Increase of Electric Range for PHEVs Due to Intelligent Thermal Management

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An optimized thermal management system for Plug-in Hybrid Electric Vehicles (PHEVs) offers potential for both extending the electric range and reducing CO_2 emission in real-drive operation. Eberspächer and Fraunhofer ICT present a study that quantifies the CO_2 optimization by using a fuel-operated heater and verifies it on a chassis dynamometer.

Heating the passenger compartment significantly reduces the electric range of PHEVs under cold ambient conditions. In some vehicles, such processes lead to an immediate start of the Internal Combustion Engine (ICE), making an electric, local emission-free trip impossible [1]. For automobile manufacturers, PHEVs are an attractive option for fulfilling the CO_2 fleet limiting value because they achieve low CO_2 values in the WLTP test cycle. In everyday use, however, various factors such as driving style, charging behavior and ambient conditions can cause the CO_2 emission to rise above those from comparable motorized vehicles without electrification [1-3].

The aim of a study by Eberspächer and Fraunhofer ICT was to quantify the influence of thermal management measures on the electric range and CO_2 emission of a luxury plug-in SUV. Using a validated model of the production vehicle, measures for optimizing the thermal management system with a Fuel-operated Heater (FOH) were quantified in a virtual manner and

the corresponding modifications on the vehicle side verified on a chassis dynamometer.

VEHICLE MODEL

The virtual investigation is based on an overall vehicle simulation model from Fraunhofer ICT. Studies on a compact class passenger car describe the approach and the procedure for parameterizing and validating the subcomponents for the PHEV using measurement data from an existing test carrier [4, 5]. **FIGURE 1** visualizes the resulting performance map of the e-machine (left), as well as the dynamic battery charge limit (right) of the plug-in SUV.

The thermal management system of the vehicle, **FIGURE 2**, has two separate coolant circuits and one refrigerant circuit. The E-drive components are conditioned in dependence of the operating point using the Heat Pump (HP) evapo-

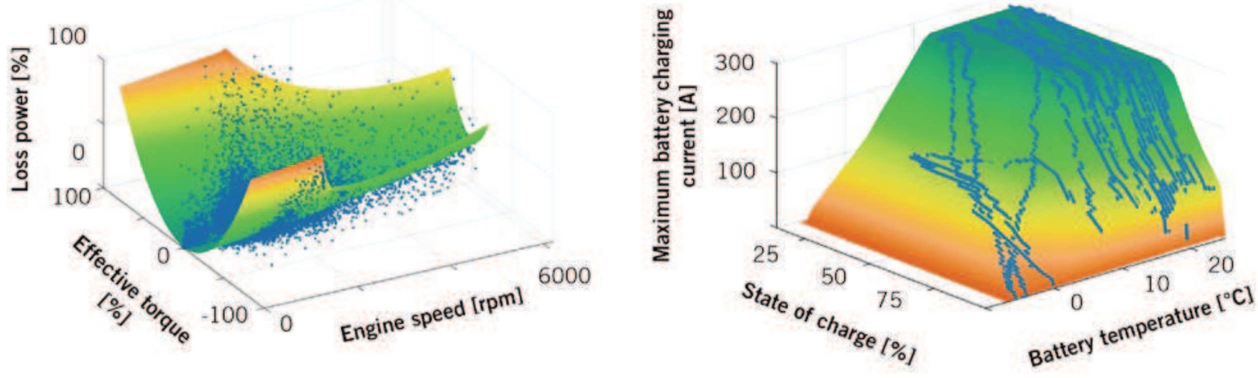

FIGURE 1 Loss power map of the electric machine (left) and current limitation (right) of the high-voltage battery as a function of state of charge and battery temperature (© Fraunhofer ICT | Eberspächer)

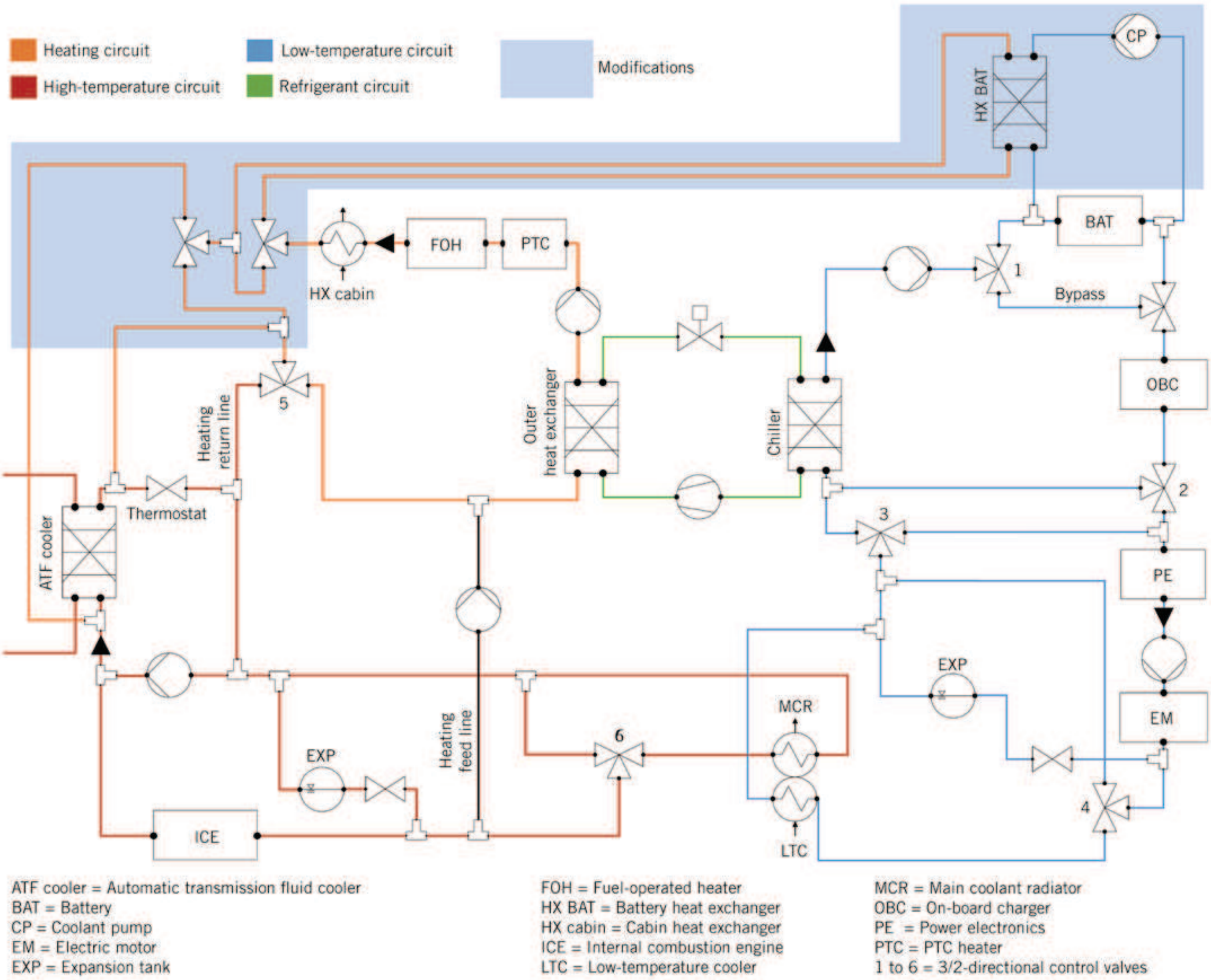

FIGURE 2 Thermal management of a luxury-class PHEV in a simplified schematic (© Fraunhofer ICT | Eberspächer)

rator or a radiator in the Low-temperature (LT) circuit. The circuit can be split to allow higher coolant temperatures in power electronics and e-machine. The heat sources of the heating circuit are the external heat exchanger of the HP, the electrical PTC heater and the FOH. A coupling to the High-temperature (HT) circuit is created when the passenger compartment is heated using the waste heat from the ICE and in conventional auxiliary heating mode, in order to pre-heat the ICE before the trip starts. The Automatic Transmission Fluid (ATF) cooler is located in the HT circuit. The coolant volume flow is controlled by a wax-type thermostat.

The model validation is based on a speed profile determined on a real track around Karlsruhe (Germany) that satisfies the dynamic RDE criteria. Due to eliminating high longitudinal dynamics, a moderate average speed and a route length corresponding to twice the electric driving range, the assessment of the thermal management system measures described in the following should be considered as a conservative one.

TABLE 1 shows, as a reference, the results from validating the simulation of the production vehicle's initial state. For a winter scenario, the chassis dynamometer and the vehicle were pre-conditioned to -5 °C. The passenger compartment air conditioning was set to 23 °C and automatic mode. The progression of the cabin temperature is also reproduced very accurately by the simulation.

VALIDATION OF VEHICLE MODIFICATIONS

With the findings from [4], modifications to the thermal management system were examined based on the reference model. The focus remains on assessing the winter scenario with heating-up of the drive components and the passenger compartment. As a result, three variants are possible:

- additional heat source: using the FOH during vehicle operation with its low electrical energy demand

Parameter	Measurement	Simulation	Deviation [%]
Total distance [km]	81.37	81.29	-0.10
Fuel consumption [l]	5.12	5.01	-2.21
CO_2 emission [kg]	13.26	13.27	0.05
Electric range [km]	23.38	23.27	-0.47
Electric energy demand [kWh]	11.61	11.58	-0.28
– Thereof thermal management system [kWh]	5.36	5.29	-0.75
– Thereof heat pump [kWh]	2.37	2.35	-1.09
– Thereof PTC heater [kWh]	2.99	2.94	-1.76

TABLE 1 Validation of the model using measurements on a certified chassis dynamometer (© Fraunhofer ICT I Eberspächer)

- (pre-)heating of the battery: reducing the internal resistance to increase the recoverable electrical energy and recuperation power
- (pre-)heating of the ATF: increasing the transmission efficiency.

In **FIGURE 2**, the modifications are highlighted in blue. The coupling of heating and LT circuit using a plate heat exchanger (HX BAT) and a Coolant Pump (CP) enables a heating of the battery. The 3/2-way valve in the heating circuit is controlled in such a manner that warm coolant at a maximum of 40 °C flows through the battery. The transmission is heated using the ATF cooler, through which coolant from the heating circuit can flow. The ICE can be conditioned by the existing coupling between heating circuit and engine circuit.

The functions are implemented by controlling the pumps and valves using a real-time system additionally installed in the vehicle. In the reference model, the FOH can exclusively be used during standstill. An additional control unit permits operation while driving.

PTC heater and HP are validated by the reference run. The models for ATF and battery heating by the FOH are validated by uncoupling the PTC heater and HP compressor. To achieve adequate component heating from the low heat output, passenger compartment heating was omitted. **FIGURE 3** (left) shows the results from measurement and simulation for the electric part of the trip with and without conditioning of the high-voltage battery at -5 °C. **FIGURE 3** (right) shows the results of the ATF conditioning. On average, 2.1 kW of heat was drawn from the battery heat exchanger and 2.4 kW from the ATF cooler.

With the simulation model, both the reference and the modified vehicle can be modelled and validated with an adequate degree of accuracy. For a reasonable technical comparison of heating components, their heat outputs have to be identical. To minimize the test effort required due to the range of variants, the results of a virtual sensitivity analysis based on the refined model are shown in the next chapter.

RESULTS OF THE SIMULATIONS

The total heat output is controlled to the fastest possible achieving and maintaining of a passenger compartment temperature of 23 °C. Two heat source configurations are investigated: PTC + HP or FOH + HP. **FIGURE 4** (top) shows the electric range and the time at which the target passenger compartment temperature is reached in the RDE driving profile. Due to the high electrical power requirement of the PTC heater, the reference (scenario a) exhibits the smallest electric range (23.78 km). By using the FOH (scenario b), a range increase of 5.82 km (+24.5 %) is achieved. The scaling of the FOH output to 7 kW (scenario c) permits a simultaneous heating of the additional components without compromising passenger compartment comfort.

The biggest differences in the State-of-Charge (SoC) progression of the battery between the reference and the variants occur in the first stage of the test drive due to the replacement of the PTC heater by the FOH, **FIGURE 4** (bottom left). The use of the FOH results in a reduction of CO_2 emission between 7 and 9 % in the total balance of the RDE cycle, **FIGURE 4** (bottom right). For heating of the passenger compartment and the battery only, a 6-kW FOH will suffice (scenario d). Consequently, the passenger compartment heating, having an

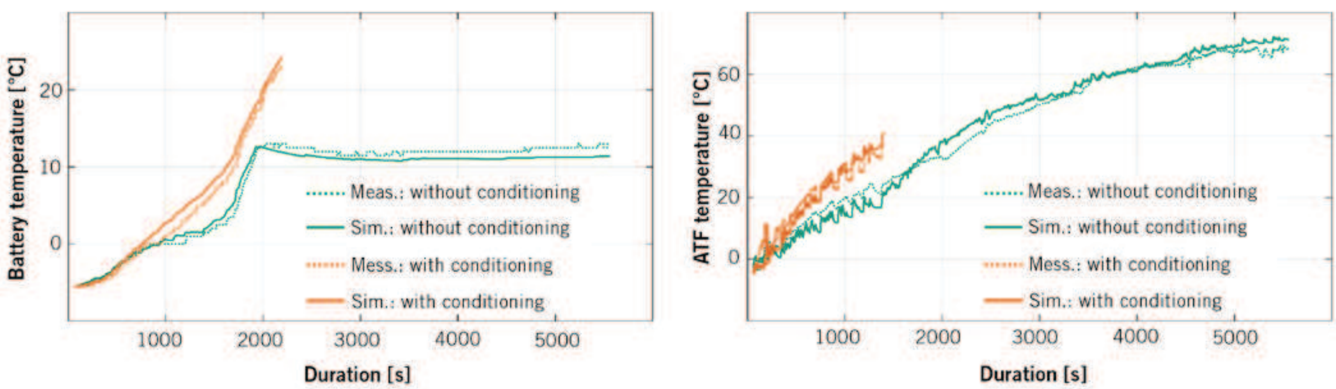

FIGURE 3 Validation of the modifications by chassis dynamometer runs at -5 °C: diagram of battery temperature (left) and Automatic Transmission Fluid (ATF) temperature (right) with and without conditioning (© Fraunhofer ICT I Eberspächer)

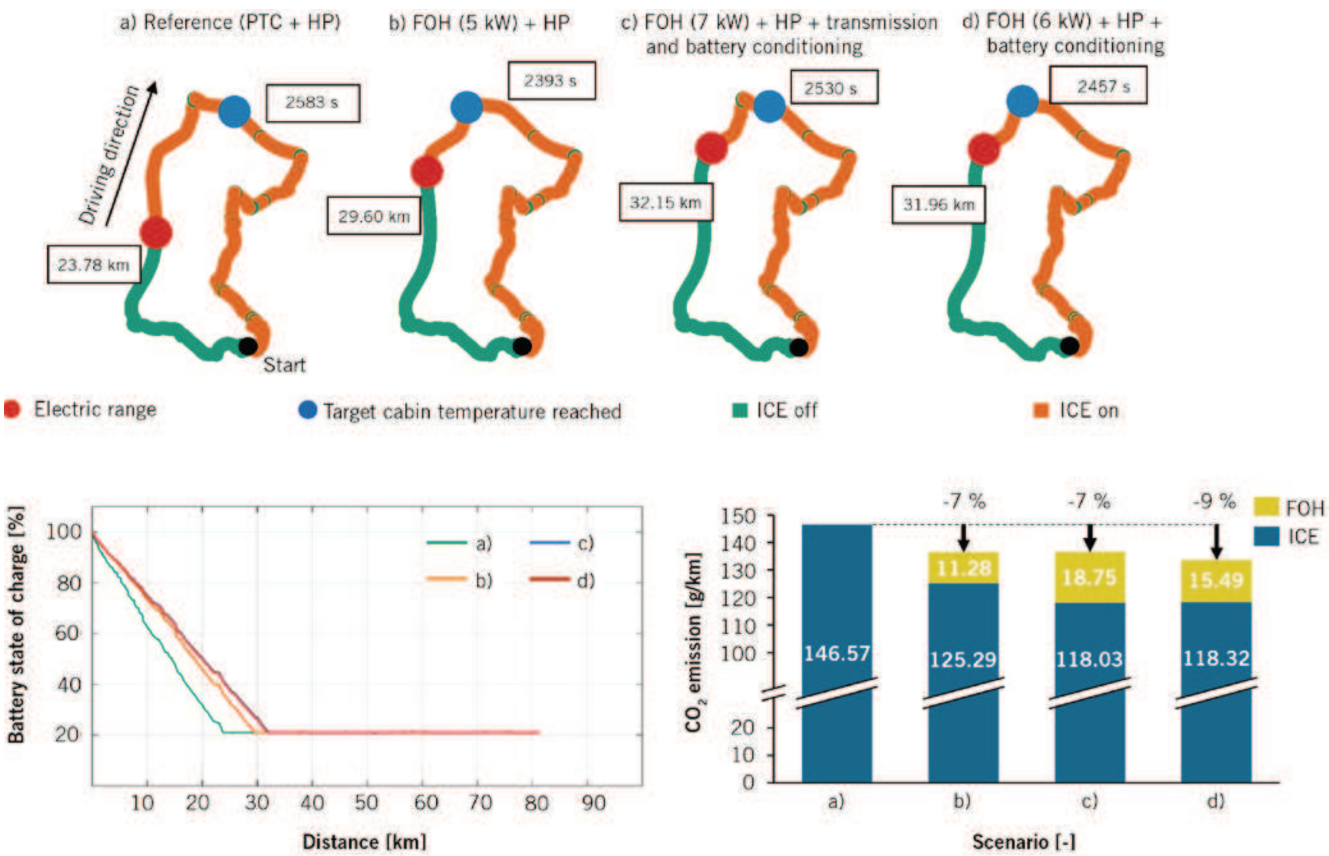

FIGURE 4 Simulation results: RDE driving profile with electric range, time at which the target passenger compartment temperature is reached (top) as well as diagrams (bottom) of state of charge and CO_2 emission at an ambient and starting temperature of -5 °C and a starting state of charge of 100 % in four scenarios a to d (© Fraunhofer ICT I Eberspächer)

increased range and reduced CO_2 emission, stays comparable with the reference. If the transmission is heated additionally, a 7-kW FOH is required for a passenger compartment heating that is comparable with the reference. Due to a higher energy demand of the HP, only a slight increase of the electric range could be achieved. However, it was not possible to further reduce the CO_2 emission beyond that of scenario d, since the increased consumption of the more powerful FOH was, in this case, higher than the fuel savings of the ICE.

FIGURE 5 shows the already mentioned scenarios a to d at an ambient temperature variation of -10 to +23 °C in the RDE cycle under consideration. Over a wide temperature range, it appears that by using an FOH in combination with an HP the electric range, **FIGURE 5** (left), can be increased and the CO_2 emission, **FIGURE 5** (right), can also be reduced. When the HP is coupled to the LT circuit, the HP is deactivated as soon as the LT coolant temperature drops below -10 °C. At an ambient temperature of -10 °C, the intrinsic heating of the components in the LT circuit is not sufficient, and therefore the HP is permanently deactivated under very cold ambient conditions.

SUMMARY AND OUTLOOK

Taking the findings of previous simulations as a basis, the thermal management measures described in this paper were implemented in the vehicle with the aim of increasing the electric range and reducing CO_2 emission of an SUV-class PHEV. The modifications were verified with chassis dynamometer tests and the resulting simulation models were validated on this basis. The tests showed that the electric range can be increased by up to 25 % with an FOH at -5 °C ambient temperature. Through additional conditioning of the traction battery and transmission fluid, the measured range increase is as high as 29 %. The optimum thermal management setup was determined using the refined model, which allows the choice of heating power independent of the restrictions of the components installed in the vehicle.

The replacement of the PTC heater with an FOH of the same power output class resulted in an electric range increase of 24.5 % and a reduction of the CO_2 emission of 7 % compared to the reference. The thermal conditioning of the battery with an FOH rated for 6 kW power was able to increase the electric range by 34.4 % and reduce the CO_2 emission by 8.7 % relative to the reference. In comparison, through thermal conditioning of the battery and transmission fluid with a 7-kW FOH, the electric range was increased by 35.2 % and the CO_2 emission was reduced by 7 %.

Due to the thermal management modifications, it was possible to furnish proof that a significant CO_2 reduction is possible during electric driving by using an FOH. This work can be used as a basis for developing further operating strategies for minimizing CO_2 and using a real vehicle to verify these strategies under a wide

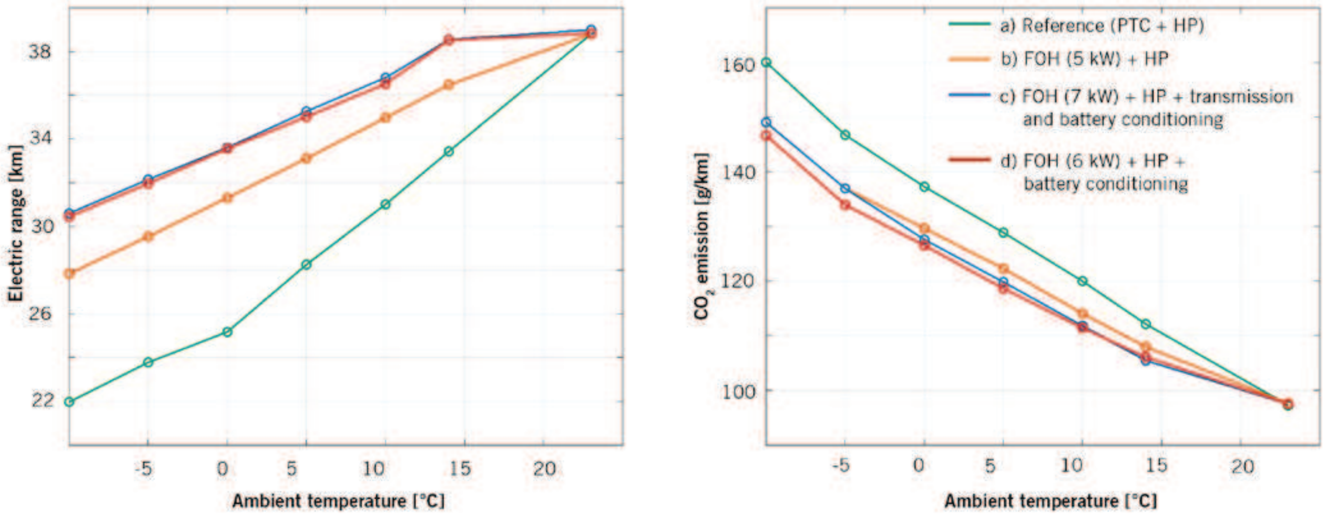

FIGURE 5 Electric range and CO_2 emission on the RDE driving profile with variation of the ambient and initial temperature and an initial SoC of 100 % in the four scenarios a to d (© Fraunhofer ICT | Eberspächer)

range of different driving profiles and ambient conditions. Considering the CO_2 emission, the potential for increasing the electric range can be utilized optimally by using an FOH with integrated catalytic converter and a heat output of 6 kW.

REFERENCES

[1] ADAC: Vergleich Plug-in-Hybride im neuen EcoTest. Online: https://www.adac.de/infotestrat/tests/eco-test/vergleich_plugin_hybride_2017/default.aspx, access: July 07, 2020
[2] ADAC: Plug-in-Hybrid: Modelle, Technik, Kosten, Ökobilanz. Online: https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/auto/plug-in-hybrid/, access: July 07, 2020
[3] Automobilindustrie: Plug-in-Hybrid: Mogelpackung oder Wegbereiter? Online: https://www.automobil-industrie.vogel.de/plug-in-hybrid-mogelpackung-oder-wegbereiter-a-946921/?cmp=nl-99&uuid=62568423-EFC6-360F-815CD0191565A4F7, access: 07 Juy 2020
[4] Eberspach, G.; Eger, J.; Fischer, T.; Burgert, T.: Range Extension of Plug-in Hybrids through Thermal Management Measures. In: ATZworldwide 3/2019, pp. 58-62
[5] Burgert, T.; Dollinger, A.; Fischer, T.: Methodology for Modelling a Plugin Hybrid Electric Vehicle Based on Data Logging. EVS32, Lyon, 2019

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