

Optimization of Electrified Powertrains for City Cars

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ABSTRACT

Sustainable and energy-efficient consumption is a main concern in contemporary society. Driven by more stringent international requirements, automobile manufacturers have shifted the focus of development into new technologies such as Hybrid Electric Vehicles (HEVs). These powertrains offer significant improvements in the efficiency of the propulsion system compared to conventional vehicles, but they also lead to higher complexities in the design process and in the control strategy. In order to obtain an optimum powertrain configuration, each component has to be laid out considering the best powertrain efficiency.

With such a perspective, a simulation study was performed for the purpose of minimizing well-to-wheel CO₂ emissions of a city car through electrification. Three different innovative systems, a Series Hybrid Electric Vehicle (SHEV), a Mixed Hybrid Electric Vehicle (MHEV) and a Battery Electric Vehicle (BEV) were compared to a conventional one. The SHEV allows the operation of the combustion engine independently from the driving situation. The MHEV combines series and parallel operation without a switchable gearbox.

The approach includes the implementation of a zero-dimensional powertrain model using the GT-Drive software with the replication of real driving behavior for the different driving profiles. Further the optimization of each powertrain and its operating strategy is based on a combination of Design of Experiment, driving cycle simulation and numerical optimization. The optimization criterion was well-to-wheel CO₂ emissions with respect to burned fuel and electric energy taken from the electric grid. These were calculated drawing on the European Union and German electric energy mixes (400 g CO₂/kWh_{el} and 590 g CO₂/kWh_{el}, respectively). In addition a number of performance constraints, such as acceleration, maximum speed, gradeability, and All Electric Range (AER) were defined and used for the optimization. In addition to the New European Driving Cycle (NEDC), four real world driving cycles were selected in order to represent the wide range of customer-relevant driving scenarios. As a result of the optimization process, for each powertrain, the optimum configuration and control strategy are provided.

In general, the MHEV has the lowest well-to-wheel CO₂ emissions as it combines the benefits of electric vehicles in urban driving cycles with those of traditional powertrains on high-speed routes. The optimal configuration is strongly dependent on the considered energy mix.

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INTRODUCTION

In response to the increasing requirements for road traffic environmental impact, the automotive industry is exerting greater and greater effort in developing new vehicle concepts with lower emissions and fuel consumption ([1,2]). A

promising approach to meet these goals is the electrification of traditional powertrains as partially realized by Hybrid Electric Vehicles (HEVs). This configuration attempts to combine the benefits of the Internal Combustion Engine (ICE) with those of the electric vehicle. As a consequence of their complexity, different types of internal combustion

engines, electric machines and transmissions can be combined, as is demonstrated by hybrid vehicles currently on the market ([3]). Fully electrified vehicles are represented by Battery Electric Vehicles (BEVs), which are driven by an electric powertrain only in order to reach a zero local emission level and to minimize well-to-wheel greenhouse gas emissions ([4],[5],[6]).

The paper presents the results of a simulation study that analyzes the impact of the electrification of city cars on their fuel consumption and performance with the purpose of reducing CO₂ emissions. A combination of simulation, Design of Experiments (DoE), parameterized description of the propulsion system and numerical optimization methods was used to design main powertrain components and operating strategies and to predict the fuel consumption reduction potential of any introduced modification ([7],[8],[9]).

METHODOLOGY

The vehicles were modeled using GT-Drive by Gamma Technologies, a tool for zero-dimensional powertrain simulation ([10]). A parametric approach was adopted for the description of the main powertrain components and the operating strategy, allowing their optimization using Procal, a DoE tool by FEV GmbH.

INTERNAL COMBUSTION ENGINE

The employed ICE is a gasoline Atkinson engine with port fuel injection, which offers the advantage of high efficiency while having the disadvantage of a lower power density compared to traditional naturally aspirated engines. This drawback however is less significant in the case of HEVs since the ICE is coupled with an electric machine and, for this reason, a lower maximum brake power of the ICE compared to conventional vehicles is required. The advantage of modern direct injection engines with homogeneous mixture compared to PFI engines is very small except for the full load area. In HEVs the full load area is less important than minimum fuel consumption as electric boost is available. Further benefits of the Atkinson engine type are its excellent friction behavior, due to the low maximum engine speed and the small valve lift, and the low cost of the engine.

The ICE is modeled using experimentally derived look-up tables (Figure 1), in which the brake specific fuel consumption (BSFC) is mapped as a function of engine speed and brake mean effective pressure (BMEP). Moreover, a parametric description of the engine, based on cylinder displacement and compression ratio and derived from various test bench data, was implemented ([7]). For the full load curve calculation, the knock behavior of the ICE was taken into consideration using empirical models ([8], [9]). Further, the variation of the ICE weight and mass inertia was taken into account.

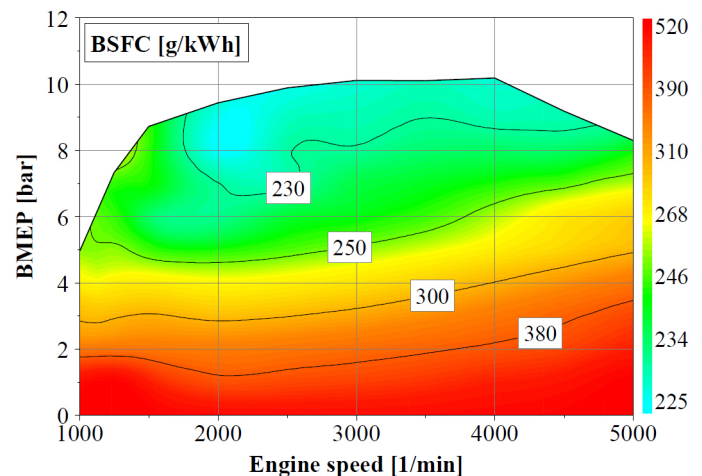


Figure 1. Atkinson engine: BSFC map (displacement: 1200 cm³, cylinders: 3, compression ratio: 12.3)

Finally a semi-empirical correlation was introduced in order to reproduce the transient coolant temperatures - to consider changes in friction losses during ICE thermal transients. Three temperature levels were considered within a zero-dimensional thermal model ([7]): cooling water, engine oil, and engine block temperatures (Figure 2). The thermal model was calibrated using available experimental data.

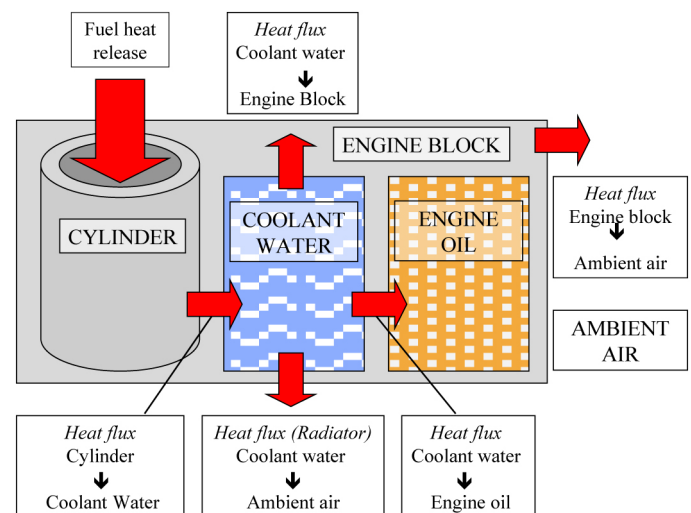


Figure 2. ICE: thermal model

ELECTRIC MACHINE

The selected electric machines are AC permanent magnet synchronous motor/generators ([11]). The electro-mechanical conversion efficiencies and friction torque losses of the electric machine are taken into consideration using experimentally derived look-up tables as a function of shaft speed and brake torque. Total efficiency (Figure 3) correlates brake power directly to electric power.

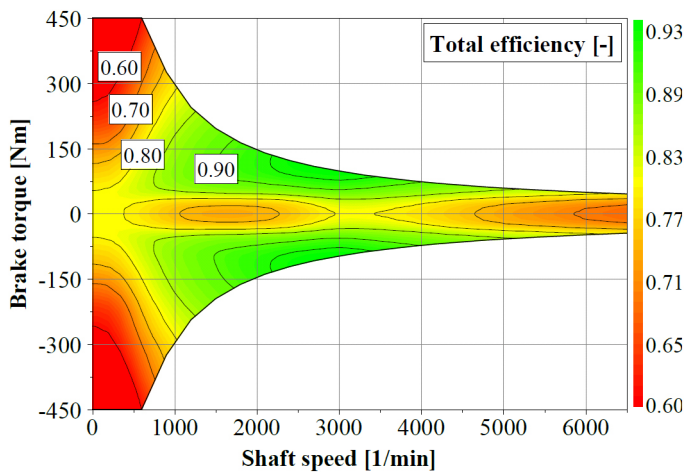


Figure 3. permanent magnet synchronous electric machine: efficiency map (max torque: 450 Nm, max power: 30 kW)

For the simulation and the optimization process, the maximum brake power is a variable factor, and supplementary load and mass inertia are added to the base vehicle depending on this value. This method represents a scaling of the length of the electric machine with constant diameter and speed range.

BATTERY

The battery pack is described by means of an equivalent circuit in which the current is a function of internal resistance, open circuit voltage, and Coulombic efficiency. Operating constraints are accounted for based on the state of charge (SOC, operating range: [0.2-0.9]) in order to improve battery durability and performance stability. A zero-dimensional thermal model for the calculation of the battery cell temperature is included, and the influence of the cell temperature on the efficiency of the passively cooled battery is also considered.

For the optimization process, the number of battery cells per string and the number of strings were considered as variable factors; the main properties of the single cell are given in Table 1. The variation of the number of cells in the battery represents the scale of the battery capacity. Supplementary load was added to the base vehicle weight depending on the resulting battery size.

Table 1. Battery cell data sheet

Electrical specification	Value	Unit of measure
Capacity	20	Ah
Nominal voltage	3.3	V
Nominal energy	66	Wh
Specific energy	85	Wh/kg
Specific power	1090	W/kg

VEHICLE

The study focuses on sub-compact class vehicles. Main features and performance requirements, taken into consideration during the optimization study as design constraints, are given in Table 2.

Table 2. Vehicle data sheet

Specifications / Requirements	Value	Unit of measure
Vehicle base mass (with driver load, 75 kg)	865	kg
Frontal area	1.83	m ²
Drag coefficient	0.3	-
Tire rolling resistance factor	0.01	-
Tire rolling radius	280.6	mm
Maximum speed (ICE alone)	160	km/h
Acceleration (0-100 km/h)	12.9	s
Elasticity (80-120 km/h)	25	s
Gradeability (33 %)	25	km/h

HYBRID POWERTRAIN LAYOUTS AND OPERATING STRATEGY

Figure 4 shows a schematic overview of the analyzed powertrains. Four different vehicle layouts were taken into consideration:

1. Conventional Vehicle, with an ICE as power source, Stop/Start enabled and a 7-speed dual-clutch transmission with dry clutch (gear ratios: I-0.56, II-0.67, III-0.84, IV-1.11, V-1.59, VI-2.48, VII- 4.15)

2. Series Hybrid Electric Vehicle (SHEV) with plug-in capability and single-gear transmission

3. Mixed Hybrid Electric Vehicle (MHEV) with plug-in capability and mechanical connection of the ICE to the wheels via a fixed gear ratio

4. Battery Electric Vehicle (BEV), with an electric machine as power source and single-gear transmission

For the simulation and the optimization of the SHEV control strategy two parameters (k_1 and k_5) were adopted:

• k_1 [kW]: the k_1 parameter defines the maximum demanded power up to which electric driving is allowed (Figure 5): if the required traction power ($P_{dem,tract}$) is lower than k_1 , the vehicle will be driven electrically, otherwise the combustion engine is turned on. If k_1 is set to 0 kW, electric driving is not allowed at all.

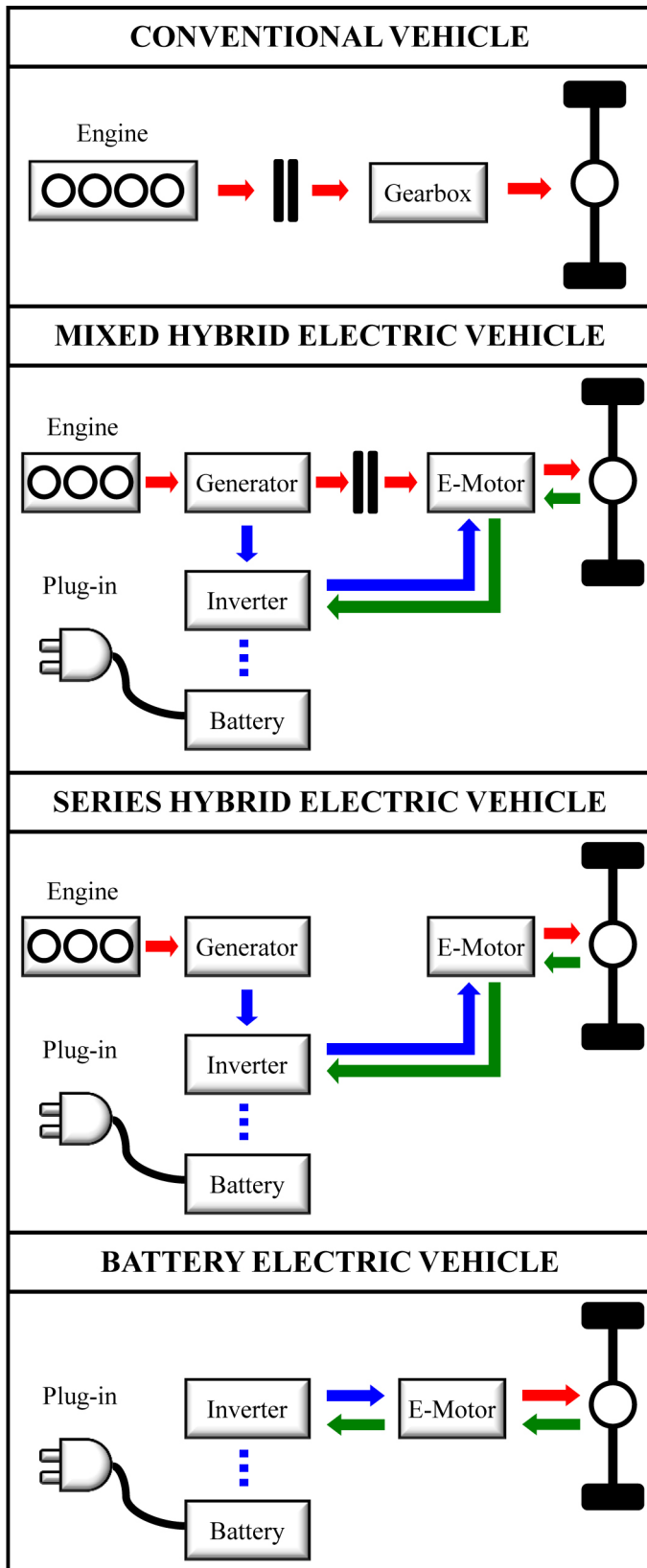


Figure 4. Schematic overview of the considered powertrains

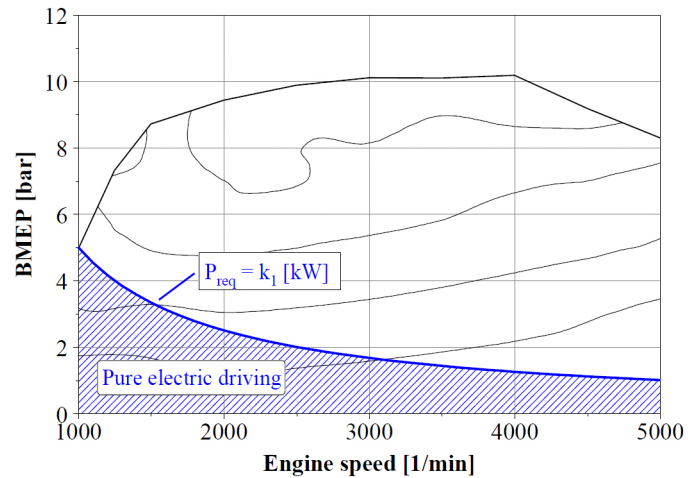


Figure 5. Hybrid operating strategy: parameter k_1

• k_5 [-]: in a series hybrid powertrain the operating condition of the ICE is completely independent from the required traction power. The ICE is forced to work only on its optimal operating line, i.e. under conditions which guarantee the minimum specific fuel consumption at a certain engine power. The basic idea is to generate exactly the electrical power that is required by the electric machine to drive the vehicle. However, it may be beneficial to operate the combustion engine at a higher load point and to store the excess energy in the battery (or vice versa). The parameter k_5 defines this load point shift along the optimal operating line (Figure 6):

$$P_{ICE,dem} = k_5(P_{dem,tract} - P_{BSFCmin}) + P_{BSFCmin} \quad (1)$$

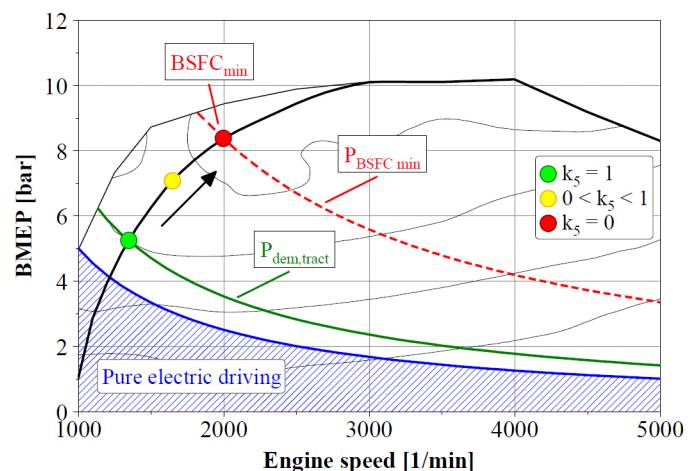


Figure 6. Hybrid operating strategy: parameter k_5

With $k_5=1$ there is no load point shift; with $k_5=0$ the engine is operated at its minimum specific fuel consumption point only.

For the MHEV, in addition to k_1 and k_5 , three more parameters are employed:

- **k_2 [kW/ Δ SOC]** (active only in parallel mode): the k_2 parameter describes the battery recharging strategy dependent on the difference between optimal SOC and actual SOC (Figure 7). Such an optimum SOC (SOC_{opt}) is a variable factor in the optimization process. If the actual SOC in charge sustaining mode is lower than the optimal SOC, the engine operating point is shifted to a higher power than required for driving, and the battery is recharged by the combustion engine and the generator. If the battery SOC is higher than the optimal SOC, the electric machine assists the combustion engine in driving the vehicle and the battery is discharging.

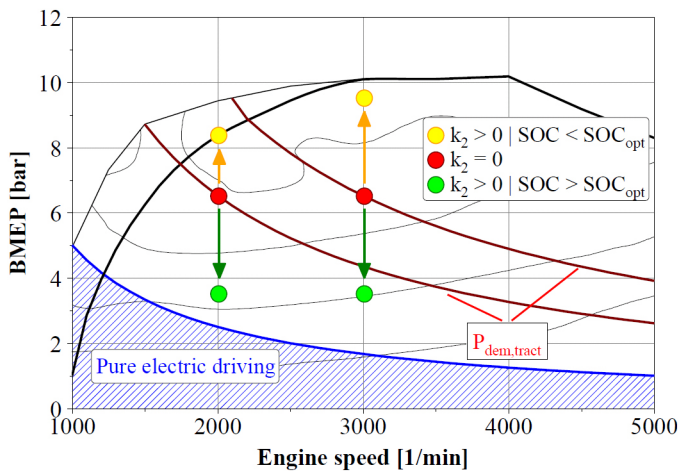


Figure 7. Hybrid operating strategy: parameter k_2

Parameter k_2 is then introduced in the model, taking into consideration the kinetic energy recoverable through regenerative braking. An overall recharge efficiency of the vehicle's kinetic energy of $\eta_{rech}=0.6$ is assumed for the calculation of SOC_{opt} . With increasing vehicle speed the kinetic energy of the vehicle and the potential for brake energy recuperation increases, while the optimal SOC decreases according to formula 2. The parameter k_2 forces the discharge of the battery to SOC_{opt} , and during braking the battery is recharged again.

$$SOC_{opt}^* = \frac{E_{batt} SOC_{opt} - \eta_{rech} \frac{1}{2} M_{veh} v_{veh}^2}{E_{batt}} \quad (2)$$

If k_2 is set to 0 kW/%SOC_{deviation} a deviation in SOC does not have any influence on the demanded power, whereas large k_2 values result in a high demand for battery charging/discharging:

$$P_{ICE,dem} = P_{dem,trac} + k_2 (SOC_{opt}^* - SOC_{act}) \quad (3)$$

Moreover, in case of a positive load point shift for charging ($SOC_{act} < SOC_{opt}$), the increase of the power demanded from the ICE is limited to its optimal operating line.

- **k_6 [kW]**: this parameter defines the required traction power at which the operating mode is switched from series to parallel (Figure 8): if k_6 is lower than k_1 no series mode is allowed and the operating strategy changes directly from electric to parallel; if k_6 is higher than the maximum required power, no parallel mode is allowed.

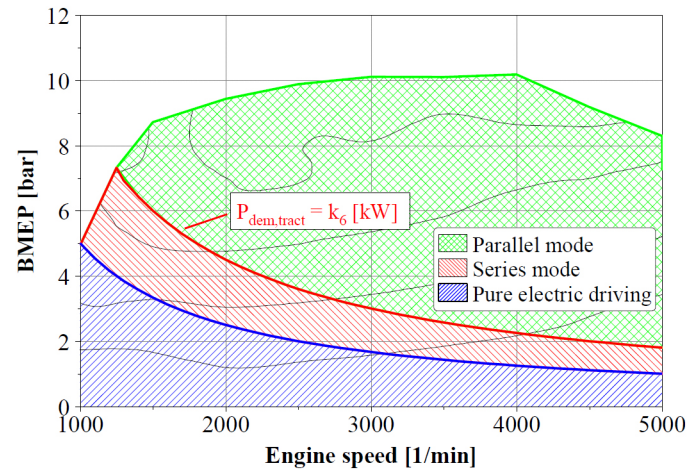


Figure 8. Hybrid operating strategy: parameter k_6

- **k_7 [km/h]**: the parameter defines the vehicle speed at which the series mode is turned off and the parallel mode is activated (Figure 9).

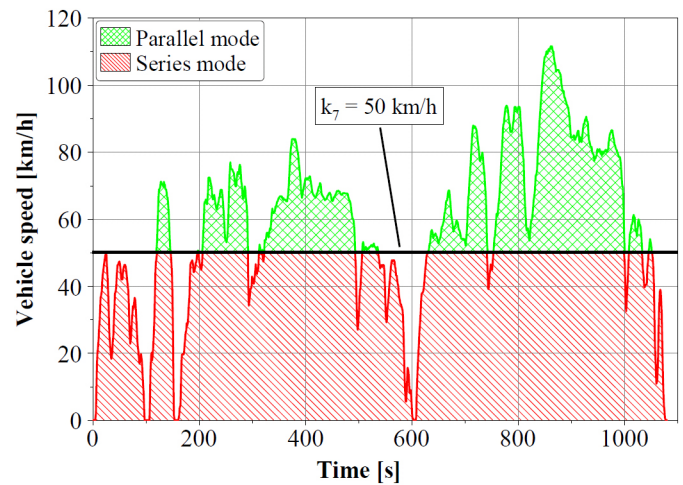


Figure 9. Hybrid operating strategy: parameter k_7

If k_7 is set to 0 km/h the series mode is not allowed and the operating strategy switches directly from electric to