DESIGN OPTIMIZATION OF POWERTRAINS FOR FULL AND PLUG-IN HYBRID ELECTRIC DELIVERY VANS

A PROJECT REPORT

Submitted by

MAATOUK MAYA

in partial fulfillment for the award of the degree

of

MASTER'S DEGREE

in

MECHATRONIC ENGINEERING

DEPARTMENT OF AUTOMATIC AND COMPUTER SCIENCE

POLITECNICO DI TORINO

October 2021

ABSTRACT

In order to improve the fuel economy and to satisfy the customer acceptance constraints, Hybrid Electric Vehicles (HEVs) were introduced in the market. By integrating an internal combustion engine and an electrical system (one or more electric motor/generators (MGs) and a battery) in the powertrain, HEVs can combine the benefits of electrical vehicles and conventional internal combustion engine vehicles.

In this research project, the problem of optimizing the design of parallel P2 full and plug-in HEVs powertrain was addressed considering as test vehicle the Fiat Ducato delivery van. The exploration of the design space is done using a brute force, by varying only two design parameters and fixing the others (the 7 design parameters are: engine power scale, hybridization factor, battery capacity and gear ratios), the best candidates which are the best design solutions for our hybrid delivery van are identified based on multiple performance objectives: the fuel consumption, battery energy consumption, CO2 emissions, total cost and 0-100km/h acceleration time test.

We used as control algorithm to accelerate the prediction of the fuel economy the near-optimal off-line control algorithm known as SERCA algorithm starting from a vehicle model implemented in MATLAB software and various predefined drive missions. Then the particle swarm optimization algorithm was employed to calculate the best CO2 emission minimization and best total cost.

ACKNOWLEDGEMENT

I would like to express my special thanks of gratitude to my project guide Prof. ANSELMA Pier Giuseppe as well as our principal Prof. BELINGARDI Giovanni who gave me the golden opportunity to do this wonderful project on the topic 'DESIGN OPTIMIZATION OF POWERTRAINS FOR FULL AND PLUG-IN HYBRID ELECTRIC DELIVERY VANS', which also helped me in doing a lot of research and I came to know about so many new things I am really thankful to them.

Secondly, I would also like to thank my parents and friends who helped me a lot in finalizing this project within the limited time frame.

Table of Contents

List of figures

List of tables

Definitions, Acronyms, Abbreviations

HEV- Hybrid electric vehicle

EV- Electric vehicle

BEV- Battery electric vehicle

MG- Motor/Generator

EM- Electric motor

ICE- Internal combustion engine

ZEV- Zero-emissions vehicle

PHEV- Plug-in hybrid electric vehicle

CS- Charge sustaining

CD- Charge depleting

eVT- Electrically variable transmission

SGT- Stepped gear transmission

SERCA- Slope weighted energy based rapid control analysis

DP- Dynamic programming

PSO- Particle swarm optimization

AT- Automatic transmission

FD- Final drive

SOC- State-of-charge

HIL- Hardware in the loop

EMS- Energy management strategy

PMP- Pontryagin's minimum principle

PEARS- Power-weighted efficiency analysis for rapid sizing

EECRS- Efficiency evaluation real-time control strategy

GA- Genetic algorithm

DIRECT- Divided rectangles

CO- Convex optimization

SQP- Sequential quadratic programming

Kg- Kilogram

m- Meter

L- liter

N- Newton

h- Hour

Km- Kilometer

WLTP- Worldwide harmonized light vehicles test procedure

NREL Baltimore- National renewable energy laboratory Baltimore drive cycle

Chapter 1

Introduction

1.1-Background:

For decades, the automotive industry has been concerned about dwindling natural resources such oil and gas, as well as noise and hazardous exhaust emissions. Car makers have been under constant pressure to resolve these issues by developing new vehicles platforms with lower fuel consumption and emissions.

1.1.1-Electric vehicles:

Electric vehicles (EVs) were introduced as a feasible alternative to gas-guzzling, noisy internal combustion engines (ICEs). EVs eliminate the need for direct fossil-fuel usage and emits no noise, or tailpipe emissions by relying solely on electrical energy from the battery system for power. Despite these benefits, EVs have yet to make a substantial influence on global vehicle markets, which are still dominated by traditional ICE vehicles. This is largely due to the expensive cost of electric vehicles and their restricted range.

As a result, vehicle manufacturers have had to build platforms that can effectively bridge the gap between ICE and zero-emissions (ZEV) vehicles, functioning as transition technologies until the EVs can more completely infiltrate the consumer market. As they work to resolve these flaws. Full and plug-in HEVs are the product of this endeavor.

1.1.2-Hybrid electric vehicles:

HEV is a transitional solution that combines technologies from both the EV and ICE platforms by integrating electric motors from the EV with an internal combustion engine from conventional vehicles to provide an alternative source of energy for vehicle propulsion. Therefore, the electric system embedded in HEV powertrains makes them more efficient than traditional vehicles since it assists the engine in functioning in its most efficient range, such as allowing it to charge the battery using excess power or turn the engine off during idling time leading to a lower fuel consumption. Additionally, energy lost while braking can be recovered and used to charge the batteries. All of these benefits contribute to increase fuel efficiency. While HEVs cannot run solely on electricity and must consequently burn some fuel, they can be considered a viable mid-term alternative until zero-fuel, zero-emissions EVs are fully achieved.

1.1.3-Plug-in hybrid electric vehicles:

A plug-in hybrid electric vehicle is a HEV whose battery can be charged externally from the electric grid. This type of architecture is characterized by two distinct battery operation modes: charge sustaining (CS mode) and charge depleting (CD mode). PHEVs have greater battery capacities than full HEVs, allowing them to travel further on electric mode. As a result, plug-in HEVs combine the advantages of HEVs and EVs, which make them the best solution on the automotive market today.

According to the position of the power components and the type of transmission embedded in the powertrain we can define different categories of HEV powertrain architecture:

1.1.4-HEV powertrain architectures:

Full and Plug-in HEVs powertrains embed four main components: an ICE, an electric motor, a generator and a battery pack. These components can be connected to each other in many different ways, depending on the division of power between the sources; however, the three configurations typically seen in HEVs/PHEVs are series, parallel and power split.

A. Series architecture:

The generator and battery are connected to the electric motor in series architecture (Figure 1), which pushes the vehicle by itself. In this system, the ICE works in tandem with the generator to charge the battery or power the electric motor. At lower speeds, the series design is more efficient, making it ideal for city driving.

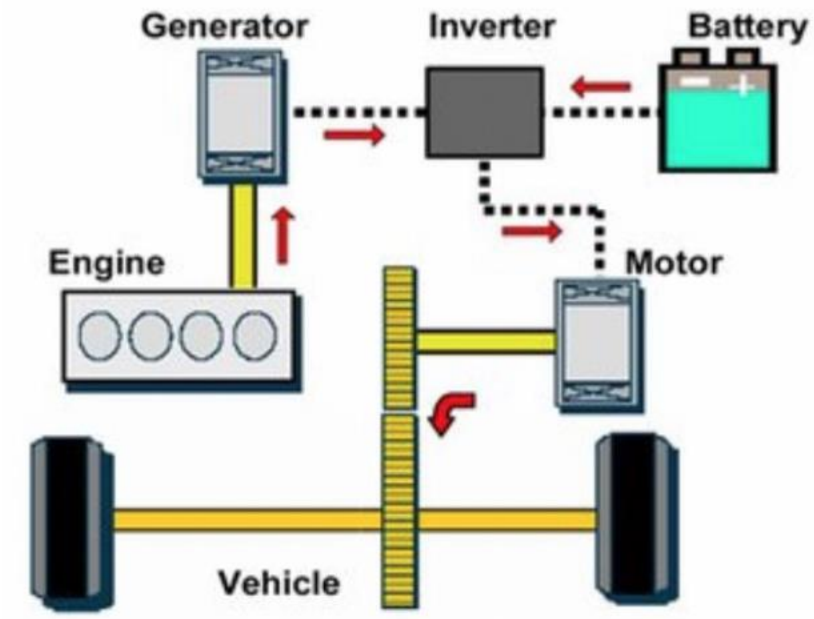


Figure 1- Series HEV configuration [37]

B. Parallel architecture:

In parallel configuration (Figure 2), both the ICE and the electric motor are connected to the transmission, which can drive the wheels at the same time. As a result, this setup is suitable for highway driving at greater speeds.

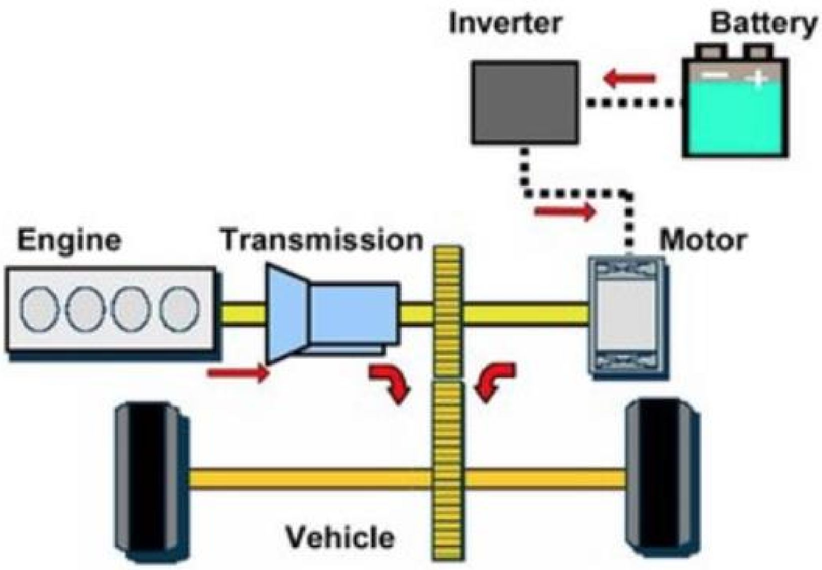


Figure 2-Parallel HEV configuration [37]

C. Power split architecture:

The power-split configuration (Figure 3) combines the advantages of series and parallel architectures, making it the most efficient but also the most difficult to design. The transmission is a planetary gear, and the electric motor, generator and ICE are connected to the ring, sun and carrier gears, respectively.

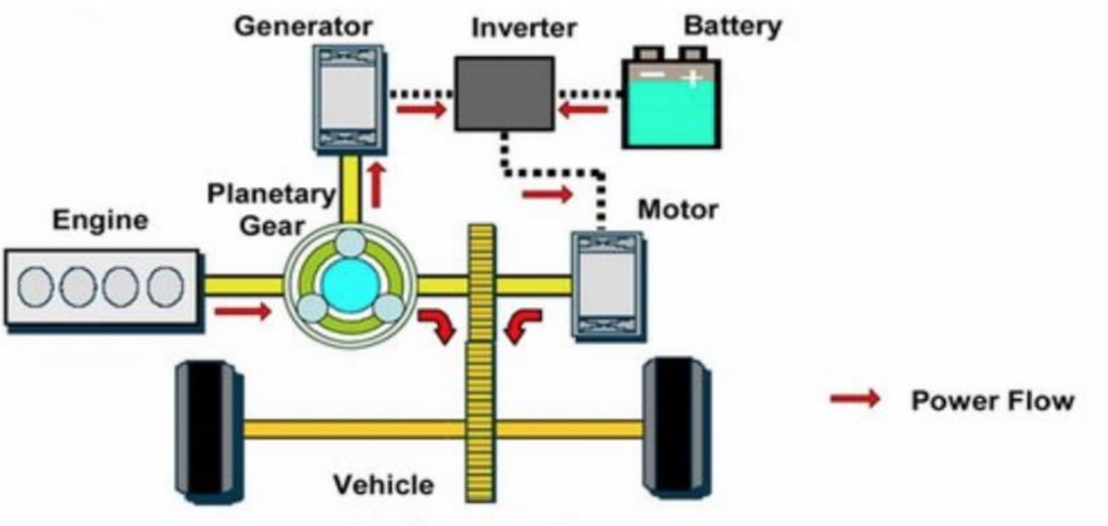


Figure 3- Power split HEV configuration [37]

1.1.5-Electric motor(s) positions in the powertrain:

One or more electric motor/generator (MGs) can be added to the powertrain at the positions specified by the designers, these positions are [1]:

-P0: MG is located upstream the ICE (belt-driven)

-P1: MG is located downstream the ICE (keyed directly onto the same shaft)

-P2: MG is located between the ICE and the transmission gearbox (being linked through clutch connections)

-P3: MG is located between the transmission gearbox and the final drive
-P4: MG is located separately from the ICE in the rear axle (that performs as pure electric driven axle)

1.1.6-Transmission technologies:

HEVs may be categorized into electrically variable transmission (eVT) and stepped gear transmission (SGT) kind.

eVT HEVs are primarily based on planetary gear sets composed of a ring gear, a sun gear and a carrier, which permits decoupling of the ICE rotational speed from the vehicle linear speed, hence increasing fuel economy potential through increased operational flexibility [2,3].

SGT HEVs, on the other hand, are equipped with an ICE, a clutch, gearbox and a final drive-in sequence, which preserves the normal structure of road vehicle drivetrain [4].

1.1.7-Degree of hybridization:

HEVs can be micro, mild, full or plug-in hybrids depending on the powertrain electrification. Micro and mild hybrid vehicles have the least degree of hybridization. Known as start-stop vehicles, micro vehicles turn off the car engine when it comes to a stop and then restart when the driver commands. The battery has been upgraded to allow for this large number of starts due to the intense operation. Beyond start-stop operation, mild vehicles use regenerative braking to recharge the battery from the vehicle's kinetic energy, allowing the electric motor to work in tandem with the combustion engine to supply power to the vehicle.

Full and plug-in hybrid vehicles have the maximum degree of hybridization. The battery should be able to pull the car without the help of the ICE in both cases. The difference between both technologies is the ability to recharge the battery from an outlet, which means that electricity can be supplied to the accumulator from a source outside the car [5].

1.2-Objective:

Growing environmental concerns have compelled all governments in the world to enact new, far-reaching restriction that will result in automobiles that are more fuel efficient and emit less pollutants in the near future. Therefore, automakers are under constant pressure to reduce the fuel consumption of their vehicle fleets. Electric vehicles (EVs) technologies are good answer to these standards, but they have significant drawbacks that limit costumer appeal, especially cost and driving range. Thus, discovering new ways to reduce fuel consumption is constantly a priority for automotive researchers and manufacturers. Consequently, this research has attempted to reduce fuel consumption as much as possible in full and plug-in HEVs, in particular the parallel P2 Fiat Ducato delivery van.

There are several options for achieving this goal. One strategy, and the one used here, is to size the HEV's primary components in such a way that they consume the least amount of fuel while retaining adequate vehicle performance. A vehicle model and an optimization algorithm are prerequisites for optimizing the size of components.

For modelling, the well-known backward quasi-static approach is used to model our test vehicle with Fiat Ducato characteristics, and for what concerns the power components, they are modeled through their empirical operational lookup tables.

We used to estimate fuel economy the SERCA algorithm by driving the vehicle through standard drive cycles, in our case study we used WLTP and NREL Baltimore cycles. And for the optimization of the HEV design firstly we use a brute force method, by exhaustively exploring the design space (fixing five parameters and varying only two) and comparing the obtained results, to see the effect of each component parameter on the fuel economy, battery energy consumption, CO2 emission, 0-100km/h acceleration time and total cost to end up with the best configurations that satisfy our requirements. Secondly, we used as a search algorithm to find the best powertrain design ensuring the lowest CO2 emission and the least total cost respecting some performance requirements the derivative free algorithm which is the Particle Swarm optimization (PSO).

1.3-Outline:

The content of this thesis is divided into five chapters. Chapter 1 presents a brief introduction to the hybrid vehicles and the general goal of this study, this chapter is followed by Chapter 2 which provides a review of the literature relating to the modeling, control and sizing optimization of HEVs. Chapter 3 describes the modeling of the parallel P2 HEV, as well as the control utilized for fuel economy prediction. In Chapter 4, the sizing of the powertrain components is addressed by using first an exhaustive search and then applying PSO algorithm. Finally, the overarching conclusions that can be drawn from this research are outlined.

Chapter 2

Literature review

HEVs are currently a profitable technology that can help customers meet their needs while also complying with stringent CO2 emission rules around the world. Nonetheless, compared to both conventional vehicles (i.e., those powered exclusively by an internal combustion engine (ICE)) and battery electric vehicles (BEV), HEVs have a substantially more difficult design environment, involving hundreds of design parameters.

As a result, each parameter must be carefully selected at the design stage to achieve better HEV performance. Because prototyping and testing each design combination is costly and time-consuming, optimization algorithms and simulation techniques that simplify validation operations are essential for attaining optimal component sizing at a low cost.

This chapter present some challenges related to modeling, control and design optimization of HEVs.

2.1-Powertrain modeling:

Different types of physics-based dynamic modeling or empirical modeling (using look-up tables or maps) can be used to construct a HEV model, depending on the level of details required. Nevertheless, there is a trade-off between model quality and runtime; greater fidelity models, which more accurately capture a system ‘s behavior, often take longer to compute and simulate. Having said that, a model should always be built with enough accuracy to address the intended application and goal. The evaluation of a control plan, for example, necessitates a more fidelity and detailed model. There are three types of models: steady state, quasi-static and transient [6]. Transient models offer more features and dynamical information for the components considered than steady state models, while quasi-static models are middle between the two. Fully detailed transient modeling is typically employed in real-time and HIL simulations, and it takes longer to compute.

Models can be split into backward and forward categories from another standpoint. The driving cycle is the input for a backward model, which assumes the model follows it exactly. As a result, the model assumes that the vehicle speed and acceleration are known beforehand and estimates the required power. Backward modeling is commonly used in steady-state models [6].

Because of its simplicity and quick computation time, backward modeling is an excellent method for sizing components.

Forward modeling tries to imitate real-world driving; hence it takes longer to simulate. These models receive the driver's acceleration and braking commands as input and output the vehicle's performance.

The MATLAB/Simulink environment is used by many of the tools and simulation packages developed for car powertrain modeling. Other modeling simulators on the market include ADVISOR, V-Elph, MapleSim, PSAT and Autonomie. Each offers a user-friendly setting [7,8,9].

As a result, work on HEV modeling can be classified according to which simulation tool was used, what type of architecture was addressed, and which components were modeled. In terms of model fidelity, however, it can be stated that the tendency is toward constructing models that contain sufficient information and depth while yet requiring short simulation periods.

2.2-HEV control:

The fuel efficiency potential of HEV design alternatives is explored in early vehicle development phases by using HEV powertrain energy management strategies. The chosen energy management algorithm then optimizes the powertrain operations (e.g., number of gears engaged, torque split) to forecast the optimal fuel consumption value. A successful HEV energy management strategy (EMS) should also show the ability to efficiently produce acceptable hybrid powertrain drivability and comfort behavior. HEV control can be classified into two types: off-line and online controls, based on whether the future driving missions are known a priory or not.

Major evolutions in on-line control can be divided into three categories; the enhanced calibration or rule-based strategies (both heuristic and fuzzy-logic based) based on off-line optimization processes [10,11,12,13], the development of battery state -of-charge adaptive control strategies, usually ECMS-based [14,15,16], and the first adoption of machine learning techniques to optimally control HEVs [17,18,19,20,21,22,23,24].

As what concern the off-line HEV control, we have two different approaches to solve this control, known as global optimal control and rapid near-optimal control. Both global optimal control and rapid near-optimal control begin by exploring all feasible sub-solutions (which are the control actions) for each sub-problem (time instant) of the maintained driving cycle. While the former can produce a global optimal solution via an exhaustive search that is typically computationally expensive, the other can rapidly obtain a heuristic approximation of the global optimal solution.

Dynamic Programming (DP) is currently the most widely used method for obtaining a global optimal solution for the control problem. DP is an exhaustive search algorithm that finds the best solution using a discretized state vector, backward induction and the Bellman equation [25]. One of the most significant disadvantages of DP is its high computational cost. To get around this limitation, scientists and researchers have recently been inventing near-optimal algorithm capable of approaching the global optimal solution obtained by DP while also reducing the required computational cost. The Pontryagin's Minimum Principle (PMP), which executes a local optimization using a dual-term cost function, is one of the most well-known near-optimal HEV control in this context [26]. Zhang et al. in 2013 [27], Qin et al. in 2018 [28], and Anselma P., Biswas A., Belingardi G. and Emadi A. [4,29], respectively, introduced three additional rapid near optimal HEV off-line control techniques: the power-weighted efficiency analysis for rapid sizing (PEARS), the efficiency evaluation real-time control strategy (EERCS) and the slope-weighted energy based rapid control analysis (SERCA). The SERCA algorithm is an improved version of the PEARS algorithm which inherited from it the iterative electric-to-hybrid replacement process. These algorithms have been demonstrated generating results closer to DP and remarkably reduce the corresponding needed time to estimate the fuel consumption [4].

2.3-Powertrain component sizing methodology:

The following is a summary of efforts to optimize HEV component sizing. The components evaluated, the objectives pursued, the optimization methods employed can all be described as part of this field's work.

2.3.1-Powertrain components:

The goal is to size the essential powertrain components, the engine, the electric motor, the battery and the transmission, such that they can meet the vehicle's requirements throughout a variety of driving scenarios, such as braking, accelerating and cruising.

2.3.2-Design space exploration:

When looking at numerous aspects of the transportation industry, it becomes evident that one powertrain may not be the best option in every circumstance. When choosing the component sizes for the HEV powertrain, we must strike the best trade-off between fuel economy, drivability, and vehicle cost. The process of determining the best powertrain configuration is known by design space exploration, which is commonly framed as a multi-objective optimization problem [30].

The design space exploration method starts by defining an initial large design space which contains all the possible component sizes. After that, each of the HEV configuration is evaluated against some performance requirements and the design space is reduced to contain only the feasible solutions that satisfy these requirements. Then the fuel economy prediction is evaluated for these feasible candidates to end up with the best design solution [31].

2.3.3-Optimization algorithms:

Three main approaches used to solve the design optimization problem [30]:

- Exhaustive search
- Derivative-free algorithms: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Divided rectangles (DIRECT), and Nelder-Mead Simplex algorithm
- Gradient-based algorithm: Convex optimization (CO) and sequential quadratic programming (SQP).

Evolutionary methods are used to explore the design space described by the objective and constraint function and determine a point(s) that maximize or minimize the design criteria.

Exhaustive search is a simplistic but time-consuming approach because the design space grows exponentially with the number of components that are optimized. When gradient-based optimization algorithms, such as the well-known SQP algorithm, rely on erroneous gradient information to establish search paths and convergence, they can get into troubles. These issues can be addressed using derivative-free optimization techniques.

Chapter 3

Powertrain modeling and HEV control

This chapter describes the HEV layout used in this study which is the single motor parallel P2 as well as the modeling approach used to present it and the control used to estimate the fuel economy potential.

3.1-Powertrain modeling:

3.1.1-Parallel P2 HEV:

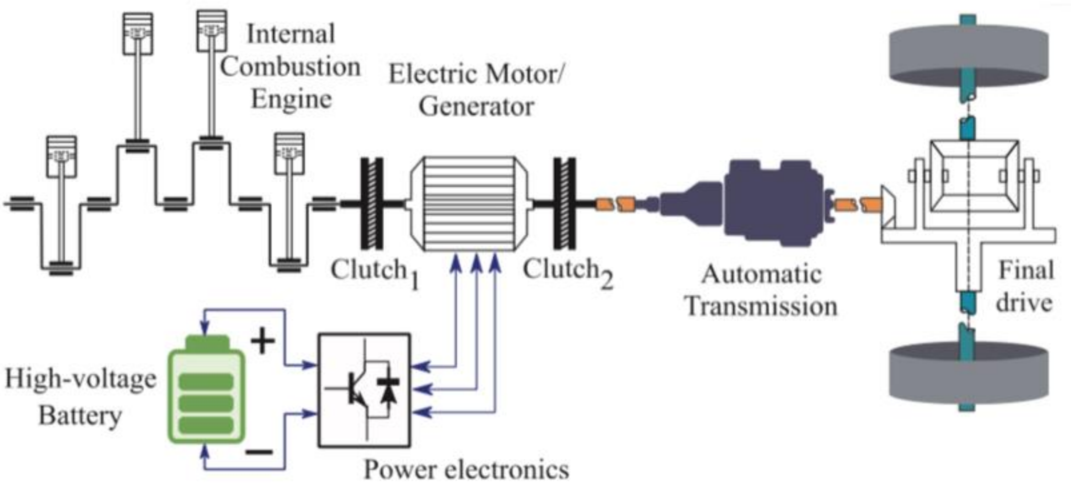


Figure 4- Parallel P2 HEV layout [4]

We can see from Figure 4 that illustrates the parallel P2 HEV layout that the torques provided by the ICE and the MG are related by the following equation:

$$T_{ICE} + T_{MG} = T_{AT} \tag{1}$$

Where T_{ICE} ,T_{MG} and T_{AT} are the ICE torque, the MG torque and the torque at the input shaft of the automatic transmission, respectively.

Clutch1 is responsible for connecting the ICE to the driven wheels and allowing engine cranking actions, while Clutch2 is responsible for enabling the gear shifting in the automatic transmission.

In this HEV architecture we can distinct 3 different operating modes, called pure electric, torque assist and battery charging modes. These three operating modes are enabled depending on the state of ICE, if it is activated and is propelling the vehicle or not and depending on the T_{ICE} value.

In pure electric mode, Cluch1 is disengaged and the ICE is turned off, in this case we don't have a torque from the engine and then the torque at the input of the AT is equal to the MG torque meaning that the MG is only power source propelling the vehicle. In the torque assist mode, Clutch1 is engaged, the ICE and MG torques are both positive and the torque provided to the AT shaft is the sum of them. In battery charging mode, the torque provided by the engine is higher than what is requested by the driver, in this mode the MG operates as generator to absorb the excess of torque and charge the battery [4].

3.1.2-HEV modeling approach:

The well-known backward quasi-static technique is used to model our HEV architecture in this research. The vehicle model is supposed to follow the predetermined simulated driving mission velocity profile v(t). The traction force required at the wheels is calculated as follows [30]:

$$F_{trac} = F_{roll} + F_{misc} + F_{aero} + m_{veh_{eq}}(n_{gear}).a$$

With:

$$F_{roll} = m_{veh}.g.f_0$$

$$F_{misc} = m_{veh}.g.\sin(\alpha) + k.v$$
$$F_{aero} = \frac{1}{2}.\rho.S.C_x.v^2 \quad (2)$$

F_{roll}, F_{misc}, and F_{aero} represent resistive load terms provided by the rolling resistance, some miscellaneous terms (e.g., transmission losses, side forces, road slope) and the aerodynamic drag, respectively.

a is the acceleration or deceleration of the vehicle as requested at each time instant of the driving mission [4].

m_{veh} is the vehicle mass and $m_{veh_{eq}}$ is vehicle equivalent mass which considers both the inertia of the powertrain rotating components (wheels, shafts, ICE and MG) and the value of the gear ratios for the gear engaged n_{gear}.

ρ, g and α are the air density, the gravity's acceleration and the road slope, respectively.

f_0, k, S and C_x stand for the rolling force coefficient, a miscellaneous loss coefficient, the frontal area of the vehicle and the drag coefficient, respectively.

The traction force is limited by the wheel friction coefficient in the contact patch. Then, the maximum friction force that allows traction is:

$$F_f = m_{veh} * g * \mu * c_1 \quad (3)$$

Where μ and c_1 are the friction coefficient and front wheel load coefficient (our test vehicle is front drive wheel), respectively.

The wheel torque is calculated as:

$$T_{wheel} = r_{wheel}.F_{trac} \quad (4)$$

Where r_{wheel} represents the wheel effective ratio.

The torque at the input shaft of the automatic transmission T_{AT} can then be obtained by evaluating the torque balance between the automatic transmission's input and output [4]:

$$T_{AT} = T_{out}.\frac{i_{FD}.i_{n_{gear}}}{(\eta_{FD}.\eta_{AT})^{sign(T_{out})}} \tag{5}$$

η_{FD}, η_{AT} represent the efficiency values for the final drive and the AT gearbox respectively, and they are considered constant in our study and are powered to the output torque sign to distinct between propelling and braking cases.

And the gear ratios of the final drive and the engaged gear number are presented by i_{FD} and $i_{n_{gear}}$ respectively.

For what concern the modelling of the power component, they are modeled using empirical lookup tables. The ICE fuel consumption and the electrical losses for the MG are represented by the fuel map and the electric loss tables, respectively, with torque and speed as independent variables.

The related variation in the state-of-charge (SOC) is calculated when the total amount of electrical power exchanged between power components and battery is determined (P_{batt}). By using an equivalent open circuit model for the battery, $S\dot{O}C$ can be derived as follow:

$$S\dot{O}C = \frac{V_{OC}(SOC) - \sqrt{V_{OC}(SOC)^2 - 4.R_{in}(SOC).P_{batt}}}{2.R_{in}.Q_{batt}} \tag{6}$$

R_{in} and V_{OC} represent the internal resistance and the open-circuit voltage of the battery, respectively, both are function of the current battery state-of-charge value according to empirical lookup tables. And Q_{batt} is the battery capacity (in ampere-second).

The backward quasi-static approach's key advantage is its computing efficiency. As a result, this approach is used in the early stage of the HEV architectural selection and powertrain design process. Indeed, including transient events and high-fidelity powertrain models in the preliminary HEV analysis would significantly raise the computational cost. The MATLAB software is used in this study to implement both the indicated vehicle and powertrain model as well as the HEV control techniques.

3.2-HEV control:

3.2.1-HEV off-line control:

Off-line control is often used to examine the behavior of HEV architectures and sizing candidates in a variety of pre-determined driving scenarios. This is how the fuel economy capabilities of each design choice is determined. The problem of HEV off-line control can be stated as follows [4]:

$$\min \{ J = \int_{t_0}^{t_{end}} L(t)dt \}$$

With:

$$L = \dot{m}_{fuel} + \alpha_1.ICE_{start} + \alpha_2.gear_{shift}$$

Subject to:

$$n_{gear_{min}} \leq n_{gear} \leq n_{gear_{MAX}}$$

$$\omega_{ICE_{min}} \leq \omega_{ICE} \leq \omega_{ICE_{MAX}}$$

$$T_{ICE_{min}} \leq T_{ICE} \leq T_{ICE_{MAX}}$$

$$\omega_{MG_{min}} \leq \omega_{MG} \leq \omega_{MG_{MAX}}$$

$$T_{MG_{min}} \leq T_{MG} \leq T_{MG_{MAX}}$$

$$S\dot{O}C = f(SOC, \omega_{MG}, T_{MG})$$

$$SOC_{min} < SOC < SOC_{MAX}$$

$$\text{In case of full HEV: } SOC(t_0) = SOC(t_{end}). \tag{7}$$

Where L is the instantaneous cost function to minimize, that includes the instantaneous fuel consumption rate $\dot{m}_{fuel}$ given by the ICE fuel table and the two terms representing the ICE activation and gear shifting events which are ICE_{start} and $gear_{shift}$ respectively. α_1 and α_2 are constant weighting factors.

In case of Full HEV, and in order to achieve the charge sustained powertrain operation, equal battery SOC values are imposed at the start and the end of the considered driving mission, while in Plug-in HEV powertrains, the vehicle has two different battery operation modes, i.e., charge depleting (CD) where the battery SOC decreases to the minimum SOC called CS SOC (as battery only operation) and charge sustained (CS) mode as in the Full HEV case. When the introduced control problem is solved, the evaluation of control actions connected with the specific HEV configuration is determined through time. These control actions are related to the control variables values. The control variable set U_{P2} of our parallel P2 HEV layout is:

$$U_{P2} = \begin{pmatrix} n_{gear} \\ T_{ICE} \end{pmatrix} \tag{8}$$

We used for solving the illustrated control problem a rapid near-optimal control called SERCA algorithm which will be illustrated in the next paragraph.

3.2.2-SERCA algorithm:

This paragraph briefly describes the SERCA algorithm [4], which was created to improve the fuel efficiency prediction of parallel P2 HEV layouts.

The SERCA algorithm is divided into 3 main steps which are:

-The exploration of sub-problems (time instants)

-The identification of the optimal operating points

-The achievement of the charge sustained mode

SERCA works by iteratively replacing the pure electric operation with the hybrid operation in the most convenient time instants of the drive cycle defined beforehand, where the optimal operating points are determined by maximizing the slope between the recharged battery energy and the corresponding instantaneous fuel consumption, until the charge sustained battery operation is achieved. The SERCA algorithm receives as input the vehicle parameters, HEV powertrain components and driving mission, and outputs the estimated fuel consumption and the time histories of control variables and vehicle states. The workflow of the SERCA is shown in the figure bellow:

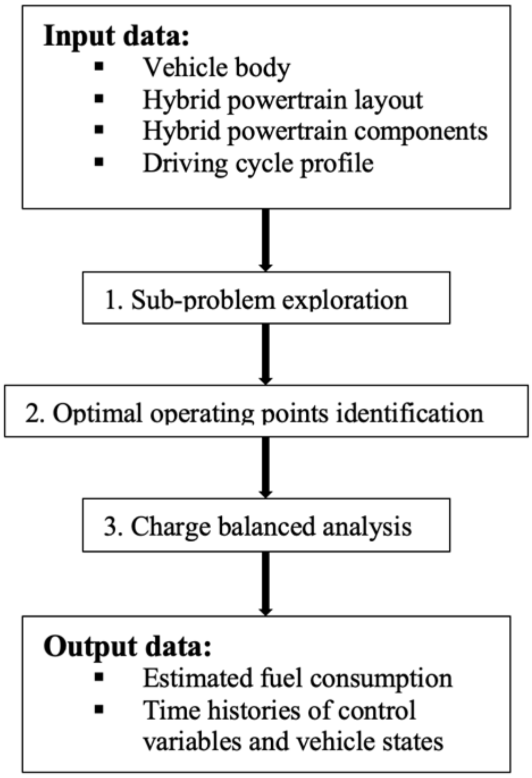


Figure 5- Workflow of SERCA algorithm

Chapter 4

Simulation and Results

HEVs are an important step forward in the global transition to electric transportation. Nonetheless, in comparison to both traditional ICE and battery electric vehicles, they have a fairly complex design environment. where the component sizing is typically a difficult and time-consuming undertaking. To effectively handle the rising complexity of HEV development processes, innovative and advanced design tools are necessary.

In this research, sizing parameters for a parallel electrified powertrain are considered including the internal combustion engine size, the electric motor/generator size, the transmission ratios, number of gears in the gearbox, the final drive ratio and the battery capacity. And the SERCA algorithm is used here to rapidly assess each size option’s fuel economy capability in a variety of driving cycles, considering the WLTP and the NREL Baltimore drive cycles in our study. While searching for the optimal sizing possibilities, the implemented sizing methodology integrates drivability criteria along with the fuel economy potential, which is the 0-100km/h acceleration time test.

4.1-Baseline data and sizing parameter:

We start our work from baseline data (Table 1) of a Fiat Ducato delivery van which are the data of the vehicle that will not be changed, a baseline engine that we can scale it linearly up and down in order to have different powers, a baseline electric motor which could also be linearly scaled, and the characteristics of cells in a battery pack where the battery capacity is varied according to the number of cells.

Table 1- Baseline data of the vehicle under study

component	parameter	Value
vehicle	Mass (baseline)	2100 Kg
	Wheel dynamic ratio	0.3306 m
	Curb cost	20000 USD
ICE	Capacity	2.3 L
	Maximum power	90 kW
	Maximum torque	320 Nm
Transmission	Efficiency	0.9
MG	Maximum power	72 kW

And the considered design parameters that form the design space are presented in Table 2 with their limits, which will be varied in order to end up with the best HEV design that ensure the best trade-off between fuel economy capability, CO2 emission, total cost, and 0-100km/h acceleration time.

Table 2-HEV sizing parameters and their limits

parameter	Min value	Maximum value
Total ratio (ratio_tot)	3	6.5
Gear number (number_gears)	2	6
Final drive ratio (diff_prim_ratio)	2.6	4.6
Ratio between EM and differential (gear_ratio_EM_to_trans)	0.5	4
Hybridization factor (hybridiz_factor)	0.35	1
Number of cells in the battery pack (but_num_serie)	500	10000
ICE power in kW (ice_power_scale)	50	300

4.2- 0-100km/h acceleration time test:

To accelerate the exploration of the design space, our candidates must guarantee a 0-100km/h acceleration time less than 9.7 sec, which it is also a mandatory drivability requirement.

To simulate the 0-100km/h acceleration time test, we have to do the opposite of the backward modelling approach because we need to calculate the velocity of the vehicle, and to do that we start by calculating the maximum output torque using the maximum torques that the ICE and the EM could provide.

$$T_{ICE} + T_{MG} = T_{AT}$$

Where T_{AT}, $T_{ICE}$and T_{MG} are the torque at automatic transmission input shaft, ICE torque and electric motor torque respectively.

Then the output torque is calculated by [30]:

$$T_{out} = T_{in} * \eta * \gamma. \tag{9}$$

Where η is the gear ratio and γ is the efficiency.
And we have:

$$T_{out} = \left(F_{roll} + F_{misc} + F_{aero} + m_{veh_{eq}} * a\right) * r_{wheels} \quad (10)$$

Where F_{roll} , F_{misc}, F_{aero} are the resistive forces, $m_{veh_{eq}}$is the vehicle equivalent mass, a the vehicle acceleration, and r_{wheels} is the wheels radius.
The acceleration of the vehicle is then:

$$a = \frac{T_{out} - T_{RL}}{m_{veh_{eq}} * r_{wheels}} \quad (11)$$

Where T_{RL}=$(F_{roll} + F_{misc} + F_{aero}) * r_{wheels}$ which is the road load torque.

After that the velocity is calculated by integrating the acceleration, so by iterating the procedure at each time starting by initial speed v_0=0 km/h and taking the time step t=0.1 sec until we reach the 100 km/h speed:

$$v = a * t + v_0 \quad (12)$$

And the 0-100km/h acceleration time is obtained.

To see the impact of each parameter on the 0-100km/h acceleration time, we vary one parameter while fixing the other ones.
By varying the ICE power scale and fixing the other 7 parameters (Figure 6) we remarque that by increasing it the 0-100km/h acceleration time decreases. And also, we have the same results by varying the total ratio (Figure 7), the gears number (Figure 8), final drive ratio (Figure 9), the ratio between EM and transmission (Figure 10) and the hybridization factor (Figure 11) but only in the case of the ICE power scale, ratio between EM

and transmission, and hybridization factor variation we can obtain a 0-100km/h acceleration time less than 9.7 sec because these parameters are related to the power component that are responsible of propelling the vehicle.

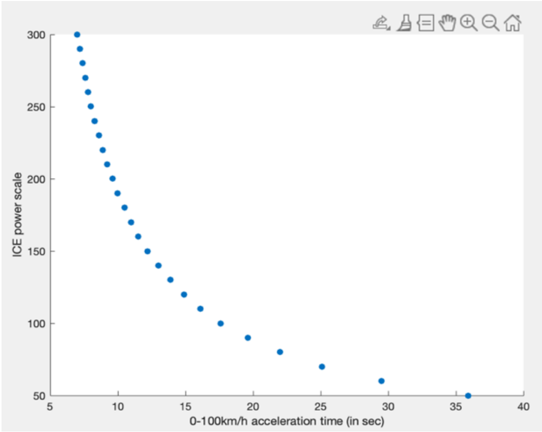


Figure 6-Variation of the ICE power scale in function of the 0-100km/h acceleration time

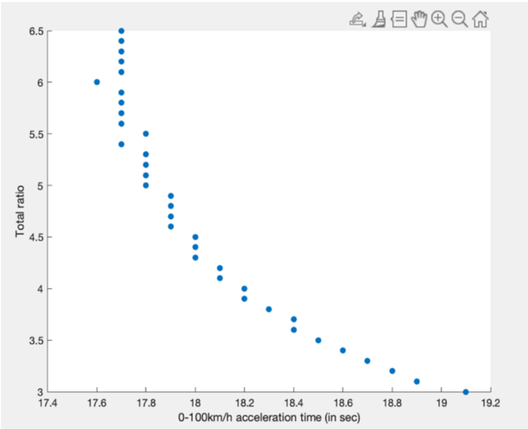


Figure 7-Variation of the total ratio in function of the 0-100km/h acceleration time

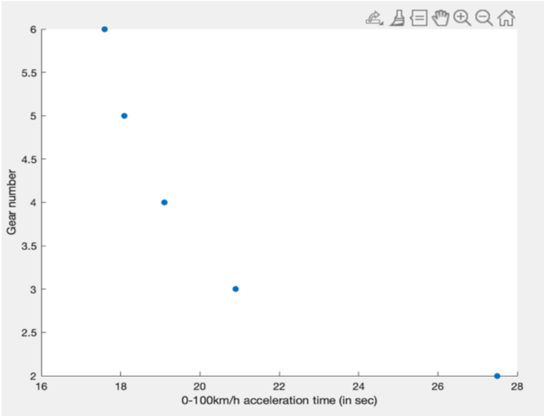


Figure 8- Variation of the gears number in function of the 0-100km/h acceleration time

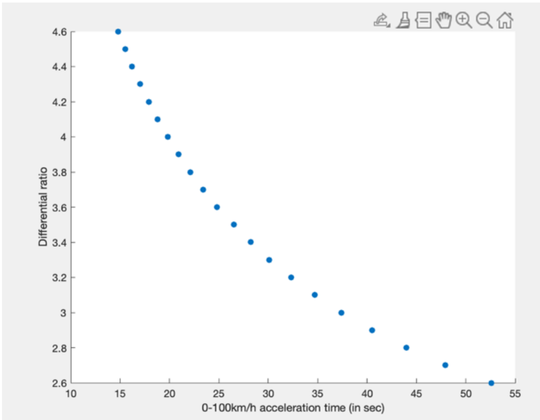


Figure 9- Variation of the final drive ratio in function of the 0-100km/h acceleration time

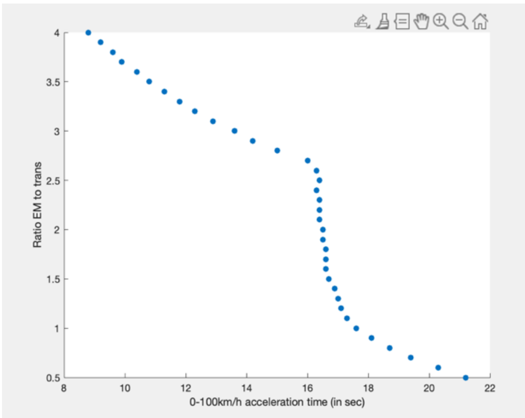


Figure 10- Variation of the ratio between EM and transmission in function of the 0-100km/h acceleration time

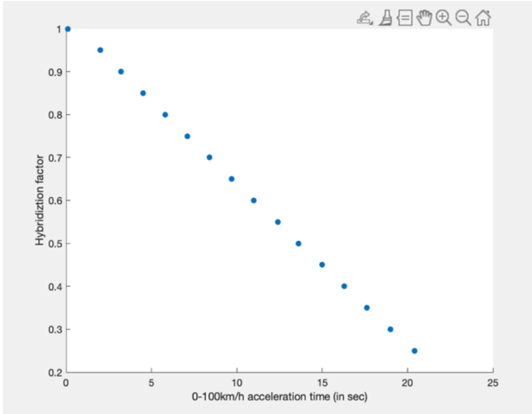


Figure 11-Variation of the hybridization factor in function of the 0-100km/h acceleration time

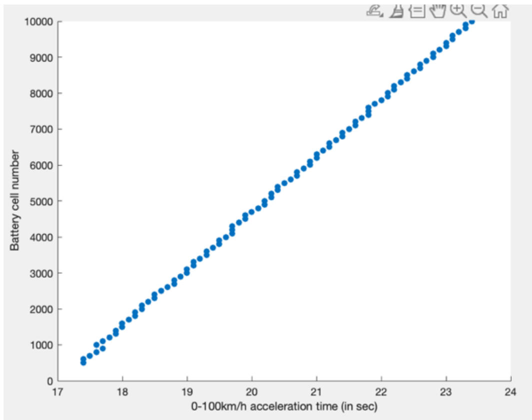


Figure 12- Variation of the battery cell number in function of the 0-100km/h acceleration time

In the case when we vary the number of cell in the battery pack (Figure 12), we remark that the 0-100km/h acceleration time increases by the increase of this parameter, because increasing the number of cells will increase the weight of the battery and thus the overall vehicle mass, making the vehicle need more time to accelerate.

As a result, for ensuring a 0-100km/h acceleration time less than 9.7 sec we should increase all the parameters except one which is the battery capacity.

4.3- Fuel consumption estimation:

Aside from drivability, the second key factor to consider while the evaluating size option is the fuel economy. Two driving missions for the parallel P2 HEV are addressed in this research, then using the SERCA algorithm, the fuel economy capabilities of each sizing option in each contemplated driving cycles is tested in charge sustaining mode.
Also, the amount of the CO_2 emissions and the battery energy consumption are calculated through the SERCA algorithm.

4.4-Drive Cycles:

In our case study we used 2 drive cycles which are the WLTP and NREL Baltimore drive cycles.
The WLTP cycle specifications are given in Table 3. It is obvious from Figure 13 that during this cycle, which has maximum speed 131.3 km/h and total distance of 23.25 km, the vehicle could be propelled by only the electric system of the vehicle, with small activation of the engine (as we obtained in our first simulation). For that reason, we used a cycle which is the multiplication of this cycle three times in order to achieve nonzero fuel consumption.

Table 3- WLTP characteristics

Description	Value
cycle time	1800 sec (30 min)
Road distance	23.25 km
Maximum speed	131.3 km/h
Average speed	46.5 km/h
Stop time	12,5%

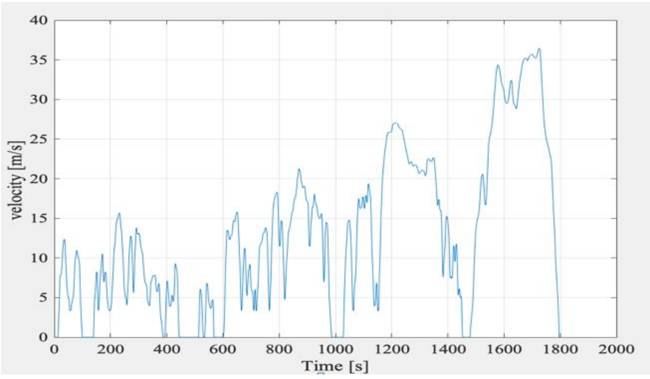


Figure 13- WLTP drive cycle

The NREL Baltimore drive cycle is shown in Figure 14, and its specifications are illustrated in Table 4 We had also to use a 3*NREL Baltimore for simulation for the same reason as in the WLTP case.

Table 4-NREL Baltimore characteristics

Description	Value
cycle time	3854 sec
Road distance	32.18 km

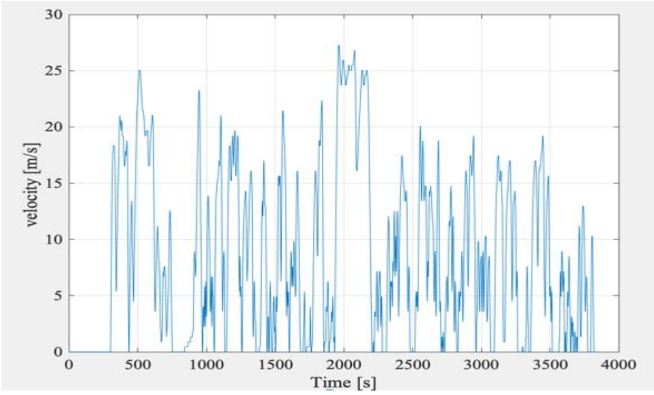


Figure 14-NREL Baltimore drive cycle

4.5- Calculation of the total mass and total cost of the vehicle:

4.5.1-Total vehicle mass:

Each component of the powertrain is correlated with a weight that changes depending on the size of that component. The overall mass of the vehicle is calculated as follow [32]:

$$m_{veh_{total}} = m_{veh_{base}} + m_{veh_{payload}} + m_{batt} + m_{MG} + m_{ICE} + m_{trans} \tag{13}$$

Where, $m_{veh_{base}}$ is the mass of the vehicle baseline and $m_{veh_{payload}}$ is the mass of the payload (as we are considering a delivery van). m_{batt}, m_{MG}, m_{ICE}, and m_{trans} are the mass of the battery, electric motor, internal combustion engine, and the transmission, respectively, and they are calculated by the following equation:

$$m_{batt} = \frac{Q*1.5}{140} \tag{14}$$

Where Q is the capacity of the battery [33].

$$m_{MG} = 10.8 + 0.532 * P_{MG_{MAX}} \tag{15}$$

Where, $P_{MG_{MAX}}$ is the maximum power of the electric motor.

$$m_{ICE} = 1.757 * P_{ICE_{MAX}} + 26.7 \tag{16}$$

$P_{ICE_{MAX}}$ is the maximum power of the internal combustion engine.

m_{trans} is calculated depending on the number of gears in the gearbox.

Figure 15 shows the MATLAB script of the vehicle mass calculation.

```
%% Calculate HEV mass

veh_mass_baseline = 2100; % kg empty vehicle + driver
veh_mass_payload =0; % kg payload mass

% Reference : Finesso R, Misul D, Spessa E, Venditti M. Optimal Design of Power-Split HEVs Based on Total Cost of Ownership and
mass_battery = Q0/140*1.5; % kg battery mass
mass_MG_P2 = 10.8 + 0.532 * (max(MG_tor_max.*MG_vel_index_tor_max))/1000; % kg mass MG P0
delta_mass_ICE = 1.757 * (max(ice_trq_wot.*ice_rev_index_wot)/1000 - 90); % delta kg mass ICE
delta_mass_transmission = max(ice_trq_wot.*ice_rev_index_wot)/1000*...
    interp1([2 6],[0.28 0.76],length(gear_ratios)) - 0.76*90; % delta kg mass transmission

veh_mass = veh_mass_baseline + veh_mass_payload +  mass_battery + mass_MG_P2 + delta_mass_ICE + delta_mass_transmission; % kg
```

Figure 15- MATLAB code for the vehicle mass calculation

4.5.2-Total cost:

The total cost of the vehicle is sum of the powertrain cost, which is the cost of all the component of the vehicle, and the operating cost (fuel consumption, electricity usage).

The total operation cost is calculated considering the total mileage over 10 years of operation, based on 30000 km yearly mileage for the delivery van.

$$C_{veh_{total}} = C_{powertrain} + C_{operation} \tag{17}$$

And:

$$C_{powertrain} = C_{base} + C_{add} + C_{batt} + C_{MG} + C_{ICE} + C_{trans} \tag{18}$$

Where C_{base} and C_{add} are the base cost and the additional component cost, respectively.

And C_{batt}, C_{MG}, C_{ICE} and C_{trans} are the costs of the battery, electric motor/generator, internal combustion engine, and the transmission, respectively. These costs are calculated based on [32][33] by the following equations:

$$C_{batt} = Q * 0.268 \tag{19}$$

$$C_{MG} = 417.5 + 19.71 * P_{MG_{MAX}} \tag{20}$$

$$C_{ICE} = 12.83 * P_{ICE_{MAX}} + 566. \tag{21}$$

And the C_{trans} is calculated as in the case of the m_{trans} depending on the number of gears chosen in the gearbox.

The operation cost is:

$$C_{operation} = C_{maint} + C_{fuel} + C_{elec} \tag{22}$$

Where C_{maint}, C_{fuel} and C_{elec} are the maintenance, the fuel consumption and electricity consumption costs, respectively, and calculated depending on [32].:

$$C_{maint} = C_{main_0} * \sum_{y=0}^{N_y-1} \frac{1}{(1+r_n)^y} \tag{23}$$

The maintenance cost is calculated from C_{main_0} which is the average annual cost, and the discount rate r_n. N_y is the vehicle lifetime and it is considered 10 years in our study.

The total fuel consumption C_{fuel} is calculated by:

$$C_{fuel} = \frac{1}{\rho_{fuel}} \sum_{y=0}^{N_y-1} \frac{FC_y * FP}{(1+r_n)^y} \tag{24}$$

Where, FC_y is the total fuel consumption per year. FP is the fuel price (is 1.863 USD/L from [34]) and ρ_{fuel} is the fuel density (0.83 kg/L).

C_{elec} is calculated depending on the energy consumed in the charge depleting operation in the plug-in HEV case only [35].

Figure 16 shows the MATLAB code for calculating the total vehicle cost.

```
%% Calculate HEV cost
% powertrain costs
cost_ICE = 12.83 * max(ice_trq_wot.*ice_rev_index_wot)/1000 +566;
cost_MG_P2 = 417.5 + 19.71 * (max(MG_tor_max.*MG_vel_index_tor_max))/1000;
cost_battery=Q0*0.268; %K. Hamza, K. Laberteaux, K.C. Chu, "On Modeling the Total Cost of Ownership of Electric and Plug-in Hyb
cost_transmission = 1.17*max(ice_trq_wot.*ice_rev_index_wot)/1000*...
        interp1([2 6],[4.35 9.32],length(gear_ratios));
cost_base = 20000;
cost_add_comp=325;
total_veh_powertrain_cost = cost_ICE + cost_MG_P2 + cost_battery + cost_transmission + cost_base + cost_add_comp;
% operating costs
% maintenance cost
    Cm=0;
    for y=0:1:9
       C=1/power(1.01,y);
       Cm=C+Cm;
    end
        C_maint=267*Cm;
% the total fuel consumption cost
VKT=30000;         % vehicle kilometers of travel
m_dis=23.25*3;     % drive cycle distance WLTP
nm=VKT/m_dis;      % number of trips per year over a specific driving mission
   C_fuel=0;
for y=0:1:9
      C_f=(1/0.83)*(fuel_cons_CD_l_100_km/100*m_dis*1.863*nm)/power(1.01,y);
      C_fuel = C_f + C_fuel;
    end
C_elect=batt_energy_cons_CD_kWh_km/100*0.26*nm*10;
total_veh_operating_cost = C_maint + C_fuel + C_elect;

total_cost = total_veh_powertrain_cost + total_veh_operating_cost;
```

Figure 16- MATLAB code of Total cost calculation in WLTP drive cycle

4.6-Optimal sizing of powertrain components:

4.6.1-Two variables optimization:

We started the optimization by exploring the design space using a brute force method. This method consists at varying 2 design parameters among the 7 parameters while fixing the other 5.

First, each powertrain sizing option should satisfy a 0-100km/h acceleration time test less than 9.7 sec to be a feasible solution and considered in the next evaluation which is the fuel consumption estimation using SERCA algorithm.

We used two cycles for our study, the WLTP and NREL Baltimore as was illustrated before.

NREL Baltimore and WLTP short are used in first step, but since they are short cycles, the vehicle could be propelled using the electrical system solely with small possibility of activating the engine. Then we used a multiplication three times of these cycles to have longer drive cycles.

In our thesis we consider full and plug-in HEVs. The full HEV is simulated by considering only the charge sustaining operation, while in the plug-in HEV we consider both the charge sustaining and charge depleting operations.

The table below illustrates the default values of the design parameters:

Table 5- The default values of the design parameters

ratio_tot	Number of gears	Diff Prim ratio	gear_ ratio_ EM_to_ trans	Hybridiz_ factor	Batt_ num_ serie	Ice_ power_ kW_ scale
3.727/0.585	6	4.222	1	0.35	1000	100

A-NREL Baltimore short drive cycle:

This paragraph represents the results obtained by using NREL Baltimore short (32.18 km).

- **Full HEV:**

The charge sustaining mode State of charge (SOC_CS) is equal to 0.5and the payload is 800kg.

I. ICE power scale variation:

a. Battery cell numbers variation:

Table 6- Table representing the powertrain configurations that ensure fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and battery number of cells

Best fuel economy				Best 0-100km/h acceleration time			
Batt_ num_ serie	Ice_ power_ kW_ scale	Best Fuel consumption(in l/100km)	0-100 km/h accelerationtime (in sec)	Batt_ num_ serie	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4500	300	5.09	9.7	500	300	9	5.64
				1000	300	9	5.42

Trade-off			
Batt_ num_ serie	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
2500	300	9.3	5.16

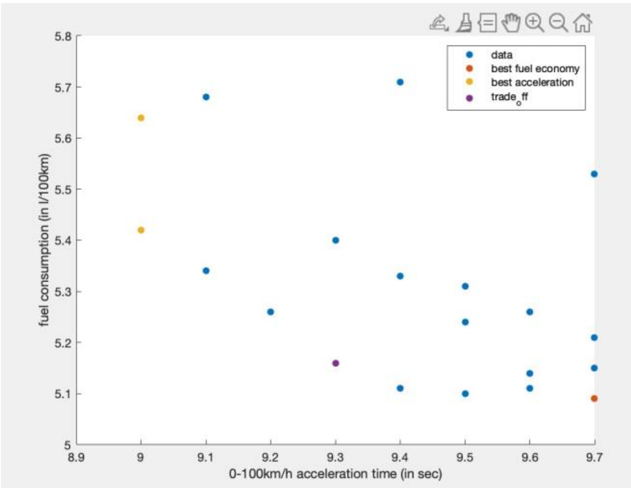


Figure 17- Pareto-Frontier of the results obtained by the variation of ICE power scale and the number of cells in the battery

b. Total ratio variation:

Table 7- Table representing the powertrain configurations that ensure the best fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and total ratio

Best fuel economy				Best 0-100km/h acceleration time			
ratio_tot	Ice_ power_ kW_ scale	Best Fuel consumption(in l/100km)	0-100 km/h accelerationtime (in sec)	ratio_tot	Ice_ power_ kW_ scale	Best Fuel consumption (in l/100km)	0-100 km/h acceleration time (in sec)
4.5	280	5.27	9.7	6.5	300	5.41	9
Trade-off							
ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
5.5	290	9.3	5.32				

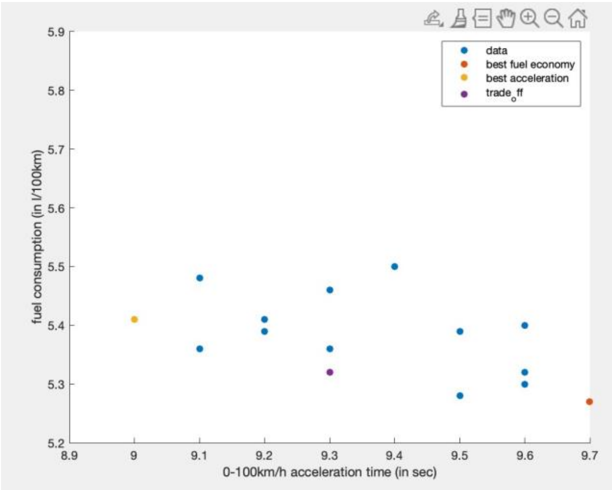


Figure 18- Pareto-Frontier of the results obtained by the variation of ICE power scale and total ratio

c. Number of gears variation:

Table 8- Table representing the powertrain configurations that ensure the best fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and gears number

Best fuel economy				Best 0-100km/h acceleration time			
Numbers gears	Ice_ power_ kW_ scale	Best Fuel consumption(in l/100km)	0-100 km/h accelerationtime (in sec)	Numbers gears	Ice_ power_ kW_ scale	Best Fuel consumption (in l/100km)	0-100 km/h acceleration time (in sec)
6	280	5.31	9.5	6	290	5.39	9
Trade-off							
Numbers gears	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
6	290	9.3	5.39				

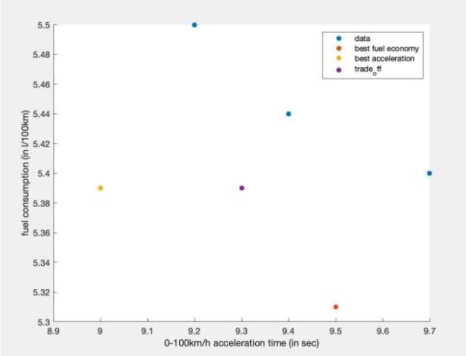


Figure 19- Pareto-Frontier of the results obtained by the variation of ICE power scale and gears number

d. Differential ratio variation:

Table 9-Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and final drive ratio

Best fuel economy				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	Best Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Diff Prim ratio	Ice_ power_ kW_ scale	Best Fuel consumption (in l/100km)	0-100 km/h acceleration time (in sec)
4.6	230	5.12	9.4	4.6	300	5.25	7.6
Trade-off							
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
4.6	250	8.8	5.14				

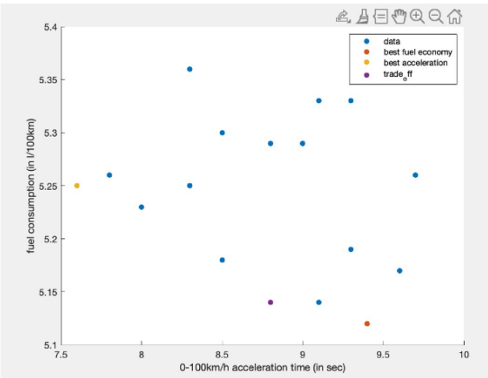


Figure 20- Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and final drive ratio

e. Ratio EM to trans variation:

Table 10- Table representing the powertrain configurations that ensure the best fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and ratio between EM and transmission

Best fuel economy				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	Best Fuel consumpt ion(in l/100km)	0-100 km/h accelerat iontime (in sec)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	Best Fuel consumption (in l/100km)	0-100 km/h acceler ation time (in sec)
1	280	5.25	9.5	4	300	8.94	4.6
Trade-off							
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
3	300	7	9.01				

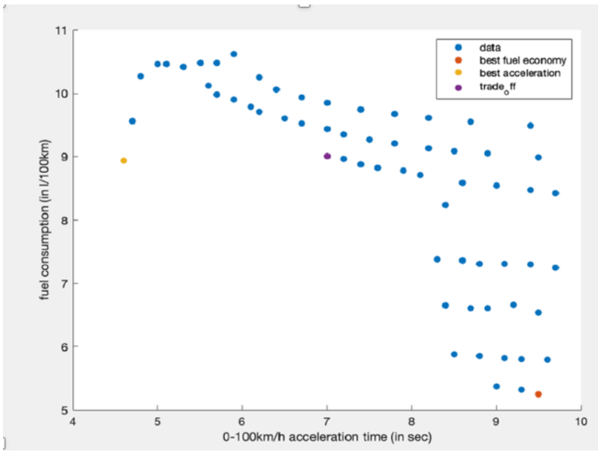


Figure 21- Pareto-Frontier of the results obtained by the variation of ICE power scale and ratio between EM and transmission

f. Hybridization factor variation:

Table 11-Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of ICE power scale and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz _factor	Ice_ power_ kW_ scale	Best Fuel consumpt ion(in l/100km)	0-100 km/h accelerat iontime (in sec)	Hybridiz _factor	Ice_ power_ kW_ scale	Best Fuel consumption (in l/100km)	0-100 km/h acceler ation time (in sec)
0.65	140	5.09	9.6	0.95	220	13.54	1.5
				0.95	230	14.3	1.5
Trade-off							
Hybridiz _factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
0.75	220	5.62	4.9				

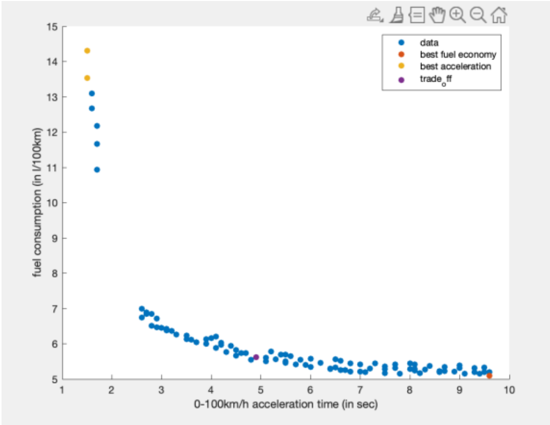


Figure 22-Pareto-Frontier of the results obtained by the variation of ICE power scale and hybridization factor

We remark that we obtain a lot of feasible solution when we vary the ICE power scale with the ratio between EM and transmission and the hybridization factor.

II- Hybridization factor variation:

a. Total ratio variation:

Table 12- Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of hybridization factor and total ratio

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz _factor	ratio_tot	Best Fuel consumpt ion(in l/100km)	0-100 km/h accelerat iontime (in sec)	Hybridiz _factor	ratio_tot	0-100 km/h accelerat iontime (in sec)	Best Fuel consumptio n(in l/100km)
0.75	4	4.99	9.7	0.95	5.5	2.4	6.98
				0.95	6	2.4	6.97
				0.95	6.5	2.4	6.89
Trade-off							
Hybridiz _factor	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
0.85	5.5	5.9	5.33				

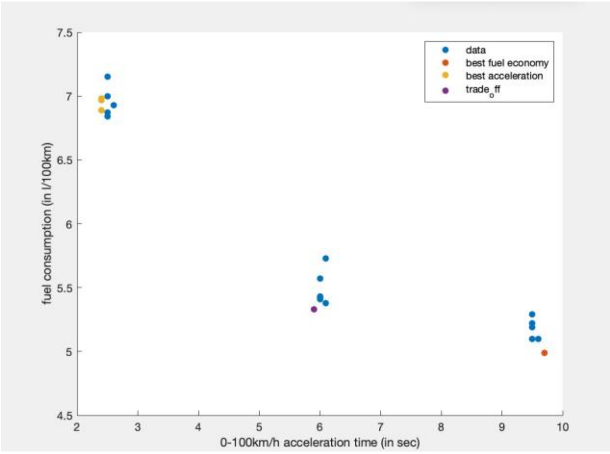


Figure 23- Pareto-Frontier of the results obtained by the variation of hybridization factor and total ratio

b. Gear number variation:

Table 13- Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of hybridization factor and gears number

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz _factor	Numbers gears	Best Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Hybridiz _factor	Numbers gears	0-100 km/h acceleration time (in sec)	Best Fuel consumption(in l/100km)
0.85	6	5.19	9.5	0.95	5	2.5	6.93
Trade-off							
Hybridiz _factor	Numbers gears	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)				
0.85	6	5.9	5.40				

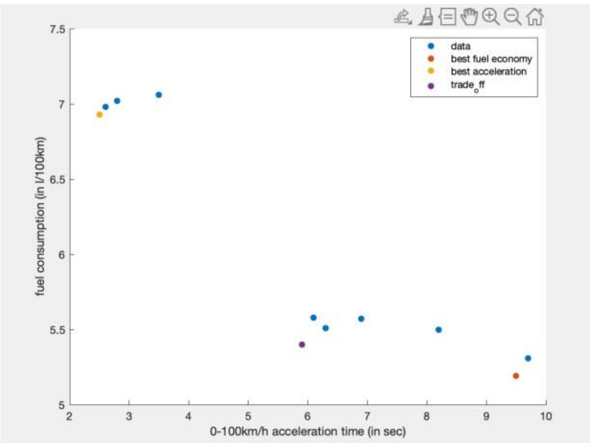


Figure 24-Pareto-Frontier of the results obtained by the variation of hybridization factor and gears number

c. Differential ratio variation:

Table 14- Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of hybridization factor and final drive ratio

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz _factor	Diff Prim ratio	Best Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Hybridiz _factor	Diff Prim ratio	0-100 km/h acceleration time (in sec)	Best Fuel consumption(in l/100km)
0.75	4.2	5.11	9.6	0.95	4.6	2.1	6.94

Trade-off			
Hybridiz _factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	4.4	5.5	5.43

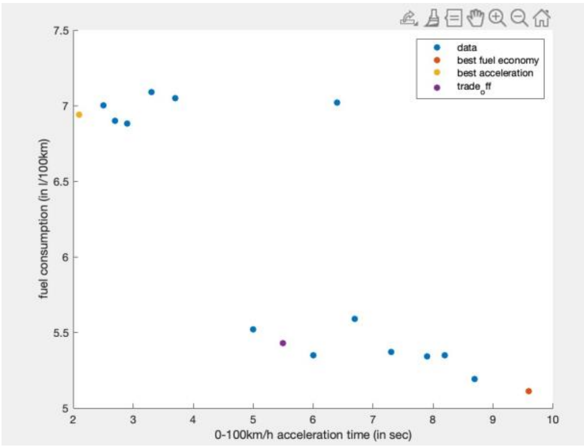


Figure 25- Pareto-Frontier of the results obtained by the variation of hybridization factor and final drive ratio

d. Ratio EM to trans variation:

Table 15-Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of hybridization factor and ratio between EM and transmission

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz _factor	gear_ ratio_ EM_to_ trans	Best Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Hybridiz _factor	gear_ ratio_ EM_to_ trans	0-100 km/h acceleration time (in sec)	Best Fuel consumption(in l/100km)
0.75	1	5.16	9.5	0.95	0.5	4.3	5.58

Trade-off			
Hybridiz _factor	gear_ ratio_ EM_to_ trans	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	1	5.9	5.39

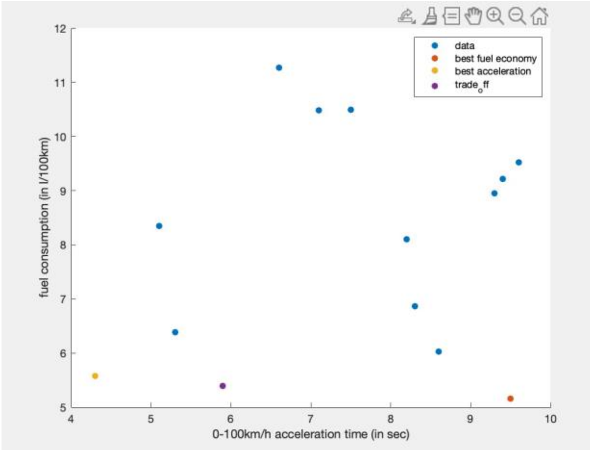


Figure 26- Pareto-Frontier of the results obtained by the variation of hybridization factor and ratio between EM and transmission

e. Battery cell number variation:

Table 16- Table representing the powertrain configurations that ensure the fuel economy, best 0-100km/h acceleration test and the trade-off by the variation of hybridization factor and battery cell number

Best fuel economy			
Hybridiz _factor	Batt_ num_ serie	Best Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)
0.75	2000	4.98	9.7

Best 0-100km/h acceleration time			
Hybridiz _factor	Batt_ num_serie	0-100 km/h acceleration time (in sec)	Best Fuel consumption(in l/100km)
0.95	500	2.4	7.33
0.95	2000	2.4	6.61

Trade-off			
Hybridiz _factor	Batt_ num_ serie	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	1000	5.9	5.3

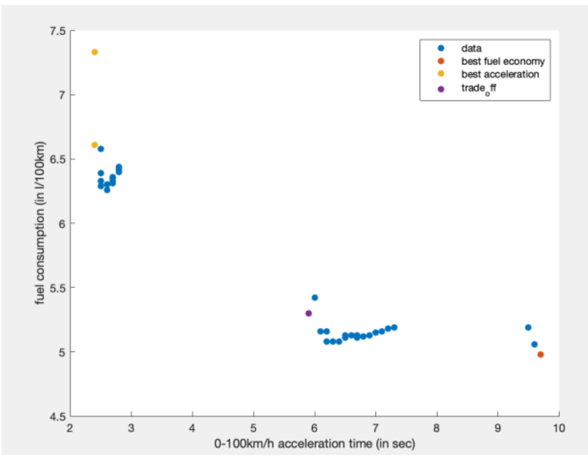


Figure 27- Pareto-Frontier of the results obtained by the variation of hybridization factor and battery cell number

- **Plug-in HEV:**

  The delivery van leaves the warehouse fully charged (initial battery State of charge(SOC)=0.95 and with payload 800kg)

  I- ICE power scale variation:

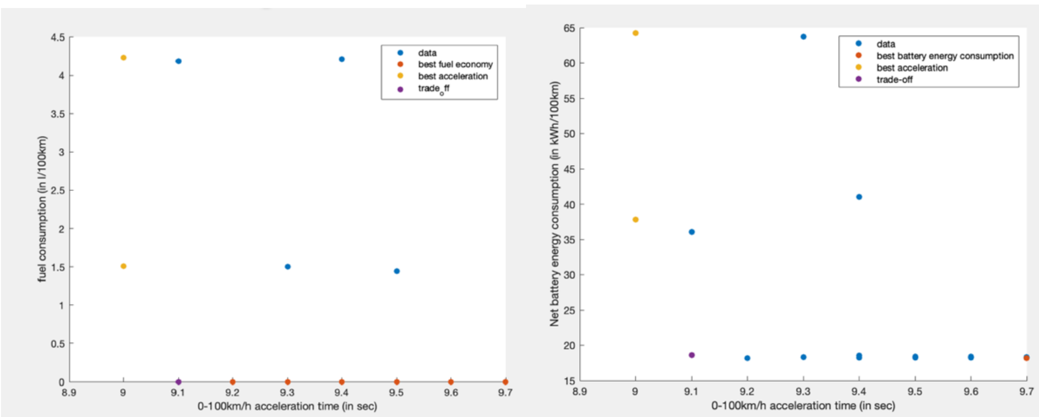
  a. Battery cell numbers variation:

Table 17- Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and battery cell number

Best battery energy consumption				Best 0-100km/h acceleration time			
Batt_num_serie	Ice_power_kW_scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	Batt_num_serie	Ice_power_kW_ scale	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
2000	280	18.17	9.69	500	300	8.99	37.83
				1000	300	8.99	64.22

Trade-off			
Batt_num_serie	Ice_power_kW_scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kwh/100km)
1500	300	9.09	18.59

Trade-off between fuel consumption and 0-100km/h acceleration time			
Batt_num_serie	Ice_power_kW_scale	0-100 km/h Acc. time (in sec)	Fuel consumption(in l/100km)
1500	300	9.09	0



(a) (b)

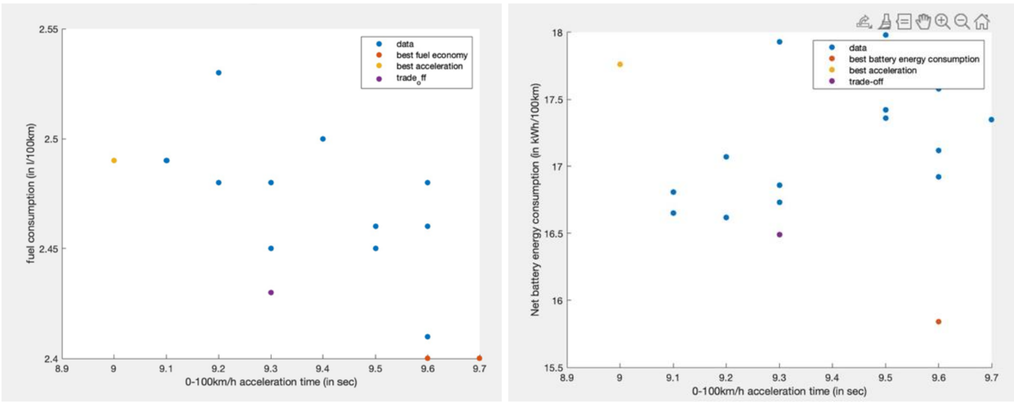
Figure 28-Pareto-Frontier of the results obtained by the variation of ICE power scale and battery cell number , (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

b. Total ratio variation:

Table 18-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and total ratio

Best fuel economy				Best 0-100km/h acceleration time			
ratio_tot	Ice_power_kW_scale	Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	ratio_tot	Ice_power_kW_ scale	0-100 km/h accelerationtime (in sec)	Fuel consumption (in l/100km)
4.5	280	2.4	9.69	6.5	300	9	2.49
5	280	2.4	9.59				
Trade-off							
ratio_tot	Ice_power_kW_scale	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)				
5.5	290	9.3	2.45				

Best battery energy consumption				Best 0-100km/h acceleration time			
ratio_tot	Ice_power_kW_scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	ratio_tot	Ice_power_kW_ scale	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
5.5	280	15.84	9.6	6.5	300	9	17.76
Trade-off							
ratio_tot	Ice_power_kW_scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kwh/100km)				
5	290	9.3	16.49				



(a) (b)

Figure 29- Pareto-Frontier of the results obtained by the variation of ICE power scale and total ratio, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

c. Number of gears variation:

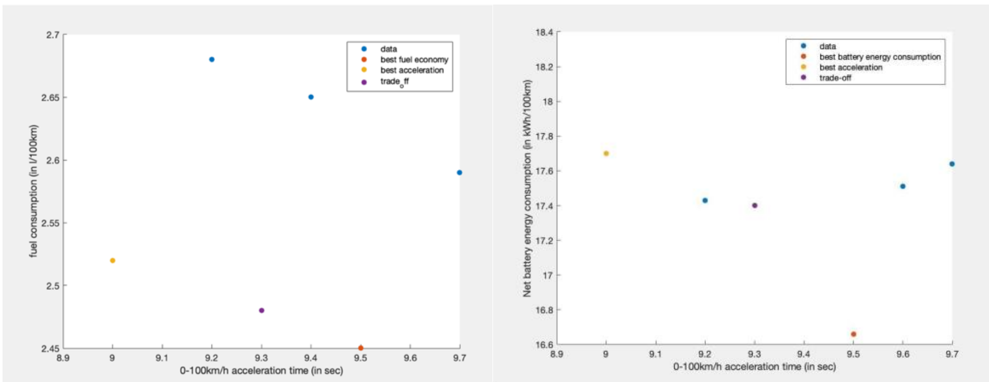
Table 19- Table representing the powertrain configurations that ensure the best battery energy consumption,fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and gears number

Best fuel economy				Best 0-100km/h acceleration time			
Numbers gears	Ice_ power_ kW_ scale	Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Numbers gears	Ice_ power_ kW_ scale	Fuel consumption (in l/100km)	0-100 km/h accelerationtime (in sec)
6	280	2.45	9.5	6	300	2.52	9

Trade-off			
Numbers gears	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)
6	290	9.3	2.48

Best battery energy consumption				Best 0-100km/h acceleration time			
Numbers gears	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	Numbers gears	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
6	280	16.66	9.5	6	300	17.7	9

Trade-off			
Numbers gears	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
6	290	17.40	9.3



(a) (b)

Figure 30-Pareto-Frontier of the results obtained by the variation of ICE power scale and gears number, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

d. Final drive ratio variation:

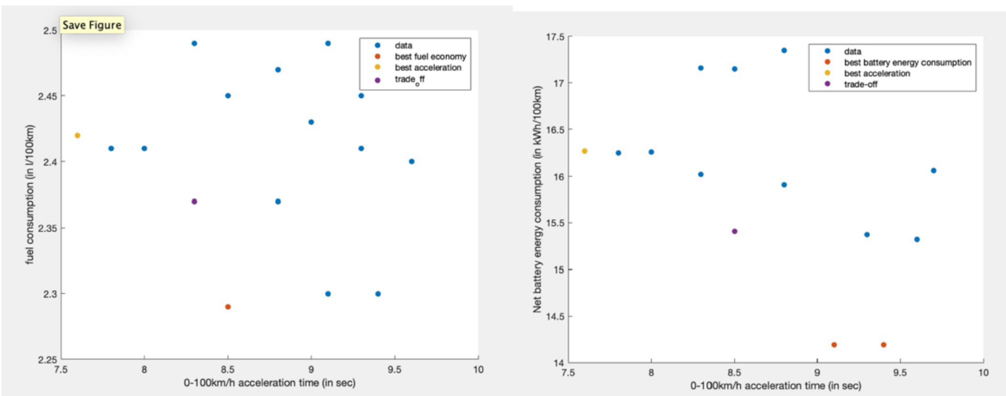
Table 20- Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and final drive ratio

Best fuel economy				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Diff Prim ratio	Ice_ power_ kW_ scale	Fuel consumption (in l/100km)	0-100 km/h accelerationtime (in sec)
4.6	260	2.29	8.5	4.6	300	2.42	7.6

Trade-off			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)
4.6	270	8.3	3.37

Best battery energy consumption				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	Diff Prim ratio	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
4.6	230	14.19	9.4	4.6	300	16.27	7.6
4.6	240	14.19	9.1				

Trade-off			
Diff Prim ratio	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
4.6	260	15.41	8.5



(a) (b)

Figure 31-Pareto-Frontier of the results obtained by the variation of ICE power scale and final drive ratio, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

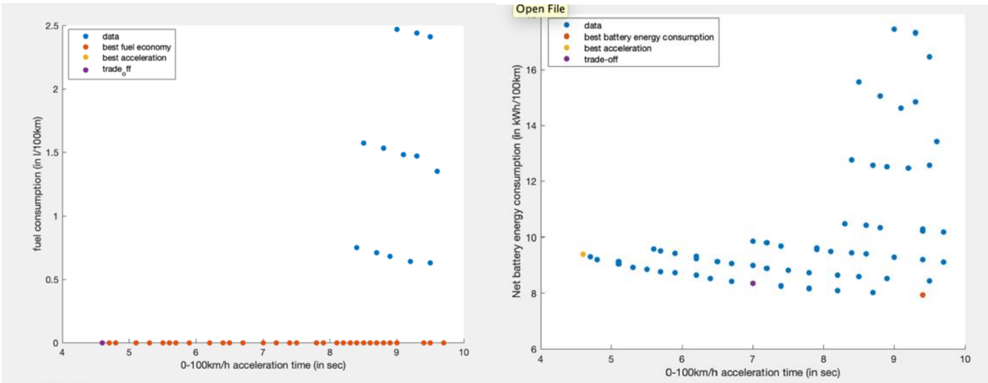
e. Ratio EM to trans variation:

Table 21- Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and ratio between EM and transmission ratio

Trade-off between fuel consumption and 0-100km/h acceleration time			
gear_ ratio_ EM_to_trans	Ice_ power_kW_ scale	0-100 km/h Acc. time (in sec)	Fuel consumption(in l/100km)
4	300	4.6	0

Best battery energy consumption				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
4	130	7.94	9.4	4	300	9.39	4.6

Trade-off			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
4	180	8.34	7



(a) (b)

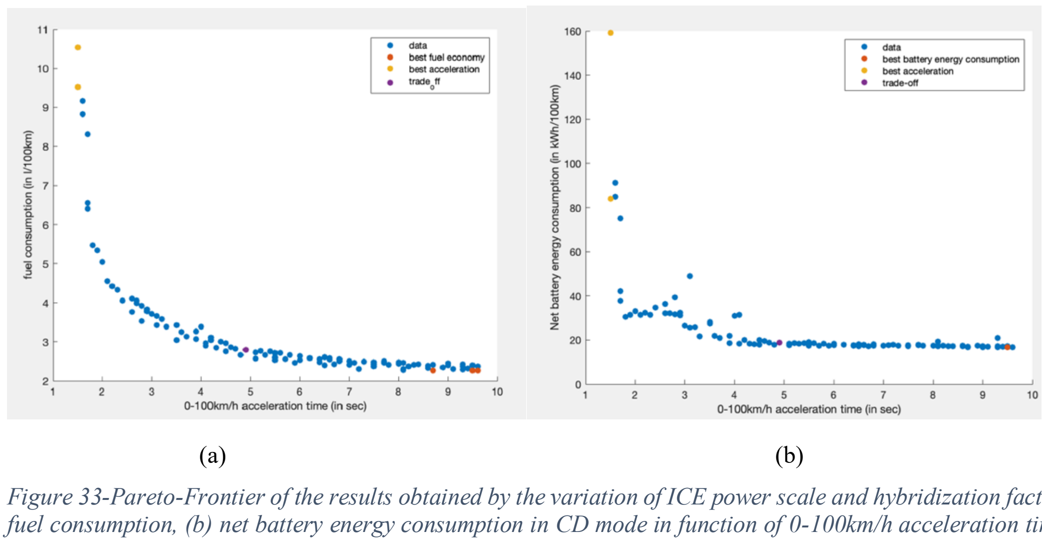
Figure 32-Pareto-Frontier of the results obtained by the variation of ICE power scale and ratio between EM and transmission, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

f. Hybridization factor variation:

Table 22-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of ICE power scale and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	Fuel consumptio n(in l/100km)	0-100 km/h accelera tion time (in sec)	Hybridiz _factor	Ice_ power_ kW_ scale	Fuel consumption (in l/100km)	0-100 km/h accelerat iontime (in sec)
0.75	100	2.27	9.5	0.95	220	9.52	1.5
0.75	110	2.27	8.7	0.95	230	10.54	1.5
0.65	140	2.27	9.6				
Trade-off							
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)				
0.75	220	4.9	2.79				

Best battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	Net battery energy consumptio n (in kwh/100km)	0-100 km/h acceler ation time (in sec)	Hybridiz _factor	Ice_ power_ kW_ scale	Net battery energy consumption (in kwh/100km)	0-100 km/h accelera tion time (in sec)
0.35	280	16.6	9.5	0.95	220	83.92	1.5
				0.95	230	159.27	1.5
Trade-off							
Hybridiz_ factor	Ice_ power_ kW_ scale	Net battery energy consumptio n (in kwh/100km)	0-100 km/h acceler ation time (in sec)				
0.75	220	18.84	4.9				



(a) (b)

Figure 33-Pareto-Frontier of the results obtained by the variation of ICE power scale and hybridization factor , (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

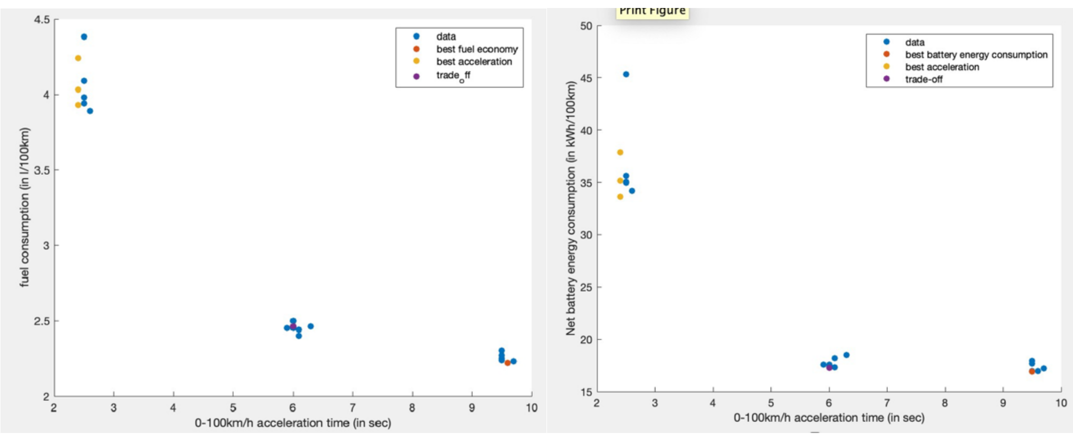
II- Hybridization factor variation:

a. Total ratio variation:

Table 23-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of hybridization factor and total ratio

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	Fuel consumption(in l/100km)	0-100 km/h acceleration time (in sec)	Hybridiz_factor	ratio_tot	Fuel consumption (in l/100km)	0-100 km/h accelerationtime (in sec)
0.75	4.5	2.22	9.6	0.95	5.5	2.4	3.93
				0.95	6	2.4	4.24
				0.95	6.5	2.4	4.03
Trade-off							
Diff Prim ratio	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)				
0.85	5	6	2.46				

Best battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	Hybridiz_factor	ratio_tot	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
0.75	6.5	16.92	9.5	0.95	5.5	2.4	35.15
				0.95	6	2.4	37.85
				0.95	6.5	2.4	33.62
Trade-off							
Hybridiz_ factor	ratio_tot	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)				
0.85	6.5	6	17.26				



(a) (b)

Figure 34- Pareto-Frontier of the results obtained by the variation of hybridization factor and total ratio, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

b. Gear number variation:

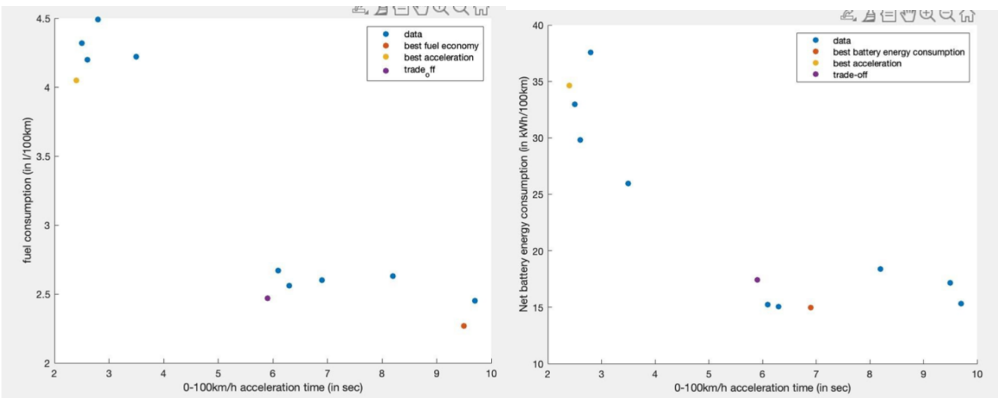
Table 24-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of hybridization factor and gears number

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Number gears	Fuel consumptio n(in l/100km)	0-100 km/h accelera tion time (in sec)	Hybridiz _factor	Number gears	Fuel consumption (in l/100km)	0-100 km/h accelerat iontime (in sec)
0.75	6	2.27	9.5	0.95	6	4.05	2.4

Trade-off			
Diff Prim ratio	Number gears	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)
0.85	6	5.9	2.47

Best battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Number gears	Net battery energy consumptio n (in kwh/100km)	0-100 km/h acceler ation time (in sec)	Hybridiz _factor	Number gears	Net battery energy consumption (in kwh/100km)	0-100 km/h accelera tion time (in sec)
0.85	3	14.98	6.9	0.95	6	34.63	2.4

Trade-off			
Hybridiz_ factor	Number gears	Net battery energy consumptio n (in kwh/100km)	0-100 km/h acceler ation time (in sec)
0.85	6	5.9	17.43



(a) (b)

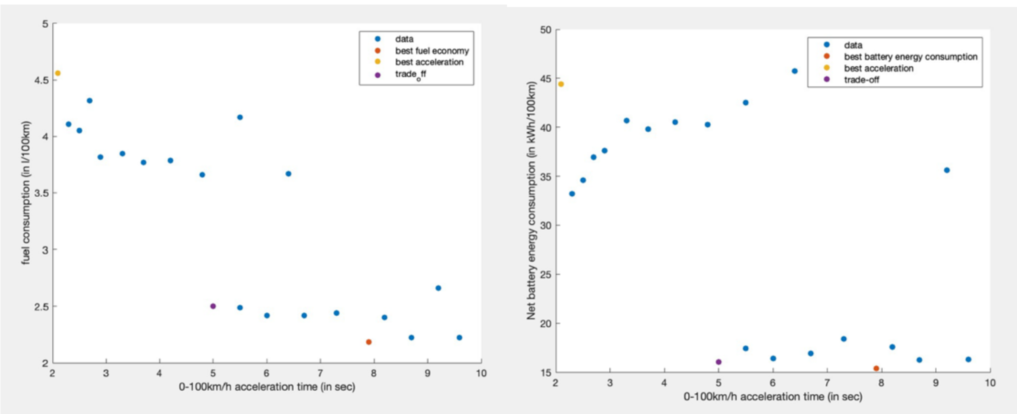
Figure 35-Pareto-Frontier of the results obtained by the variation of hybridization factor and gears number, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

c. Final drive ratio variation:

Table 25- Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of hybridization factor and final drive ratio

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	Fuel consumptio n(in l/100km)	0-100 km/h accelera tion time (in sec)	Hybridiz _factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)
0.75	4.6	2.18	7.9	0.95	4.6	2.1	4.56
Trade-off							
Diff Prim ratio	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel consumption (in l/100km)				
0.85	4.6	5	2.5				

Best battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	Net battery energy consumptio n (in kwh/100km)	0-100 km/h acceler ation time (in sec)	Hybridiz _factor	Diff Prim ratio	0-100 km/h acceler ation time (in sec)	Net battery energy consumption (in kwh/100km)
0.75	4.6	15.39	7.9	0.95	4.6	2.1	44.38
Trade-off							
Hybridiz_ factor	Diff Prim ratio	0-100 km/h accele ration time (in sec)	Net battery energy consumption (in kwh/100km)				
0.85	4.6	5	16.03				



(a) (b)

Figure 36- Pareto-Frontier of the results obtained by the variation of hybridization factor and final drive ratio , (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

d. Ratio EM to trans variation:

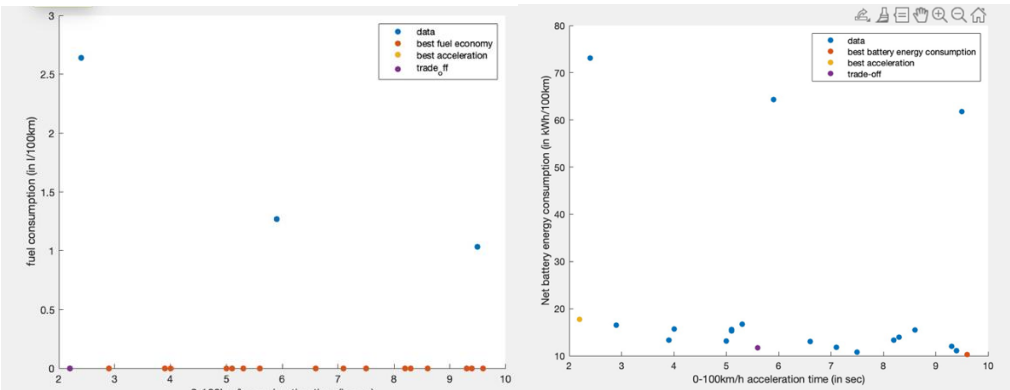
Table 26-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of hybridization factor and ratio between EM and transmission

Trade-off between fuel consumption and 0-100km/h acceleration time			
Hybridiz_ factor	gear_ ratio_ EM_to_trans	0-100 km/h Acc. time (in sec)	Fuel consumption(in l/100km)
0.85	4	2.2	0

Best battery energy consumption			
Hybridiz_ factor	gear_ ratio_ EM_to_ trans	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)
0.45	4	10.28	9.6

Best 0-100km/h acceleration time			
Hybridiz _factor	gear_ ratio_ EM_to_ trans	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
0.85	4	2.2	17.73

Trade-off			
Hybridiz_ factor	gear_ ratio_ EM_to_ trans	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
0.65	4	5.6	11.7



(a) (b)

Figure 37-Pareto-Frontier of the results obtained by the variation of hybridization factor and ratio between EM and transmission, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

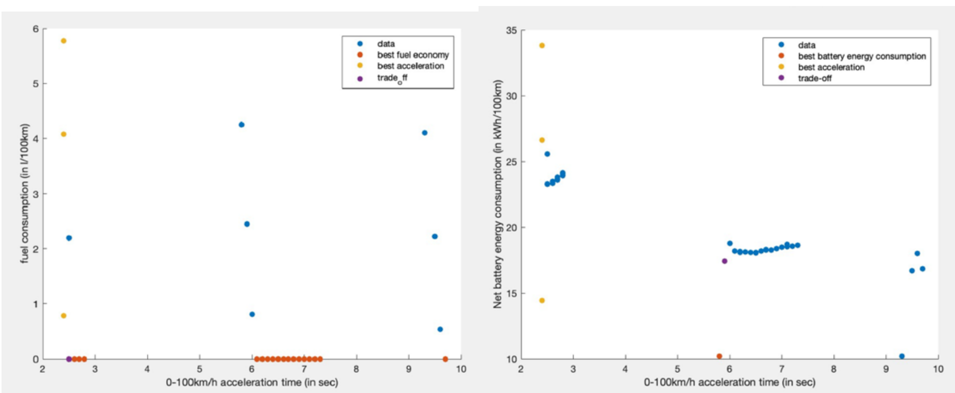
e. Battery cell number variation:

Table 27-Table representing the powertrain configurations that ensure the best battery energy consumption, fuel economy, best 0-100km/h acceleration test, and trade -off by the variation of hybridization factor and battery cell number

Best battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Batt_ num_ serie	Net battery energy consumption (in kwh/100km)	0-100 km/h acceleration time (in sec)	Hybridiz _factor	Batt_ num_serie	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
0.85	500	10.19	5.8	0.95	500	2.4	14.44
				0.95	1000	2.4	32.82
				0.95	2000	2.4	16.63

Trade-off			
Hybridiz_ factor	Batt_ num_ serie	0-100 km/h acceleration time (in sec)	Net battery energy consumption (in kwh/100km)
0.85	1000	5.9	17.42

Trade-off between fuel consumption and 0-100km/h acceleration time			
Hybridiz_ factor	Batt_num_serie	0-100 km/h Acc. time (in sec)	Fuel consumption(in l/100km)
0.95	2500	2.5	0
0.95	3000	2.5	0
0.95	3500	2.5	0



(a) (b)

Figure 38-Pareto-Frontier of the results obtained by the variation of hybridization factor and battery cell number and transmission, (a) fuel consumption, (b) net battery energy consumption in CD mode in function of 0-100km/h acceleration time, and the trade-off

When we fix the ICE power scale and the hybridization factor at the same time and we vary the other parameters, we don't obtain any results. The candidates don't ensure a 0-100km/h acceleration time less than 9.7 sec because the ICE power scale and the hybridization factor are parameters related to the engine and the EM respectively, which are responsible at propelling the vehicle.

B-WLTP short drive cycle:

This paragraph represents the results and observations obtained by using WLTP short drive cycle (23.25 km).

- **Full HEV:**

The charge sustaining mode State of charge (SOC_CS) is equal to 0.5 and the payload is 1500kg.

I- ICE power scale variation:

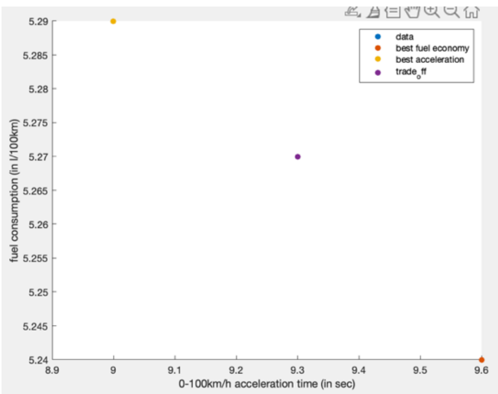
a. Final drive ratio variation:

Table 28-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and differential gear ratio

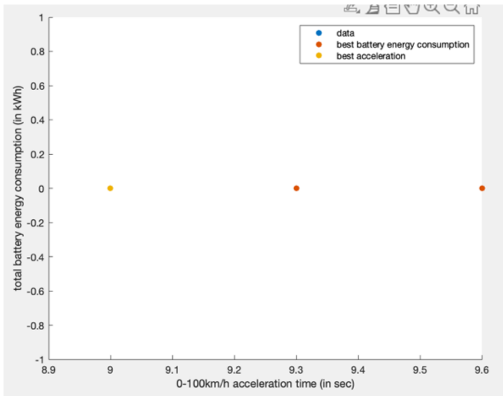
Best fuel economy				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4.6	280	9.6	5.24	4.6	300	9	5.29

Trade-off			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4.6	290	9.3	5.27

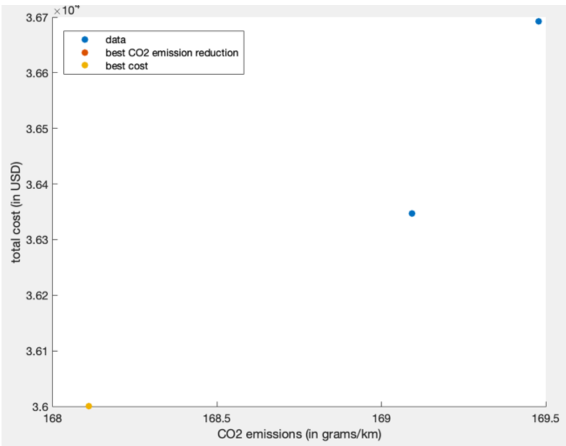
Best cO2 emission reduction				Best HEV cost			
Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4.6	280	168.1097	36000.9	4.6	280	168.1097	36000.9



(a)



(b)



(c)

Figure 39-Pareto-Frontier of the results obtained by the variation of ICE power scale and differential gear ratio, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

By varying ICE power scale and the final drive ratio, we have a small number of feasible candidates which all have the same final drive ratio but different ICE power scales (those are satisfying 0-100km/h acceleration time less than 9.7sec).

We remark that the configuration having the smallest ICE power scale has the smallest fuel consumption, CO2 emission and total cost but higher 0-100km/h acceleration time. Also, the feasible configurations have the highest final drive ratio value.

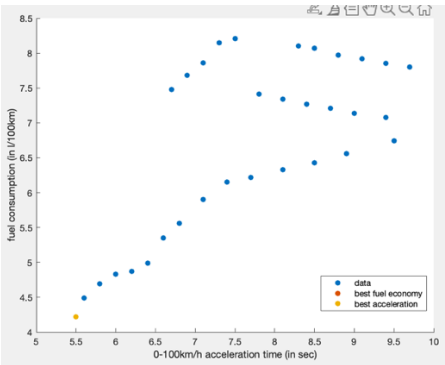
b. Ratio EM to trans variation:

Table 29-Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and gear ratio between EM and transmission

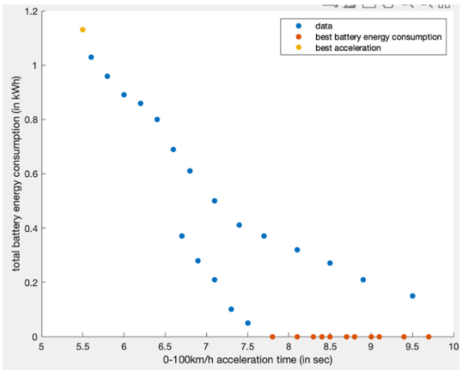
Best fuel economy				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4	300	5.5	4.22	4	300	5.5	4.22

Best cO2 emission reduction				Best HEV cost			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4	300	135.3546	36595.5	4	160	210.4874	32017.67

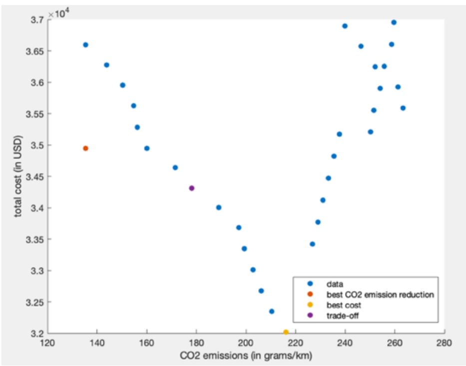
Trade-off			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4	230	178.1319	34313.5



(a)



(b)



(c)

Figure 40-Pareto-Frontier of the results obtained by the variation of ICE power scale and differential gear ratio, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

By varying the ICE power scale and the ratio between EM and the transmission, we obtain feasible candidates by taking the ratio higher than 3. And by choosing the highest ratio (which is 4) and highest ICE power scale we get the best fuel economy, the best 0-100km/h acceleration time but the total cost is very high.

II. Hybridization factor variation:

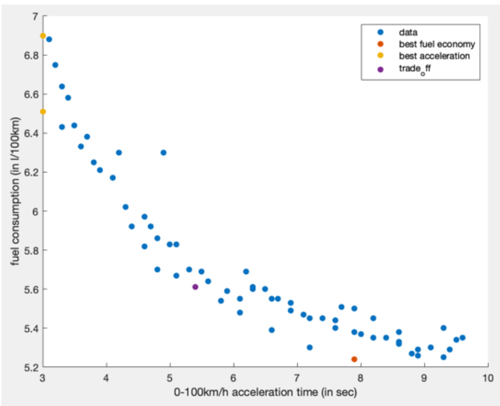
a. ICE power scale variation:

Table 30- Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and hybridization factor

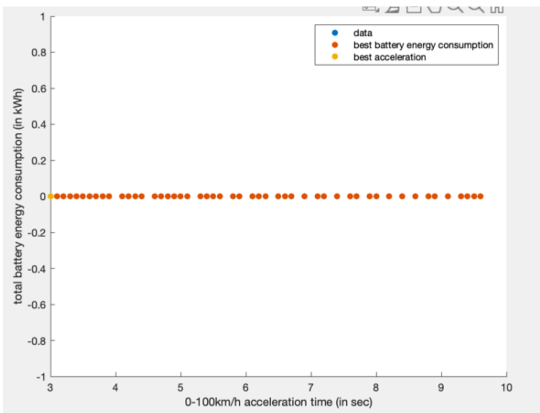
Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	90	7.9	5.24	0.95	90	3	6.51
				0.85	300	3	6.9

Tarde-off			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	140	5.4	5.61

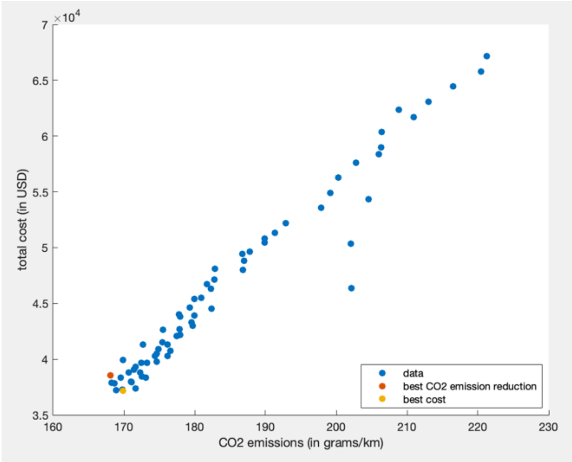
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	90	168.08	38571.75	0.75	130	169.917	37161.21



(a)



(b)



(c)

Figure 41-Pareto-Frontier of the results obtained by the variation of ICE power scale and hybridization factor, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

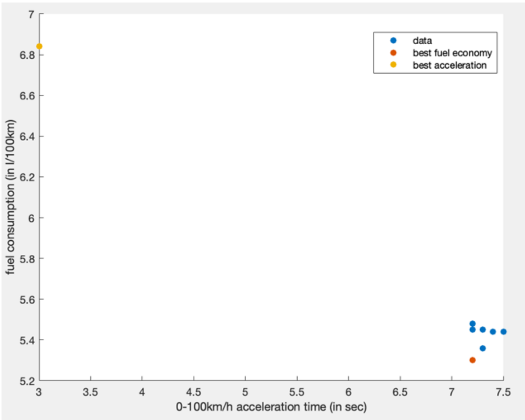
When we vary the hybridization factor and the ICE power scale, we have that for each value of the hybridization factor and by increasing the ICE power scale the fuel consumption is increased, by consequence the CO2 emission is increased too, while the 0-100km/h acceleration time is decreased. But the best solution ensuring the less fuel consumption and less CO2 emissions is the one that has high hybridization factor and small ICE power scale.

b. Total ratio variation:

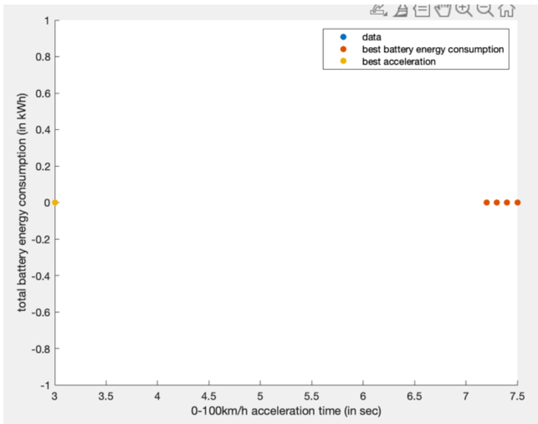
Table 31-Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of total ratio and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	6.5	7.2	5.3	0.95	3	3	6.84

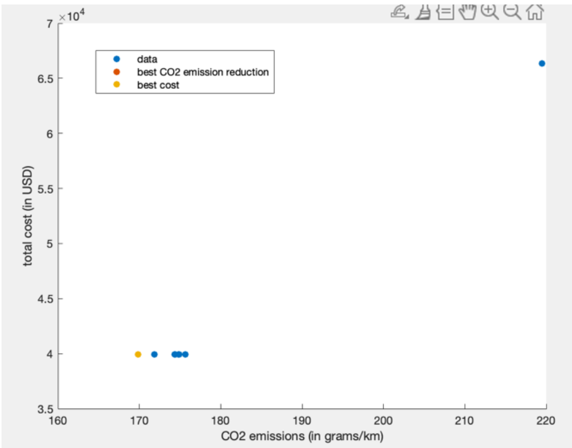
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6.5	169.87	39931.15	0.85	6.5	169.87	39931.15



(a)



(b)



(c)

Figure 42-Pareto-Frontier of the results obtained by the variation of total ratio and hybridization factor, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

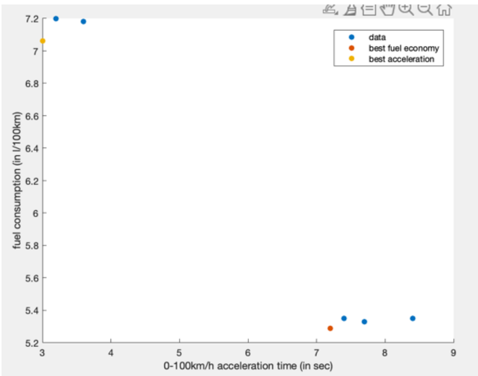
For high hybridization factor and highest value of the total ratio we obtain the best fuel economy and then best CO2 emission. And for each hybridization factor value, by varying the total ratio the fuel is consumed in the same range, only when we change the hybridization factor, we see a remarkable change in the fuel consumption.

c. Number of gears variation:

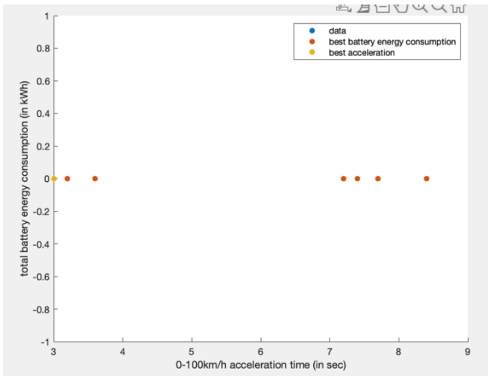
Table 32- Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	6	7.2	5.29	0.95	4	3	7.06

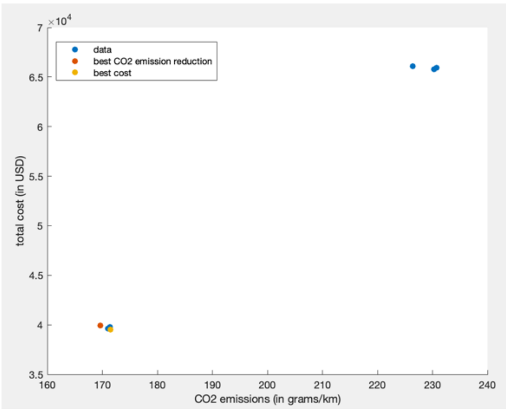
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Numbers gears	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Numbers Gears	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6	169.66	39930.56	0.85	3	171.435	39499.54



(a)



(b)



(c)

Figure 43-Pareto-Frontier of the results obtained by the variation of gears number and hybridization factor, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

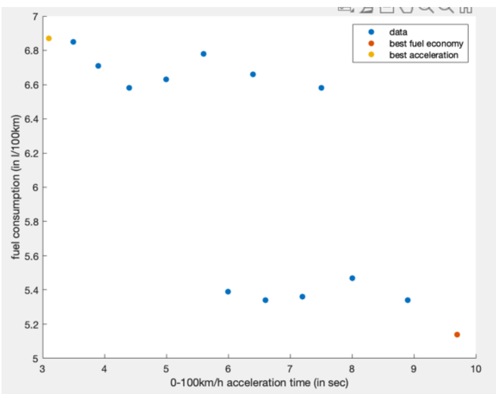
The same observation as in the variation of the total ratio is obtained here. The change of the hybridization has only the remarkably effect on the fuel consumption and 0-100km/h acceleration test.

d. Final drive ratio variation:

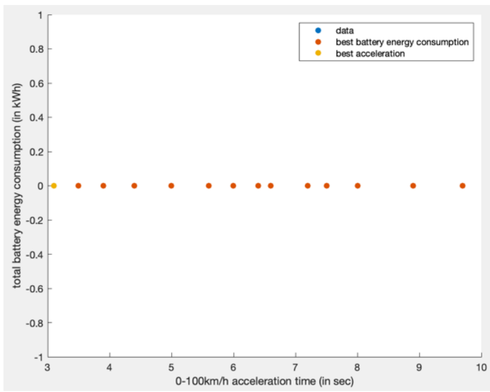
Table 33-Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive ratio and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.75	4.6	9.7	5.14	0.95	4	3.1	6.87

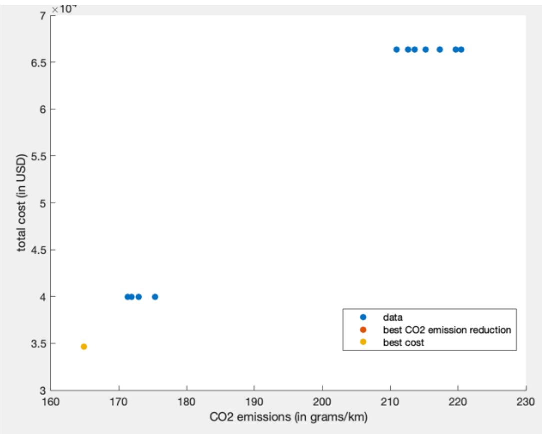
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)
0.75	4.6	164.88	34660.78	0.75	4.6	164.88	34660.782



(a)



(b)



(c)

Figure 44-Pareto-Frontier of the results obtained by the variation of final drive ratio and hybridization factor, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

By varying the hybridization factor and the final drive ratio, for each fixed value of the hybridization factor the fuel consumptions and the CO2 emissions are varied in specific interval while the 0-100km/h acceleration time is changed significantly. The 0-100km/h acceleration time decreases by the increase of the final drive ratio.

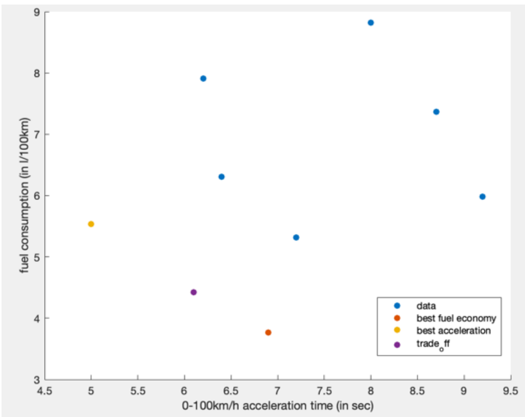
We obtain different fuel consumptions and CO2 emissions only when we change the hybridization factor. And we get the smallest CO2 emissions with the configuration having the smallest hybridization factor.

e. Ratio EM to trans variation:

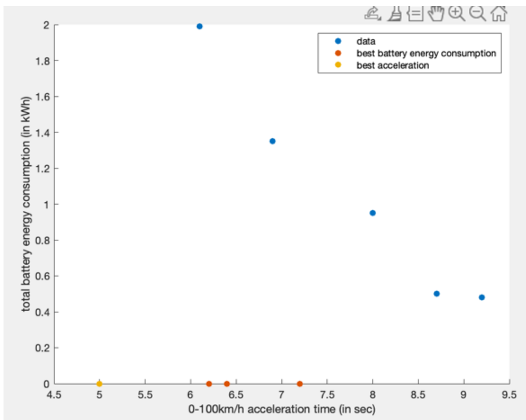
Table 34-Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.65	4	6.9	3.77	0.95	0.5	5	5.54

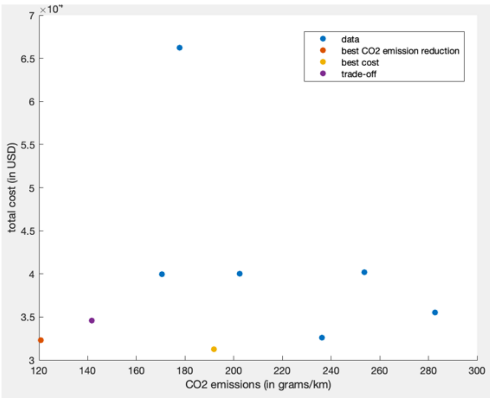
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)
0.65	4	120.74	32283.5 1	0.55	4	191.75	31235.05 9
Trade-off							
Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)				
0.75	3.5	141.5886	34599.5 0				



(a)



(b)



(c)

Figure 45-Pareto-Frontier of the results obtained by the variation of ratio between EM and transmission and hybridization factor, (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

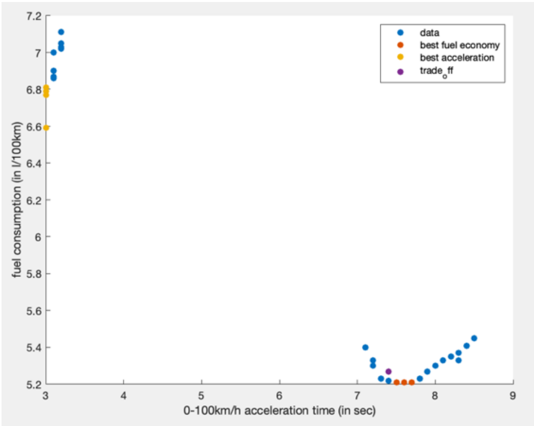
By increasing the ratio between EM and transmission and decreasing the hybridization factor we obtain the smallest CO2 emission and total cost while increasing the 2 parameters leads to have the smallest 0-100km/h acceleration time.

f. Battery capacity variation:

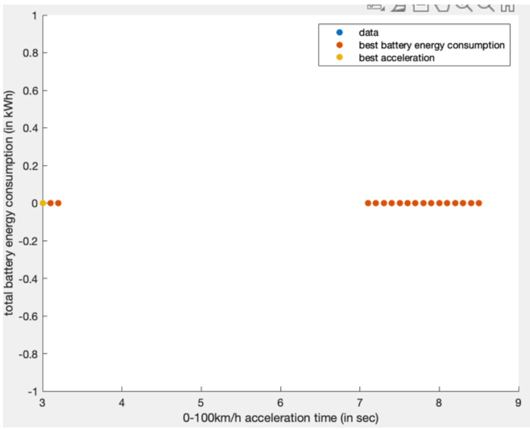
Table 35-Table representing the powertrain configurations that ensure the fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of battery capacity and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	26600	7.5	5.21	0.95	34200	3	6.77
0.85	30400	7.6	5.21	0.95	38000	3	6.59
0.85	34200	7.7	5.21	0.95	41800	3	6.81
				0.95	45600	3	6.79

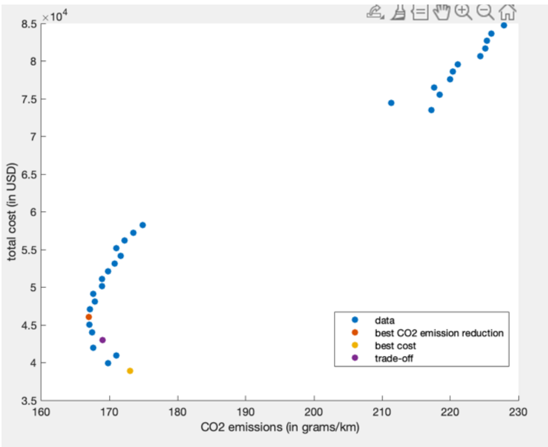
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	30400	166.93	46033.10	0.85	3800	173.041	38921.88



(a)



(b)



(c)

Figure 46- Pareto-Frontier of the results obtained by the variation of battery capacity and hybridization factor , (a) fuel consumption, (b) total battery energy consumption all in function of 0-100km/h acceleration time, (c) total cost in function of CO2 emission and the trade-off

The increase of the hybridization factor and the battery capacity leads to the increase of the CO2 emissions and while the decrease in the battery capacity decreases the 0-100km/h acceleration time.

But for each specific hybridization factor value the CO2 emissions vary in small range when varying the battery capacity while by changing the hybridization factor the CO2 emission values are significantly changed that means that the hybridization factor has the remarkable effect.

- **Plug-in HEV:**

The charge sustaining mode State of charge (SOC_CS) is equal to 0.3 and thedelivery is fully charged at the beginning of the cycle (when it leaves the warehouse the initial State of charge (SOC_init) is equal to 0.95) and the payload is 1500kg.

I- ICE power scale variation:

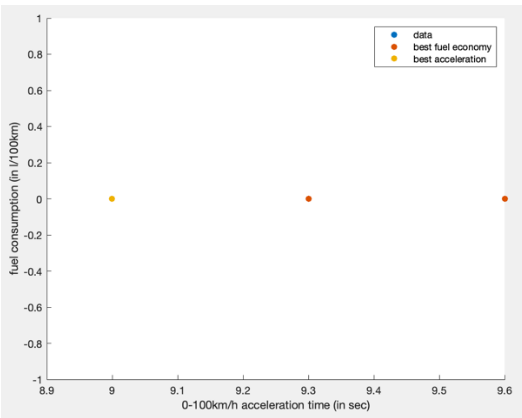
a. Final drive ratio variation:

Table 36-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and final drive ratio

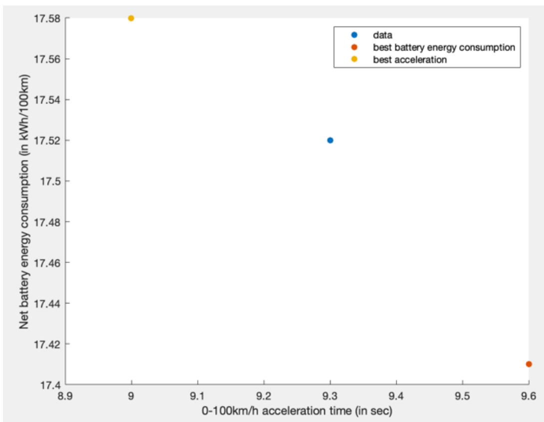
Best Net battery energy consumption				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
4.6	280	9.6	17.41	4.6	300	9	17.58

Trade-off			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
4.6	290	9.3	17.52

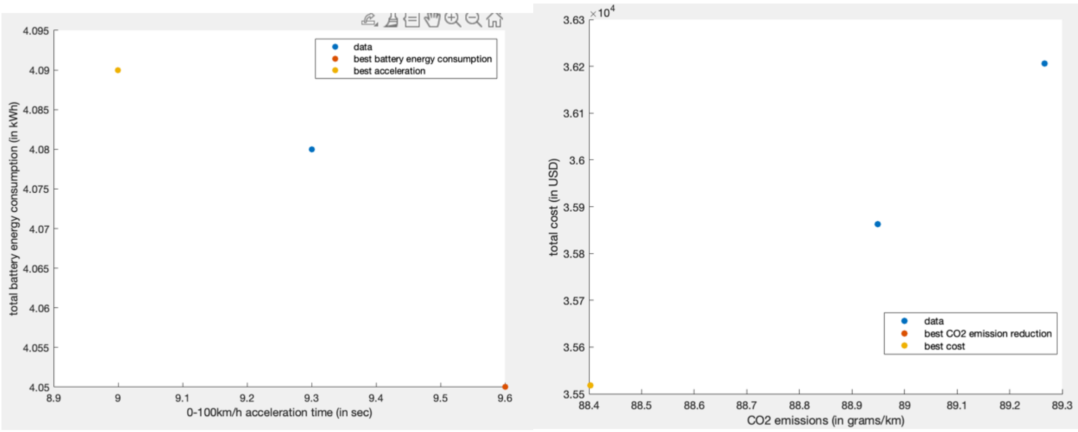
Best cO2 emission reduction				Best HEV cost			
Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4.6	280	88.40	35518.6	4.6	280	88.40	35518.6



(a)



(b)



(c) (d)

Figure 47-Pareto-Frontier of the results obtained by the variation of ICE power scale and differential gear ratio, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

By varying the ICE power scale and the final drive ratio, we obtain a small number of feasible candidates and we remark that by increasing the final drive ratio with the ICE power scale we can ensure 0-100km/h acceleration time less than 9.7 sec.

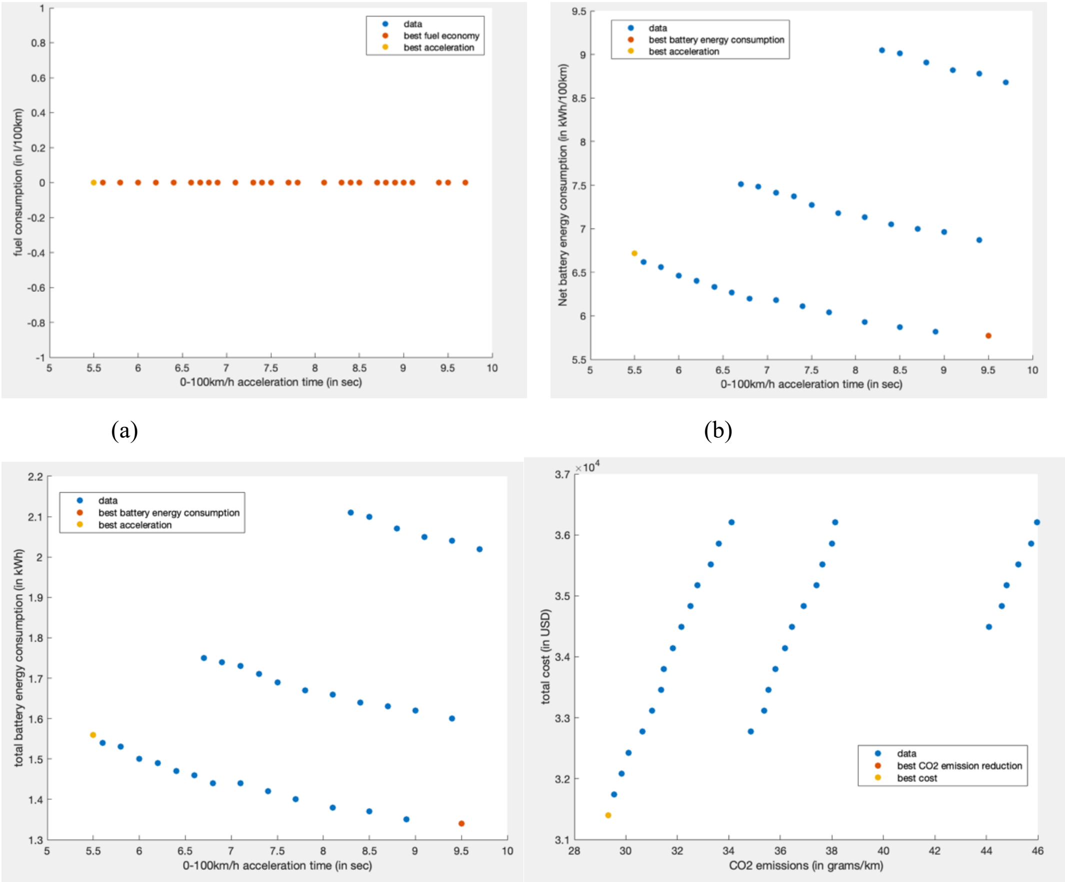
Between the feasible candidates, the configuration having the smallest ICE power scale, it has the smallest CO2 emission, battery energy consumption and the smallest cost but the highest 0-100km/h acceleration time.

b. Ratio EM to trans variation:

Table 37-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and gear ratio between EM and transmission

Best Net battery energy consumption				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
4	160	9.5	5.77	4	300	5.5	6.72

Best cO2 emission reduction				Best HEV cost			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4	160	29.32	31395.6	4	160	29.32	31395.6



(a) (b)

(c) (d)

Figure 48-Pareto-Frontier of the results obtained by the variation of ICE power scale and gear ratio between EM and transmission, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

With the variation of the ICE power scale and the ratio between EM and transmission, we obtain feasible candidates by increasing the ratio between EM and transmission to a value higher than 3. We remark that for each specific value of the gear ratio and by varying the ICE power scale, the battery energy is consumed in a specific interval. But by increasing the gear ratio and decreasing the ICE power scale, the battery energy consumption, the CO2 emission and the total cost decrease.

II- Hybridization factor variation:

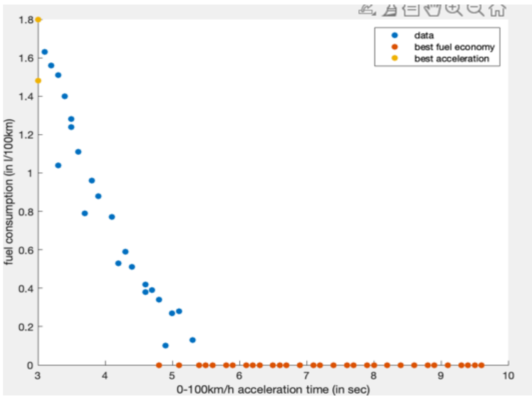
a. ICE power scale variation:

Table 38- Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and hybridization factor

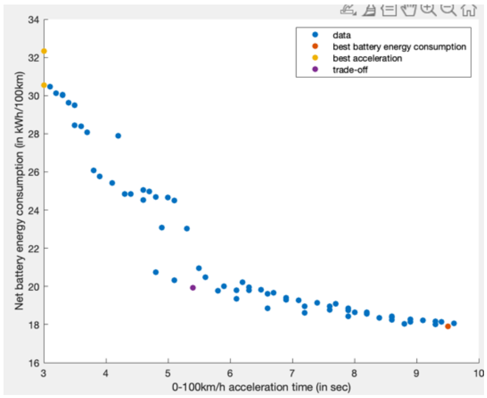
Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.45	290	9.5	17.9	0.85	300	3	32.34

Trade-off			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	140	5.4	19.92

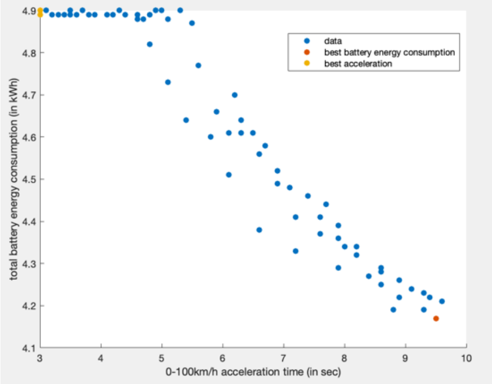
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
0.45	290	90.88	37461.05	0.75	130	92.54	36673.83



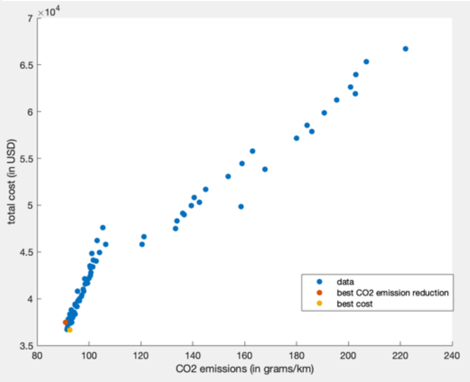
(a)



(b)



(c)



(d)

Figure 49-Pareto-Frontier of the results obtained by the variation of ICE power scale and hybridization factor, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

The variation of the hybridization factor and the ICE power scale leads to a huge number of feasible candidates because the EM and ICE are responsible of propelling the vehicle, in consequence, decreasing the 0-100km/h acceleration time to satisfy a value less than 9.7 sec.

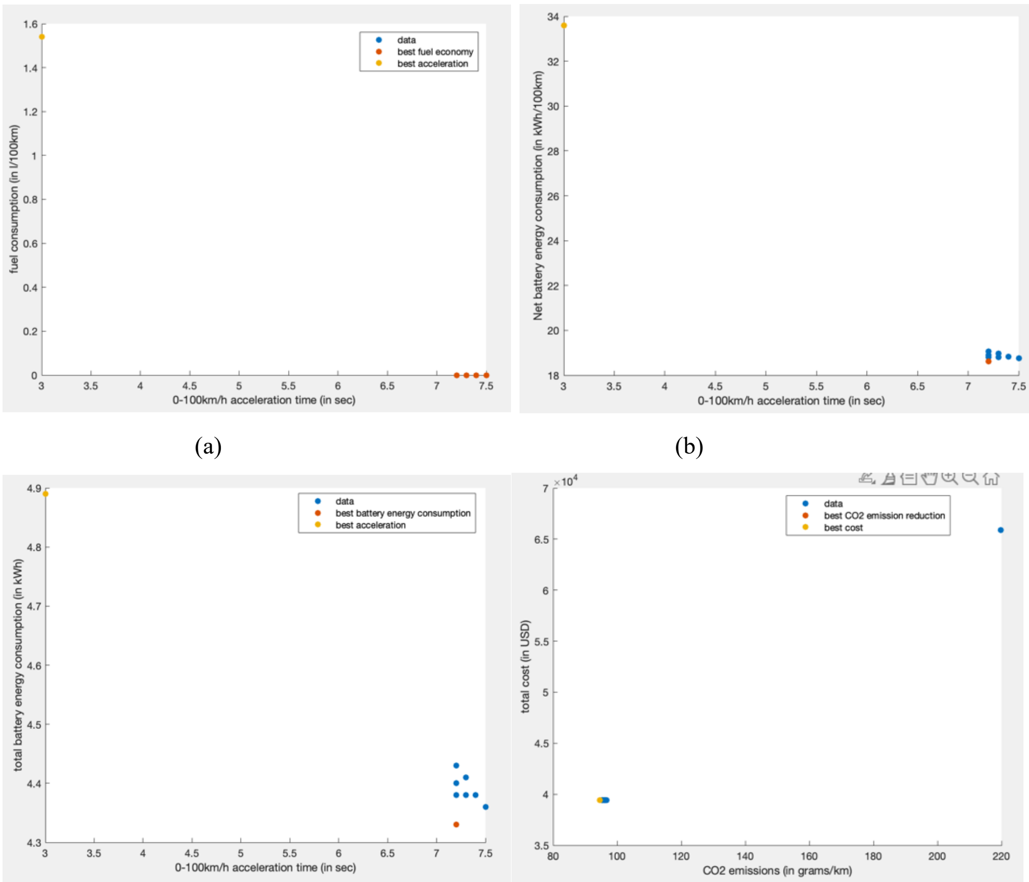
But we remark that by increasing the ICE power scale and decreasing the hybridization factor and vice versa, we obtain smallest CO2 emission and smallest cost. In the other hand, we obtain the smallest 0-100km/h acceleration time by increasing the two parameters at the same time.

b. Total ratio variation:

Table 39-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of total ratio and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	6.5	7.2	18.62	0.95	3	3	33.58

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6.5	94.56	39443.94	0.85	6.5	94.56	39443.94



(a) (b)

(c) (d)

Figure 50-Pareto-Frontier of the results obtained by the variation of total ratio and hybridization factor, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

By varying the total ratio and hybridization factor, we obtain a small number of feasible solutions (satisfying 0-100km/h acceleration time less than 9.7 sec). These feasible solutions have high hybridization factor (more than 0.85).

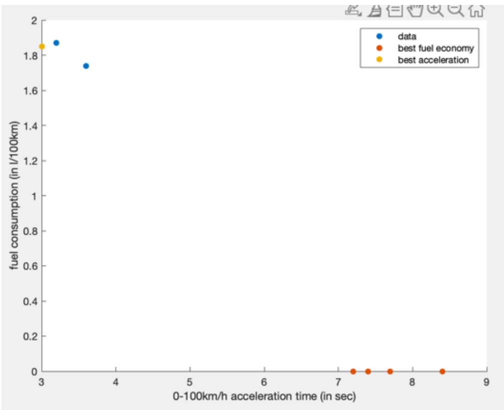
All the feasible solutions that have the same hybridization factor but different total ratio, they have closed values of battery energy consumed and therefore closed CO2 emission and also closed 0-100km/h acceleration times. But once we change the hybridization factor, we obtain a remarkable different value of CO2 emission. Then, the hybridization factor has the high impact on the battery consumption and the CO2 emissions.

c. Number of gears variation:

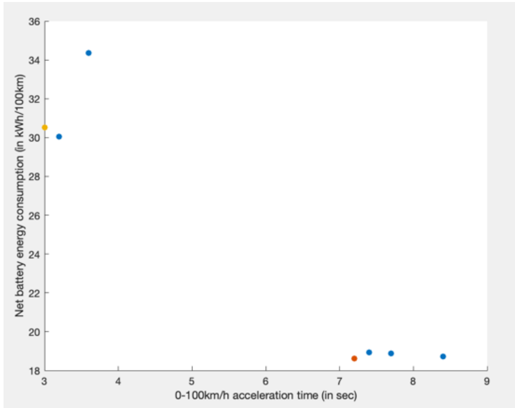
Table 40- Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	3	8.4	18.71	0.95	4	3	30.53

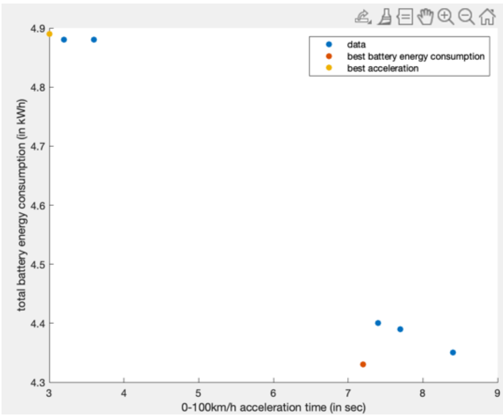
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Numbers gears	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Numbers gears	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6	94.57	39443.94	0.85	3	94.99	39007.84



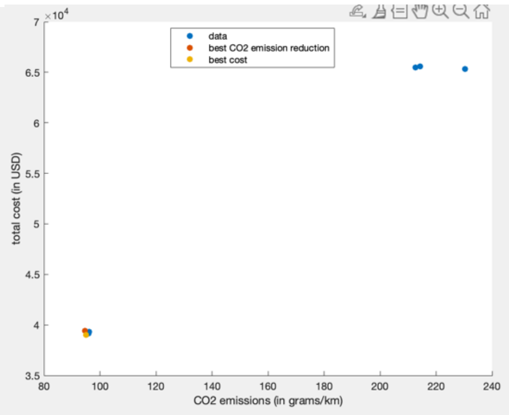
(a)



(b)



(c)



(d)

Figure 51-Pareto-Frontier of the results obtained by the variation of gears number and hybridization factor , (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

Here we observe the same results as in the variation of the total ratio.

d. Final drive ratio variation:

Table 41-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive ratio and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.75	4.6	9.7	17.45	0.95	4	3.1	33.35

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)
0.75	4.6	88.63	34187.81	0.75	4.6	88.63	34187.81

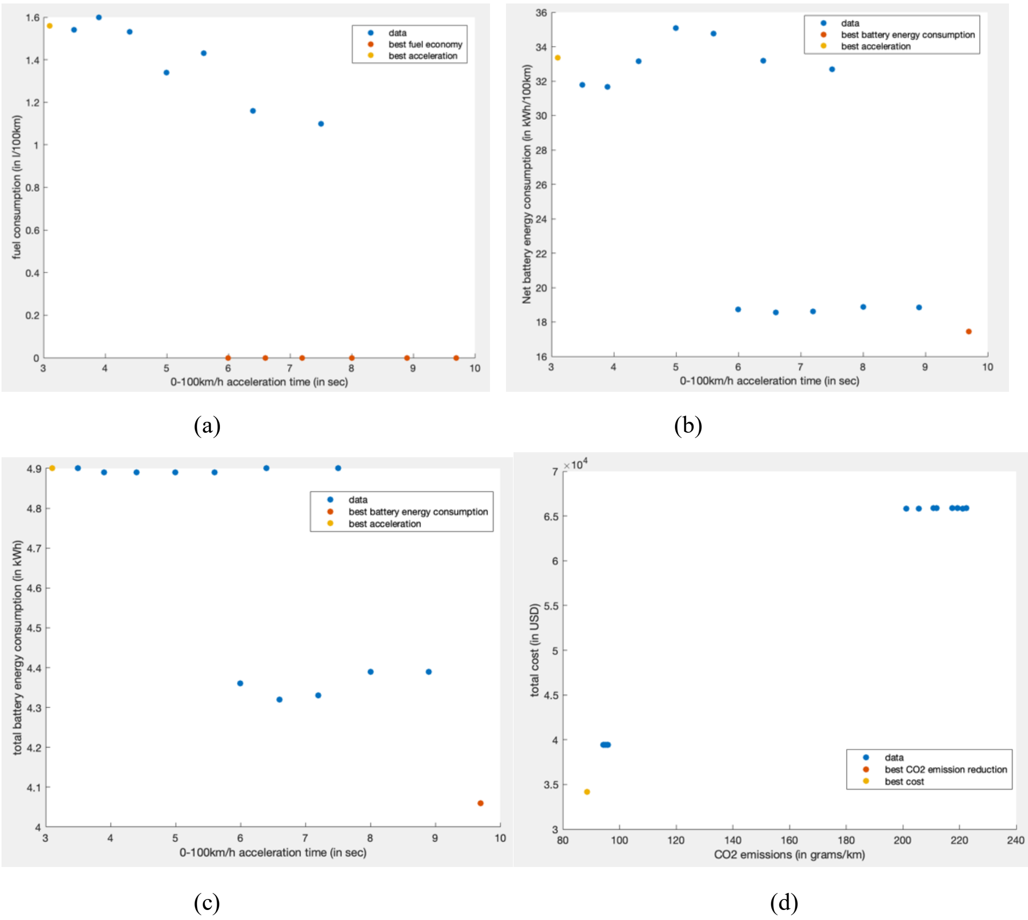


Figure 52-Pareto-Frontier of the results obtained by the variation of final drive ratio and hybridization factor, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

By varying the hybridization factor and the final drive ratio. For each fixed value of the hybridization factor the battery energy consumption and the CO2 emissions are varied in specific interval while the 0-100km/h acceleration time is changed significantly. The 0-100km/h acceleration time decreases by the increase of the final drive ratio.

We obtain different CO2 emissions only when we change the hybridization factor. And we get the smallest CO2 emissions with the configuration having the smallest hybridization factor.

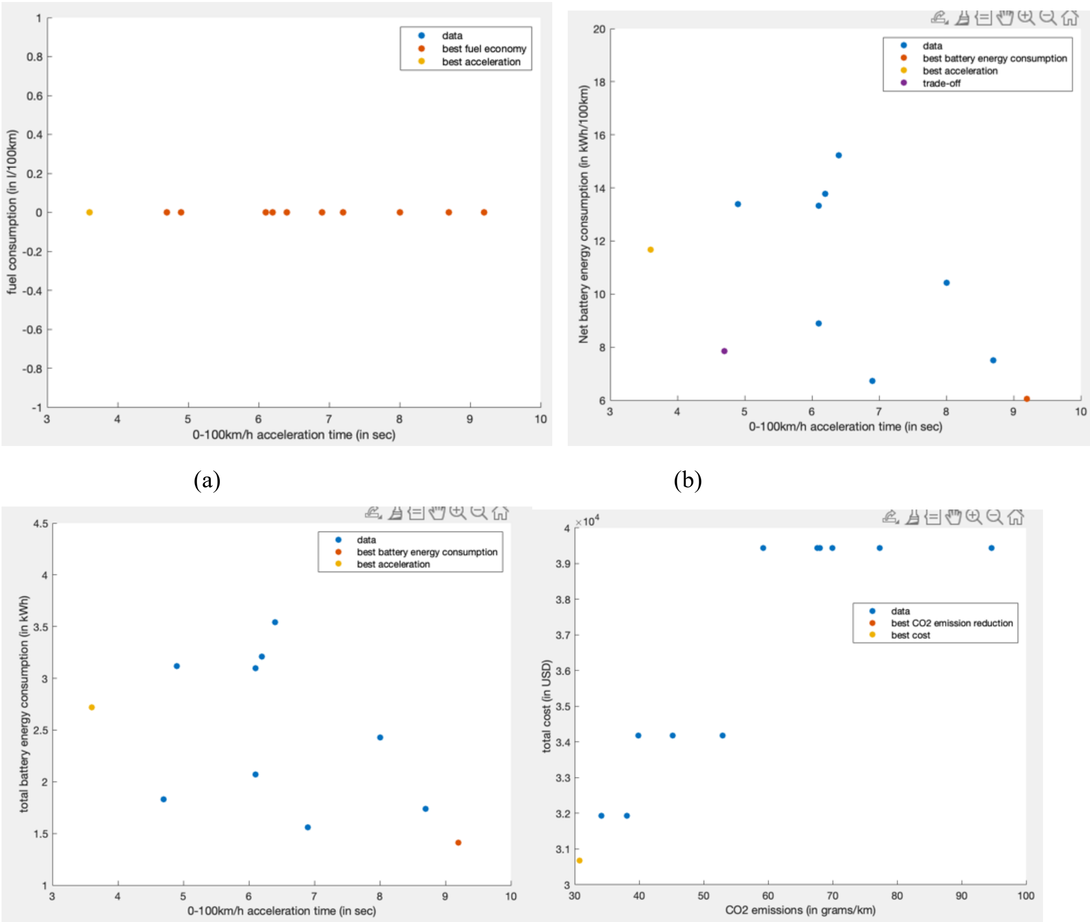
e. Ratio EM to trans variation:

Table 42-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.55	4	9.2	6.06	0.85	3.5	3.6	11.67

Tarde-off			
Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.75	4	4.7	7.85

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)
0.55	4	30.79	30682.54	0.55	4	30.79	30682.54



(a) (b) (c) (d)

Figure 53-Pareto-Frontier of the results obtained by the variation of the ratio between EM and transmission and hybridization factor, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

By increasing the ratio between EM and transmission and decreasing the hybridization factor we obtain a small CO2 emission while by increasing the 2 parameters we have the smallest 0-100km/h acceleration time.

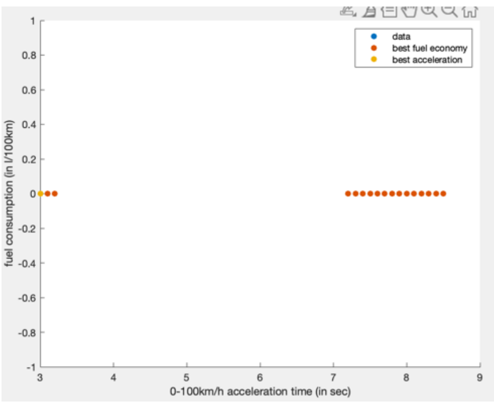
In this case we obtain the best CO2 emission reduction among all the other solutions.

f. Battery capacity variation:

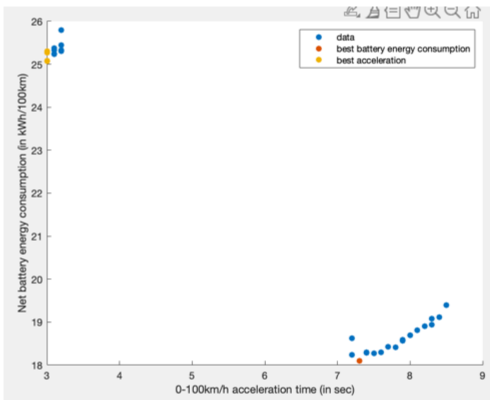
Table 43-Table representing the powertrain configurations that ensure the best battery energy consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of battery capacity and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	15200	7.3	18.1	0.95	34200	3	25.08
				0.95	38000	3	25.07
				0.95	41800	3	25.3
				0.95	45600	3	25.27

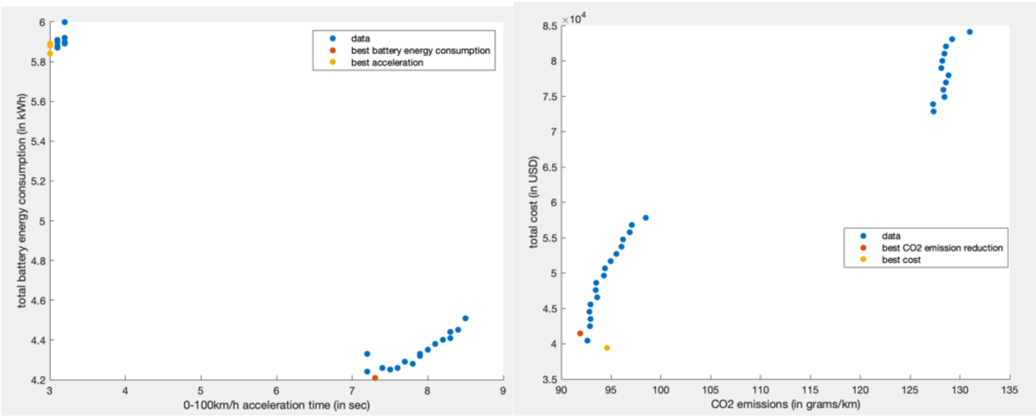
Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	15200	91.89	41480.69	0.85	7600	94.58	39443.94



(a)



(b)



(c) (d)

Figure 54-Pareto-Frontier of the results obtained by the variation of battery capacity and hybridization factor, (a) fuel consumption, (b) net battery energy consumption in CD mode, (c) total battery energy consumption all the 3 in function of 0-100km/h acceleration time, (d) total cost in function of CO2 emission and the trade-off

The increase of the hybridization factor and the battery capacity leads to the increase of the CO2 emissions and the battery energy consumption, while the decrease in the battery capacity decreases the 0-100km/h acceleration time.

But for each specific hybridization factor value the CO2 emissions vary in small range when varying the battery capacity while by changing the hybridization factor the CO2 emission values are significantly changed that means that the hybridization factor has the remarkable effect.

Since we have different characteristics for each drive cycle, the fuel and battery energy consumption are not the same, we have more fuel consumption in NREL Baltimore because it is longer and have more stops than WLTP (Figures 13 and 14).

C-WLTP long drive cycle:

This paragraph represents the results and observations obtained by using WLTP long drive cycle (69.75 km).

- **Full HEV:**

The charge sustaining mode State of charge (SOC_CS) is equal to 0.5 and the payload is 1500kg.

I- ICE power scale variation:

a. Final drive ratio variation:

Table 44-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive ratio and ICE power scale

Best fuel economy				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4.6	210	9.6	4.85	4.6	300	7.1	5.13

Trade-off			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4.6	250	8.3	4.99

Best cO2 emission reduction				Best HEV cost			
Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4.6	210	155.59	66282.04	4.6	210	155.59	66282.04

b. Ratio EM to trans variation:

Table 45-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and ICE power scale

Best fuel economy				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
1	270	9.2	5.01	3	300	6.3	10.71

Trade-off			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
4	160	6.8	6.59

Best cO2 emission reduction				Best HEV cost			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
1	270	160.62	69900.6	1	260	161.47	69635.39

c. Gears number variation:

Table 46-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and ICE power scale

Best fuel economy				Best 0-100km/h acceleration time			
Gears number	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Gears number	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
6	260	9.5	4.98	6	300	8.4	5.14

Trade-off			
Gears number	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
6	280	8.9	5.03

Best cO2 emission reduction				Best HEV cost			
Gears number	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Gears number	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
6	260	159.57	69254.6	6	260	159.57	69254.6

d. Total ratio variation:

Table 47-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of total ratio and ICE power scale

Best fuel economy				Best 0-100km/h acceleration time			
ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
6.5	260	9..5	4.99	5.5	300	8.5	5.16
				6	300	8.5	5.18
				6.5	300	8.5	5.16

Trade-off			
ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
5.5	280	9	5.03

Best cO2 emission reduction				Best HEV cost			
ratio_tot	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	ratio_tot	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
6.5	260	160.01	69343.4	6.5	260	160.01	69343.4

e. Battery capacity variation:

Table 48-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of the battery capacity and ICE power scale

Best fuel economy				Best 0-100km/h acceleration time			
Battery capacity in (Wh)	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Battery capacity in (Wh)	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
7600	280	9.5	9.5	3800	300	8.4	5.27
				7600	300	8.4	5.17

Trade-off			
Battery capacity in (Wh)	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
7600	280	8.9	5.03

Best cO2 emission reduction				Best HEV cost			
Battery capacity in (Wh)	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Battery capacity in (Wh)	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
7600	260	159.57	69254.65	7600	260	159.57	69254.65

II- Hybridization factor variation:

a. ICE power scale variation:

Table 49-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of the ICE power scale and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.65	180	9.4	4.98	0.95	90	3	6.4
0.55	240	9.3	4.98	0.85	300	3	6.79

Tarde-off			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.75	200	6.3	5.39

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
0.55	240	159.53	69427.88	0.75	130	160.2	68856.77

b. Total ratio variation:

Table 50-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of the total ratio and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	6.5	7.2	5.03	0.85	5	7.2	5.26
				0.85	5.5	7.2	5.19
				0.85	6	7.2	5.21
				0.85	6.5	7.2	5.03

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6.5	161.4	71867.96	0.85	6.5	161.4	71867.96

c. Gears number variation:

Table 51-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Numbers gears	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	6	7.2	5.1	0.95	4	3	6.81

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Numbers gears	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Numbers Gears	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	6	163.54	72299.09	0.85	3	164.72	72100.08

d. Final drive ratio:

Table 52-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive ratio and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.75	4.6	9.7	4.85	0.95	4	3.1	6.87

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)
0.75	4.6	155.47	65421.962	0.75	4.6	155.47	65421.962

e. Ratio between EM and transmission variation:

Table 53-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	1	7.2	5.03	0.85	2	6.2	7.96

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	1	161.25	71839.3	0.85	1	161.25	71839.3

f. Battery capacity variation:

Table 54-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of battery capacity and hybridization factor

Best fuel economy				Best 0-100km/h acceleration time			
Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)	Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Fuel Con. (in l/100km)
0.85	7600	7.2	5.03	0.95	34200	3	6.57
0.85	15200	7.3	5.03	0.95	38000	3	6.57

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	15200	161.11	73847.7	0.85	7600	161.42	71872.75

- **Plug-in HEV:**

The charge sustaining mode State of charge (SOC_CS) is equal to 0.3 and thedelivery is fully charged at the beginning of the cycle (when it leaves the warehouse the initial State of charge (SOC_init) is equal to 0.95) and the payload is 1500kg.

I- ICE power scale variation:

a. Final drive ratio variation:

Table 55- Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive and ICE power scale

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Diff Prim ratio	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
4.6	210	9.6	9.93	4.6	300	7.1	37.64

Best cO2 emission reduction				Best HEV cost			
Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Diff Prim ratio	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4.6	210	150.74	55259.3	4.6	270	262.54	51901.02

b. Ratio between EM and transmission variation:

Table 56-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and ICE power scale

Best Net battery energy consumption				Best 0-100km/h acceleration time			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
4	110	9.6	5.97	4	270	4.3	29.41

Best cO2 emission reduction				Best HEV cost			
gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	gear_ ratio_ EM_to_ trans	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
4	110	30.3	30724.86	4	110	30.3	30724.86

c. Total ratio variation:

Table 57-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of total ratio and ICE power scale

Best Net battery energy consumption				Best 0-100km/h acceleration time			
ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	ratio_tot	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
5.5	260	9.6	10.79	6	300	8.5	29.5
				6.5	300	8.5	28.03

Best cO2 emission reduction				Best HEV cost			
ratio_tot	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	ratio_tot	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
5.5	260	159.25	58263.7	6.5	270	192.74	51351.29

d. Battery capacity variation:

Table 58-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of battery capacity and ICE power scale

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Battery Capacity (Wh)	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Battery Capacity (Wh)	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
26600	270	9.7	18.03	7600	300	8.4	24.4

Best cO2 emission reduction				Best HEV cost			
Battery Capacity (Wh)	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Battery Capacity (Wh)	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
26600	270	91.5966	42862.0	11400	260	93.35	38356.76

e. Gears number variation:

Table 59-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and ICE power scale

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Number of gears	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Number of gears	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
6	260	9.5	24.91	6	300	8.4	25.48

Best cO2 emission reduction				Best HEV cost			
Number of gears	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Number of gears	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
6	260	193.35	50816.7	4	280	212.46	50609.95

II- Hybridization factor variation:

a. ICE power scale variation:

Table 60-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ICE power scale and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.45	230	9.7	17.32	0.85	240	3	27.3

Trade-off			
Hybridiz_ factor	Ice_ power_ kW_ scale	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	120	5.1	19.42

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Ice_ power_ kW_ scale	CO2 Emission (in grams/km)	Total cost (in USD)
0.45	230	87.96	35202.51	0.85	60	88.67	34161.09

b. Total ratio variation:

Table 61-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of total ratio and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	ratio_tot	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	6	7.2	10.8	0.85	5	7.2	11.43
				0.85	5.5	7.2	11.23
				0.85	6	7.2	10.8

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	ratio_tot	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	4	164.38	61299.069	0.85	4	164.38	61299.069

c. Gears number variation:

Table 62-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of gears number and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Number of gears	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Number of gears	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	4	7.7	26.44	0.85	6	7.2	27.83

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Number of gears	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Number of gears	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	4	201.75	52915.81	0.85	4	201.75	52915.81

d. Final drive ratio:

Table 63-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of final drive ratio and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Diff Prim ratio	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	4.2	7.2	28.22	0.95	4	3.1	40.26

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Diff Prim ratio	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	4.2	212.78	53624.50	0.75	4.6	88.63	34187.81

e. Ratio between EM and transmission variation:

Table 64-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of ratio between EM and transmission and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	gear ratio EM to trans	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.55	4	9.2	6.07	0.85	3.5	3.6	12.48

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	gear ratio EM to trans	CO2 Emission (in grams/km)	Total cost (in USD)
0.55	4	30.81	30729.19	0.55	4	30.81	30729.19

f. Battery capacity variation:

Table 65-Table representing the powertrain configurations that ensure the best fuel consumption, best 0-100km/h acceleration test, best CO2 emission and best total cost by the variation of battery capacity and hybridization factor

Best Net battery energy consumption				Best 0-100km/h acceleration time			
Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)	Hybridiz_ factor	Battery Capacity (Wh)	0-100 km/h Acc. time (in sec)	Net battery energy consumption (in kWh/100km)
0.85	7600	7.2	10.75	0.95	34200	3	25.25
				0.95	38000	3	25.26
				0.95	41800	3	25.29
				0.95	45600	3	25.28

Best cO2 emission reduction				Best HEV cost			
Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)	Hybridiz_ factor	Battery Capacity (Wh)	CO2 Emission (in grams/km)	Total cost (in USD)
0.85	26600	93.02	44676.751	0.85	22800	93.1	43658.47

We remark that we have a high total cost for Full HEV because of the high fuel consumption in comparison to Plug-in HEV, which leads to the increase of the operation cost.

We can conclude from the results obtained above, that the parameters that have the main effect on the reduction of CO2 emissions and decreasing of the 0-100km/h acceleration are the parameters related to the engine and electric motor, which are the ICE power scale, hybridization factor and the ratio between EM and transmission.

4.6.2-Particle Swarm optimization:

Kennedy and Eberthart invented Particle Swarm Optimization (PSO) in 1995 [36], which is a stochastic and population-based search technique. It is mostly influenced by the social behavior in natural systems with large groups of individuals, such as flocks of birds or swarm of bees, as well as human social systems.

The PSO algorithm's operating premise is based on simulating a simplified social system, like the behavior of a flock of birds flying across an area in search of a plentiful food source.

PSO model is made comprised of particles that move in a multi-dimensional search space and interact with one another. A current position and a velocity are two attributes of each particle. Every particle preserves the best position it has achieved in the search space (among the swarm) and is also aware of the group's best-reached position. The PSO algorithm predicts the optimum next location for the particles at each iteration by taking into account each particle's particular experience, which is the memory of its best former position, as well as the experience of the most successful particle.

In this section, we are illustrating the results obtained by applying the PSO algorithm to our design space using the WLTP long drive cycle.

The following two tables represent the configurations of the plug-in and full HEVs that provide the lowest CO2 emission and the cheapest total cost.

Table 66-PSO results for best CO2 emissions of Full and Plug-in HEV using WLTP long

Final results	**Plug- in HEV**	**Full HEV**
Total ratio	4.05	4.428
Gears number	4	3
Differential primary ratio	3.82	3.847
Gear ratio between from EM to transmission	4	0.5
Battery capacity (in Wh)	39345	21021
Hybridization factor	0.537	0.67
ICE power scale (in kW)	86.48	249
0-100km/h acceleration time (in sec)	9.5	9.3
CO2 emission (in g/km)	28.71	126.31

Table 67-PSO results for best total cost of Full and Plug-in HEV using WLTP long

Final results	**Plug- in HEV**	**Full HEV**
Total ratio	5.313	3
Gears number	3	4
Differential primary ratio	4.6	4.106
Gear ratio between from EM to transmission	2.722	3.744
Battery capacity (in kWh)	8.7	3.875
Hybridization factor	0.32	0.403
ICE power scale (in kW)	162.635	101.247
0-100km/h acceleration time (in sec)	9.6	9.4
CO2 emission (in g/km)	37.927	188.856
Fuel consumption (in L/100km)	2.71	5.89
Total cost (one year of operation) (in USD)	29544	28899
Powertrain cost + baseline in (USD)	28571	26057

By comparing the two architectures, we remark that with a plug-in HEV we obtain more fuel economy, thus less CO2 emission, but this type of vehicles have more expensive powertrain cost than the Full HEV where we have more fuel consumption and then more CO2 emissions, by consequence higher operation cost. As result, the plug-in HEVs are more efficient in reducing the emissions.

Conclusion and further work

In this thesis, we developed parallel P2 Full and Plug-in HEV models based on the Fiat Ducato platform. Using the SERCA algorithm, a rapid near optimal solution for the HEV off-line control, and the 0-100km/h acceleration time test, we were able to determine optimized sizes for ICE, electric motor, battery and transmission that enhance the fuel economy capability and reduce the CO2 emissions and the total cost. Therefore, ICE power scale, hybridization factor, battery capacity, total ratio, final drive ratio, ratio between EM and transmission and the number of gears were considered as our design parameter. A brute force method, which aims at varying two parameters and fixing the others, is firstly used to explore the design space and to see how sizing affected fuel consumption and vehicle performance starting from predefined driving missions including the NREL Baltimore and the WLTP drive cycles. Then, the Particle Swarm Optimization (PSO) algorithm was employed as an optimization algorithm for our case study.

From this research we can conclude that the rate of fuel consumption is related to the selected driving cycle, because each driving cycle has characteristics that differ from each other.

We can also come to a conclusion that, the three parameters whish have the main effect on the reduction of the 0-100km/h acceleration time and the fuel consumption are the parameters related to the power components which are the ICE power scale, the hybridization factor and the ratio between EM and transmission, while the other parameters don’t have that main impact. And the change of the other parameters while fixing these three parameters cannot ensure a 0-100 km/h acceleration time less than 9.7sec and are considered as infeasible candidates in the research.

By decreasing the ICE power scale, the fuel consumption decreases, but the hybridization factor should be increased to guarantee a 0-100km/h acceleration time less than 9.7 sec. Hence, the two parameters most be handled to ensure a trade off between fuel economy and performance. The increase of the battery capacity leads to the increase of the 0-100km/h acceleration time, but it increases the distance driven in the EV mode, which limits the ICE activation and by consequence minimizes the fuel consumption. Also, it cannot be increased a lot due to the limitations on the vehicle mass and then vehicle performance. By taking the highest ratio between EM and transmission we obtained the lowest CO2 emission in the two HEV powertrains.

The identification of the optimal powertrain component sizing will lead to a high reduction in fuel consumption and therefore the CO2 emission. And by comparing the two HEV powertrains, we can see that the plug-in HEV ensures a significant reduction in the CO2 emission, but it has an expensive powertrain cost in comparison to the full HEV where the CO2 emission is higher. What makes the plug-in HEV efficient powertrains to comply with the worldwide tightening CO2 emission regulations.

Further work could be by considering an exploration based on varying more than 2 parameters at the time and evaluating other performance requirements and drive cycles. In addition, we can simulate the delivery van in more realistic way, by using a variable payload mass related to the drive cycle used.

References

[1] Zhuang, W., (Eben), S. L., Zhang, X., Kum, D., Song, Z., Yin, G., & Ju, F. (2020, February 15). *A survey of powertrain configuration studies on hybrid electric vehicles*. Applied Energy. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0306261920300659

[2] Lee, S. D. (2013). *Modeling and validation Of Power-Split and P2 parallel hybrid electric vehicles*. SAE International. Retrieved from: https://www.researchgate.net/publication/289416422_Modeling_and_Validation_of_Power-Split_and_P2_Parallel_Hybrid_Electric_Vehicles

[3] Yang, Y., Schofield, N., & Emadi, A. (2016, June). *Integrated electromechanical double-rotor compound hybrid transmissions for hybrid electric vehicles*. IEEE Xplore. Retrieved from: https://ieeexplore.ieee.org/document/7289469.

[4] Anselma, P. G., Biswas, A., Belingardi, G., & Emadi, A. (2020, June 22). *Rapid assessment of the fuel economy capability of parallel and series-parallel hybrid electric vehicles*. Applied Energy. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S030626192030831X.

[5] ITEMM. *Vehicle hybridization*. (n.d.). Retrieved from: http://www.itemm.org.br/en/informes-tecnicos/hibridizacao-veicular-2/.

[6] Tara, E., Shahidinejad, S., Filezadeh, S., & Bibeau, E. (2010, July). *Battery storage sizing in a RETROFITTED plug-in hybrid electric vehicle*. IEEE Xplore. Retrieved September from: https://ieeexplore.ieee.org/document/5438793.

[7] Mapelli, F. L., Transitano, D., & Stefano, A., (2012). *Plug-in hybrid electrical commercial vehicle: Modeling and prototype realization*. IEEE Xplore. Retrieved from: https://ieeexplore.ieee.org/abstract/document/6183179.

[8] Cheli, F., Mapelli, F. L., Manigrasso, R., & Transitano, D., (2008). *Full energetic model of a plug-in hybrid electrical vehicle*. IEEE Xplore. Retrieved September from: https://ieeexplore.ieee.org/document/4581319.

[9] Butler, K. L., Ehsani, M., & Kamath, P. (1999). *A matlab-based modeling and simulation package for electric and hybrid electric vehicle design*. IEEE Xplore. Retrieved from: https://ieeexplore.ieee.org/document/806769.

[10] Anselma, P.G., Huo, Y., Roeleveld, J., Belingardi, G. et al., "*Real-Time Rule- Based Near-Optimal Control Strategy for a Single-Motor Multimode Hybrid Electric Vehicle Powertrain*," in 2018 FISITA World Congress, Chennai, India, Oct. 2018, 1-14. Retrieved From: https://www.researchgate.net/publication/328028500

[11] Goerke, D., Bargende, M., Keller, U., Ruzicka, N. et al., "*Optimal Control Based Calibration of Rule-Based Energy Management for Parallel Hybrid Electric Vehicles*," SAE Int. J. Alt. Power. 4(1):178-189, 2015, doi:10.4271/2015-01-1220. Retrieved from: https://www.sae.org/publications/technical-papers/content/2015-01-1220/

[12]. Finesso, R., Spessa, E., and Venditti, M., "*An Unsupervised Machine-Learning Technique for the Definition of a Rule-Based Control Strategy in a Complex HEV*," SAE Int. J. Alt. Power. 5(2):308-327, 2016, doi:10.4271/2016-01-1243. Retrieved from: https://www.researchgate.net/publication/294580135

[13]. Zhuang, W., Zhang, X., Yin, G., Peng, H. et al., "*Mode Shift Schedule and Control Strategy Design of Multimode Hybrid Powertrain,*" in IEEE Transactions on Control Systems Technology, online Feb. 11, 2019. Retrieved from: https://ieeexplore.ieee.org/document/8638810

[14.] Musardo, C., Rizzoni, G., and Staccia, B., "*A-ECMS: An Adaptive Algorithmfor Hybrid Electric Vehicle Energy Management*," in Proceedings of the 44th IEEE Conference on Decision and Control, Seville, Spain, 2005, 1816-1823. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0947358005710487

[15] Lacandia, F., Tribioli, L., Onori, S., and Rizzoni, G., "*Adaptive Energy Management Strategy Calibration in PHEVs Based on a Sensitivity Study,*" SAE Int. J. Alt. Power.2(3):443-455, 2013, doi:10.4271/2013-24-0074. Retrieved from: https://www.jstor.org/stable/26169028

[16] Onori, S. and Tribioli, L., "*Adaptive Pontryagin's Minimum Principle Supervisory Controller Design for the Plug-In Hybrid GM Chevrolet Volt*," Applied Energy 14:224-234, 2015. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0306261915000276

[17] Murphey, Y.L., Park, J., Kiliaris, L., Kuang, M. et al., "*Intelligent Hybrid Vehicle Power Control - Part II: Online Intelligent Energy Management,*" IEEE Transactions on Vehicular Technology 62(1):69-79, 2013. Retrieved from: https://ieeexplore.ieee.org/document/6296724

[18] Won, J.-S. and Langari, R., "*Intelligent Energy Management Agent for a Parallel Hybrid Vehicle - Part II: Torque Distribution, Charge Sustenance Strategies, and Performance Results,*" IEEE Transactions on

Vehicular Technology 54(3):935-953, May 2005. Retrieved from: https://ieeexplore.ieee.org/document/1433239

[19] Park, J. et al., "*Intelligent Vehicle Power Control Based on Machine Learning of Optimal Control Parameters and Prediction of Road Type and Traffic Congestion*," IEEE Transactions on Vehicular Technology 58(9):4741-4756, Nov. 2009. Retrieved from: http://www.cs.cmu.edu/~cga/ok/Park.pdf

[20] Anselma, P.G., Huo, Y., Roeleveld, J., Belingardi, G. et al., "*From Off-Line to On-Line Control of a Multimode Power Split Hybrid Electric Vehicle Powertrain,*" in 9th IFAC International Symposium on Advances in Automotive Control, Orléans, France, June 24-27, 2019. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2405896319306421

[21] Biswas, A., Anselma, P.G., and Emadi, A., "*Real-Time Optimal Energy Management of Electrified Powertrains with Reinforcement Learning*," in 2019 IEEE Transportation Electrification Conference and Expo, Novi, MI, June 2019,19-21. Retrieved from: https://ieeexplore.ieee.org/document/8790482

[22] Feng, L., Liu, W., and Chen, B., "*Driving Pattern Recognition for Adaptive Hybrid Vehicle Control,*" SAE Int. J. Alt. Power. 1(1), 2012, doi:10.4271/2012-01-0742. Retrieved from: https://www.sae.org/publications/technical-papers/content/2012-01-0742/

[23] Biswas, A. and Emadi, A., "*Energy Management Systems for Electrified Powertrains: State-of-the-Art Review and Future Trends*," IEEE Transactions on Vehicular Technology 68(7):6453-6467, 2019. Retrieved from: https://ieeexplore.ieee.org/document/8704902

[24] Asher, Z.D., Galang, A.A., Briggs, W., Johnston, B. et al., "*Economic and Efficient Hybrid Vehicle Fuel Economy and Emissions Modelling Using an Artificial Neural Network*," SAE Technical Paper 2018-01-0315, 2018, doi:10.4271/2018-01-0315. Retrieved from: https://www.sae.org/publications/technical-papers/content/2018-01-0315/

[25] Sniedovich, M. (2011). *Dynamic programming: Foundations and principles*. CRC Press.

[26] Paganelli, G., Guezennec, Y., & Rizzoni, G. (2002, March 4). *Optimizing control strategy for hybrid fuel cell vehicle*. Optimizing Control Strategy for Hybrid Fuel Cell Vehicle. Retrieved from: https://www.sae.org/publications/technical-papers/content/2002-01-0102/.

[27] Zhang X, Peng H, Sun J. *A near-optimal power management strategy for rapid component sizing of power split hybrid vehicles with multiple operating modes.* American Control Conference (ACC) 2013:5972–7. Retrieved from: https://ieeexplore.ieee.org/document/6580775

[28] Qin Z, Luo Y, Zhuang W, Pan Z, Li K, Peng H. *Simultaneous optimization of topology, control and size for multi-mode hybrid tracked vehicles*. Appl Energy 2018; 212:1627–41. Retrieved from: https://www.researchgate.net/publication/322357038

[29] Anselma PG, Huo Y, Roeleveld J, Belingardi G, Emadi A. *Slope-weighted energy based rapid control analysis for hybrid electric vehicles*. IEEE Trans Veh Technol 2019;68(5):4458–66. Retrieved from: https://ieeexplore.ieee.org/document/8642373

[30] Jung, D., Ahmed, Q., Zhang, X., & Rizzoni, G. (2018, April 3). *Mission-based design space exploration for Powertrain electrification of Series plugin hybrid electric delivery truck*. Mission-based Design Space Exploration for Powertrain Electrification of Series Plugin Hybrid Electric Delivery Truck. Retrieved from; https://www.sae.org/publications/technical-papers/content/2018-01-1027/.

[31] Jokela, T., Iraklis, A., Kim, B., & Gao, B. (2019, April 2). *Combined sizing and EMS optimization of Fuel-Cell hybrid powertrains for commercial vehicles*. Combined Sizing and EMS Optimization of Fuel-Cell Hybrid Powertrains for Commercial Vehicles. Retrieved September 12, 2021, from https://www.sae.org/publications/technical-papers/content/2019-01-0387/.

[32] Finesso, R., Misul, D., Spessa, E., & Venditti, M. (2018, July 1). *Optimal design Of Power-split Hevs based on total cost of ownership and co2 Emission Minimization*. MDPI. Retrieved September from https://www.mdpi.com/1996-1073/11/7/1705.

[33] Hamza, K., Laberteaux, K., & Chu, K.-C. (2020, April 14). *On modeling the total cost of ownership of electric and plug-in hybrid vehicles*. On Modeling the Total Cost of Ownership of Electric and Plug-in Hybrid Vehicles. Retrieved from: https://www.sae.org/publications/technical-papers/content/2020-01-1435/.

[34] *Prix de l*. GlobalPetrolPrices.com. (n.d.). Retrieved from: https://fr.globalpetrolprices.com/gasoline_prices/.

[35] Alves, B. (2021, August 10). *Electricity prices by country 2020*. Statista. Retrieved from: https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/.

[36] J. F. Kennedy, J. Kennedy, and R. C. Eberhart, Swarm intelligence. Morgan Kauf-mann, 2001.

[37] J. Liu and H. Peng, "Modeling and Control of a Power-Split Hybrid Vehicle," in *IEEE Transactions on Control Systems Technology*, vol. 16, no. 6, pp. 1242-1251, Nov. 2008, doi: 10.1109/TCST.2008.919447. Retrieved from: https://ieeexplore.ieee.org/document/4475524