

Energy Management and Thermal Simulation of Hybrid Commercial Vehicles

Martin Ackerl

TU Graz / Institute of Automotive Engineering

Inffeldgasse 11, +43 (316) 873 – 5264, martin.ackerl@tugraz.at

Josef Hager, Klaus Prenninger, Martin Winter

MAGNA Powertrain, ECS

Steyrer Straße 32, +43 (7435) 501 0, office@ecs.steyr.com

Abstract

There is high potential in the hybrid drive technology for reducing fuel consumption and CO₂ emissions. The use and requirements of a hybrid drive for commercial vehicles differ in many ways from the one of hybrid passenger cars. The success of hybrid solutions for commercial vehicles relies primarily on significant fuel savings, whereas energy storage and energy management play an important role.

This paper shows a simulation model which has been used for the dimensioning and detailed simulations of hybrid drive trains. To simulate the thermal effect, a co-simulation environment between longitudinal dynamics and thermal management software has been applied. The longitudinal dynamics software calculates the propulsion power which determines the thermal load of the components. Particular attention has been directed to electrical and thermal behavior of the high-traction battery. The coupling of longitudinal and thermal simulation enables a realistic calculation of the energy use, since the effects such as the change of efficiency by temperature and load effect can be considered. This behavior also plays an important role in the development and tuning of the vehicles' components and operating strategy.

Finally this application shows simulated data of a hybrid commercial vehicle with a lithium-ion battery. For these simulations standardized driving cycles (HUDDS, JE05, ...) and also cycles with a high proportion of urban driving have been simulated. These simulations show a meaningful influence on the temperature of the components, especially the battery.

For a higher hybrid market share in the future, the development of electrical components, especially energy storage systems with high power and energy densities and the reduction of system cost and weight will be essential.

1. Introduction

The development of improved commercial vehicle drives is necessary to fulfill the increasing regional and global requirements for emission regulations in the future. The most popular topic at the moment is the reduction of CO₂ emissions. Figure 1.1 (left diagram) shows the global CO₂ emissions of different categories. One of the biggest parts is the transportation sector with 31% and a big part of this pie chart (right diagram) is the truck segment with 28%. Another reason for researchwork on new commercial vehicle drives is the increase of the long-term oil price. This topic leads to the differences between passenger vehicles and commercial vehicles. One of the most important criteria for selling commercial vehicles is costs. This means the purchasing costs, but also the maintenance costs which include the fuel costs. For passenger vehicles, the costs do not play that foreground role as in commercial vehicle business.

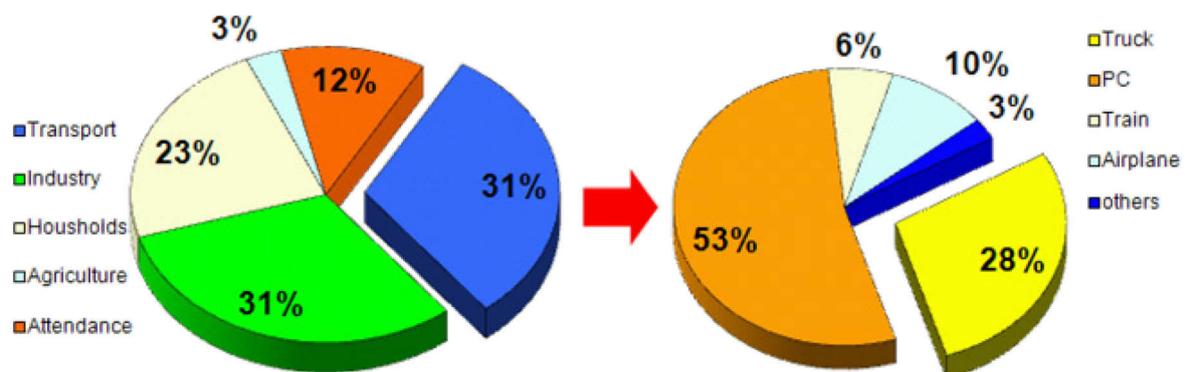


Figure 1.1: CO₂ emissions in different divisions

The following chapters describe the energy and fuel saving potentials of a hybrid commercial vehicle and the energy consumption. A special focus is kept on additional cooling systems for battery, electric motor and inverters. These components are also being powered from the electrical components generator or battery, which implies a direct relation to the fuel consumption.

2. Hybrid Vehicle

2.1. Vehicle Configuration

For vehicle simulation, a truck has been chosen which is already available on the emerging market. Therefore, the simulation results can be verified easier. The conventional powertrain of the truck has been modeled in a longitudinal driving simulation program. The main data of the vehicle is shown in Table 2.1.

Original Truck Configuration	
Type	6x2/2
Engine Power	184kW / 250hp
Gearbox	6 gears
GVW	24tons

Table 2.1: Standard Vehicle Configuration

The powertrain of the basic vehicle will be extended to a parallel hybrid drivetrain, with an electric motor between the engine and the new automatic gearbox. The battery will be mounted on the frame and also the additional cooling package. This cooling package is necessary to cool down the electric motor, the DC/AC inverter, the DC/DC inverter, the electric auxiliaries and the battery. The additional components are numbered in Figure 2.1.

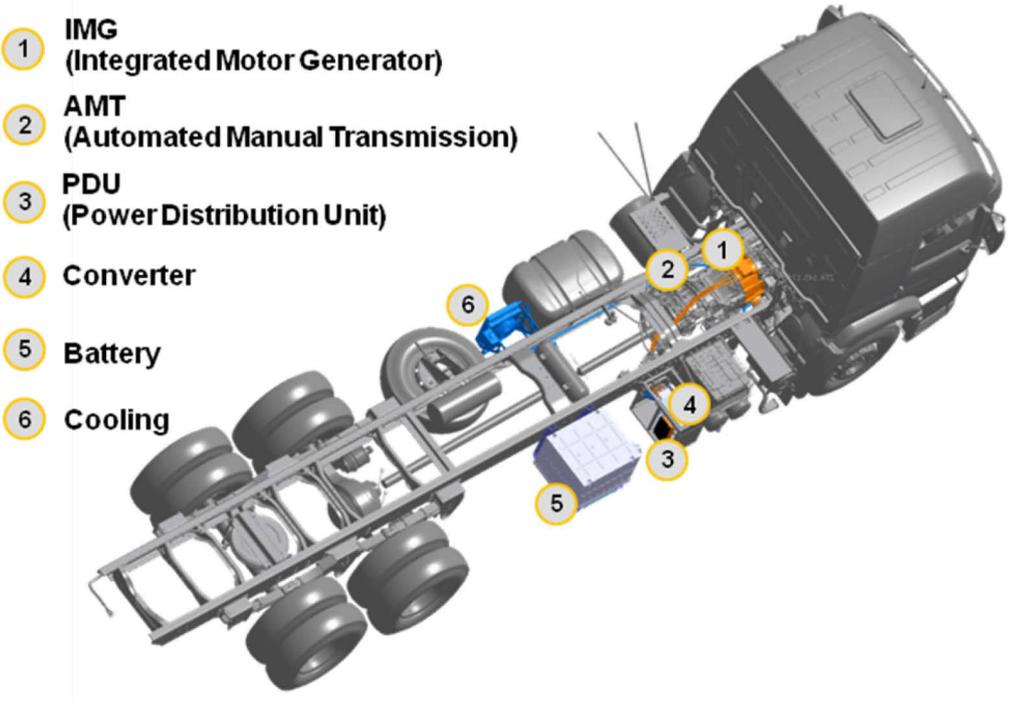


Figure 2.1: Hybrid Vehicle Layout

2.2. Additional Components of Hybrid Vehicle

For hybridization, off-the-shelf components have been chosen. Therefore, there are valid data for simulation available. One advantage is also, that these components are quickly available to build up a demonstrator vehicle. Table 2.2 shows details of these additional parts.

Hybrid Components	
Electric Motor nominal Power	70kW
Battery Energy Content (installed)	4,7kWh
Battery nominal Voltage	650V
Automated Manual Transmission	12 gears

Table 2.2: Additional Hybrid Components

These components have been modeled in the longitudinal driving simulation with the available data. The standard manual gearbox has been replaced by an automated manual transmission.

2.3. Energy Management

The energy management consists of a heuristic control strategy for traction application. This kind of control law has been derived in an intuitive way in order to guaranty robustness. The six operation modes of the traction control are explained in Table 2.3.

<i>Operation States</i>	
<i>Start Stop</i>	During stop, the engine shuts off. All auxiliaries are driven by electric motors, powered by the battery.
<i>Electric Drive</i>	The vehicle is driven up to a speed of 50km/h electrically, if the battery state of charge (SOC) allows.
<i>Load Point Shifting</i>	At low battery SOC, the engine is driven in a higher power level as needed for traction. The additional mechanical power will be converted by the generator into electrical power, to charge the battery.
<i>Recuperation</i>	In coasting or braking mode the traction motor is used as generator and charges the battery if the SOC allows. The engine will not be declutched, because of safety reasons.

Boost	Additional torque to the engine torque is delivered by the electric motor at low engine speed.
Engine Drive	If the engine is driven in an area of good efficiency, the electric motor is not involved in traction operation.

Table 2.3: Operation States for traction application

The energy management control of the cooling system consists of controllers, which can manipulate the fluid pump revolutions of the additional cooling circuits. If the battery cooling circuit is not able to cool down the losses of the battery, a refrigerant circuit can be switched on and the revolutions of the air conditioning compressor can be controlled to keep the battery temperature in the range of operation. These revolutions are continuously adjustable because it is assumed that these auxiliaries are driven by electric DC motors. Additional controllable components are the fan in the cooling package and the PTC heater, which can be switched on and off.

3. Simulation

3.1. Longitudinal Simulation Model

The vehicle model is implemented as a single-track model for longitudinal dynamics. This modeling depth is suitable for simulation of energy management controls. This modeling depth is also sufficient for fuel consumption calculation. The implemented model and its fuel consumption results have been compared to measurements of the basic vehicle. A company specific city driving cycle provided a basis.

	Measurement	Simulation
Total cycle fuel consumption [l]	5,5	5,4
l/100km–consumption [l/100km] fuel consumption analyzer	33,3	34,8
l/100km–consumption [l/100km] CAN-Signal	35,3	

Table 2.4: Comparison between measured and simulated fuel consumptions

The simulation results match the measurement results very closely. Table 2.4 shows such measured fuel consumption in comparison to the simulated fuel consumption. Hence, there is a verified vehicle model with a conventional drivetrain for simulation, which is also a good basis for hybrid drivetrain simulation.

A consumption map describes the fuel consumption of the modeled engine, which is an indicator for efficiency and CO₂ emission. For hybridization, additional components like an electric motor and a battery have been added to the simulation. Electric motor losses are considered on the basis of an efficiency map.

The battery has been modeled as a simple electric RC-circuit for every cell, where the parameters can be estimated from cell data sheets. Figure 2.2 shows such a cell model which can be extended to a battery with individual number of serial or parallel cell configurations. This model also considers the temperature dependency of the internal resistance and the open-circuit voltage. Batteries' power outputs depend on the cell temperatures and thence, this behavior has been included in a simulation model, too. Therefore, the cooling system for the battery also needs to be built-in. This topic is handled in section 3.2.

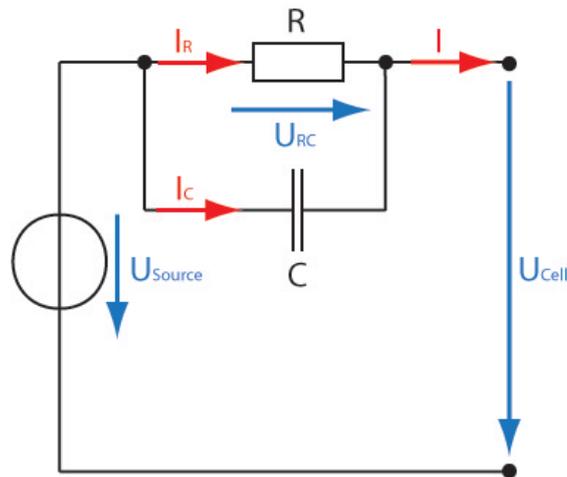
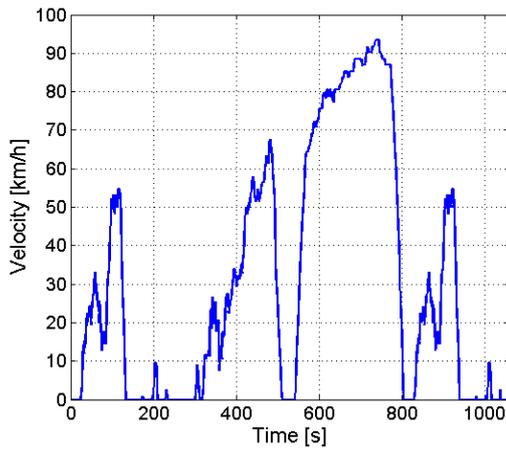
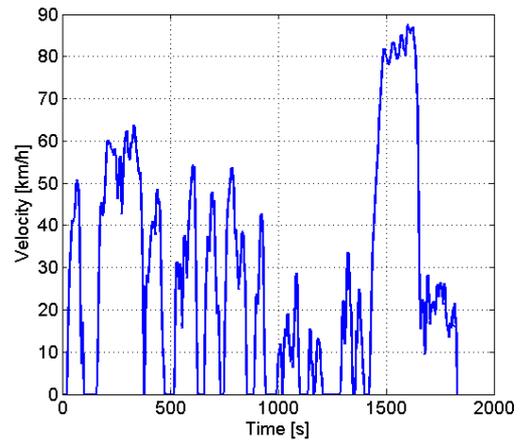


Figure 2.2: Battery's Cell Model

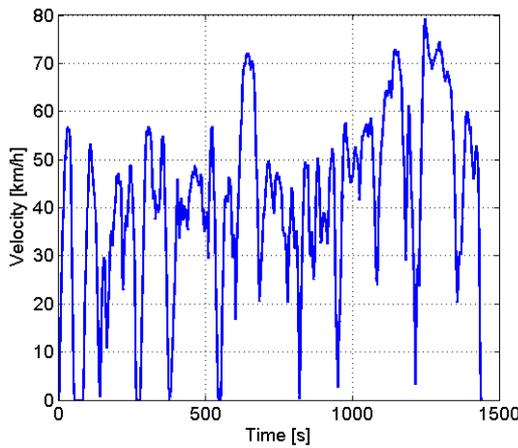
The simulation has been done for different driving cycles. Two standardized cycles and one company specific city driving cycle with different velocity profiles have been chosen. Table 2.5 shows the velocity profiles and explains the reasons why this driving cycles have been selected.



a)



b)



c)

- a) HUDDS (Heavy-Duty Urban Dynamometer Driving Schedule): high amount of idle time and peaks at slow velocities.
- b) JE05: Japan transient cycle with medium velocity rates.
- c) Company specific city cycle: high dynamics

Table 2.5: Velocity profiles of different driving cycles

3.2. Thermal Simulation Model

For the thermal management of the hybrid components an auxiliary cooling package has been installed. The configuration of the engine cooling package is the same as for the conventional vehicle. An auxiliary cooling package has been attached to the frame close to the fuel tank (Figure 2.1). A thermal simulation model has been set up using the software KULI. In Figure 2.3 a 3-d-view of the cooling packages can be seen. The cooling package for the engine cooling consists of an air conditioning condenser, a charge air cooler, a radiator and a mechanically driven fan. The auxiliary cooling package contains the air to fluid cooler for the battery and for the electrical machine. While the air flow through the engine cooling package is supported by the ram air at increasing driving speeds for the auxiliary package, the flow must be generated by the fan only. These effects have been considered in the simulation model.

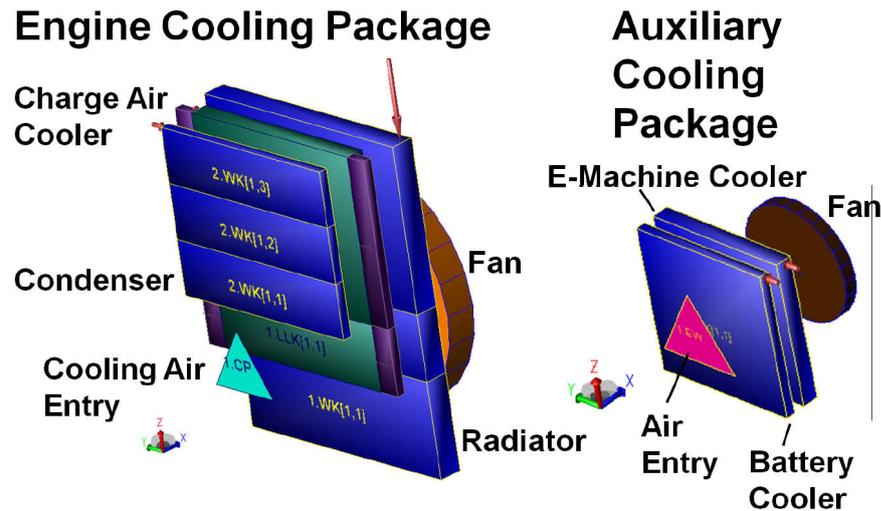


Figure 2.3: Main cooling package and auxiliary cooling package

For the e-machine, the power electronics and various auxiliaries a separate coolant circuit has been chosen (Figure 2.4). The temperature level of the coolant at the exit of the e-machine cooler of 65°C has been mainly determined by the e-machine. Besides e-machine and power electronics also AC-compressor, power steering pump and air compressor have been included in the coolant circuit. There are three parallel flow paths for the heat removal. The e-machine cooler has been arranged downstream of the battery cooler because the required temperature level for power electronics and e-machines is higher than that for the battery. One optimization target is the distribution of the coolant flow for the individual paths according to the cooling demands. For this reason maximum allowable temperature levels and temperature differences have been specified for all components. As the software KULI is capable handling optimization runs with multiple optimization targets this task could be done automatically.

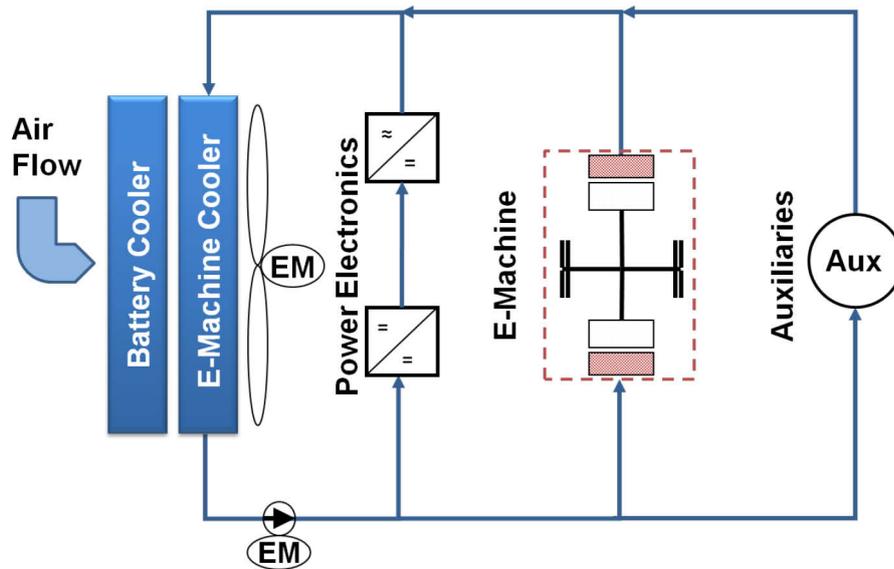


Figure 2.4: Fluid circuit for cooling of power electronics, e-machine and auxiliaries

To keep the fluid inlet temperature level of the power battery in the range of 20 - 30°C for all operating conditions a rather complex thermal management system is necessary. The cooling system for the battery contains a coolant circuit and a refrigerant circuit (Figure 2.5). The refrigerant circuit have to be included in the battery cooling system to be able to maintain the required battery temperatures at high ambient temperatures. To avoid the installation of an additional refrigerant circuit, a dual-loop refrigerant circuit has been chosen. This way the required cooling power can be generated by modifying the existing refrigerant circuit for the air conditioning of the driver's cabin. The heat transfer from the coolant circuit to the refrigerant circuit occurs in the chiller. Dual loop refrigerant circuits are well known from passenger cars, e.g. for individual air conditioning of front and rear air zones. Using two expansion valves, the chiller and evaporator can be controlled individually (see also simulation model, Figure 2.6).

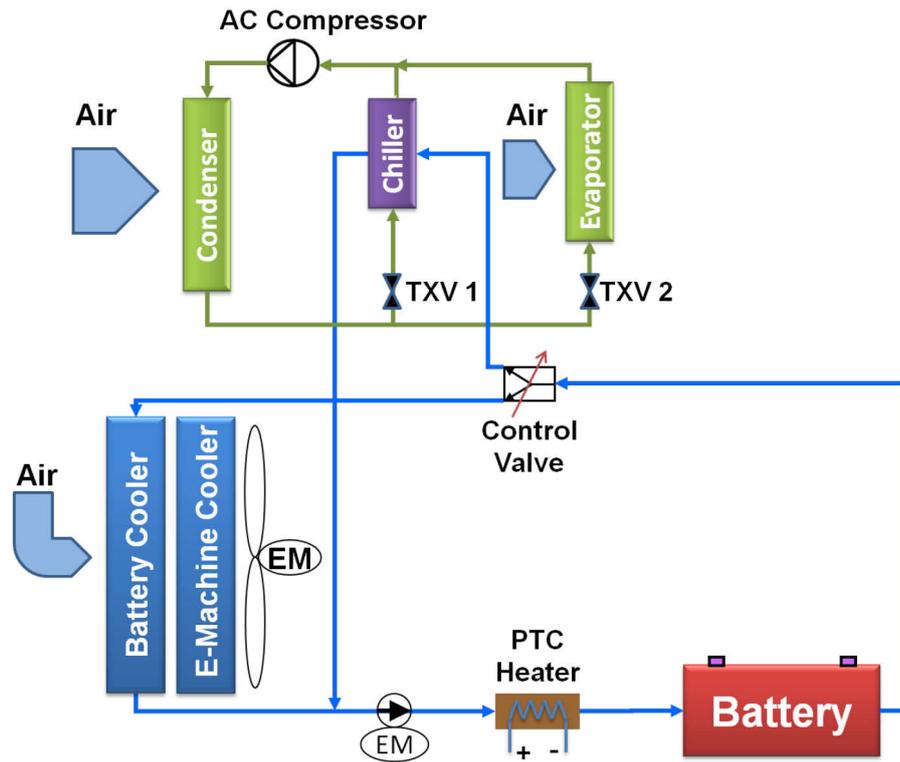


Figure 2.5: Thermal management layout for power battery

At low ambient temperatures the coolant circuit is used to cool the battery. A control valve selects the according flow, either through the chiller or through the battery cooler. Using the coolant cooler, the cooling power can be provided more efficiently than using the AC system, as no driving power for the AC compressor is necessary.

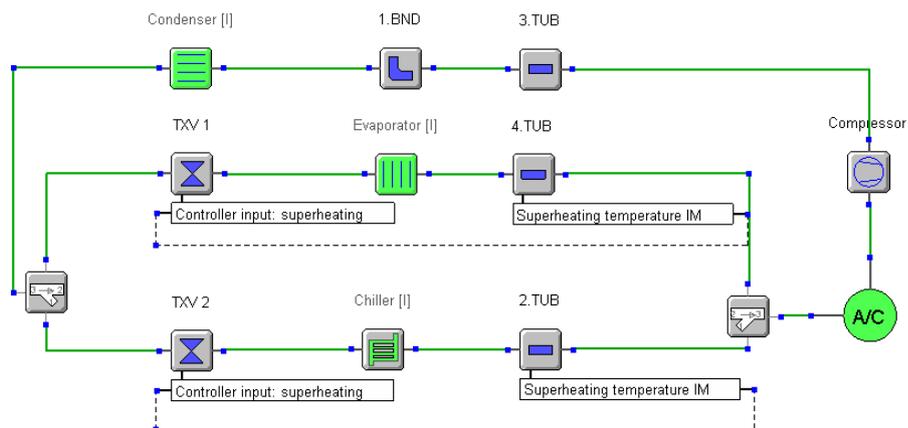


Figure 2.6: Simulation model for dual-loop refrigerant circuit

To avoid a reduction of the life time of the battery, the temperature level must be kept constant during operation whenever possible. To reach the optimum temperature as soon as possible after a cold start a PTC heater has been installed. The heater warms up the coolant upstream of the battery, as long as the fluid temperature has not been reached the desired level.

3.3. Co-Simulation

To combine the longitudinal driving simulation and the thermal simulation, co-simulation technique is used. The master simulation program is a driving simulation in MATLAB/Simulink. Thermal simulation with KULI has been integrated into the master simulation as a MATLAB S-Function. Interfaces have been defined in the thermal simulation program KULI. After the definition of these interfaces, they can be imported into the driving simulation. Table 2.7 shows, that the thermal simulation model receives the power loss results of the electric components (electric motor and battery) from the driving simulation.

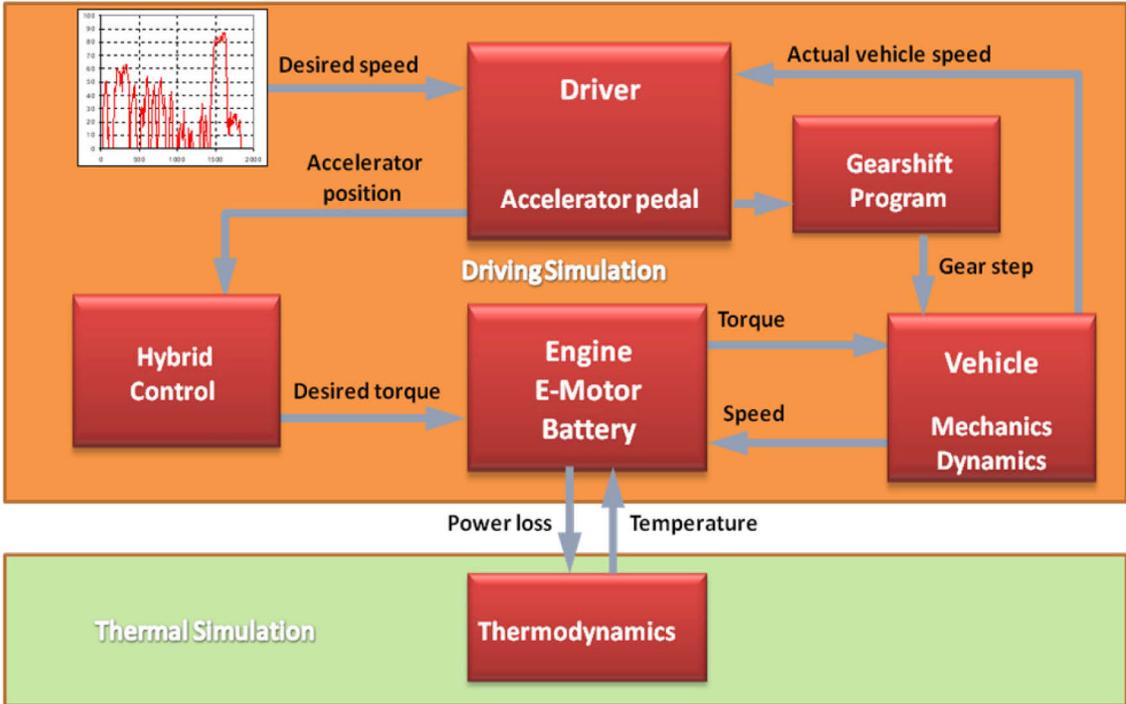


Figure 2.7: Scheme of Co-Simulation

To accelerate the simulation runs, different time step sizes for driving simulation and thermal simulation have been used. Because of the thermal inertia of the cooling system, the simulation time step size of the thermal simulation is much larger than that of the driving simulation.

3.4. Results

The following results are depending on the driving cycles shown in Table 2.5. All given values are related to the standard vehicle configuration. Without consideration of the cooling systems energy consumption, fuel saving potential of the hybrid vehicle results between 9% and 13%. Table 2.6 shows the total fuel consumption over one cycle run for the standard vehicle configuration and the hybrid vehicle configuration (GVW 24ton).

<i>Cycle</i>	<i>Standard Vehicle Fuel Consumption [l]</i>	<i>Hybrid Vehicle Fuel Consumption [l]</i>	<i>Fuel saving</i>
HUDDS	4.01	3.48	13%
JE05	5.50	5.03	9%
Company Specific City Cycle	6.50	5.68	13%

Table 2.6: Comparison of Total Fuel Consumptions

If the power consumption of the additional cooling system is considered, the fuel saving values will change, too.

The battery needs an optimal fluid temperature at the inlet of 28°C and a flow rate of 20 l/min. The control strategy tries to reach the optimal battery coolant entrance temperature as soon as possible, regardless of the start temperature or the ambient temperature. Figure 2.8 shows the temperature characteristics of the battery cooling fluid at different start temperatures which are also the ambient temperatures. It can be seen that the battery will not reach its nominal operating temperature during this short cycle at low ambient temperature. Therefore, a short “warm up” cooling circuit should be added which includes only the fluid pump, the PTC-Heater and the battery.

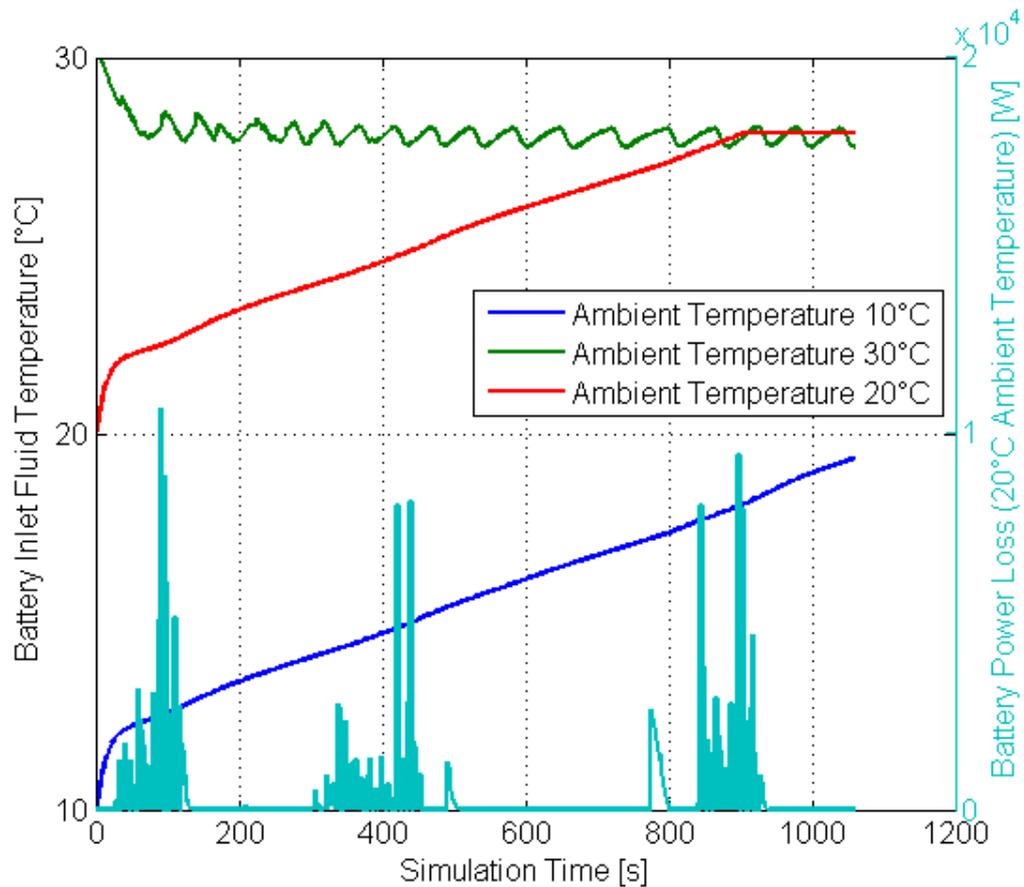


Figure 2.8: Battery „warm up“

For the simulation has been presumed that only the fluid temperature at the battery inlet has been measured. If this temperature is much lower than the optimal battery fluid inlet temperature the PTC-Heater will be activated, if it is much higher, the AC control valve will be opened and the AC compressor will be activated. Such fluid temperature changes require an amount of energy. A part of this additional electric energy must be produced by the engine, which results in increasing fuel consumption. The average power consumptions of the additional cooling components at different start temperatures and different driving cycles can be seen in Table 2.7. These values includes the power consumption of additional components: fluid pumps for the battery cooling circuit and the electric motor cooling circuit, the AC compressor, the PTC-Heater and the fan at the cooler package.

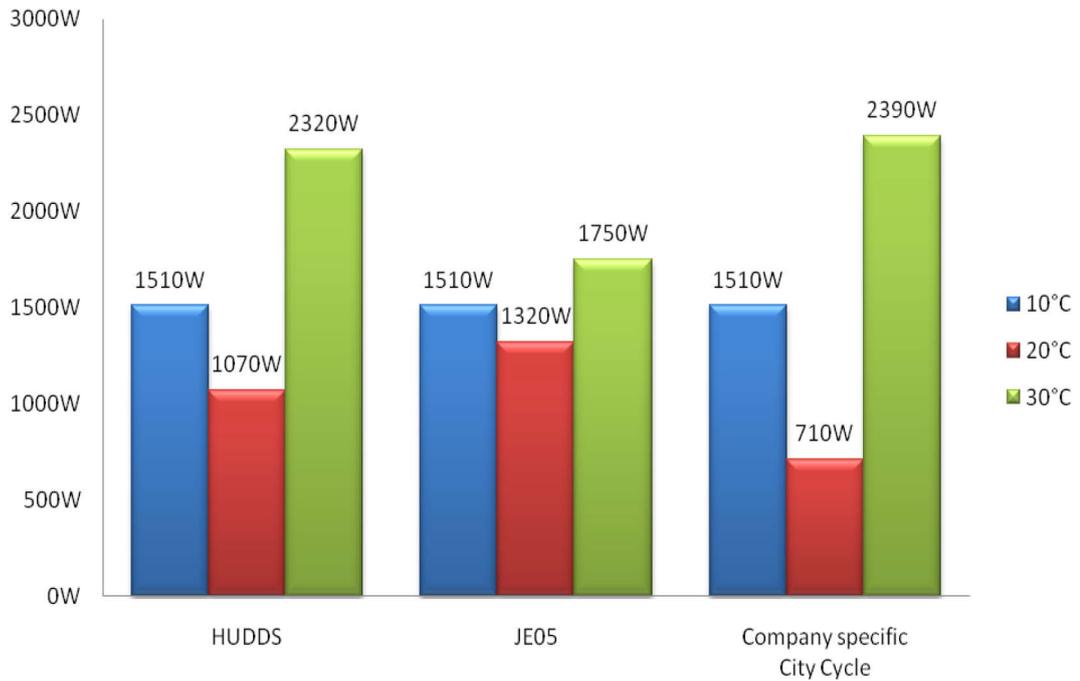


Figure 2.9: Average power consumption of additional cooling components

An additional energy consumer is the coolant pump in the battery cooling circuit. This pump operates in two revolution speed stages, which depend on the refrigerant circuit being activated or not. This pump is working permanently, because the battery has to provide energy during the driving cycle for traction and auxiliary powering application.

Also the fluid pump for the cooling system of the DC/DC-Inverter, DC/AC-Inverter and the electric motor needs energy during driving. This fluid pump should not be switched off during driving, because this cooling circuit includes other auxiliaries which need to be cooled permanently (e.g. an air compressor or a power steering pump). The rotational speed of the fluid pump will be reduced, if the electric motor and the DC/AC-Inverter are not in operation. Figure 2.8 shows the consumption at the different driving cycles and ambient temperatures with respect to the additional auxiliaries' energy consumption.

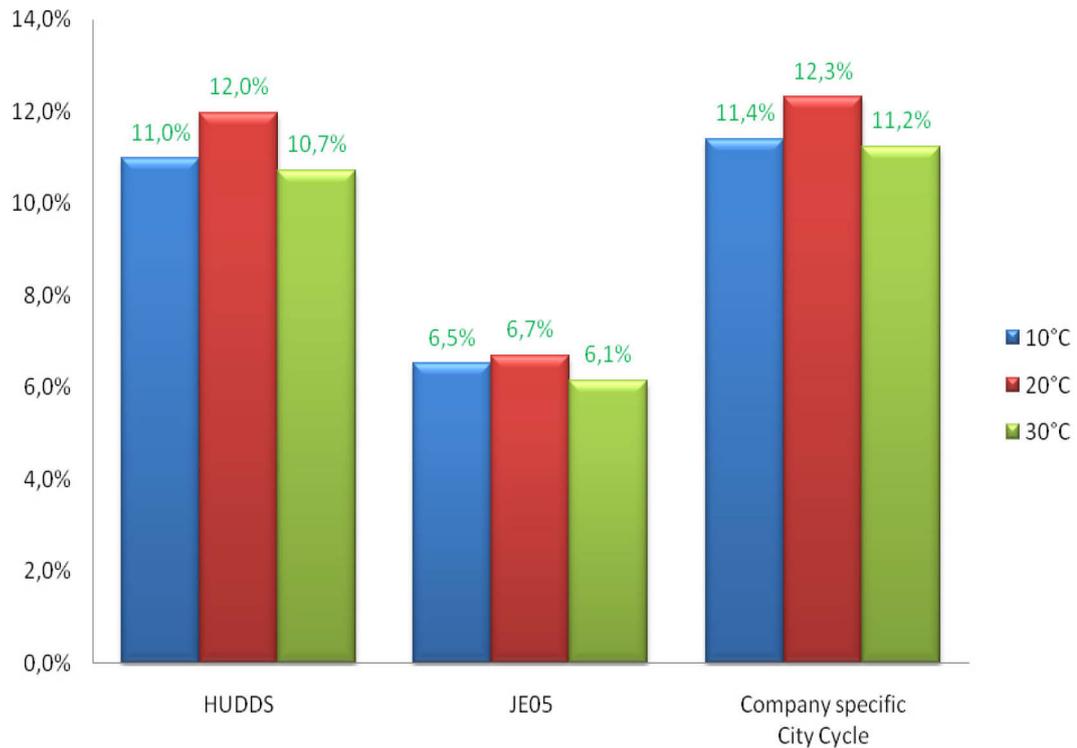


Figure 2.10: Comparison of Fuel Consumptions (auxiliaries' energy consumption included)

4. Summary

Hybridization has a high potential in fuel saving and CO₂ reduction. But there is a higher effort on additional cooling requirements compared to conventional drive trains. Especially the thermal behavior of the battery system must be considered, because of temperature dependence on power supply and life time. Therefore, thermal simulation is absolutely necessary for component dimensioning.

Another point is that the additional cooling components in a hybrid commercial vehicle also need electric energy and in case of parallel hybrid power trains this energy has to be delivered from the battery in many driving situations. A big part of this energy must be produced by the engine with efficiency losses because of energy transformations. Therefore, the fuel saving potential is derogated but it is still great in many application cases. A new challenge will be to activate the additional electrical energy consumers “on demand” and control them optimally to reduce energy consumption again.

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