Case Study

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A Simulation-Based Concept Design Approach for Combustion Engine and Battery Electric Vehicles

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Abstract

The early concept design of a vehicle is becoming increasingly crucial to determine the success of a car. Broaden market competition, more stringent regulations and fast technological changes require a prompt response from carmakers and Computer-Aided-Engineering (CAE) has emerged in recent year as the promising way to provide more efficient and cost-effective design and to cut development time and costs. The work presented in this paper shows an approach based on CAE to determine vehicle's energy consumption and performance. The different vehicle's subsystem are first analyzed separately by using dedicated simulation tools and then integrated to obtain the entire vehicle. The work covers a wide range of vehicle layouts. Combustion engine and battery electric vehicles (BEVs) are considered and various transmission configurations are contemplated with respect to some of the most adopted solutions for these vehicles. The simulation results allow to identify the most effective design variables and to compare the different layouts over various car segments.

Keywords

Vehicle design, combustion engine, electric motor, transmission, energy consumption, performance, integrated system, simulation

Introduction

The automotive industry is facing new and pressing challenges from increasing market competition, more stringent environmental regulations and new technologies that contribute to change drastically the current scenario. Modern vehicles must comply with several standards and policies, fulfil customers' expectations, and nevertheless be profitable for carmakers. In this context, decision-making becomes crucial already at the very early phase of vehicle design. Nowadays, this aim is pursued more and more extensively through Computer-Aided-Engineering (CAE). It allows cutting development time and expensive prototypes production by reducing the need for experimental procedures and, from the very beginning of the vehicle development, provides a broaden analysis over different vehicle solutions.

The most common approach for complex systems design is based on the decomposition of the system into its subsystems and furthermore to its components, in a cascade manner up to the desired level of detail. Applications in automotive field using this approach are proposed by Ford [1], however further references can be found in aerospace industry as shown by Airbus [2]. At each stage, mathematical models are defined to evaluate properly the quantities of interest. A wide range of models can be adopted, from simplest empirical formulations or data collection to more complex dedicated software packages, depending on trade-off choices regarding computational time, available data, expertise and desired results' accuracy.

The integration of the various models up to the vehicle system level gives the opportunity to assess vehicle performances and furthermore, to highlight which design variables have greater impact on fulfilling vehicle requirements. Through optimization techniques, it is possible to explore rapidly the design variables space and thus the various vehicle design solutions. Areas for possible improvements and most effective parameters can be detected, providing guidelines towards better and more efficient design solutions. The introduction of optimization techniques in the early phase of the vehicle design clearly helps to gain a better, deeper and earlier understanding of design limitations and potential problems allowing for anticipated and more effective modifications. The automotive industry employs these techniques over the comprehensive product development process (PDP), particularly in the car body design many studies are proposed by automotive manufacturers like Daimler [3], BMW [4] and Ford [5].

The work presented in this paper shows how CAE can be adopted during the early phase of a vehicle design to analyze various vehicle layouts, to identify the most significant design variables and their mutual interaction. The vehicle design focuses on the study of the powertrain, in particular conventional combustion engine and increasingly popular battery electric layouts are considered. Considering the growing importance of emission standards, fuel economy is a primary aspect in this study. Nevertheless, speed and acceleration performances are at the foundation of a car success, especially when moving from city cars to the more luxury and sport segment. Therefore, fuel consumption and straight line dynamic performance are chosen as key vehicle requirements.

The proposed methodology is based on a bottom-up approach, moving from the individual powertrain subsystems to the entire vehicle. Each subsystem is analyzed through appropriate modelling techniques and optimization algorithms are applied to the components design. The use of specific tools to evaluate the complex behavior of the different subsystems provides more reliable and accurate results with respect to commonly adopted mean-value-models (MVM) which are mainly used due to extremely low computational cost. Many examples of MVMs can be found in the literature for both combustion engine vehicle [6,7,8,9,10] and battery electric vehicle [7,10,11] applications. The entire vehicle model results from combing the different subsystems models while key performances indicators are evaluated considering specific driving cycles. Data collected over the most common vehicles in current market are used to compare the different vehicle layouts. A correlation analysis is performed to identify the most effective design variables of internal combustion engine and electric motor and their effect on the vehicles' consumption and performances. A similar approach is provided in other studies focusing on specific vehicle requirements: gear shifting strategy [12], air conditioning system [13] and active suspension [14]. Finally, a sensitivity analysis is applied to consider also the effectiveness of lightweight design on vehicles' requirements.

Therefore, the overall results provide an overview on a broader range of vehicles allowing to extend the considerations from the previous works of Baglione [15] and Kolekar [16] that focused on a specific vehicle.

Vehicle model

The vehicle model section describes the different considered subsystems: internal combustion engine, electric traction system, transmission, chassis and control system. It shows the main features considered to design and model the various components of each subsystem. In particular, emphasis is given to the definition of the workflow used to evaluate the subsystems performances starting from few main design variables. The models developed in this work are functional to the assessment of vehicle requirements. Hence, they focus on providing estimation of power performance and efficiency. Engine and electric motor models consist of a two-level decomposition. At the vehicle system level, simplified models are realized in order to keep a reasonable computational time. However, maintaining the necessary accuracy is a crucial aspect and this purpose is accomplished by using a response surface approach, developed through dedicated software packages.

Internal Combustion Engine

The internal combustion engine (ICE) represents the historical traction system used in automotive industry. During recent years, market competition and more stringent emission regulations have pushed carmaker to heavy investments towards ICE improvements. EPA [17] and ICCT [18] reports show how technologies like fuel direct injection and variable valve timing and lift are increasingly adopted not only in luxury vehicles, but also in lower segment cars. Engine downsizing offers the solution for more energy efficient engines without loss of power performance.

Following these considerations, with the aim of providing the most advanced solutions and due to recent scandals [19] and increasing restrictions [20] over Diesel engines, this work treats only a limited range of engines. Specifically, the models cover turbocharged, fuel direct injection, variable valve time and lift petrol engines.

Engine model

The ICE modeling involves a complex system where different physical phenomena occurs: gas dynamics, chemical reactions, heat exchange, mechanical interactions, etc. The engine model is implemented in the commercial software Dymola®. It uses maps to compute engine fuel consumption, while a simplified thermal model provides actual engine oil temperature, which is crucial in fuel consumption assessment. Furthermore, the model accounts for the starter motor, ancillary loads and the idle speed controller. The workflow shown in Figure 1 provides the engine maps. The problem is break up into different stages that interface with each other through input-output connections involving data exchange. It is realized through the commercial software iSight®.

The engine main parameters represent the workflow inputs and their values correspond to real-world engines data obtained from automotive manufacturers datasheets [21]. The actual main parameters used and their range of values are listed in Table 1.

The first step of the workflow focuses on the combustion with the aim of defining the ignition timing map to be subsequently used in the engine simulation. The model basis on a set of empirical and analytical formulations to estimate the phenomena occurring in the cylinder.

Table 1. Engine data statistics (Values range)

Parameter	*Min*	*Max*
Bore [mm]	70.8	98
Stroke [mm]	69.9	97
Compression Ratio [-]	8.7	12
Number of Cylinders [-]	3	8
Displacement [l]	1	5.6
Number of Engines	87	

The gas thermodynamics study is based on energy-balance equations involving: combustion heat, work exchange with the piston and heat exchange with the cylinder's wall. The combustion is defined through the Wiebe's function [22] and correction factors depending on engine speed and load level [23]. The work exchanged with piston considers classic ideal gas equations [24] while the Woschni empirical correlation [25] is adopted to evaluate the heat exchange with the cylinder wall. Varying the ignition time provides conflicting solutions between increasing the efficiency and reducing the maximum pressure. The ignition map is obtained by choosing a trade-off solution between these two objectives at different engine speeds and load levels.

The next step involves valve timing optimization and this procedure requires accurate knowledge of the mass flow occurring in the engine. The commercial software WAVE® from Ricardo is used to develop a model to solve the gas dynamics and thermal problem through one-dimensional CFD. The model architecture is kept simple in order to easily parametrize the definition of all the components: ducts, junctions, compressor, turbine, valves and cylinders. Table 2 presents the dependencies and the method used to parameterize the components sizing.

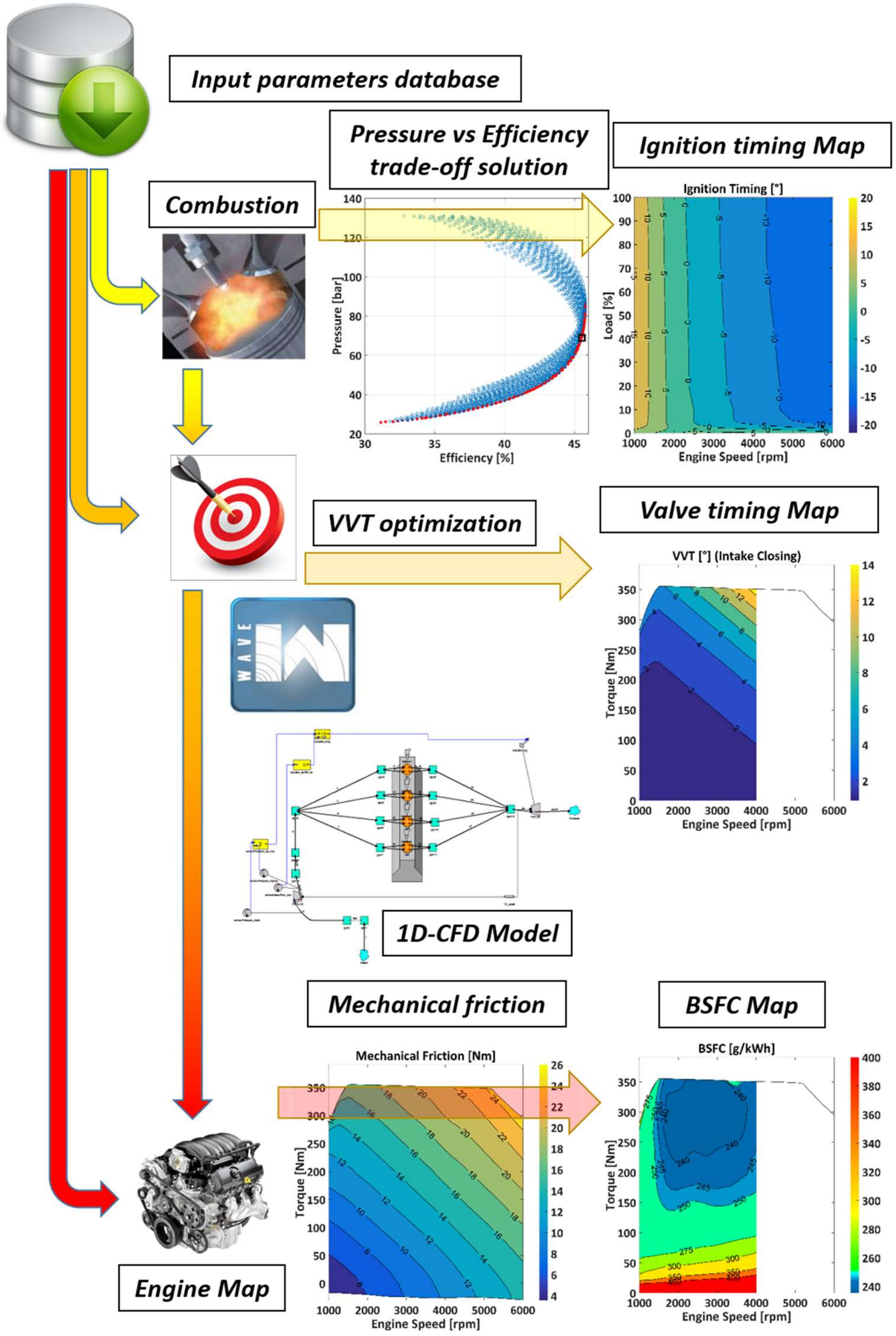


Figure 1. Engine modeling workflow

The VVT optimization employs an exploratory technique that considers a limited set of possible valve opening and closing configurations. The number of configurations to be simulated is strongly limited due to high computational cost involving the engine map calculation. Interpolations methods provide the results for the intermediate configurations. The optimal solution is chosen by minimizing the fuel consumption per torque.

The last step provides the engine fuel consumption map by considering mechanical losses. Sandoval [26] developed a friction model for spark ignition engines that considers losses from crankshaft, reciprocating elements in the piston assembly and valvetrain. Furthermore, it allows to consider the effect of oil viscosity, which strongly affects engine friction losses at cold-start [27].

Table 2. Engine 1D-CFD components sizing

Component	**Parameters**	**Method**
Ducts	Bore, Stroke, Cylinders, Max Engine speed, Turbo pressure boost	Avoid gas flow chocking condition [6] and optimize wave and inertial effects [28]
Junctions (intake and exhaust manifold)	Displacement	Torque increase and response lag reduction [29]
Compressor/Turbine	Bore, Stroke, Max Engine speed, Turbo pressure boost	Trial-and-error approach to identify compressor and turbine geometry scaling to improve low-end torque and avoid flow chocking. Compressor and turbine experimental maps from [30]
Valves	Bore	Reference parameterized values from [25]
Cylinders	Bore, Stroke, Compression Ratio, Number of Cylinders	Main engine parameters
	Turbo pressure boost = 1.2 bar , Max Engine speed = 7000 rpm	

Engine model validation

The engine model is validated using engine data from Volkswagen 2.0l EA888 Gen 3 [31]. The engine main parameters used in the simulation are listed in Table 3.

Table 3. Volkswagen 2.0l main engine data

Parameter	**Value**
Bore [mm]	82.5
Stroke [mm]	92.8
Compression Ratio [-]	9.6
Number of Cylinders [-]	4

The simulation covers full load range up to engine speed of 4000 rpm, at higher speeds only no-load and full load conditions are considered. In this manner is possible to reduce the extremely high computational time and still obtain all the necessary data to assess vehicle fuel economy and performance. Figure 2 shows Brake Specific Fuel Consumption (BSFC) maps from real engine data and simulation results.

The simulated consumption minimum value is around 2% higher, the contour levels are mainly in good agreement and only at high loads are slightly shifted upwards. The maximum torque curve predicts accurately the peak value, while the low-end torque is overestimated and the flat region extends 500 rpm wider at high engine speed. Bearing in mind that the entire model is based on a very limited amount of input parameters and that no particular data-matching fitting was performed, it is possible to state that the proposed workflow provides reasonably good results with respect to real-world engines and it can be employed in the assessment of vehicles consumption and performance.

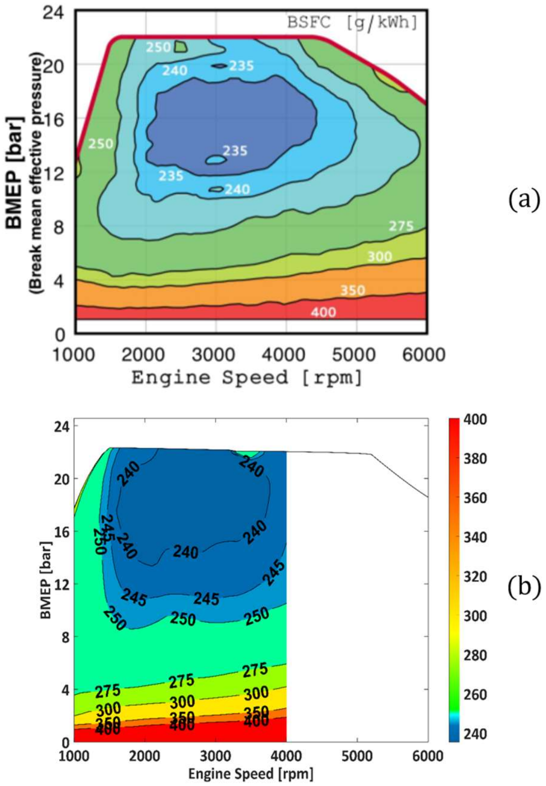


Figure 2. Engine BSFC comparison: real data (a) vs simulation results (b)

Electric Traction System

The battery electric vehicles (BEV) have emerged as a promising solution to face emission reduction and uncertainty over fossil fuels future availability. During recent years, the sales are continuously growing, although their market share is still limited to 0.5% in Europe [32]. Furthermore, powertrain electrification is becoming increasingly popular as it is adopted in conjunction with conventional vehicle's layout through hybridization technology.

The electric traction system consists of battery pack, inverter, electric motor and thermal management system. Particular layouts can adopt further electric components such as DC/DC converters to regulate the voltage between the battery pack and the inverter [33].

Battery model

The battery pack identifies the energy source in BEV. It consists of cells connected in series and in parallel to provide the desired voltage and current capacity. The physical behavior involves chemical reactions that supply the required current flow. The complexity of the problem can be simplified by using an equivalent electric circuit that allows to consider the system's dynamic behavior and energy losses [34]. The model used in this work is based on the commercial library EPTL in Dymola® and it is coupled with a thermal model. The battery pack is based on Panasonic 18650 cells, the equivalent electric circuit parameters are given in [35] while thermal data are provided in [36]. The battery absorbs the loads from the traction system, as it interfaces with the inverter, and from the thermal management system, which consists of compressors used to cool down the inverter, the motor and the battery pack itself. The importance of providing a thermal model arises when dealing with vehicle performances study. As the battery temperature rises, reaching a critical temperature, the maximal current is reduced to ensure the battery safety.

The battery pack's number of series and parallel cells is design, according to cell characteristics, to match the electric motor's voltage and current.

Inverter model

The inverter is the electronic device that changes direct current (DC) from the battery to alternating current (AC) provided to the electric motor. The model is based on a set of analytical equations that describe the time-averaged behavior of the inverter [37] and the required coefficients are obtained from Infineon datasheets [38]. The inverter operates with a two-stage variable frequency drive. An instantaneous approach would, otherwise, drastically increase the computational time as it requires an integration time dependent on the switching frequency, which is generally in the range from 1 to 10 kHz. The electrical system is coupled with a thermal model, it interfaces with the thermal management module that controls the cooling system to avoid overheating.

The inverter design is based on the maximum voltage and current. These values are chosen accordingly to the electric motor's voltage and current with a safety factor of 1.5. The operating condition requires to define the switching frequency. In this case, the procedure considers the electric motor speed at which vehicle top speed is reached and a multiplier factor of 8 is adopted. This value is assumed to be a reasonable compromise to between torque ripple caused by higher harmonics and switching losses that are proportional to the switching frequency. The variable frequency inverter is operated so that only half of the switching frequency is used up to half of the vehicle's speed range.

Electric motor model

The Electric Motor (EM) converts the electrical energy from the inverter into the mechanical energy transferred to the transmission. Various EM types are available in the market, the most adopted solutions in BEV rely on AC motors, in particular permanent magnet (PM) motors are used by most of the carmakers (Toyota, Nissan, Ford, BMW, Mercedes, Ferrari, Porsche, …) while only Tesla has largely made use of induction motors (IM).

The EM model developed in Dymola® uses a map-based approach to evaluate the electrical quantities (voltage, current and power factor) depending on motor torque and speed. The battery voltage affects the actual behavior of the electric motor. To consider this, a simplified approach is pursued by applying a scaling factor to the electric motor voltage and speed when evaluating the maps. The system is coupled with a thermal model that focuses on the winding temperature and, as for the inverter, interfaces with the thermal management module to avoid winding overheating.

The EM operating principle depends on the magnetic field to produce torque [39] and geometrical and material nonlinearities make it very difficult to predict analytically the motor behavior. Furthermore, motor operating conditions generally require iterative approaches to set properly the control strategy's parameters. For these reasons, as for the ICE, a specific software package is used to compute the required maps. The commercial software Motor-CAD® provides the capabilities to evaluate accurately the motor characteristics through electro-magnetic FEM. It requires a detailed description of the motor geometry and the materials' properties. Two-dimensional FEM is applied to the motor's cross-section and the desired electrical, thermal and mechanical quantities are calculated over the operating range of interest. At the same time, appropriate control strategies are defined, respectively maximum torque per ampere (MTPA) for PM motors and slip control for IM motors.

The study considers real-world motors used in automotive application: Nissan Leaf [40], BMW i3 [41], Ferrari LaFerrari [42] and Tesla Model S [43]. Motor Design Limited (MDL) has extensively validated the models realized through Motor-CAD as reported in [44] and in [45].

In order to analyze a more broaden variety of motors, the baseline motors have been modified in terms of geometry and electrical properties. The main parameters used and the methods applied are presented in Table 4. Other approaches can be found in [46].

Table 4. Electric motors scaling procedure

Parameter	**Method**
Geometry Scaling Factor (SF)	Applied uniformly to all geometrical lengths PM : $\pm 20\%, \pm 40\%$, IM (high power motor) : $-40\%, -20\%$
Peak Voltage	$SF \times (100 \pm 10)\%$ from nominal value
Peak Current	$SF^2 \times (100 \pm 10)\%$ from nominal value (limits on current density)

Figure 3 shows an example of the efficiency maps and performances results over different geometrical scaling factors, ±20 %, with respectively ±10 % scaling of voltage and current for the BMW i3.

The electric motor development considers also the design of the cooling system. The parameters considered are the coolant flow and its temperature increase across the motor, which will depend on the particular geometry of the cooling ducts. The design considers a trade-off solution between the cooling capacity and the obtainable continuous peak power, an example is shown in Figure 4.

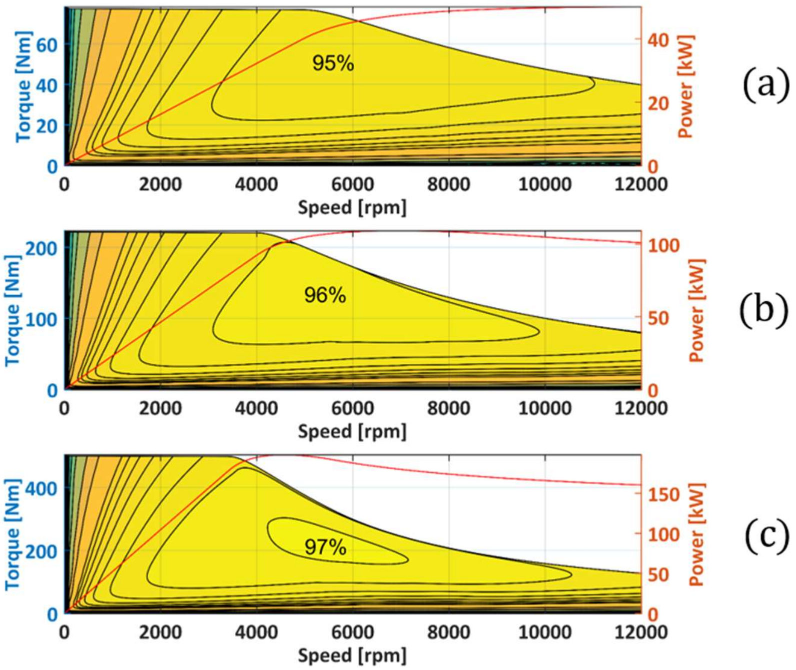


Figure 3. BMW i3 efficiency maps: down scaling (a), nominal (b), up scaling (c)

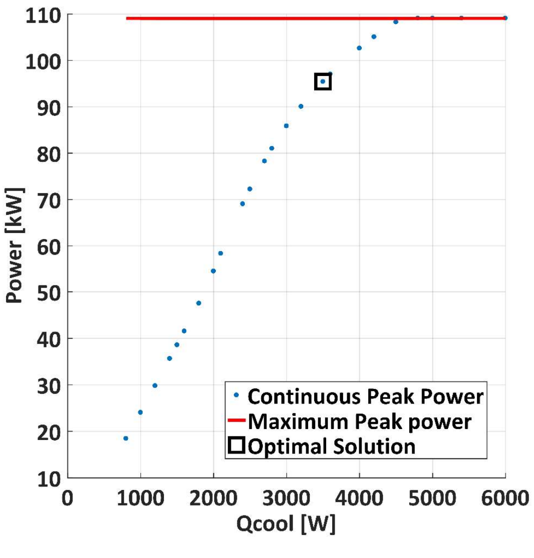


Figure 4. Electric motor cooling system design: motor peak continuous power vs cooling

Transmission

The transmission system provides the link between the power unit and the wheels. Conventional vehicles adopt a large variety of possible layouts depending on many factors: performances, fuel economy, comfort, etc. Multi-speed configurations are required due to the very narrow operating range of the internal combustion engine. Conversely, the electric motor does not suffer from poor behavior at low speeds and it can additionally reach speeds up to 20000-25000 rpm. These characteristics led to the use of simple transmissions.

Table 5 shows the list of the transmission layouts developed in this work for both combustion engine and electric vehicles.

Table 5. Transmission layouts

Vehicle	**Transmission**
ICE	Manual Transmission transverse 5/6-speed, cylindrical gear differential
	Manual Transmission inline 6-speed IV/Vth direct gear, bevel gear differential
	Dual-Clutch Transmission inline 7-speed, bevel gear differential
BEV	Manual Transmission transverse 1/2 speed, cylindrical gear differential

Transmission model

The transmission model considers a two-stage workflow process based on different levels of detail. The first stage focuses on the role of the transmission in the entire vehicle system and provides the design of the gear ratios. Based on the transmission layouts considered, different approaches are used for combustion engine and electric vehicles. The procedures are briefly presented in Table 6. For the ICE vehicle, a standard methodology can be found in [47] and in [48], while for the BEV specific approaches are employed depending on the number of gears used.

Table 6. Gear ratios design methods

Parameters	**Vehicle**	**Approach**
▪ *Engine/Motor torque and power curve* ▪ *Transmission number of gears* ▪ *Chassis parameters:* • *mass* • *vertical load distribution* • *aerodynamic drag* • *tire properties (radius, rolling resistance and vertical stiffness)*	ICE	1st gear Constrained solution based on: • pull-away maneuver at high slope • maximum acceleration • maximum vehicle speed with engine speed @1000 rpm
		Top speed gear (5th gear, 6th for DCT 7sp): • maximum engine power
		Geometric gear ratio design for other gears (split in case of direct gear layouts)
	BEV	One-speed fixed gear: • weighted solution between maximum acceleration and top speed • constrained to pull-away maneuver at high slope Two-speed layout: • 2nd gear design based on top speed • 1st gear design constrained to pull-away maneuver at high slope, targets at maximum acceleration or splits uniformly the motor operating range over the vehicle speed range (depends on 2nd gear design)
• *Differential gear ratio design*	Minimizes the gear spread in the gearbox	

Figure 5 shows the results of the gear ratio design procedure for ICE vehicles and BEVs over different power classes and the different gears, where *ratio_G[i]* and *ratio_D* stand for the i-th gear ratio of the gearbox and the differential gear ratio. For ICE vehicles, it is possible to notice a clear trend with the power for each gear. This is due to the fact the developed engines actually belong to the same "type" as explained in the "Engine model" paragraph and the chassis parameters are chosen in a peculiar way that will be clarified in the next paragraph “Chassis model”. For the BEVs, the values show a similar trend with respect to the power but they appear much more distributed. Very different motors are considered and nevertheless, the scaling applied to voltage and current can deeply modify the motor’s torque curve. As it could be expected, the one-speed fixed-gear ratio is generally a compromise solution with respect to 1st and 2nd gear ratios used in the two-speed layout.

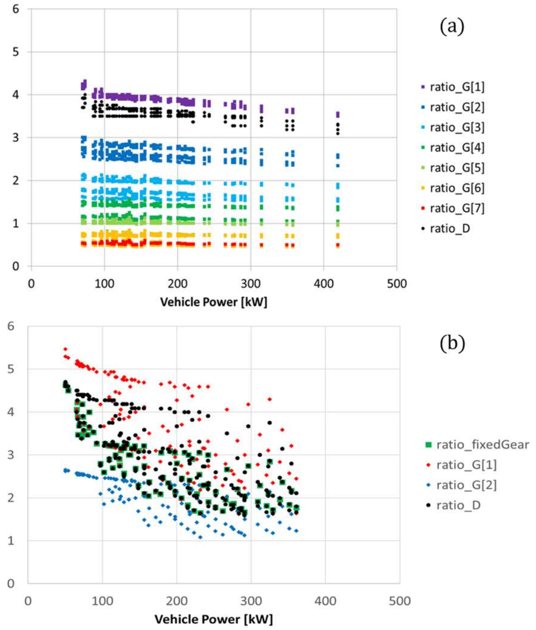


Figure 5. Gear ratios of Gearbox (ratio_G) and Differential (ratio_D) for ICE vehicles (a) and BEVs (b)

The second stage of the workflow provides a more detailed description of the transmission components. The components of the gearbox and the differential considered in this work are:

- shafts;
- gears;
- bearings;
- seals and rotary unions;
- synchronizers, clutches and pumps.

Common values, depending on input torque and transmission layouts, of shafts’ center distance and of gears’ number of teeth, module, pressure angle and helix angle are provided in [48] and in [47]. The design of the bearings and the other ancillary components, previously listed, follows from shafts’ diameter and the input torque. Only for the gears, a more refined approach is used considering standard equations for cylindrical gears from [49].

These values are then fed to the model developed in Dymola® to simulate the dynamic behavior of the transmission and to evaluate the power losses. Table 7 provides the list of the models associated to the different components.

Table 7. List of power loss models for transmission components

Component	**Model**
Gears	ISO/TR 14179-2 [49,50]
Bearings	SKF Model [51]
Seals and rotary unions	Constant drag torque depending on the diameter [52,53]
Synchronizers, clutches and pumps	Speed dependent drag torque based on data from [54,55,56,57,58,59]

Chassis

The chassis model is developed in Dymola® and it consists of tires, brakes and vehicle’s body. The tires are based on a 3 degree-of-freedom (d.o.f.) model that allows to compute the vertical displacement, depending on the vertical load, and the contact slip, since rotation and longitudinal motion are evaluated separately. Therefore, the power loss from the tires obtained from tire’s slip and rolling resistance. The brakes allows to decelerate the vehicle through mechanical friction. The vehicle’s body uses a 3 d.o.f. model based on pitch rotation, vertical and longitudinal displacement. It considers the entire vehicle mass and the aerodynamic drag.

Since this work focuses on the study of the different powertrain solutions, the parameters of the chassis are defined in a parametric form so that the parameters actually represent an average vehicle. A fitting procedure is applied to the ICE vehicles data collected from [21], allowing to identify a correlation between the parameters of interest and the engine displacement. The comparison between the raw data and the fitting results for the vehicle's mass and the aerodynamic drag coefficient are shown in Figure 6. For other parameters like frontal area, tire rolling resistance and friction coefficients, values or parametric estimations are taken from [60,61,62]. Furthermore, a correlation between engine displacement and power is obtained in order to use similar expressions for the BEVs.

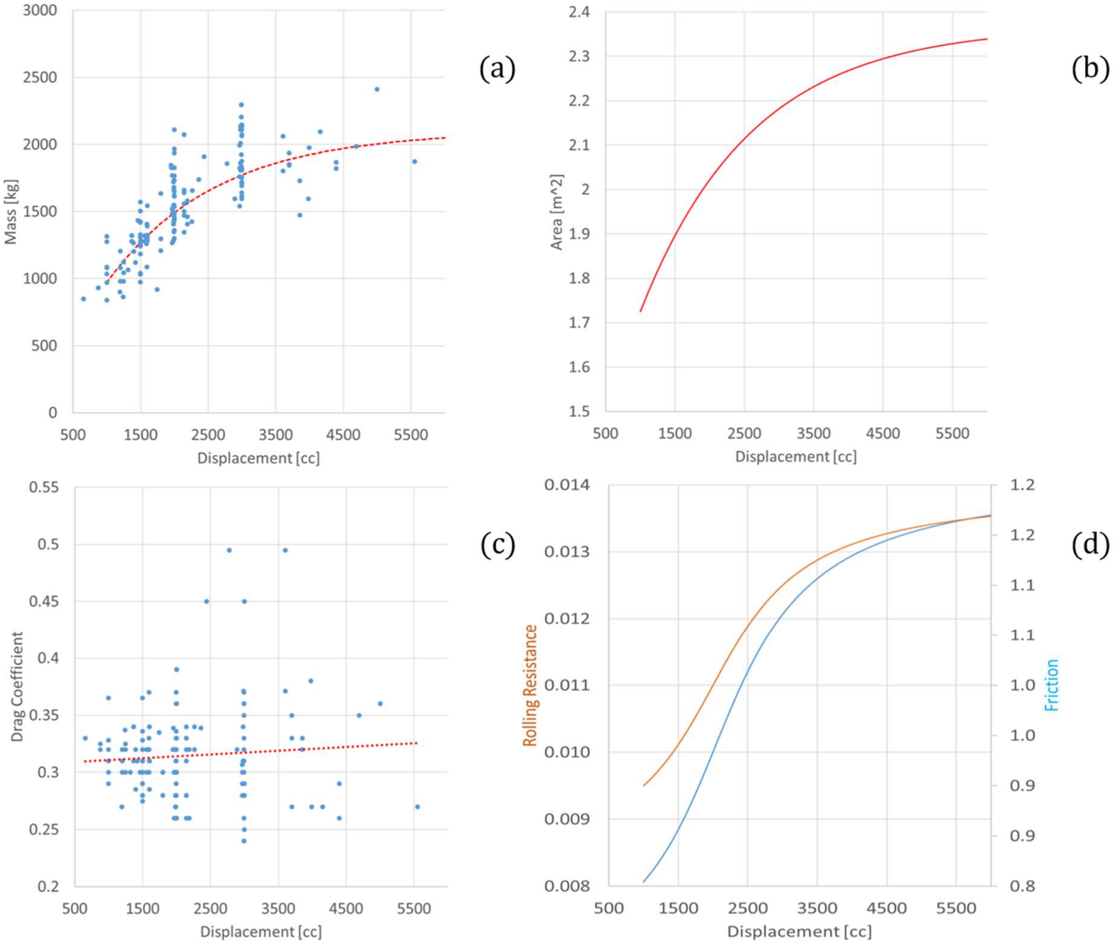


Figure 6. Data fitting of vehicle mass (a) and drag coefficient (c) vs engine displacement, estimated parameters of vehicle's frontal area (b) and tire's rolling resistance and friction coefficient (d) vs engine displacement (right)

Control system

The control system is introduced in the vehicle model to manage traction control, shifting strategy, thermal management and regenerative braking.

The traction control acts on the engine torque by receiving the slip measurements from the tires.

The shifting strategy is defined for both combustion engine and electric motor layouts. In case of ICE vehicles, the control requires the definition of a minimum engine speed for downshift and a maximum engine speed for upshift. Inside this range, it further uses the engine map to optimize the fuel consumption. Current engine speed and torque are measured and compared to that at higher gear. Since the engine efficiency increases at higher loads, if the upshifted torque does not exceed the maximum torque then the gear is upshifted. The actual control uses a value of torque equal to the 90% of the maximum torque, this choice leaves some residual acceleration to the vehicle and furthermore, the engine efficiency reduces when approaching the maximum torque. Figure 7 shows the results obtained during Worldwide harmonized Light vehicles Test Procedure (WLTP). Power increase provides higher top speed and therefore increases gear ratio spread reducing the number of gearshifts. Increasing the number of gears and setting to higher gears the direct gear leads to more gearshifts if comparing vehicles with the same power. The increase due to higher number of gears is more relevant in the 7-speed gearbox since the 6th gear is design to provide the vehicle's top speed while both 5-speed and 6-speed gearboxes are design to achieve top speed in 5th gear.

A more simple strategy is applied to BEV. Since in that case the motor efficiency increases with both load and speed, the gear shifting is only based on the vehicle speed and the reference speed is chosen to equally split the vehicle operating range across the gears.

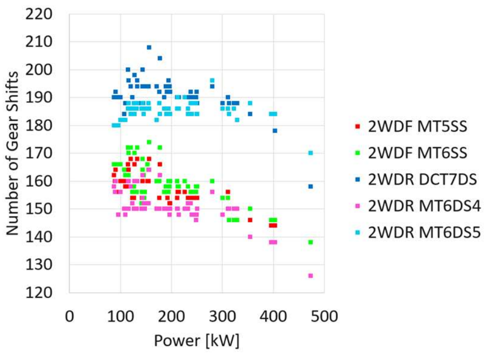


Figure 7. Simulation results of the number of gearshifts for ICE vehicles (see Table 8) in WLTP driving cycle

The thermal management is introduced in BEVs to handle the cooling system in order to avoid overheating of the battery pack, the inverter and the electric motor. Based on temperature measurements, the coolant flow is regulated and when critical temperatures are reached the current flow from the battery is limited.

The regenerative braking controls the braking from the electric motor. The maximum value is limited to half of the maximum torque due to battery limitations. Furthermore, an active control regulates the distribution of braking force between the electric motor and the mechanical brakes depending on the vehicle deceleration [63].

The simulation-based approach used in this works, requires also to define the driver behavior as a controller. The feedback PID controller targets at the desired velocity, a feedforward controller is set in parallel and it computed the power request by analytically compute the road loads on the vehicle according to the desired velocity and acceleration. This method allows to avoid the noisy control signal when only the feedback PID is used and furthermore, no particular tuning procedure over the controller's gain were necessary. As an example, the results of vehicle speed and error for an ICE vehicle and a BEV simulation are reported in Figure 8.

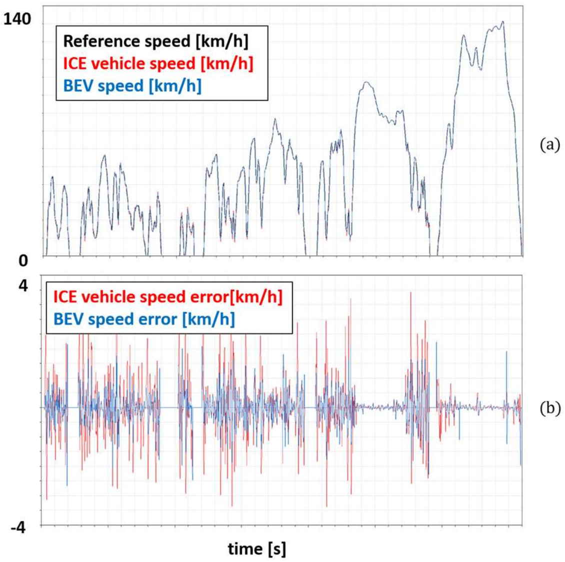


Figure 8. Vehicle speed (a) and error (b) for ICE vehicle and BEV simulations

Methodology

The methodology developed in this work relies on a model-based description of the vehicle and a specific workflow defines the vehicle characteristics, as presented in the "Vehicle model" section. The workflow is implemented in the commercial software iSight®, so that it can be easily automated for a large amount of simulations. Then, by using Design Of Experiment (DOE) techniques, a first analysis over the different vehicle layouts is performed to evaluate fuel economy and longitudinal dynamic performances. The fuel economy assessment considers WLTP driving cycle while performances are evaluated on straight-line driving. The layouts cover the different transmissions, as presented in "Transmission model", and, for BEVs, also the number of electric motors, considering 1, 2 and 4 electric motors configurations.

The sensitivity analysis uses the previously simulated vehicles to provide the correlation between the power unit (combustion engine and electric motor) main parameters and the vehicles' consumption and performances. Subsequently, the model-based approach is further used to assess the effectiveness of lightweight design.

Results

DOE results

The ICE vehicles layouts used in the DOE analysis are listed in Table 8. Two-wheel drive layouts are adopted with different transmission solutions for rear and front drive. The results in Figure 9 compare fuel consumption, top speed and acceleration. The driving axle, front against rear, clearly affects the acceleration performances. Increasing the number of gears generally provides more efficient vehicles and improvement of acceleration can be achieved by introducing DCT, since shifting time is reduced.

Table 8. ICE vehicle layouts for DOE analysis

Code	**Characteristics**
ICE-2WDF-MT5SS	2-wheel front drive, Manual Transmission transverse 5-speed
ICE-2WDF-MT6SS	2-wheel front drive, Manual Transmission transverse 5-speed
ICE-2WDR-DCT7DS	2-wheel rear drive, Dual Clutch Transmission inline 7-speed
ICE-2WDR-MT6DS4	2-wheel rear drive, Manual Transmission inline 6-speed, direct gear 4th
ICE-2WDR-MT6DS5	2-wheel rear drive, Manual Transmission inline 6-speed, direct gear 5th

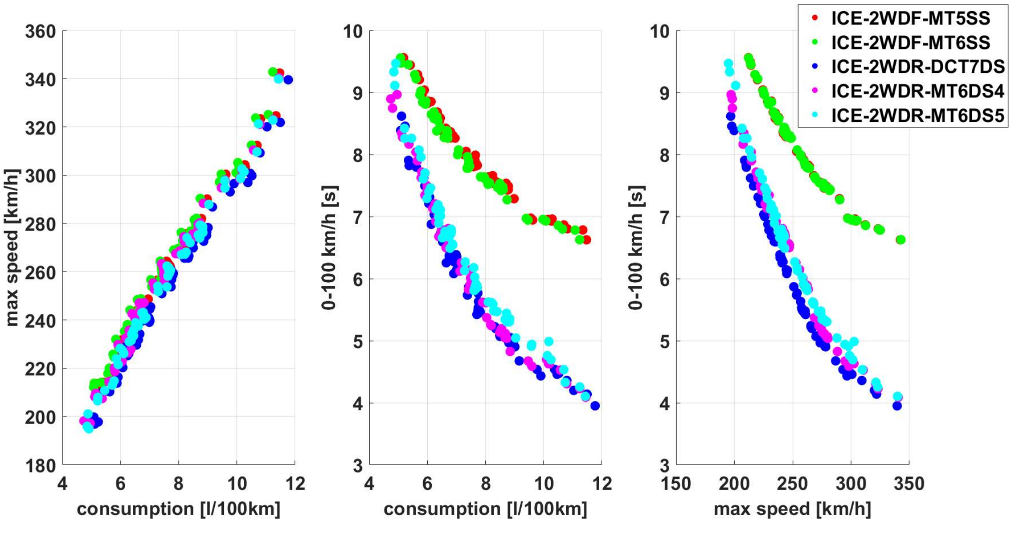


Figure 9. ICE vehicle (see Table 8) results: fuel consumption, top speed and acceleration

From the DOE results, it is also possible to make considerations over the powertrain thermal behavior and the energy loss distribution over the entire vehicle. Figure 10 provides the mean oil temperature in the engine and in the gearbox during the WLTP driving cycle. The temperature slowly decrease with increasing class, based on power, of vehicle. Vehicles with higher power require greater amount of oil due to their volume and the maximum power that the oil undergoes, thus the increased thermal capacity of the oil causes average lower temperatures. It can be further noticed, that the values are grouped according to the engine number of cylinder and the gearbox layout.

The energy losses distribution are presented in Figure 11 and results from an averaging procedure over the different layouts. It is easy to appreciate how the engine plays the major role with values over 70%. The engine contribution increases with the power and it is directly related to the higher mechanical friction losses. Focusing only on the other contributions, the road loads coming from brakes, aerodynamic and tires drag contribute up to 80% of the energy losses while transmission is below 20%.

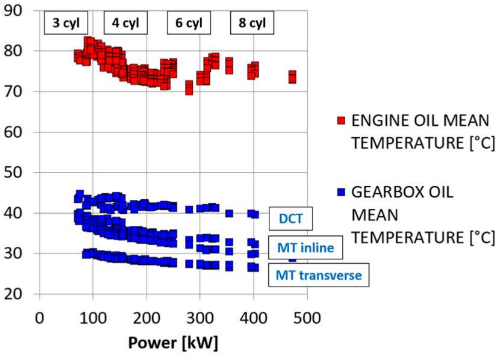


Figure 10. ICE vehicles engine and gearbox oil mean temperature

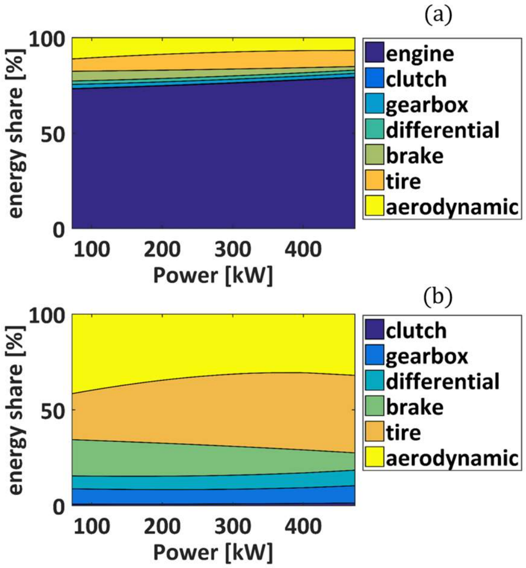


Figure 11. ICE vehicles energy share: vehicle (a) and vehicle without engine (b)

The BEVs layouts used in the DOE analysis are listed in Table 9. The study considers 1, 2 and 4 EM layouts. The single motor layout covers both front and rear wheel drive with 1-speed and 2-speed gearbox. The 2 EM layout uses one motor per axle and again, both gearboxes configurations are evaluated. The 4 EM layout provides one motor per wheel and considers a single-speed fixed gear gearbox. The results in Figure 12 compare energy consumption, top speed and acceleration. To provide better clarity of the results' analysis a polynomial regression over the pareto set obtained from energy consumption and performances is applied and the curves are provided in Figure 13. The driving axle, front against rear, clearly affects the acceleration performances as for the ICE vehicles.

By analyzing more in detail the different layouts, the following considerations can be made:

- front wheel drives' design is sensitive to the limits over acceleration and therefore the gearbox design allows higher top speeds with respect to rear wheel drive with 1-speed;
- this limitation in the rear wheel drive can be overcome by using 2-speed gearbox;
- increasing the number of electric motors generally provides better performances but causes higher energy consumption, the explanation could rely on the fact that this design leads to load distribution over the motors which then operate at lower efficiency.

Table 9. BEV layouts for DOE analysis

Code	**Characteristics**
BEV-2WDF-1EM-T1	2-wheel front drive, 1 electric motor, Transmission 1-speed
BEV -2WDF-1EM-T2	2-wheel front drive, 1 electric motor, Transmission 2-speed
BEV -2WDR-1EM-T1	2-wheel rear drive, 1 electric motor, Transmission 1-speed
BEV -2WDR-1EM-T2	2-wheel rear drive, 1 electric motor, Transmission 2-speed
BEV -4WD-2EM-T1	4-wheel drive, 2 electric motor, Transmission 1-speed
BEV -4WD-2EM-T2	4-wheel drive, 2 electric motor, Transmission 2-speed
BEV -4WD-4EM-T1	4-wheel drive, 4 electric motor, Transmission 1-speed

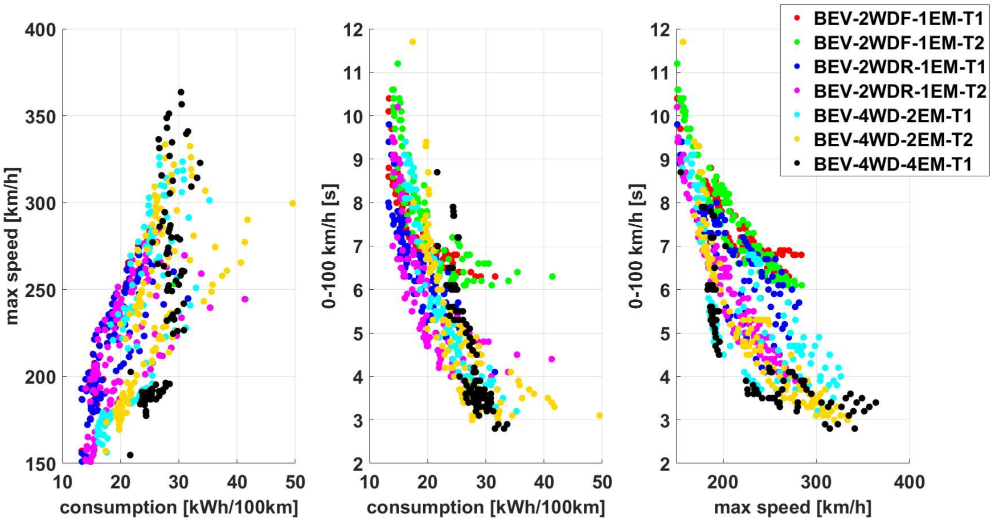


Figure 12. BEV (see Table 9) results: energy consumption, top speed and acceleration

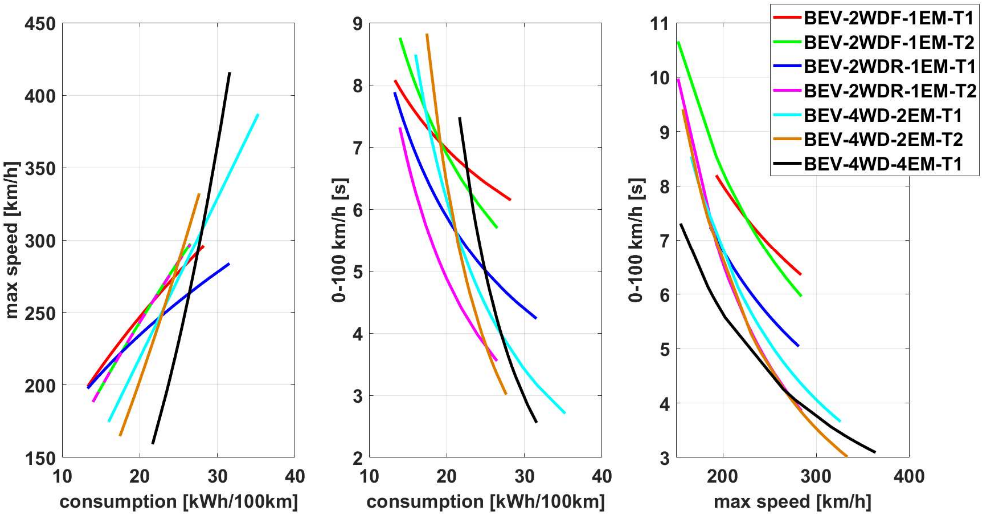


Figure 13. BEV (see Table 9) regression results: energy consumption, top speed and acceleration

The energy losses contributions are shown in Figure 14 and are averaged over the different BEV layouts. The major difference with respect to ICE vehicles regards the role of the power unit, which is not the predominant term. Road loads share more than 50% of the losses while power unit is generally lower than 35%. The transmission contribution, which in ICE vehicles was around 5%, is also increased to 10%.

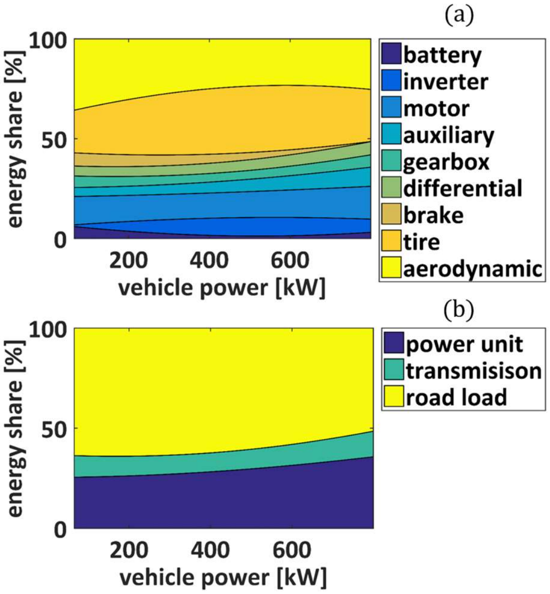


Figure 14. BEVs energy share: components (top) and subsystems (bottom)

Sensitivity analysis results

The sensitivity analysis results show the power unit main parameters correlation with vehicle consumption and performances and the effectiveness of lightweight design.

The correlation analysis of ICE vehicles first considers the engine displacement and the compression ratio. Figure 15 shows the simulation results compared with polynomial regression to better visualize the trend. The displacement appears to have the predominant role over both consumption and performances. Therefore, the correlation analysis is extended to consider more in detail the engine displacement parameters: bore, stroke and number of cylinders. Spearman correlation coefficient is calculated to determine the ranking among the different parameters. The values are reported in Figure 16 and the main influencing parameters are the bore and the number of cylinders which are highly related to vehicle performances but at the same time also to the consumption. Therefore, by comparing the relative values over all the vehicle's objectives it's not possible a priori to exclude the stroke from more detailed analysis during the design phase. Nevertheless, the compression ratio is the only design variable that allows to improve both fuel consumption and performance.

The correlation analysis of BEVs follows the same approach presented for the ICE vehicles. In this case, the considerations are limited to the single electric motor layout and the first major parameter of the vehicle used is the battery rate since it defines the powertrain power class. From Figure 17 can be easily seen that vehicles' consumption and performances are strongly related to battery rate and the values' dispersion is mainly related to the different drivetrain configurations and the various motor types analyzed.

A more detailed overview on the battery is proposed by considering the voltage and the peak current and a more broaden is given by considering also the motor scaling and thus, its weight. Figure 18 shows the correlation results for the BEVs. All the parameters show similar correlation, however when looking more closely to the values, the mass seems to be the more effective design parameter to improve performances while affecting less the consumption. Comparing the electrical parameters it is clear that the current allows to more effectively improve the top speed while the voltage leads to better acceleration. The major drawback with increasing voltage regards the higher energy consumption.

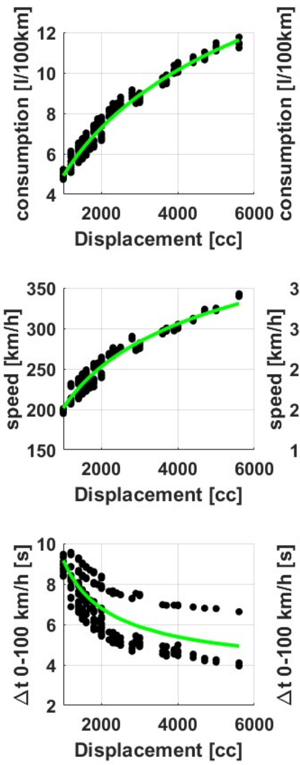
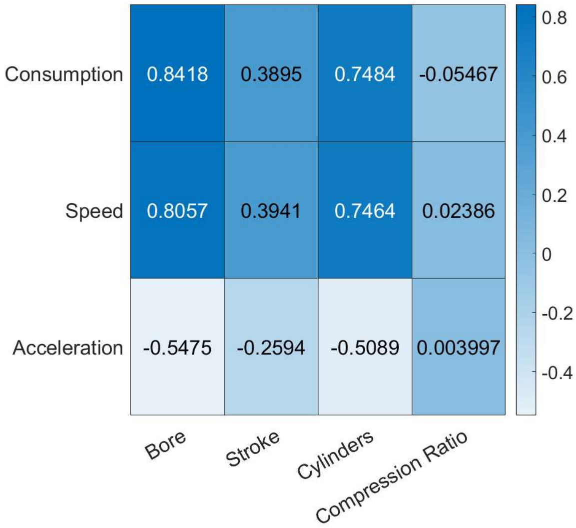


Figure 15. ICE vehicles correlation graphs: simulation results (black) and polynomial regression (green)



	Bore	Stroke	Cylinders	Compression Ratio
Consumption	0.8418	0.3895	0.7484	-0.05467
Speed	0.8057	0.3941	0.7464	0.02386
Acceleration	-0.5475	-0.2594	-0.5089	0.003997

Figure 16. ICE vehicles correlation table

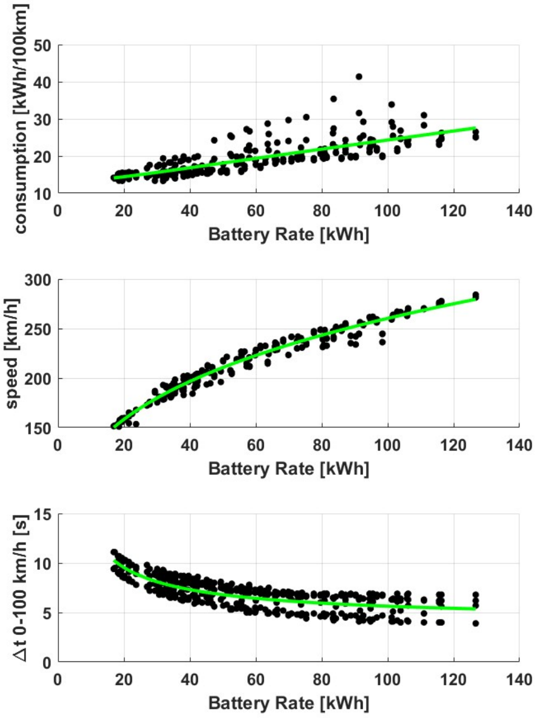
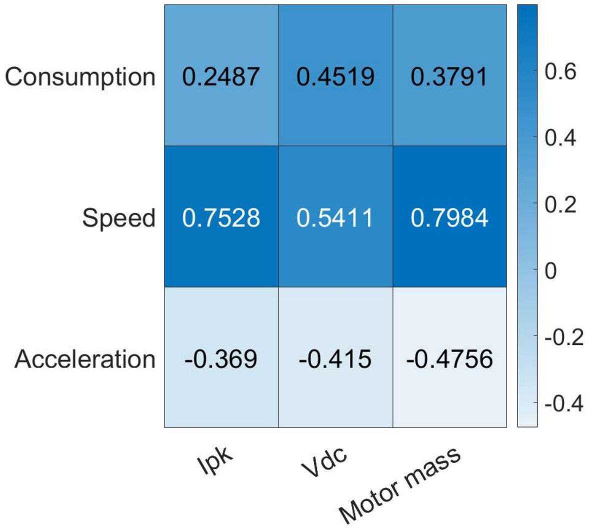


Figure 17. BEVs with single EM correlation graphs: simulation results (black) and polynomial regression (green)



	Ipk	Vdc	Motor mass
Consumption	0.2487	0.4519	0.3791
Speed	0.7528	0.5411	0.7984
Acceleration	-0.369	-0.415	-0.4756

Figure 18. Correlation table for BEVs

The sensitivity analysis on the lightweight design of the vehicle considers mass reductions of 10% and 20%. ICE vehicles simulations are limited to FWD MT6SS and RWD DCT7DS layouts, while for BEVs FWD

1EM T2 and RWD 1EM T2 layouts are evaluated. Figure 19 and Figure 20 show consumption and acceleration performance results respectively for ICE vehicles and BEVs. It is interesting to notice how, especially for FWD vehicles, the acceleration time tends to approach a limit value, which depends on the vehicle load distribution and on the tire friction. Focusing on the energy consumption a basic statistic is provided and similar the percentage advantage offered by lightweight design is quite similar for ICE vehicles and BEVs. Furthermore, the consumption reduction shows very small dispersion, this is mainly due to the parametric approach used to design the various vehicles.

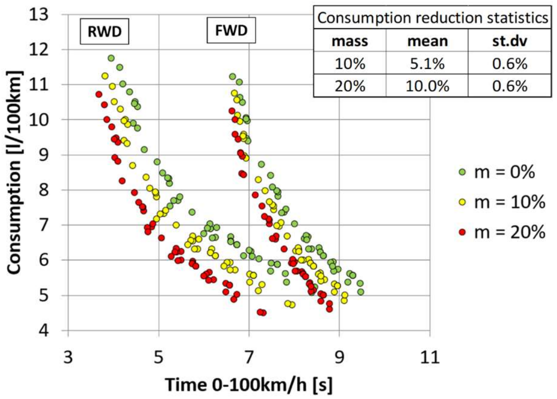


Figure 19. ICE vehicles lightweight sensitivity analysis

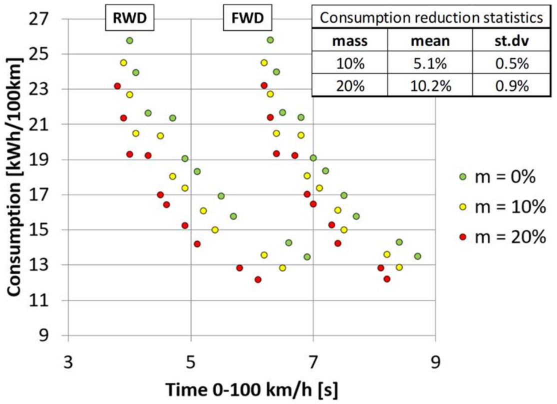


Figure 20. BEV lightweight sensitivity analysis

Conclusions

The work presented in this paper provides a detailed approach to analyze different vehicles at the early concept design phase by focusing on vehicle's energy consumption and performance. The approach is based on a bottom-up procedure moving from the different subsystems to the entire vehicle. For each subsystem, the main components are described providing design guidelines and modeling techniques to estimate the physical behavior. In particular, numerical methods based on 1D-CFD and FEM are used to evaluate the combustion engines and the electric motors.

The analyzed vehicle layouts consider conventional combustion engine and battery electric traction systems and, for each, various transmission configurations are used.

The transmission design plays a major role in the integration procedure of the different subsystems by coupling the characteristics of the power unit and the chassis.

The results provide an overview on energy consumption and performance of a wide range of vehicle segments and clearly show the conflicting nature of these objectives. Figure 21 provides consumption and acceleration performance for the different vehicles and clearly shows the benefits of BEVs over conventional ICE vehicles. The major drawback still relies on the range of BEVs, shown in Figure 22, which especially for low-power battery packs is not competitive with ICE vehicles. The range can be extended by increasing the battery rate but this way also the vehicle weight increases.

The transmission layout can strongly affect both energy consumption and performance. The driving wheel has naturally great impact on the acceleration while the different gearbox's layouts may further affect the energy consumption and performance. In particular for BEVs, the use of a two-speed gearbox can improve the vehicle's performance.

The results are accompanied with a study on the energy distribution on the different subsystems during a WLTP driving cycle. The combustion engine accounts for approximately

70% of the overall losses for conventional vehicles while for BEVs the energy share is more equally distributed by the road loads (tire rolling resistance and aerodynamic drag) and the entire powertrain, with values respectively of 60% and 40%.

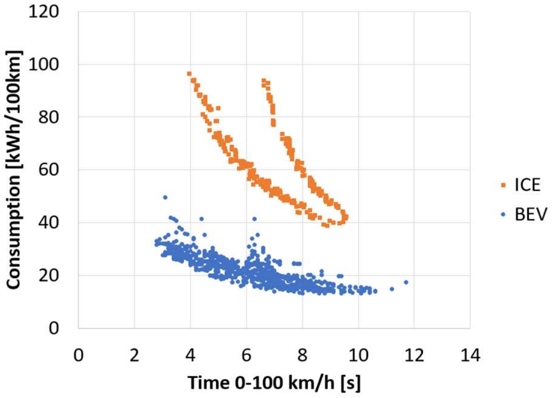


Figure 21. ICE vehicles and BEVs results: consumption vs acceleration performance

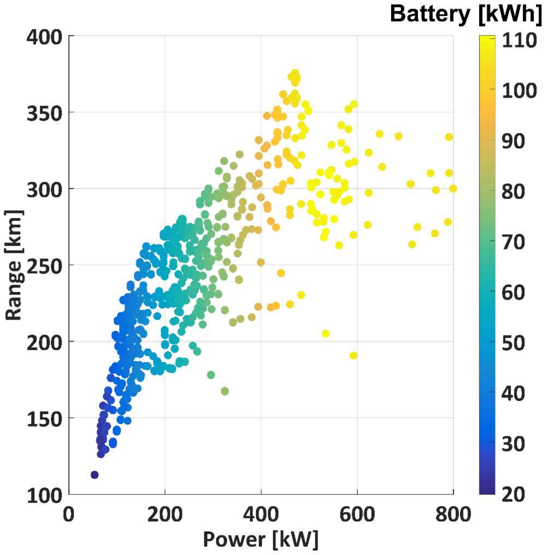


Figure 22. BEVs range based on WLTP driving cycle

Finally, a sensitivity analysis is presented to show the influence of the main design variables. For the ICE vehicles, the main engine design variables considered are bore, stroke, number of cylinders and compression ratio. A clear ranking among these parameters appears in order to improve performance or energy consumption. However, if both these objectives are considered a more refined analysis is required since all the design variables, except for the compression ratio, almost equally provide conflicting correlations. For the BEVs, the main electric motor design variables are the motor mass, the voltage and the current. All the design variables show similar correlations. The motor mass appears as the favorable design variable to find a good compromise between energy consumption and performance while voltage should be chosen carefully to avoid an excessive increase of energy consumption.

The lightweight design considers as the main design variable the vehicle mass. The results are quite similar for ICE vehicles and BEVs as a mass reduction of 10% and 20% provides respectively a reduction of energy consumption of 5% and 10%. The acceleration performance is also improved especially for lower power vehicle. High power vehicles are less affected since they experience limitations due to tire traction slip limits.

Future works will address to include also hybrid electric vehicles (HEVs) to provide a more comprehensive view on the current automotive market scenario. HEVs can actually offer a suitable solution towards reducing energy consumption without affecting vehicle's range.

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Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, end/or publication of this article.

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