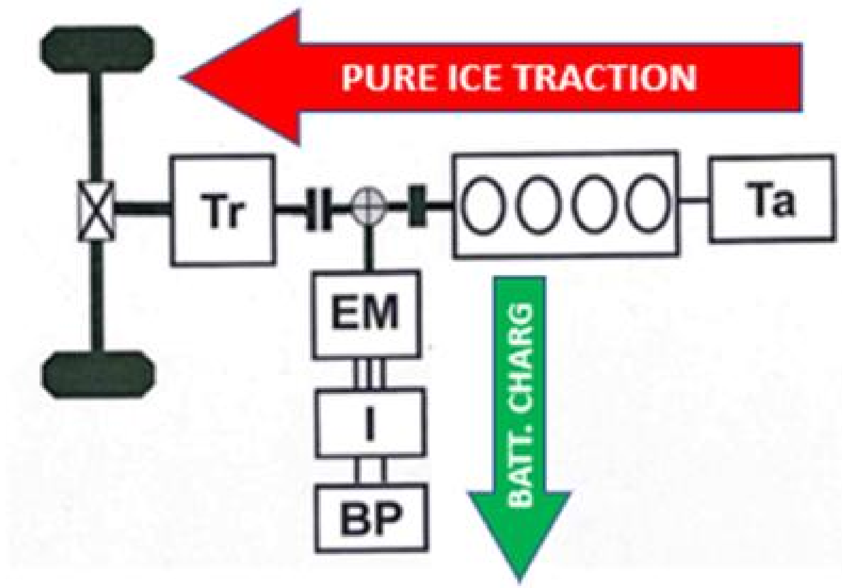

Figure 7: Pure ICE power flow scheme

- Power split: In this mode the traction power is provided both by ICE and Electric motor in the proportions decided by the control strategy. The electric part can be used as a booster or to store energy in regenerative braking mode. Both the clutches are engaged, the inverter is enabling the electric machine to act as motor or as generator according to the necessities. Typical conditions to use a power split in booster mode is for transitory phases such as an overcome or a lift off manoeuvre where the internal combustion engine is providing the larger amount of power and the electrical part is supporting to shorten the time required for the overcome of a vehicle, for example. Another condition useful to adopt power split is the regenerative braking: approaching to a stop or a traffic light and acting on the brake, part of the brake torque will be applied by conventional brakes, part can be used to activate the electric motor as generator and producing current to recharge the battery.

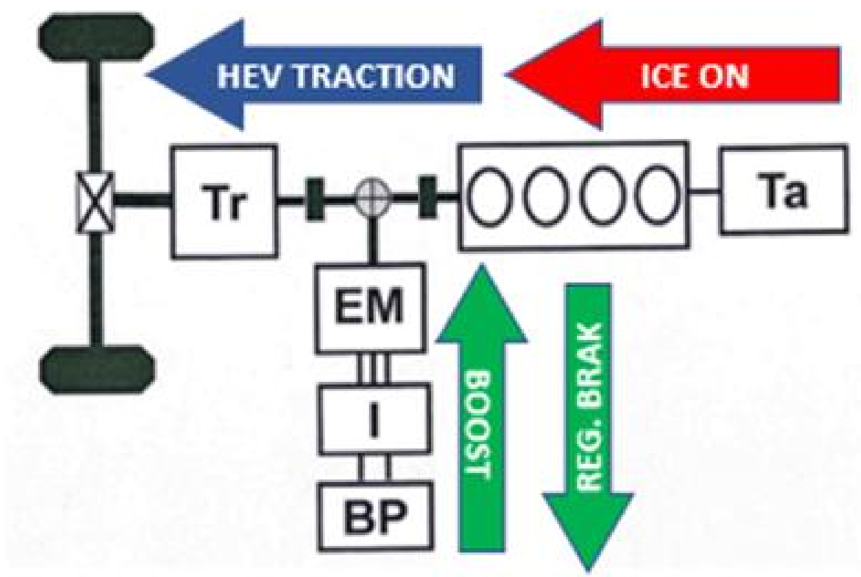

Figure 8: Power split scheme

- Battery charge: in this working operation the conventional thermal engine produces more power than the one required for propulsion and the power in excess is used to recharge the battery. This mode can happen basically if are satisfied two conditions: the battery is not fully charged, otherwise it is not possible to store the energy produced, and the second condition is that the required propulsion power is lower than the maximum available from the internal combustion engine. Typical situations to adopt this configuration are the sub-urban roads, where the requested power is not so high and so the battery alone is not capable of providing the propulsion, and the engine works at low load. Optimal solution is find allowing the engine to work at higher loads that are far more efficient, while charging the battery. It is possible to notice that the clutch of the thermal engine is engaged and so the one linked to the electrical part to allow the battery charging.

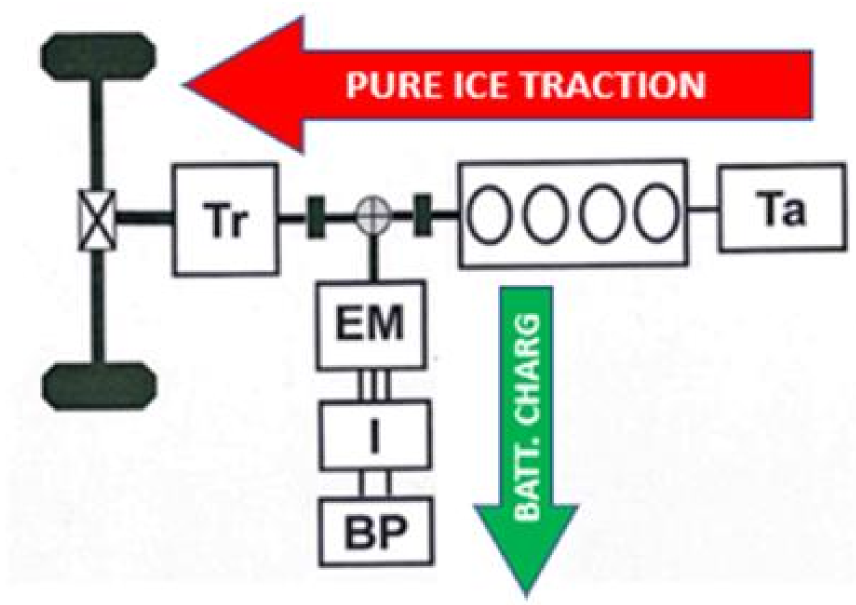

Figure 9: Battery Charge power split scheme

2. OVERVIEW ABOUT HEVBOX MATLAB CODE

In the second chapter is presented and described the MATLAB code used for the calculation developed foreword in this thesis. The current section is essential to understand where the controller optimization is located, and upon which factors it acts. The code tasks can be synthetized into three main steps: loading input files, developing calculations and finally elaboration of the results.

2.1 Loading input files

The data the code uses for calculations are in the “input” folder and can be selected in the “main” MATLAB script.

In the first phase the code reads the user configuration selected in the main, then it starts to import data and store them in many structs.

2.1.1 Vehicle data

The data collected are related to:

- Road Load: the resistance the vehicle has to overcome to move, so the contributions related to rolling resistance (rolling radius, tyre length, Rolling coefficient, gear ratios..), aerodynamic resistance (Cx, frontal Area, Air density..) and Grade resistance (slope of the road)

- Vehicle components: are loaded the parameters of the conventional part of the vehicle, so the part related to Internal Combustion Engine (Engine Maps, NOx Emission Maps, Efficiency maps..) and the components relative to the electric side, such as battery size, inverter efficiency, electric motor size…

- Vehicle Mission: in this part is loaded the speed versus time trace that the vehicle has to follow. As an example of input cycle mission is reported the schematization of the NEDC cycle.

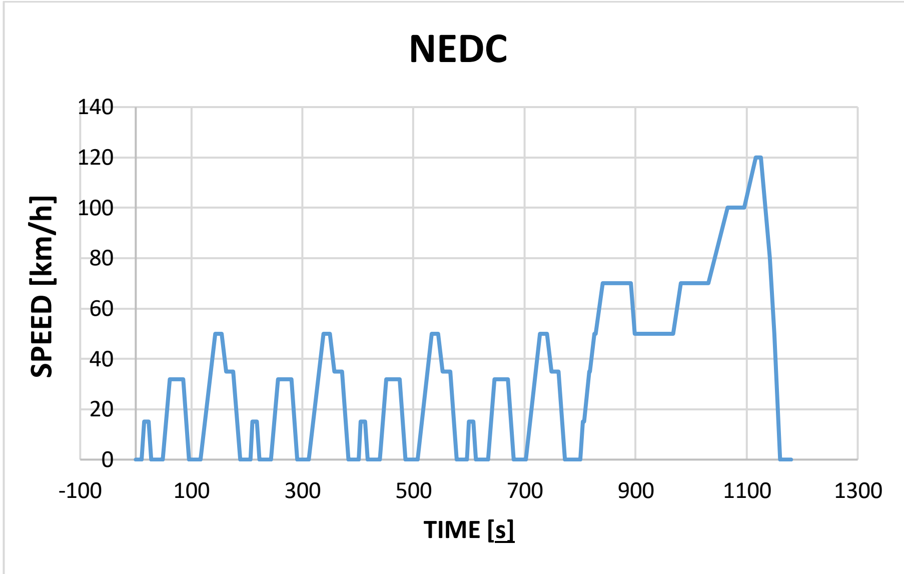

Figure 10: New European Driving Cycle

- <u>Control Variable definition:</u> Once defined all the vehicle components, control variables are set: they are the parameters that are changing in order to optimize the controller. In this case the control variables are the Gear Number (GN) and the Power Flow (PF) between thermal and electric part of the vehicle. GN can vary from 1 to 6, whether the PF are set to 11.

In computing the total number of possible cases, it is needed to consider the thermal Engine Status (ES): 1 if it is ON and 0 if it is OFF; so the total configurations are:

$$GN * PF * ES - -\rightarrow 6 * 11 * 2 = 132$$

2.2 Performing calculations

The HEVBOX tool performs calculation following the kinematic approach: so starting from the vehicle mission that is given as input, is calculated the vehicle resistance to motion time by time ignoring the driver effect. The idea is that the vehicle follows exactly the mission that is given as input.

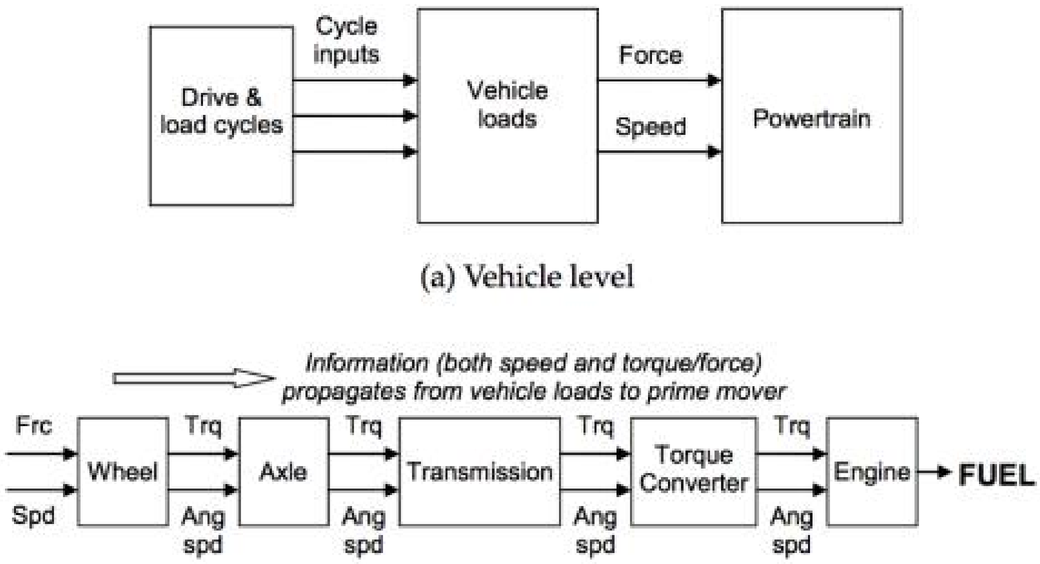

Figure 11: Kinematic approach basic scheme

Once find the vehicle resistance in every second of the mission selected by the user, for each possible combination of the control variables listed above, are computed all the vehicle main output to satisfy the input path.

In particular, the parameters target for the optimization are the CO_2 emissions and the Fuel Consumption (FC); so are computed all the variables related to conventional and electrical part of the vehicle, such as for example the engine RPM or the power required to the battery, in order to obtain the target parameters for each couple of Power flow and Gear Number.

The goal is to create a configuration matrix with all the results of the commutations second by second and store it a memory device so that is possible to implement a real time controller whose main task is to select the best possible combination of PF and GN avoiding all the calculations, that are time and resources consuming.

2.3 Elaboration of the results

The final operation of the HEVBOX is the elaboration of the results so, once obtained the configuration Matrix, a controller, according to the optimization strategy selects the GN and PF, and for each second of the mission selects and stores the results in a dedicated struct.

The results of main interest that will be treated in this thesis are the CO_2 emission, the Fuel Consumption and the battery charge at the end of the cycle mission, estimated with a variable called battery SOC that stands for State Of Charge.

3 CONTROLLERS

In this section are described and analysed the main types of optimization algorithms that can be implemented as controller of the HEVBOX.

3.1 DP: Dynamic Programming

The dynamic programming is a strategy of global optimization: it finds the best possible solution for a discretized problem that must be known a priori.

Taking as a reference the picture below, to go from point A to point B there are many possible paths that can be chosen and to go from a point to another the cost is indicated by the arrow: the DP algorithm is capable of giving as output the cheapest possible way to go from A to B

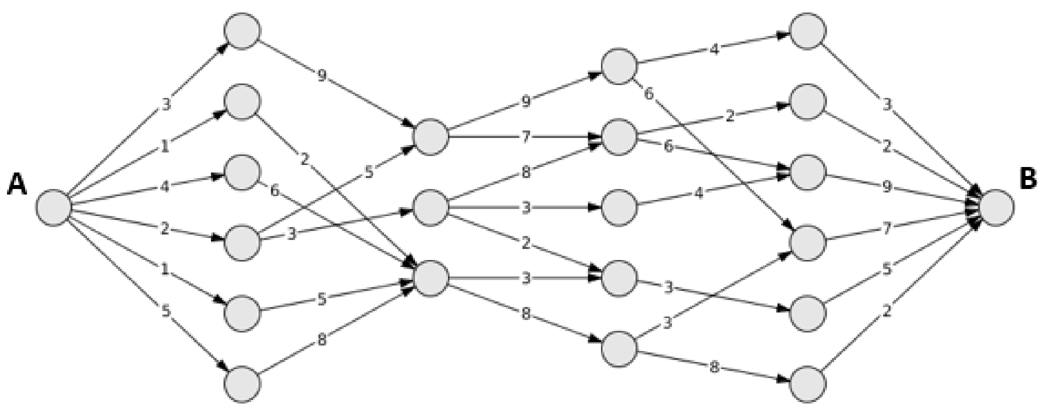

Figure 12: DP problem example

DP code consists mainly of two phases: forward and backward.

In the forward phase the algorithm reads steps by steps the costs indicated by the arrows to go from a point to another, analysing all the possible paths.

Once completed the forward phase, starts the backward phase that has the target to compare the values obtained in the previous step and so giving back as an output the cheapest possible way.

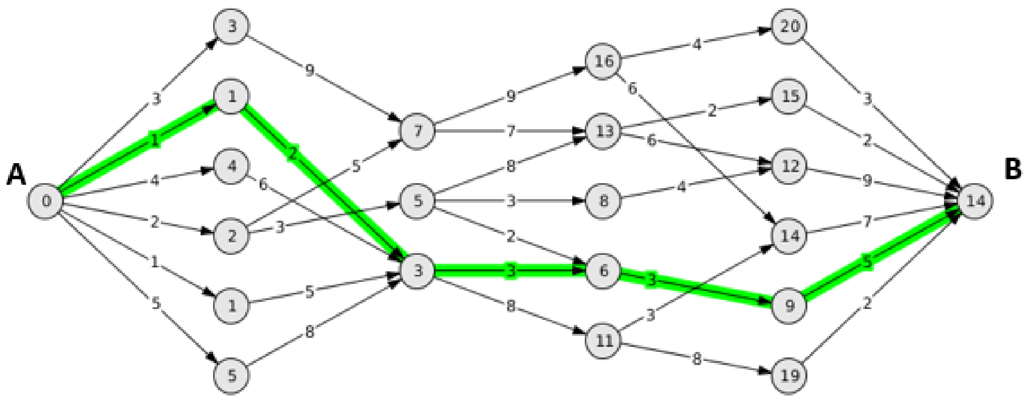

Figure 13: DP optimal solution

Applying the DP algorithm to the optimization problem of an hybrid powertrain is possible: it takes as input the cycle discretized in steps, reads all the values of the results reported in the CM and gives back the optimal solution: the best achievable control choice that can be found for this problem.

The DP solution has the drawback that it is not suitable for real-time implementation since it requires the cycle to be known a priori and high computational demand to ECU, that cannot be definitive possible in a real-world practical application.

Even if the DP cannot be implemented it is used for the purpose of benchmark, to compare how close is the real time solution to the optimal DP solution.

3.2 RB: Rule based controller

The Rule base controller is an optimization strategy strictly depended on the application on which it is implemented since it relies upon rules, specific for each product.

The process of rules definition and calibration can be very long since a lot of parameters have to be considered.

In the HEVBOX application the rules are defined according to the type of powertrain to be optimized and are based on empirical rules requiring a lot of work to calibrate them to the application, defining specific tuning parameters. Obviously, changing the application, the calibration has to start again from new.

The great advantage of the Rule Based controller with respect to the Dynamic Programming one is that it is suitable for implementing in real time application since it requires low computational effort.

On the other end, as drawback, the Rule based controller finds out a local solution, not global as Dynamic Programming, and often the RB outcomes are far from the optimal solution.

Below is reported an explicative picture to compare at first glance the main differences between DP and RB controllers: with the first one, the DP, is obtained as a result an optimal solution but it is very time and energy consuming; on the contrary with RBC the computation time is very low but the distance from the optimality is relevant.

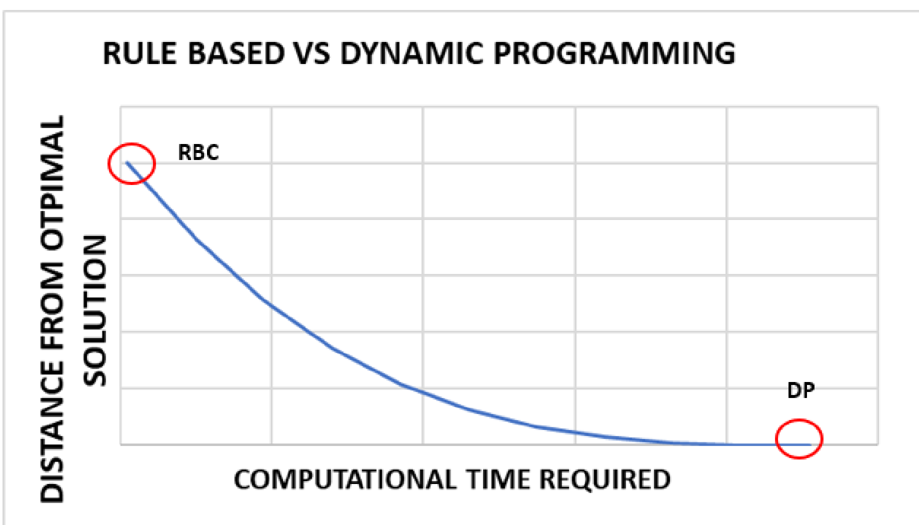

Figure 14: DP versus RB

3.3 ECMS

The acronym ECMS stands for Equivalent Consumption Minimization Strategy and it is a control strategy adopted for hybrid powertrains suitable for real time implementation.

The main assumptions that are the base of this optimization strategy are three:

1. Charge sustainability: it is assumed that the electric part of the powertrain stays in charge sustaining mode, so the battery has never to be fully depleted.

2. Net Battery Variation is zero: A basic rule is that the State Of Charge (SOC) at the end of the driving mission shall be equal to the battery SOC at the start of the driving cycle.

3. All the energy ultimate comes from the fuel: this is a direct consequence of the point 2 , since the battery of the energy must be conserved during the cycle, all the energy comes from the fuel and so the electric part is just a device to increase the global powertrain efficiency.

The theory is based upon the definition of a target function J to be minimized that represents the powertrain instantaneous fuel consumption defined as the sum of the fuel flow rate plus a term representing the electric energy equivalent flow rate.

A general form of the target function J is reported in the equation below:

$$J = \dot{m}_{fuel} + k_1 * \dot{m}_{eq,el}$$

Where $\dot{m}_{eq,el}$ represents the equivalent mass flow rate of electric energy: it is estimated as the electric power required for the electric motor divided by the efficiency of the electric machine and by the lower heating value of the fuel, so that to provide a comparable term with respect to fuel mass flow rate.

It is important to underline the presence of the term k_1 that is a calibration parameter, called equivalence factor, for the target function J: the purpose k_1 is to weight the importance of the equivalent electric energy consumption with respect to the fuel flow rate term.

The calibration of the k1 factor is crucial for the success of the optimization strategy: there is the need to find a good compromise to reach a good result, in fact having an equivalence factor too high means that the cost of the electric energy is high and so the potentiality of the hybrid powertrain is not fully exploited.

On the other hand, having a k_1 too low makes the controller to do a massive usage of electric energy so that the battery is depleted too fast, losing the charge sustaining hypothesis of the ECMS.

The main drawback of the ECMS is that k_1 strictly depends on the mission, so once calibrated a k1 for a driving cycle, by changing the path, the calibration has to start again from zero, making this solution not suitable to have good results in real time.

In the chapter 4 is discussed a further step towards the ECMS implementation in real time: The Adaptive-ECMS.

3.3.1 ECMS implementation

The aim of this subchapter is to furnish a short operative guide to how implement the ECMS controller to a code, the main passages are:

- Define control variables: Power-Flow and Gear Number

- Define and discretize the range of control variables: the GN can vary from 1 to 6, while the Power-flow has 11 possible working status, reported in the table below.

PURE ELECTRIC	PURE ICE	POWERSPLIT	BATTERY CHARGE
1	0	0.1, 0.25, 0.5, 0.75	- 0.1,- 0.25,-0.5,-0.75, -1

Table 2: Power Flow configurations

- Calculate the ECMS: apply the target function J and calculate it for each configuration
- Select the couple of control variable that minimize fuel consumption

4 ADAPTIVE ECMS

This optimization strategy has been created with the precise target to overcome the problems linked to the ECMS, in particular related to the definition of the equivalence factor k_1 defined in the chapter 3.3.

The basic idea of this control technique is to adapt the equivalence factor k_1 during the driving mission, so that to be close to the optimality of solution.

In literature there are 3 main way to control the adaption of equivalence factor that will be described in this chapter.

4.1 Adaption based on the Mission prevision

The first option is built on the prevision of the cycle: by analysing past data and taking as input some relevant parameters such as, for example, the vehicle position given by the GPS, the ECU (Electronic Control Unit) should adapt the equivalence factor to obtain a proper optimization of the powertrain.

Although this approach is promising, it requires a lot of computational power to get good forecast and produce acceptable results. The more are the input parameters the more accurate are the outputs, but with the penalty of increasing computational time and load, having more inputs to process.

4.2 Adaption based on Mission recognition

The second approach is based on a similar idea with respect to the first one: a forecast of the Mission. Differently from the previous one, this method utilizes the recognition of the cycle: this implies that a great variety of missions should have been analysed and stored in the memory.

Not having to process external inputs, the algorithm is faster than the Mission Prevision one but requires much more offline training of the equivalence factor.

4.3 Adaption based on SOC feedback control

The third optimization strategy relies on adaption based on the battery State of Charge control and it is explained in detail in Chapter 5.

5 IMPLEMENTATION OF A-ECMS

After the introductive part, explaining the architecture targeted for the study, its potentiality and features, have been described the state of the art in terms of controllers for hybrid architecture, this chapter is intended to furnish a detailed description of the optimization controller implemented in the present thesis.

As anticipated the strategy algorithm is Adaptive ECMS type based on SOC feedback control, below are detailed all the passages and equation adopted.

5.1 Target function

Starting from the basic equation of ECMS, expressed by the ***Equation2***, the target function adopted has been modified as follow:

$$J = \dot{m}_{fuel} + \gamma * (k_{discharge} * \frac{P_{el}}{\eta_{em} \; * Q_{LHV}}) + (1 - \gamma\,) * (\,k_{charge} \frac{\eta_{em} * P_{el}}{Q_{LHV}})$$

Equation 3: Complete form of target equation

Where γ is the factor that accounts for the split between charge and discharge and is expressed as:

$$\gamma = \frac{1 + \sin(P_{el})}{2}$$

Equation 4: Parameter γ

Moreover, a further explanation is required for the two parameters k_{charge} and $k_{discharge}$: they are two equivalence factors of the ECMS equation respectively for the charge and the discharge process of the powertrain. The condition of charge happens when the powertrain in recharging the battery though regenerative braking or by mean of the Internal Combustion Engine: in this case the efficiency of electric machine, always less than 1 by definition, is a multiplicative term and accounts for the fact that part of electric energy is lost by intrinsic Electric Motor losses.

Vice versa in the discharge condition, in which the power coming from the battery goes towards the Electric motor, the efficiency of the electric machine is taken as quotient since it accounts for the extra energy required to the battery to cover the Electric motor losses.

To speed up the calculation an assumption has been made: k_{charge} is imposed equal to $k_{discharge}$ and called k_1; the consequences of this assumption are described and considered in the reference [1] in which a deep analysis has been carried out demonstrating the small variations in the final optimization results due to this simplification.

The final form of the target function to optimize is:

$$J = \dot{m}_{fuel} + k1 * \left[\gamma * (\frac{P_{el}}{\eta_{em} * Q_{LHV}}) + (1 - \gamma) * (\frac{\eta_{em} * P_{el}}{Q_{LHV}})\right]$$

Equation 5: Final form of the target function

5.2 Equivalence factor adaption law

This study is adopting the adaption strategy based on the feedback SOC control: k1 is adapted based on the SOC variation of the previous period and is taking into account the average value of the previous equivalence factor used. In particular the adaption law is described by the following equation:

$$k1_{j+1} = \frac{(k1_{j-1} + k1_j)}{2} + ks * (SOC_{ref} - SOC_j)$$

Equation 6: K1 adaption law based on SOC

Where:

- j is the present instant of time considered
- ks is the proportional Gain of the feedback law and it is set to 2
- SOC_{ref} is the reference state of SOC to guarantee the charge sustaining mode and it is set to 0.6

5.3 Equivalence factor adaption period

As described in the chapter 4, the fundamentals of Adaptive ECMS theory is based on the adaption of the equivalence factor: each T seconds the parameter k_1 has to be refreshed to adapt to the mission.

To properly set the refresh rate T the following steps have been carried out: first of all is identified the useful window in which T may vary, setting a T_{min} and T_{max}, then has been selected a reference mission and a sensitivity analysis is performed in order to choose the best refresh rate.

It is important to underline that in the calculation below the charge sustaining SOC window is chosen an 0.55÷0.65, where for charge sustaining windows is intended the value not to overcome to stay in charge sustain operation.

The reference cycles used to calibrate the adaption periods minimum and maximum are the WLTP3 (Worldwide harmonized Light duty Test Procedure), the reference homologation cycle used in EMEA region, and the FTP75 (Federal Test Procedure), the homologation cycle adopted in the NFTA region.

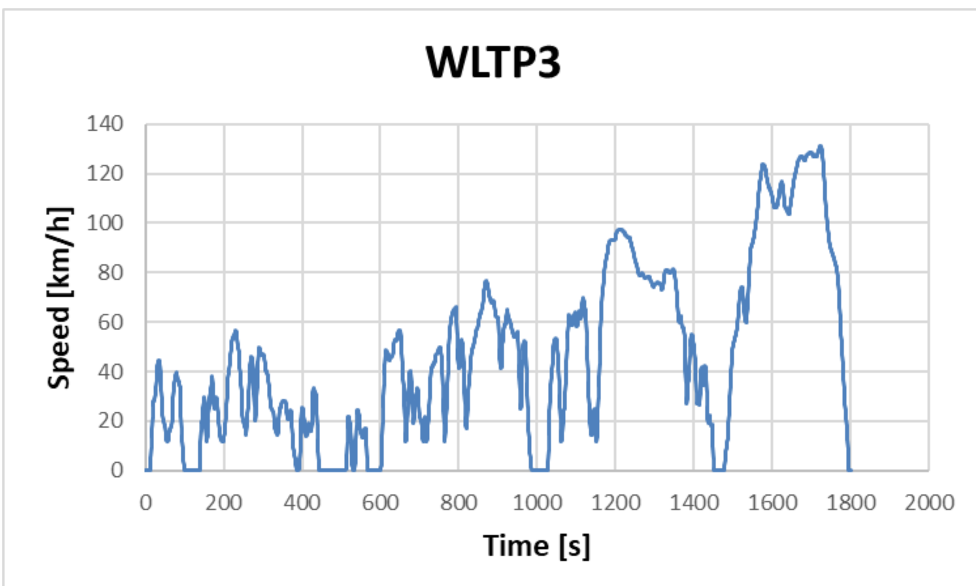

Figure 15: WLTP3 test cycle

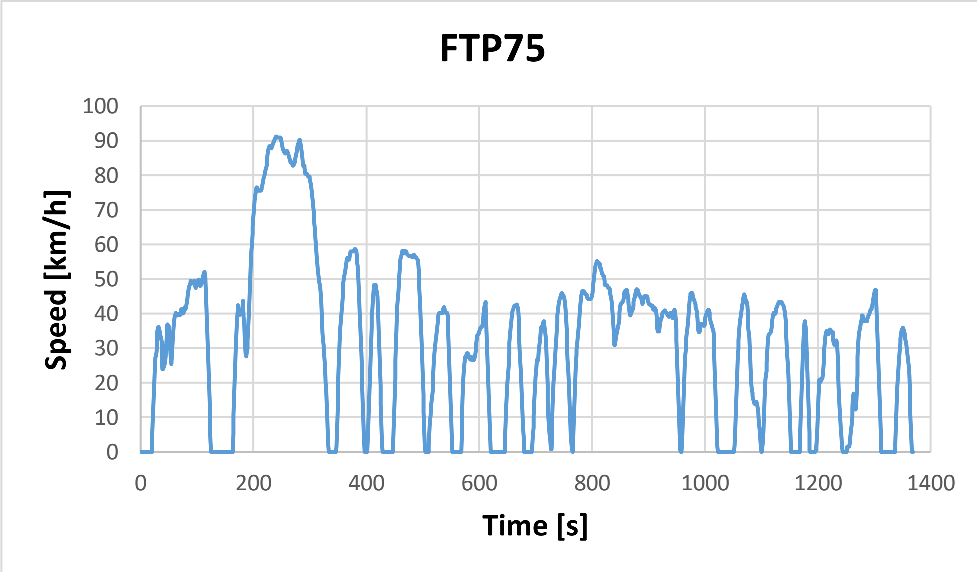

Figure 16: FTP75 test cycle

5.3.1 Selecting the maximum adaption period T_{max}

The process to select T_{max} is based on the idea that the SOC has never to overcome the limit values imposed by SOC_{max} e SOC_{min} , in order to stay in the charge sustaining window.

So, have been carried out tests with a high value of equivalence factor, set to 5, and a low value, set to 1, in order to observe when the SOC reaches the boundary value performing the two cycles set as reference. The chart below is useful to understand the passage:

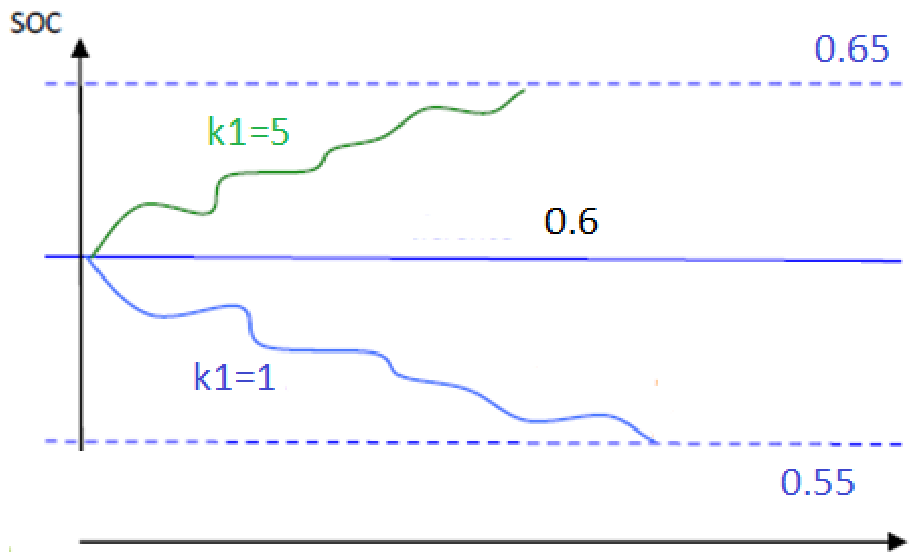

Figure 17: Selecting T_{max}

In the following table are reported the results for the simulation with k_1 equal to 1 and 5:

	k_1=1	k_1=5
WLTP3	751 s	428 s
FTP	377 s	282 s

Table 3: Results of simulation for compituing T_{max}

As an outcome, the T_{max} chosen is **282** seconds: the minimum among the results.

5.3.2 Sensitivity to choose the best adaption period

The final phase of the process to define the adaption period is a sensitivity analysis performed to select the best possible parameter suitable for the optimization.

First of all, has been chosen the cycle mission: the selection is guided by the fact that the T has to be as much as possible independent of the driving mission to give the study a general character of application, so a combination cycle has been created and utilized.

The combination mission is composed by three cycle in the following sequence: NEDC, FTP and WLTP3. The choice of the driving cycle is performed considering the fact that this sequence is representing all the possible driving scenarios:

- Urban: characterized by frequent stops and low velocities, typical of city driving.

- Suburban: defined by medium velocities, typical of extra-urban and rural roads.

- Highway: Characterized by high speeds, usually encountered in highway driving

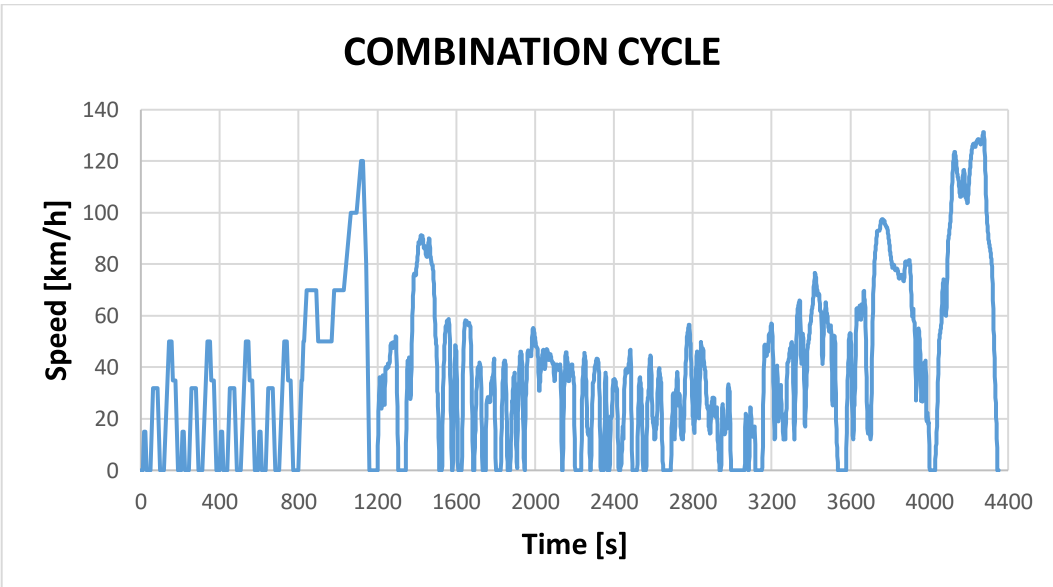

Figure 18: Combination cycle NEDC FTP WLTP

The following step is to make vary the adaption period T in the charge sustaining window to see which is the value that gives back the SOC closer to the reference SOC that is 0.6. The following table shows the results of the calculation:

T	Final SOC	FC [kg]
90	0.583	7.58
110	0.572	7.47
130	0.563	7.37
150	0.574	7.50
180	0.587	7.67
200	0.604	7.85
220	0.590	7.70
240	0.589	7.68
260	0.605	7.86

Table 4: Results of sensitivity analysis for adaption period T

It is possible to notice that, together with the final SOC, is reported the total fuel consumed in order to check how much the energy consumed by the battery influences the final result of fuel consumption.

The choice of T that gives back the best results in terms of final SOC is shown by the table and it is clearly 200 seconds with a final State Of Charge of the battery that is 0.604.

Could be noted that also 260 seconds gives back good results, very close to the 200 seconds one, that is 0.605: having T higher is better from the point of view of calculation demand because the value of equivalence factor is updated less frequently but this choice has the drawback of being accurate with respect to short driving cycles.

In the following chapter will be illustrated the main results of the implementation described in this section.

6 RESULTS

This section is completely reserved to the results coming from the implementation of the code described in the section 5. One by one the most representative driving cycles are given as input to the code and the main results are reported and commented.

6.1 Description of the main results

As already described in the abstract, the core of the thesis is to develop a controller that targets the optimization of the Fuel Consumption, the CO_2 emissions, that are closely related to FC by mean of carbon balance method, and stays in the charge sustaining SOC window already described in the previous chapters.

To have a comparison of how good the results are, the same cycles are performed by the code in Dynamic Programming optimization mode, so that to have a benchmark respect to the best possible solution.

Moreover, since the DP returns always to the initial State of Charge, to compare results in a correct way, has been quantified the fuel consumption with respect to the SOC variation.

In order to quantify the SOC variation respect to the fuel consumption has been converted the total battery energy into kilograms of fuel by means of the Lower Heating Value of the fuel and the result is that the battery fully charged is equivalent to 3.8 kilograms of fuel.

In the following subchapters will be reported charts with the SOC variation in DP mode versus the SOC variation in A-ECMS mode, the CO_2 resulting from the A-ECMS simulation, the fuel consumption in DP and in A-ECMS, this one will be reported to reference SOC by applying the following equation:

$$FC^{*} = \left(SOC_{ref} - SOC_{A-ECS}\right) * 3.8$$

Equation 7: Conversion of A-ECMS FC to reference SOC

6.2 NEDC driving cycle

The first cycle to be analysed is the New European Driving Cycle, a non-experimentally derived cycle used till some years ago as homologation reference for the EMEA region. The results are reported below:

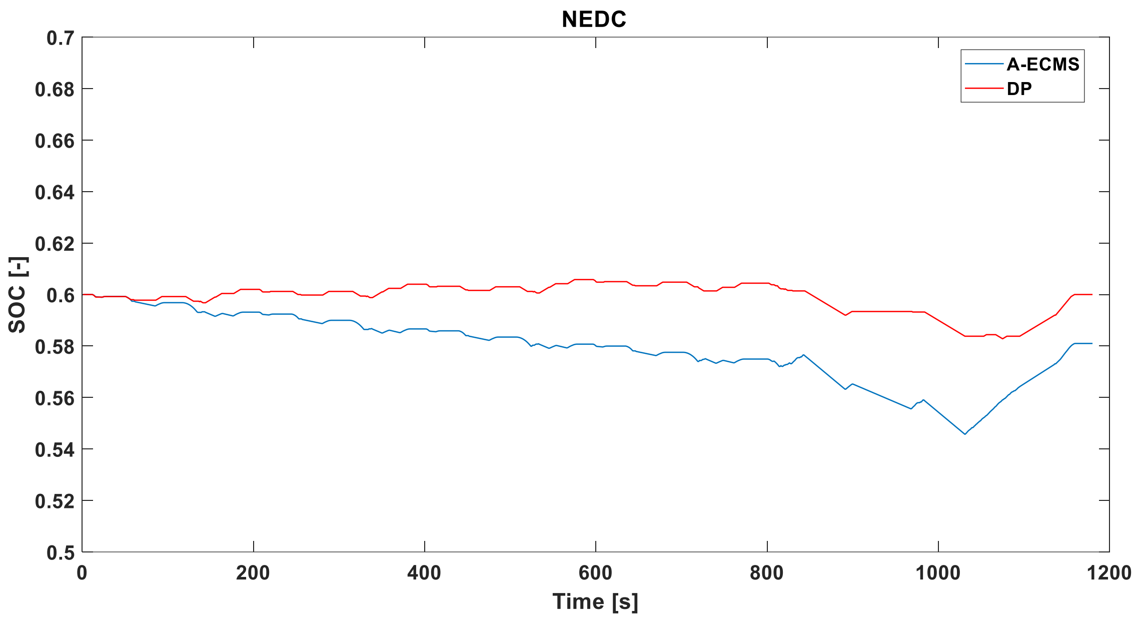

Figure 19: NEDC SOC compare

The table with the results:

$FC_{A\text{-}ECMS}$ [kg]	FC* [kg]	FC_{eq} [kg]	FC DP [kg]	CO_2 [g/km]	$SOC_{A\text{-}ECMS}$ [-]
1.43	0.08	1.51	1.20	403.83	0.58

Table 5: Main results NEDC cycle

It is possible to notice that the A-ECMS follows the same profile of the DP but more accentuated: the results in terms of SOC are very close to the reference one, so the correction calculated by mean of equation8 is very small. The delta between the best fuel consumption, calculated by DP, and the one obtained by A-ECMS is just 0.31 kilos of fuel over a cycle of 20 minutes and about 11 kilometres long.

6.3 J1015m driving cycle

This driving cycle, called Japan 10-15 modes, has been used in Japan as homologation reference: it is characterized by low speeds and frequents stops, typical of Japanese city driving. The outcomes are reported in the following:

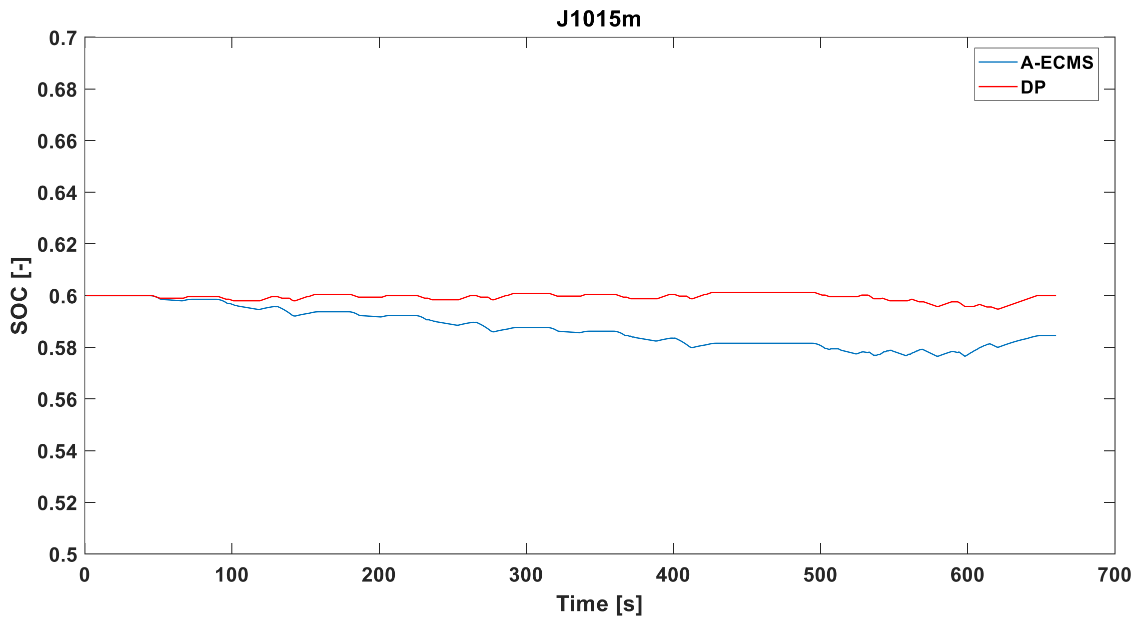

Figure 20: J1015m SOC compare

A resuming table with results:

$FC_{A\text{-}ECMS}$ [kg]	FC* [kg]	FC_{eq} [kg]	FC DP [kg]	CO_2 [g/km]	$SOC_{A\text{-}ECMS}$ [-]
0.45	0.08	0.53	0.39	324.65	0.58

Table 6: Main results J1015m cycle

At first glance is possible to observe that the SOC paths across the cycle are similar but the A-ECMS one is slightly lower, maybe due to a low value of equivalence factor. Anyway, the final SOC is just 0.02 points lower with respect to the reference on. In terms of fuel consumption, the A-ECMS utilizes 0.14 kilograms of fuel more with respect to the best possible solution across a cycle characterized by frequent stops and accelerations, that penalizes the commercial vehicle with high mass studied in the present thesis.

6.4 WHVC driving cycle

This particular test World Harmonized Vehicle Cycle is applicable to heavy duty engine and it is derived from the dataset used for the transient cycle to test heavy duty engine. Since it is a commercial vehicle, a modified version of the vehicle could be classified heavy duty engine in some region: this explains the utilization of this cycle. It is similar to WLTP and the last part is prevalently highway section, all the information are reported below:

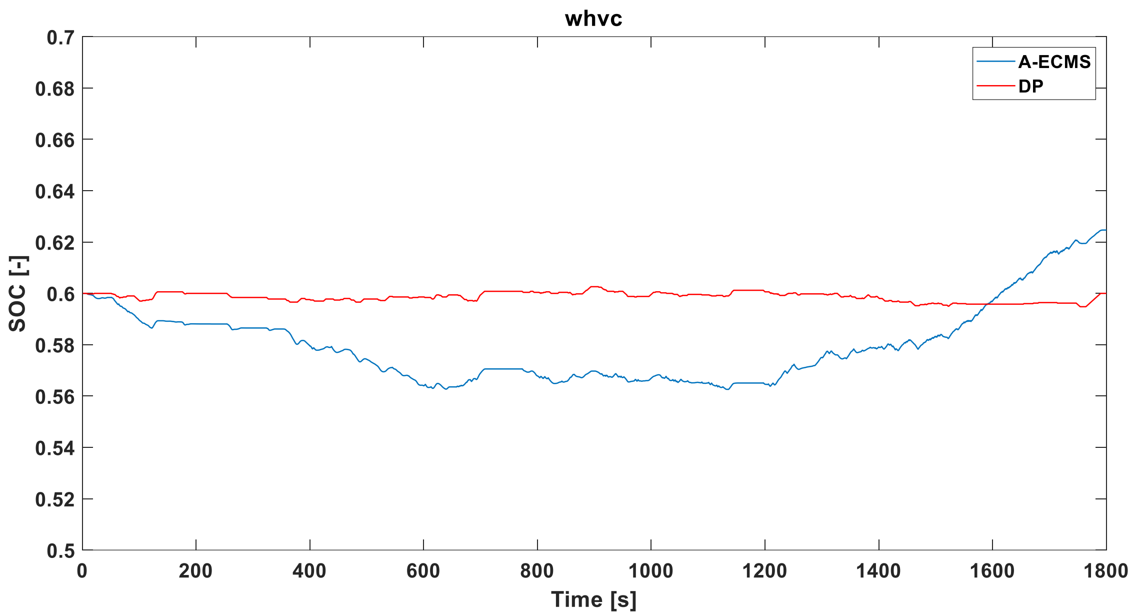

Figure 21: WHVC SOC compare

$FC_{A\text{-}ECMS}$ [kg]	FC* [kg]	FC_{eq} [kg]	FC DP [kg]	CO_2 [g/km]	$SOC_{A\text{-}ECMS}$ [-]
3.36	-0.15	3.32	2.52	502.80	0.62

Table 7: Main results WHVC cycle

It is possible to notice that the SOC path of A-ECMS is quite different from the one of the DP, being lower on the first part and higher in the last one: this could be due to the proportional gain too high that comports high variations in the equivalence factor.

By the way, the final results are not that close with respect to the benchmark since the variation is in the order of 0.7 kilograms of fuel along the 20 kilometres of the 1800 seconds cycle.

6.5 FTP75 driving cycle

The Federal Test Procedure 75 has been already mentioned in this thesis and it is the homologation reference cycle for NAFTA region. It was used also in some process of the calibration of the A-ECMS and so it is expected to have a good performance:

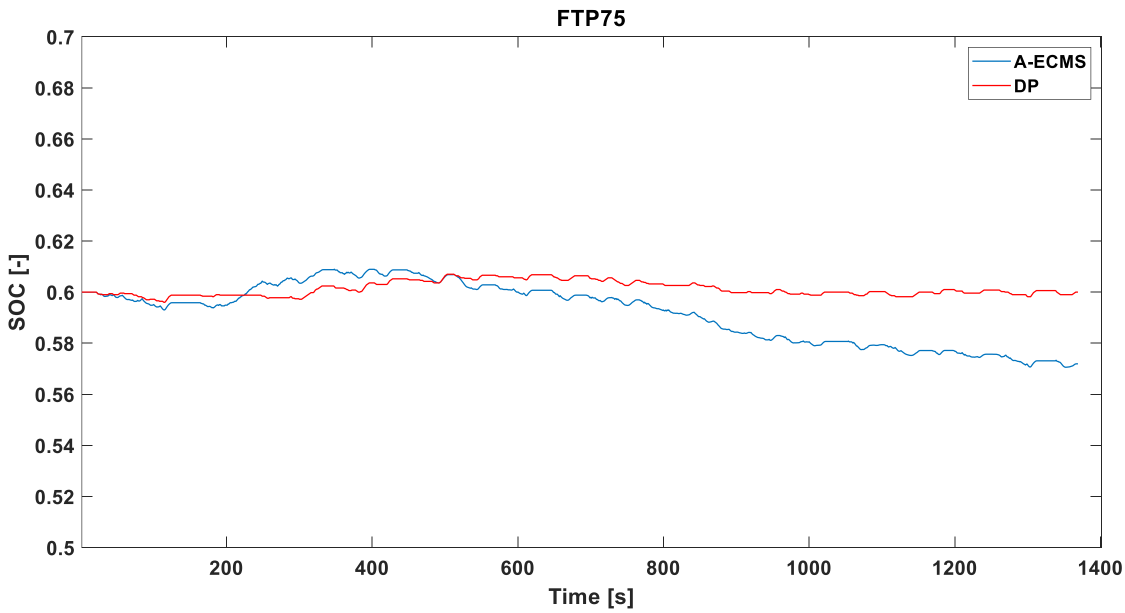

Figure 22: FTP75 SOC compare

And the table of the main results:

$FC_{A\text{-}ECMS}$ [kg]	FC* [kg]	FC_{eq} [kg]	FC DP [kg]	CO_2 [g/km]	$SOC_{A\text{-}ECMS}$ [-]
1.64	0.11	1.75	1.49	415.67	0.57

Table 8: Main results FTP75 cycle

The SOC trace of A-ECMS follows the DP one, except in the last part where the equivalence factor is lower and there is an excessive usage of the battery, anyway, staying in the charge sustaining window. As regard fuel consumption could be noted that is comparable to the benchmark one.

6.6 Resuming table

Below is reported a resuming table for all the cycles described in the present section

Cycle	$FC_{A\text{-}ECMS}$ [kg]	FC* [kg]	FC_{eq} [kg]	FC DP [kg]	CO_2 [g/km]	Final SOC [-]	Delta FC [Kg]
WHVC	3.36	-0.08	3.28	2.52	502.80	0.62	0.76
J1015m	0.45	0.08	0.53	0.39	324.65	0.58	0.14
NEDC	1.43	0.08	1.51	1.20	403.83	0.58	0.31
FTP	1.64	0.11	1.75	1.49	415.67	0.57	0.26

Reading the table is clear that the implementation A-ECMS gives as output good results both in terms of Fuel Consumption and CO_2 being, in all the cases analysed, very close to the benchmark solution and always below 1 kilogram of fuel of delta.

The A-ECMS is promising also in terms of final SOC reached, that allows the powertrain to work in Charge sustaining mode.

7 CONCLUSIONS

The aim of this final chapter is to sum up the steps done in this thesis, analysing and discussing the results, and giving possible future developments about this theme.

Starting point is to identify and characterize all the functionalities of the architecture studied: a commercial vehicle equipped with P2 hybrid powertrain with diesel and electric propulsion.

The second step is describing the model used to represent in a MATLAB environment the vehicle identified in the first step. This step includes a description of all the main functionalities of the MATLAB code.

The core of the thesis is the controller implementation: after an introduction about the state of the art concerning controllers, have been described all the main hypothesis behind and steps towards the implementation of the A-ECMS code: from the target equation used to the procedure of calibration of functional parameters such as equivalence factor and adaption period.

The final step is the validation of the hypothesis, testing the code across the main homologation cycles used all over the world such as the NEDC, J1015m, WHVC and FTP75 and comparing the results obtained with the best possible solution; obtained by running the same cycle with the Dynamic Programming optimization method.

Results are very promising; it is possible to see how the A-ECMS is close to the Dynamic Programming solutions: in most of the cases the SOC variation across the mission identified by the A-ECMS has a trend similar to the optimal solution one. This is reflected also in the final CO_2 and Fuel Consumption results that shows variation of about 20% with respect to the optimal solution proposed by the A-ECMS. In particular, it is important to notice the capability of the controller to stay in the SOC boundaries of charge sustaining in every cycle analysed: this is fundamental for a real-life application in which the mission is never known by the controller a priori.

A-ECMS with SOC feedback control is a good trade-off between low computation power required and optimality of results: a further step towards an higher accuracy of results is to integrate the controller, other than parameters intrinsic to the vehicle such as the fuel mass flow rate and the SOC state used in the present study, with inputs coming from sources external to the vehicle. As an example, the controller may be integrated with the GPS signal that today is compulsory to all new vehicle sold: this is possible also thanks to the lower and lower dimension to computational power ratio of newer processor available in the market that can be suitable for automotive application.

One last step, currently under study and development by almost all the OEMs, could be the implementation of AI, Artificial Intelligence, controller to automotive industry: by mean of machine learning the controller could forecast the usual driving mission of the user, could receive and elaborate inputs coming from GPS and traffic condition and chose the best possible optimization strategy for the hybrid architecture, also considering the user driving style and habits.

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