

Energy Management in a Parallel Hybrid Electric Vehicle for Different Driving Conditions

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ABSTRACT

Hybrid electric vehicles (HEVs) are facing increased challenges of optimizing the energy flow through a vehicle system, to enhance both the fuel economy and emissions. Energy management of HEVs is a difficult task due to complexity of total system, considering the electrical, mechanical and thermal behavior. Innovative thermal management is one of the solutions for reaching these targets.

In this paper, the potential of thermal management for a parallel HEV with a baseline control strategy under different driving cycles and ambient temperatures is presented. The focus of the investigations is on reducing fuel consumption and increasing comfort for passengers. In the first part of this paper, the developed HEV-model including the validation with measurements is presented. In the second part, the combined thermal management measures, for example the recuperation of exhaust-gas energy, engine compartment encapsulation and the effect on the target functions are discussed. Simulation results show potential of reduction fuel consumption together with increasing the comfort for the passenger cabin.

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INTRODUCTION

In the last few years, a motivated interest in reducing fuel consumption and exhaust emissions as well as advanced technologies of hybrid vehicles without sacrificing the drivability and driver comfort has increased worldwide. Due to the multiple energy sources, driving modes, environmental effects and complex configurations, the hybrid vehicle control strategies have become more complicated. In order to deal with these challenges, it is necessary to optimize the energy management strategy.

A parallel hybrid vehicle model is used to approximate the main performance characteristics and vehicle efficiency for a given driving cycle. The main aim of this work is to improve both the powertrain efficiency and thus the fuel consumption and to improve the climate comfort.

This leads to an increase in the hybrid vehicle range capability. The effect of ambient conditions on fuel economy is also included.

For a cold ICE, the coolant temperature is below an acceptable value and the emissions are relatively high since the catalysts are not reaching their operating temperature. To reduce the cold-start emissions, methods for fast engine warm-up are

needed. Unfortunately, fuel consumption increases in the warm-up phase, because the ICE sometimes operates in its low efficiency range.

ICE cold start-up and the catalyst heating function are modeled. By allowing driving at higher engine load during the warming-up phase, the ICE exhaust gas becomes hotter and can heat the catalyst more rapidly, thereby also the warm-up phase and the fuel consumption are decreased.

There are several publications on "Energy and Thermal Management" in hybrid powertrains in different environmental conditions. Serial hybrid drive concepts, plug-in hybrid vehicles as well as parallel hybrid vehicles, which are very popular in Europe, were introduced and evaluated energetically from the point of increasing powertrain efficiency, see e.g. a series of publications [25, 26, 27, 31].

In this paper, however, a complex and advanced thermal HEV model for a comprehensive study in this research area was used, where not only individual measures are evaluated, but also possible combinations are optimized. Three different driving cycles and different ambient temperatures were taken into account to analyze the climate comfort in the passenger cabin and the resulting interaction with the energy management of the vehicle.

An important part of this paper is the modeling of the integrated exhaust manifold (IEM) of the ICE, which is integrated in the hybrid powertrain, and the resulting effect on fuel consumption and climate comfort - as an individual measure as well as in combination with further energy management measures.

According to the current state of knowledge, such a detailed and in-depth energetic consideration and the associated effects on the thermal efficiency and therefore on the losses of the hybrid powertrain has never been provided before.

Part of the high level of detail of the HEV model mentioned above are, for instance, the special features to represent the mechanical losses in the ICE - the implementation of engine friction. What is distinctive about the model is that the coolant temperature and the engine load are taken into account in addition to the typical correlation variables engine speed and engine oil temperature. According to the current state of knowledge, it has not been used yet to evaluate the energy management in a thermal HEV simulation environment. A correlation of the coolant temperature, for example, is definitely required in order to evaluate the thermal management measures and their effects on mechanical losses correctly. Measurements showed that the coolant temperature correlates significantly with the friction of the pistons, which in turn play a significant part in engine friction. If only the oil or coolant temperature is assumed as thermal correlation variable - as often found in the literature [28, 29, 30] - the ICE friction calculated during the warm-up phase is too high since the coolant temperature has an higher temperature level as the engine oil.

The paper is organized as follows: at the beginning, the simulation models are described followed by validation. Then, the implementation of energy & thermal management measures is presented, especially the integrated exhaust manifold (IEM). Finally, the results are analyzed and discussed based on the simulation results of different driving conditions.

MODELING

The HEV-powertrain, components and vehicle properties were modeled using co-simulation programs consisting of a set of empirical models, test bench maps and key data. Details of HEV components such as the ICE, EM and transmission are represented as modules, as can be seen in Figure 1. The powertrain block contains the components ICE, clutches, transmission, EM and wheel. The map based chemical energy from tank to the ICE effective torque is a nonlinear function of ICE speed and indicated mean effective pressure (imep) of the ICE. The mechanical torque generated from the combustion process (indicated torque) is divided into two main parts: the first part goes to the mechanical powertrain for vehicle propulsion, while the rest goes in the ICE mechanical losses including the auxiliaries units.

The vehicle is modeled with a 7-speed dual clutch transmission. Driving resistance characteristics such as frontal area, rolling resistance, vehicle mass and drag coefficient significantly affect the requirement of the powertrain. Using a co-simulation, HEVs were driven over prescribed driving cycles in the normal case scenario of about 60% battery SoC. Three standard driving cycles were used in the HEV simulation: FTP-75, US06 and NEDC with different ambient temperatures (20°C and -7°C). The following rules were applied for the HEV simulation:

- At the end of the driving cycle, the battery SoC must have the same level as at the beginning of the cycle. During the simulations, the SoC must not exceed the upper or lower limit to avoid damage of the battery.
- Allowed difference between the desired speed and simulated speed of the driving cycle: 1km/h.

Compared to the most conventional vehicle, there is additional a low temperature coolant system in the HEV. The ICE and EM have a higher temperature level and the inverter, intercooler and turbocharger have separate coolant system with a lower temperature level. The radiator cooling fans are powered electrically.

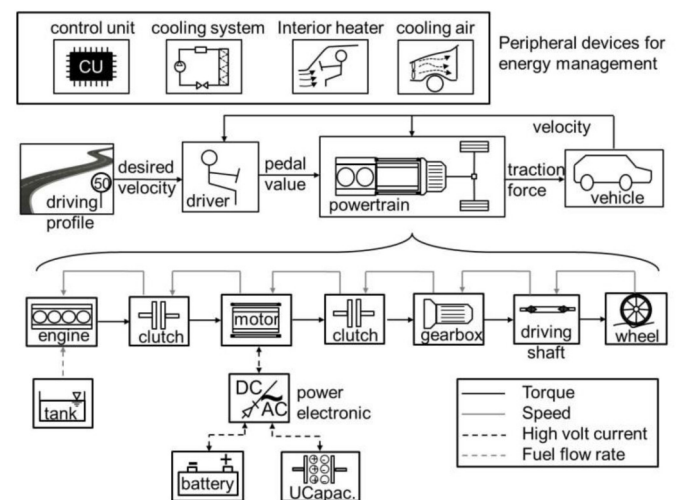


Figure 1. Modules of the hybrid powertrain model

Thermal Network - ICE

The ICE simulation model is divided into a small number of substitute masses based on [15]. By connecting substitute masses with thermal resistances, a thermal network can be generated. Every thermal mass represents a node of the network and is defined by its mass and its specific heat capacity. The number of network nodes defines the complexity of the thermal network. Every thermal mass is able to receive or emit heat. By balancing the acting heat fluxes, thermal masses can be warmed up or can be cooled down. Depending on a defined start temperature, the thermal network allows a calculation of time-depending temperature curves of each substitute mass. The model is able to simulate transient ICE behavior for different load cases.

Figure 2 shows the configuration and structure of the thermal network including all thermal resistances and substitute masses. It consists of the sub-models crankcase (CC), cylinder liner (CL), cylinder head (CH), piston (Pi), crankshaft and exhaust turbocharger. Each sub-model is divided in different metal substitute masses. The thermal masses of these components are taken from technical drawings and are therefore representing the real ICE masses. The fluid substitute masses inside the engine are divided into the four nodes coolant in the crankcase, coolant in the cylinder head, direct and indirect oil. The thermal network is able to exchange heat with the ambient on surfaces of crankcase, cylinder head, oil sump and turbocharger.

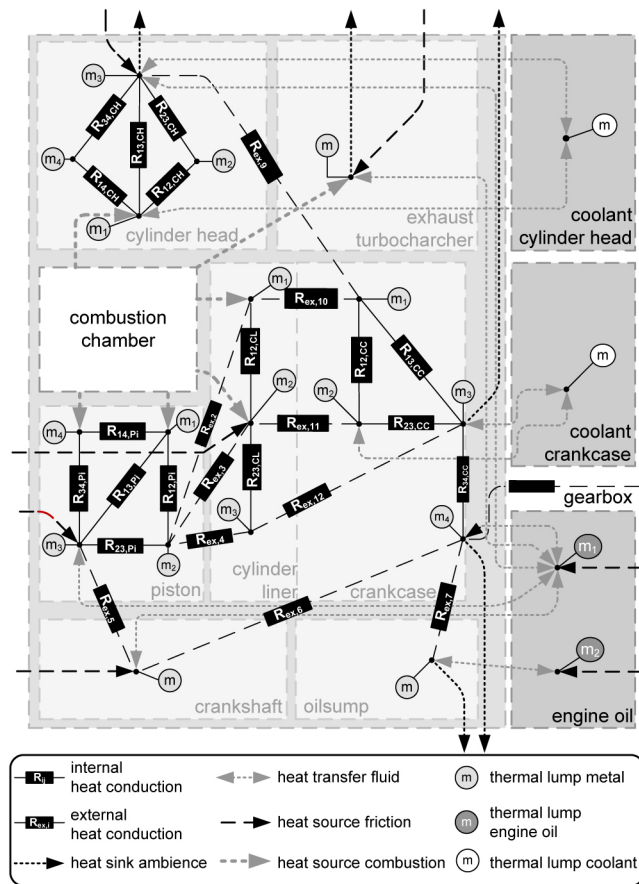


Figure 2. Thermal network of the ICE

Heat Transfer - Combustion Chamber

Figure 3 shows the determination of the combustion heat map by cylinder pressure analysis (CPA) of experimental data. Figure 3a and 3b show the measured cylinder pressure and the calculated burn rate. With the measured cylinder wall temperature and the calculated mean global gas temperature (Figure 3c) the heat flow rate through the combustion chamber boundary can be estimated under consideration of the heat transfer coefficient (Figure 3d).

$$\dot{Q}_W = \alpha \cdot A_{cylwall} (T_{gas} - T_{cylwall}) \quad (1)$$

By the integration of (1) the cumulated heat for one combustion cycle Q_W can be calculated (Figure 3f). Figure 3h and 3g show the resulting heat losses for the complete ICE operation map.

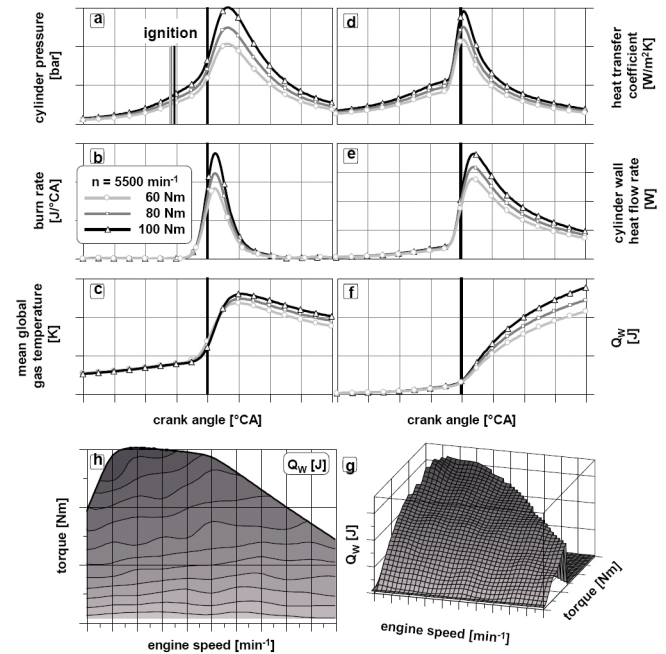


Figure 3. Derivation: Combustion chamber side heat losses map

Engine Friction Model

The heat input caused by engine friction is calculated by using an adjusted friction model, which is based on extensive strip measurements. What is distinctive about the model is that the *coolant temperature* and the *engine load* are taken into account in addition to the typical correlation variables *ICE speed* and *ICE oil temperature*.

$$\begin{aligned} f_{mep} (n_{ICE}, T_{oil}, T_{coolant}, bmep) &= \sum_i \sum_j a_{ij} \cdot b_{ij} (T_{coolant}) \\ &\cdot c_{ij} (n_{ICE}) \\ &\cdot f_{mepij} (T_{oil,ref}) \left[\frac{v(T_{oil})}{v(T_{oil,ref})} \right]^n \\ &+ \Delta f_{mep_{load}} \end{aligned} \quad (2)$$

$$\Delta f_{mep_{load}} = C(bmep) \cdot bmep \quad (3)$$

The friction mean effective pressure consists of the individual friction mean effective pressures of the components or units - the coefficient is calculated for every component (*crankshaft, piston + connecting rod, valve gear*).

In the empirical approach described in [23], the load impact, in this case for a DI (Direct-injection) gasoline engine, is added to the term of the piston group. The load-dependent friction directly correlates with the break mean effective pressure (3). The proportional coefficient $C(bmep)$ is given as a function of

bmp. It should be noted that the load-dependent term of the piston friction includes already the engine pumping losses, which normally are not part of the classic mechanical losses.

Figure 4 and Figure 5 show the validation results of the friction model.

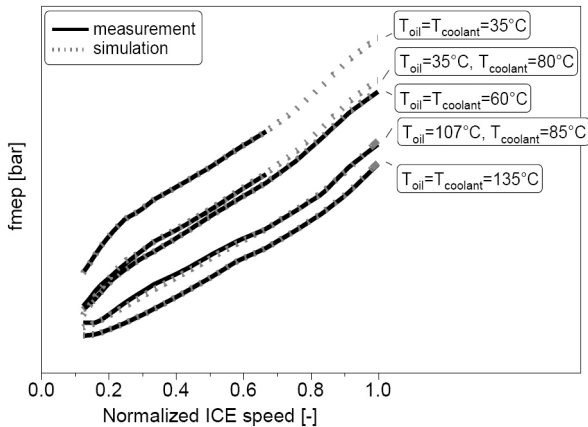


Figure 4. Validation of the ICE friction; Depends on engine speed, different oil and coolant temperatures

Figure 4 shows the first part of the verification of the friction model based on the strip measurements. The special characteristics of the measurements are the different temperature levels of coolant and engine oil. Based on this data set, the engine friction could also be modeled depending on the coolant temperature.

The results for the represented temperature levels comply very well with the measurement data. Furthermore, the comparison also shows a plausible extrapolation in terms of high engine speeds and low temperatures. Further verification calculations for the friction of the ICE are given in Figure 5.

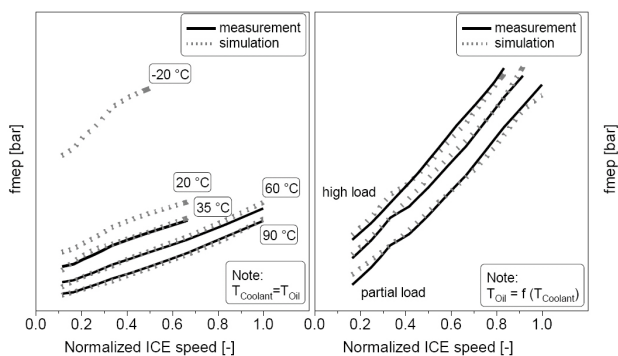


Figure 5. Validation of the engine friction; Left side depends on engine speed, oil and coolant temperature; right side: Depends on engine speed, oil, coolant temperature and engine load

On the one hand, they show a plausible extrapolation towards low temperatures (left-hand diagram) and, on the other, that the impact of the correlation variable *bmp* is represented correctly. This is clearly shown in the right-hand diagram.

With regard to the verification of the model in terms of extremely low temperatures, it should be mentioned that strip measurements unfortunately were not available for this temperature range. An overview about the calculation of the remaining powertrain losses gives Table 3 in the appendix.

VALIDATION

This section deals with the validation of the kinetic and thermal models of the HEV. The following figures show simulation and measurement results, performed on the NEDC. First, it is ensured that the load spectra match with the measurements - for the ICE and the EM. This is an important step for the correct modeling of the baseline control strategy. After this first comparison, the simulated temperatures of the powertrain fluids and components, in particular the EM and ICE, are compared with the measurement - for a cold and warm start. Finally, the fuel consumption and the state of charge of the traction battery are compared with the measured data. When the HEV validation is successfully completed, the developed model can be used as baseline for further investigations.

Figure 6 shows results of the simulated load spectrum of the ICE in the NEDC.

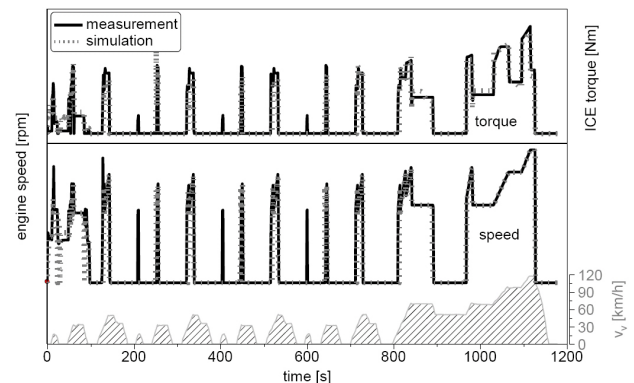


Figure 6. Validation NEDC (load spectrum - ICE)

As can be seen, the ICE speed and the ICE torque matches with the measured data. The same good results were achieved in the load spectrum of the EM (Figure 7). The first step to calculate the correct warm-up behavior of the powertrain has been successfully carried out: The operating points of the powertrain components are calculated correctly within the baseline control strategy.

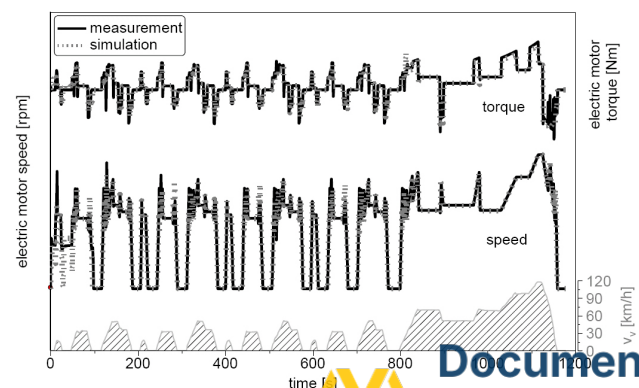


Figure 7. Validation NEDC (load spectrum - EM)

The next figure shows the fluid-temperatures during the warm up phase of the ICE (coolant in the cylinder head, oil sump), the transmission (oil sump) and a component temperature of the EM - in this case the iron stack.

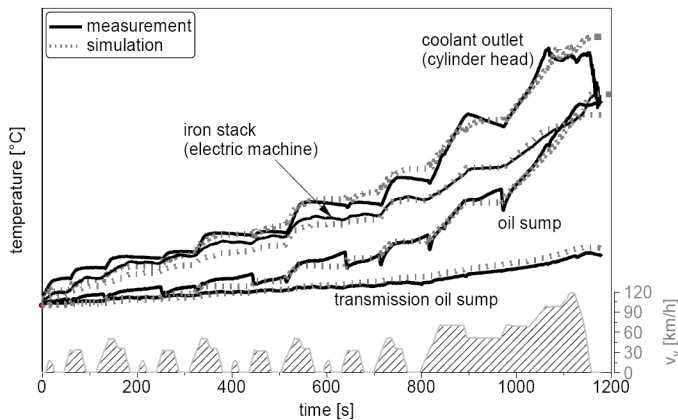


Figure 8. Validation NEDC (Powertrain - cold start)

Figure 8 clearly demonstrates that the simulation results match very well with the measured values - also under the conditions of frequent operating mode changes between the ICE and the EM.

The thermal behavior of the electric drive in the HEV is very important for the resulting losses or for the efficiency of the complete powertrain system.

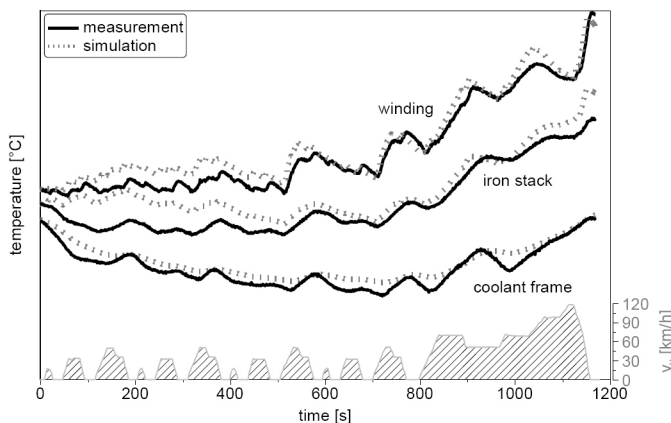


Figure 9. Validation NEDC (electric machine - warm start)

Figure 9 shows different component temperatures of the EM in the NEDC cycle, in this case a warm start. Also in this case, the transient behavior is very well reproducible and the small deviations from the measured values are acceptable.

Figure 10 shows the comparison of the fuel consumption and the state of charge of the battery with the measurement for a cold start (NEDC).

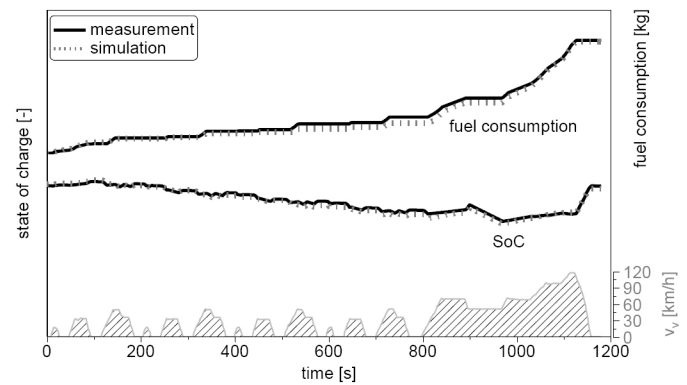


Figure 10. Validation NEDC (SoC and fuel consumption)

The engine fuel consumption is provided by steady-state maps that depend on the imep and ICE speed:

$$\dot{m}_{fuel}(t) = f(imep, n_{ICE})$$

(4)

When observing the results in Figure 10, the thermal and kinetic HEV-model has also the correct behavior in calculating the SoC and fuel consumption during the warm-up phase. This, of course, depends on factors such as the mechanical losses in the transmission and in the ICE, as well as the electrical or thermal losses of the complete powertrain. These factors depend heavily on the temperature level, which sets due to the load spectrums of the powertrain components.

CONTROL STRATEGY

The essential task of the control strategy in a HEV is to meet the driver power demand while achieving the desired torque required for the EM and ICE as well as the desired gear to achieve minimal fuel consumption and drivability of the HEV.

Additionally, the SoC should be kept at a sufficient level to be able to provide the needed power for driving the vehicle over a wide range of driving situations [3].

Control strategies have of course a significant impact on costs, component sizing, powertrain or vehicle efficiency and customer acceptance [2]. The needed variables for the control strategy are collected through sensors together with the driver desired load. As can be seen in Figure 11, the control strategy is made up of five main functions: operating mode, gear selection, SoC-control, thermal management and brake distribution. The developed baseline control strategy is scalable and can be used with any parallel hybrid vehicle under different driving conditions.

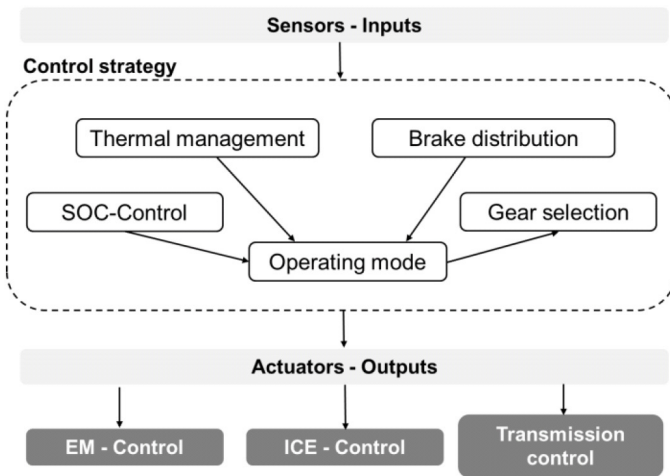


Figure 11. Structure of the control strategy as implemented in the co-simulation environment

Operating Mode

The operating mode determines the time and duration of each driving mode. The baseline control strategy which is a rule based control strategy is implemented in the HEV. This control strategy requires some information for offline optimization in order to tune the parameters of the control strategy. The HEV has several operating modes, which can be selected according to driving conditions and driver demands. The main operating modes are illustrated in Figure 12 and divided as follows:

- Electric mode: The EM alone is used to provide the entire driving torque when the power demand P_D is below ICE power threshold ($P_{ICE,MIN}$). The clutch between ICE and EM is disengaged. The electric mode is also used for launching the vehicle from a stop and for turning on the ICE. Being in this mode has an advantage because no fuel is consumed.
- ICE mode: when the vehicle power reaches $P_{ICE,MIN}$ and the battery SoC a maximum limit SoC_{high} at the same time, only the ICE turns on.
- Hybrid mode: depending on specific driving conditions, both the ICE and EM are operating in this mode to propel the vehicle. Two variations are given below:
 - ICE/motor-mode: the EM is asked to provide torque to assist the ICE.
 - ICE/generator-mode: the ICE is asked to provide more torque to charge the battery to achieve the desired SOC.
 - Regeneration mode: converting the kinetic energy during deceleration by allowing the EM to work as a generator charging the battery.
- Coasting mode: it is a transition state between driving (where the vehicle power is positive) and conventional braking/recuperation mode (where the vehicle power is equal or less than zero). The battery is not being charged in this mode.
- Conventional braking: The battery is not being charged since kinetic energy is converted into friction.

As can be seen from Figure 12, the control strategy is mainly power and SoC-based; when the HEV requires a low level of power, e.g. when the vehicle torque demand (P_D) is lower than $P_{ICE,MIN}$, the ICE is turned off and the EM/motor provides the needed drive power. When the P_D vehicle torque demand is higher than $P_{ICE,MIN}$, the ICE will be turned on and the vehicle driven by the hybrid or ICE mode. If the SoC is below the SoC_{small} limit, the hybrid mode is activated in order to provide the torque demand and/or to charge the battery. The power demand P_D generated during a given driving cycle is used as an input and expressed as:

$$P_D = \frac{1}{\eta_{Rest}\eta_T(Gear, n_T, M_T, T_T)} \left[mgf_r v_v + \frac{1}{2} c_w A_v v_v^3 \rho_{Air} (T_{Amb}, p_{Amb}) + mv_v a_v + mgsin\gamma v_v \right] \quad (5)$$

The parameters are rest powertrain efficiency η_{Rest} , transmission efficiency η_T , vehicle mass m ; rolling resistance coefficient f_r , air density ρ , front area A_v and aerodynamic drag coefficient c_w . The ICE and/or EM should be able to supply sufficient power to overcome the driving resistances and driveline losses.

When optimal power train control is applied, the ICE starts and stops frequently. This rapid on/off changing of the ICE may probably reduce the vehicle drivability. In addition, the required power is not instantaneously available from the ICE after the start since a certain amount of time is required to bring the ICE up to the transmission rotational speed to overcome the ICE friction and rotational inertia. Therefore, the ICE should turn on at least for 5s.

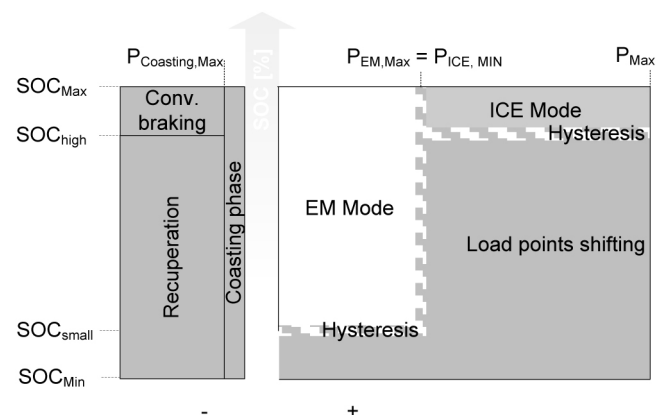


Figure 12. Simplified illustration of the rule-based strategy

The overall structure of the baseline control strategy is shown in Figure 13. The baseline control strategy has many parameters, such as load shift power P_{LPS} , actual SoC, P_D , vehicle speed, cylinder head water temperature, etc., which have to be determined in order to make the control strategy work properly. The parameters of the baseline control strategy