Proceedings
of the 4th International Modelica Conference,
Hamburg, March 7-8, 2005,
Gerhard Schmitz (editor)

L. Morawietz, S. Risse, H. Zellbeck, H. Reuss, T. Christ
TU Dresden, University of Stuttgart, BMW Group, Germany
Modeling an automotive power train and electrical power supply for HiL applications using Modelica
pp. 301-307

Modeling an automotive power train and electrical power supply for HiL applications using Modelica

Lutz Morawietz[1]   Silvio Risse[1]   Thomas Christ[2]
Hans Zellbeck[1]   Hans-Christian Reuss[3]

[1]Dresden University of Technology
Institute of Combustion Engines and Automotive Engineering
George-Baehr-Str. 1c, 01062 Dresden
{morawietz, risse, zellbeck}@ivk.tu-dresden.de

[2] BMW Group
Energy management und CO_2
80788 München
Thomas.Christ@bmw.de

[3] University of Stuttgart
Institute for Internal Combustion Engines and Automotitve Engineering
Pfaffenwaldring 12, 70569 Stuttgart
reuss@ivk.tu-stuttgart.de

Abstract

Fuel consumption and emissions are key issues in automotive development. An intelligent energy management helps to improve both factors. Tools for developing new management strategies can be off-line simulation as well as Hardware-in-the-Loop (HiL) simulation. This paper gives an overview over a joint project between Dresden University of Technology and the BMW Group. In this project an `EnergyLibrary` containing power train and electrical power net models is improved.

The paper will describe the thermodynamic model of the internal combustion engine (ICE), the alternator model, and the implemented `NeuralNetworkLibrary` in more detail. On the HiL test bench component measurements and new energy management strategies for the electrical power net can be tested.

1 Introduction

Legal regulations on fuel consumption and the rising need of comfort and safety are the main issues in automotive development.

One main field of interest is the reduction of fuel consumption by optimizing the auxiliary units, the warm-up behavior of the internal combustion engine (ICE) and the electrical power net [4].

The electrical energy management controls the energy generation, distribution and storage in the electrical power net. It enhances the robustness of the system and is capable of reducing the fuel consumption.

The interaction between the electrical power net and the drive train occurs at the alternator. A rising demand of electrical energy leads to an increased driving torque of the alternator and therefore to an increased fuel consumption. The alternator's torque demand plays an important role in the dynamic behavior of the ICE, especially at idle speed.

For fuel consumption the thermal behavior of the ICE plays another dominant role. Between 10-20% of the fuel during the New European Driving Cycle (NEDC) is used for the warm up.

This paper describes some enhancements made to the BMW model library used for energy flow prediction. The models are derived from measurements generated on an engine test bench, a Hardware-in-the-Loop (HiL) test bench, and during vehicle testing.

The presented results were developed in a joint project of Technische Universität Dresden and BMW Group.

2 Approach and Tools

The goal is to model the electrical power net, the auxiliary units, and the ICE including its thermodynamic behavior using Modelica/Dymola.

The overall vehicle model consists of objects of many different physical domains such as electronics, mechanics, thermodynamics, hydraulics, pneumatics as well as control systems and is described in section 3.1.

The model parameters are gained using different measurement environments:

(i) on an ICE test bench the ICE itself and the auxiliary units are measured

(ii) in a test vehicle all internal car data (e.g. CAN), electrical currents and voltages, pressures, temperatures and torques of engine and auxiliary units can be recorded.

(iii) HiL test bench for the electrical power net where single components of the power net, especially the alternator, can be examined

Using these test environments, realistic inputs for the HiL test bench and model validation can be generated.

The HiL test bench is especially important since one can efficiently test new components and control strategies in real time. The interaction with other subsystems in a car can be analyzed.

In real time environments high simulation speed is crucial. Therefore the models were adapted accordingly by eliminating unnecessary dynamics and expensive computations. Most of the model behavior is represented using look-up tables or Neural Networks.

At BMW more and more system simulations are carried out in object oriented simulation environments. Modelica is currently in use for the simulation of the electrical power net, the air conditioning, the fuel consumption and hybrid drive trains.

3 Model

As mentioned earlier fuel consumption is the main focus of the simulations done in this project. In the first stage the car is simplified to its longitudinal dynamics. The model frame work, the thermodynamic engine model, and the power net are described.

3.1 EnergyLibrary

The developed model library, shown in figure 1 is divided into four main packages:

(i) `DriveLine` includes `Engine`, `GearBox`, `Tank`, `Axles`, and `CargoSystems`

(ii) `DriveEnvironment` includes `Tracks`, `Driver`, and `BusSystem`

(iii) `AuxiliaryUnits` include `BeltDrive`, `ClimateUnit`, `HydraulicUnits`, and `PowerNet`

(iv) `Blocks` include non Modelica standard blocks

Each component model (e.g. the ICE) consists of the following packages:

(i) `Basis` including templates for icons, connector (e.g. rotational flanges, bus), and component specific sub models

(ii) `BusSystem` including the bus signals that the component uses for its communication

(iii) `Models` including various types of models (e.g. various warm up models). Those models can be selected via `Choice`.

(iv) `Record` which represents the parameter structure for the most commonly used models.
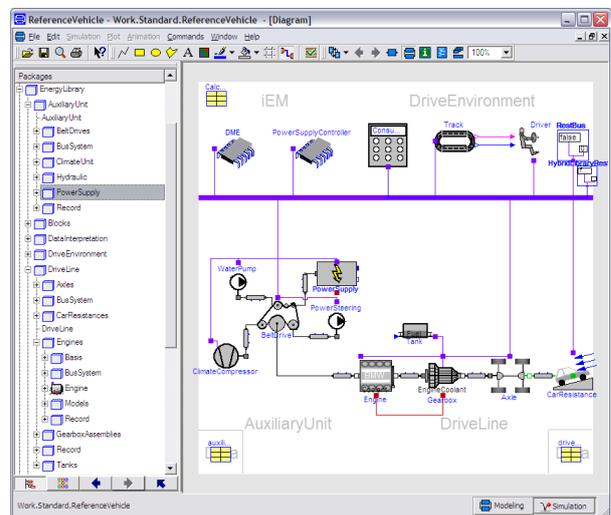
Figure 1: Library structure and vehicle model

The main model is assembled by the `Choice` blocks of each component model. That way structural changes in the model can be made comfortably.[1] The top level of the car model and the library structure can be seen in figure 1.

---

[1]For example a change between automatic and manual `GearBox`

The `Bus` and `Record` structure are assembled in a similar tree structure by instantiation. Thus the bus signals are grouped after simulation in a concise tree structure as shown in figure 2. We established the same tree structure in the model library, the simulation model, the parameters, and the bus system.
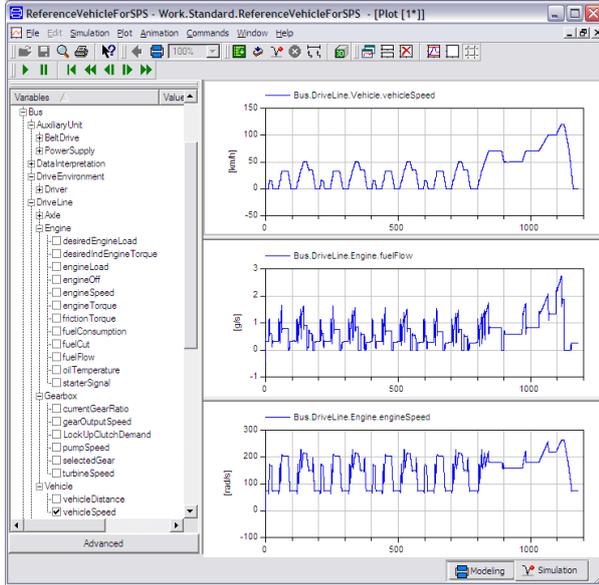
Figure 2: Simulation of the New European Drive Cycle showing the structured `Bus`

The model parameters are managed by a parameter database which also allows pre-processing.

3.2 Thermodynamic Model of an ICE

The temperature has a major impact on the behavior of the ICE and the auxiliary units. To be able to simulate the warm-up phase a thermodynamic model of the ICE is necessary. Additionally several environmental conditions and different auxiliary loads have to be taken into account.

Torque Balance

An essential requirement of the model is the determination of the relevant torques taking into account different auxiliary and engine loads. According to [3] the torque balance is given by the following equation:

$$0 = T_{ind} - T_{fric} - T_{aux} - T_{eff} \tag{1}$$

The indicated engine torque T_{ind} is defined as the possible drive torque which theoretically can be used if the engine is mechanically free of losses. T_{eff} represents the torque used for the vehicle movement. Beside the losses caused by the engine friction T_{fric} the

torque of the auxiliary systems T_{aux} has to be considered. The load torque of the auxiliary systems is determined for every relevant unit in separate models. Additionally for each torque a temperature dependence is included. These dependencies are caused by the tribological behavior.

Thermodynamic Behavior

The thermal behavior of an ICE is defined by its heat capacities, heat transfers and thermal conductivities as well as its surrounding conditions. The heat capacities can be divided into two major groups. There are constant heat capacities which arise from engine construction and varying heat capacities following from fluid systems. For the latter ones the oil and the coolant circuit are relevant. The oil temperature has a direct influence on the engine friction T_{fric}. Therefore it plays an essential role in ICE fuel consumption.

Although different thermodynamic libraries for modelling fluid flow already exist in Modelica, none of them seem able to be run on a real time platform. Due to that a more basic `FluidFlowLibrary` was developed. All fluid systems are described by a stationary pressure drop model and defined as an incompressible single medium. Because phase changing of the medium appears only locally during standard driving cycles (e.g. NEDC, FTP75) it is not taken into consideration. This has negligible influence on the thermal behavior of the overall system.

In the `FluidFlowLibrary` mainly `TwoPort`-components are used. The connectors are reduced to the variables: Pressure p, temperature T and the flow variables mass flow rate $\dot{m}$ and heat flow rate $\dot{Q}$.

```
connector Port_A
   Modelica.SIunits.Pressure p;
   flow Modelica.SIunits.MassFlowRate mdot;
   Modelica.SIunits.Temperature T;
   flow Modelica.SIunits.HeatFlowRate Qdot;
end Port_A;
```

Besides to the two connectors for the fluid transfer, a heat port `HeatPort_A` from the standard Modelica library was inserted. For each of the control volumes mass and energy balance equations are applied. The internal energy ΔU is calculated with the help of the enthalpy flows $\dot{Q}_{in}$, $\dot{Q}_{out}$ at the connectors and the heat losses $\dot{Q}_{heat}$ at the volume boundary. As a reference value the mean temperature T_{mean} of the volume is used. Work due to change of volume is not taken into account.

```
model volume
...
equation
  ...
 //energy balance equation
 dU=Qindot + Qoutdot + Qheatdot;

 // heat transfer equations
 Qindot = Port_A.mdot*cp*Port_A.T;
 Qoutdot = Port_B.mdot*cp*Port_B.T;

 //equations for heat loss
 Qheatdot=HeatPort_A.Q_dot;
 Tmean=HeatPort_A.T;

 //equation for the internal energy
 dU = m*cp*der(Tmean);
 ...
 end heater;
```

The media qualities depending on temperature, e.g. density, specific heat capacities c_p, are computed for each volume separately. Either look-up tables or polynomial functions are used for these calculations [6].
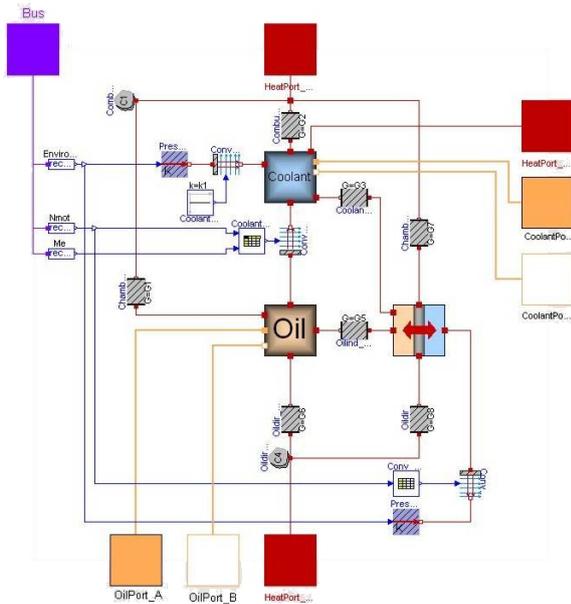
Figure 3: Thermodynamic network of the ICE model

Figure 3 shows a part of the thermodynamic network model. It consists of several heat capacities (i.e. oil, coolant, solid material of the engine) and their heat transfers. The contact to the rest of the ICE model and its environment is defined by the standard `HeatPorts`, the `Bus` connectors and the earlier described ports for the fluid flows (orange). These connectors allow the exchange of oil and coolant between ICE and other components in the cooling circuit.

3.3 Electrical Power Net

The components of the electrical power net can be divided into four parts:

(i) generators: alternator

(ii) storage devices: battery, double layer capacitor

(iii) converter: DC/DC converter

(iv) loads: seat heating, fan, driving light
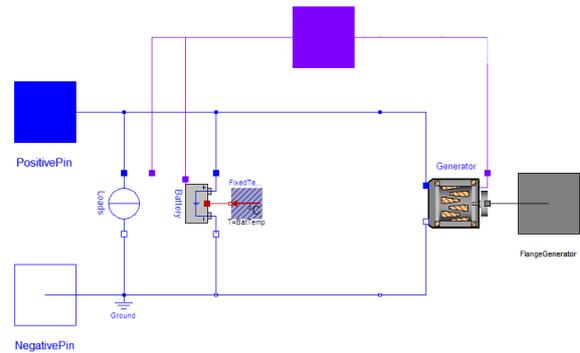
Figure 4: Object diagram of a simplified power net

Figure 4 shows the model of a simplified power net. The `Loads` are modelled in three simple ways:

ohmic resistance the resistance is independent of voltage and current

power sink the consumed power is independent of voltage and current

current sink the consumed current is independent of voltage

More effort is needed modelling storage and distribution devices and power sources.

Alternator model

In a conventional power net the alternator is the only source for electrical power. With regards to modelling two aspects are of interest:

(i) Fuel consumption caused by the alternator

(ii) Computation of the charge-balance

(iii) Dynamic behavior at changing electrical loads

The dynamic behavior of the generated current influences the voltage stability of the power net. It also causes a dynamic torque which affects the ICE. Close to idle speeds this torque causes unwanted disturbances in the engines smoothness.

In modern alternators the so-called *Load Response Control* is used to improve the engine smoothness. It limits the slew rate of the generator current.
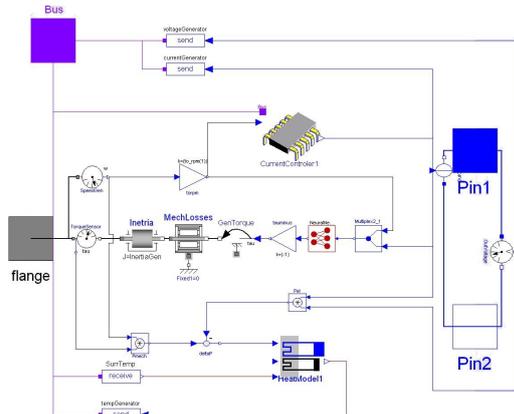
Figure 5: Model of an alternator

Figure 5 shows the connection between the thermal, mechanical, electrical and control part of the alternator.

The alternator `CurrentController` compares the reference voltage and the actual voltage and controls the current between the electrical pins.

Part of the `CurrentController` is the *Load Response Control* implemented employing a rate limiter:

```
model RateLimiter "Rate limiter"
  extends Modelica.Blocks.Interfaces.SISO;
  parameter Real RR
        "Maximum rising slew rate";
  parameter Real FR
        "Maximum falling slew rate";
  parameter Real Ts=0.01 "Sampling time";
  Real x "auxiliary variable";

equation

  if initial() then
    y = u;
    x = 0;
  end if;

 der(x) = (u - y)/Ts;
  der(y) = smooth(0,noEvent(
  if der(x) > RR then RR else if der(x) < FR
        then FR else der(x)));
end RateLimiter;
```

In order to determine the slew rate the input signal has to be derived once. For discontinuous input functions the derivation is not defined at all times. Therefore we introduce the auxiliary variable x and the sampling time Ts.

The link between the electrical and mechanical domain is realized employing a Neural Network. It evaluates the alternator torque in depending on its current and revolution speed. The `MechanicalLosses` model includes all bearing friction and fan losses.

4 Neural Network Library

At system level mechatronic components mostly exhibit strong nonlinear behavior. Often this behavior is hard to describe in a mathematical way. Even if it is described mathematically the models need a high computational power and are not usable on a real time platform. In this case another way of describing this behavior can be realized with the help of look-up tables or Neural Networks [5]. In general Neural Networks require less memory than look-up tables but employing lager networks the computational effort will rise. The lower need of memory is of greater interest for real time simulation.

To be able to use Neural Networks in Dymola a `NeuralNetworkLibrary` was developed. It can be used to simulate feed-forward networks with up to two hidden layers.
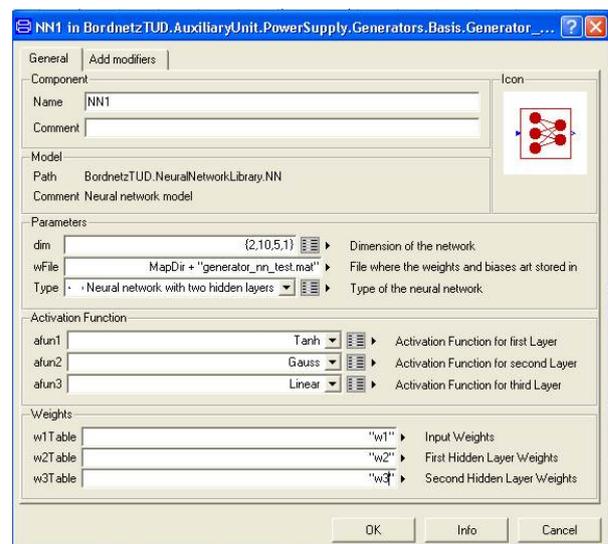
Figure 6: Parameters of the Neural Network Model

In figure 6 the parameter window of a neural network can be seen. The dimension of the Neural Network is defined as an array named `dim`. The user can choose from zero to two hidden layers. Every layer

has its own activation function. The weights and bias values are loaded from a Matlab file during initialization of the process. The input and the output are vector ports. The size of the vector depends on the number of input and output neurons, respectively.

First tests were performed at a dSPACE system to estimate the performance of the Neural Networks in comparison to look-up tables. Therefore a real time simulation was carried out on the HiL test bench described in section 5. The look-up table in the generator model (figure 5) was replaced by a fully connected Neural Network with two input neurons, one output neuron and two hidden layers. The first layer consists of 20 neurons, the second one of 10. As activation functions the hyperbolic tangent was used.

Using the explicit Euler method for inline integration the computational need of the Neural Network is only slightly higher than for look-up tables. But further work needs to be done varying the size of the Neural Network and using different activation functions.

5 Dymola in a HiL environment

For measuring component parameters and testing strategies for energy management a Hardware-in-Loop (HiL) test bench was built. It is kept modular so that the boundary between hardware and software can be shifted in a certain range. With this concept it is possible to cut free the complex system of the electrical power net to different degrees.
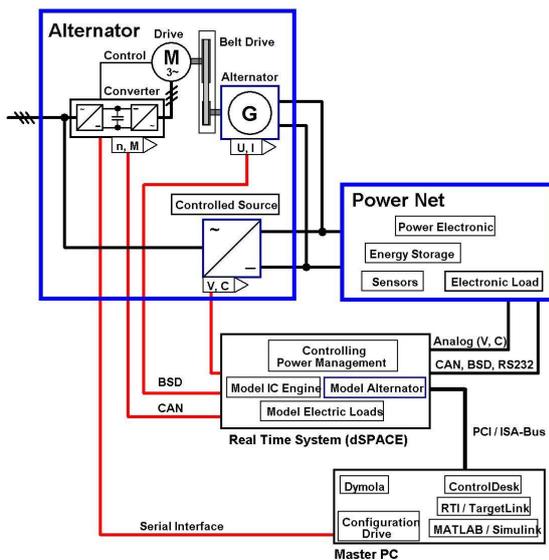
Figure 7: Schematic structure of the HiL test bench

In figure 7 a schematic of the test bench structure

can be seen. Two power sources are implemented. On one hand there is a physical alternator driven by an electric motor. On the other hand a programmable current source can be used. To emulate the alternator behavior the model described in section 3.3 is used.

A dual power net can be realized by using a system of three busbars. This way various topologies can be build up using power sources, storage devices and power electronics.
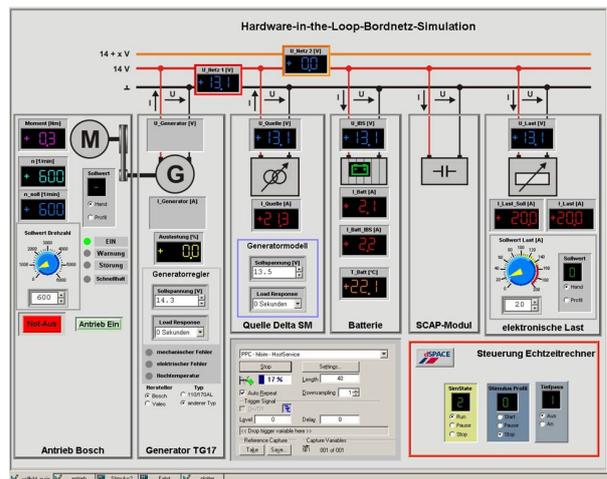
Figure 8: Operating and monitoring the HiL test bench with dSPACE ControlDesk

The HiL computer is based on a *dSPACE modular hardware* system. The core of this system is a *DS1005* where the models are computed on a 500 MHz PowerPC. Further, the *dSPACE expansion box* includes several boards for analog and digital signal I/O, CAN interfaces and digital signal processing. The user interface to the real time system is given by the software *dSPACE ControlDesk*. In figure 8 a screen shot can be seen. [1]

The task of the *dSPACE system* is both to monitor and control the HiL test bench and to simulate models under real time conditions. An electronic controlled load replaces the electrical consumer load. Its input is derived from profiles measured in a test vehicle or from the models described in section 3.3. The other necessary input data to the HiL environment, e.g. engine speed, surrounding temperature, control voltage of the generator, are gained in a similar way either by simulation or measurement.

The main goals for the HiL environment are:

  (i) compare the alternator behavior to the alternator model

  (ii) implement the model of the ICE including thermal behavior

(iii) test energy management strategies

So far the step size for the integration at the real time system is set to 1 ms.
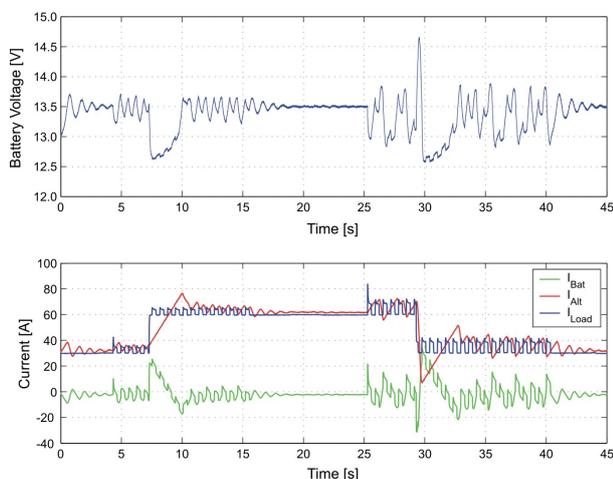
Figure 9: Example of an HiL simulation result

As an example for HiL simulation figure 9 shows an experiment using the alternator model. In this case the components of the power net are the controlled load, a real battery and the alternator model controlling the electronic power source. As load current a measured blinker current with an additional load step at 7 s was taken. The slew rate of the alternator current was limited by the earlier described *Load Response Control*. The difference between load and alternator current has to be equalized by the battery current. During this time the voltage drops from alternator voltage (13.5 V) to the battery voltage (12.6 V).

6   Conclusions

The existing model libraries for automotive power train and power net were extended for better thermal engine modeling and electrical real time simulation. The simulation platform enables us to develop new energy management strategies and test them under realistic conditions. For real time application the Modelica/Dymola models are included in a Simulink/dSpace environment. First tests are done replacing commonly used look-up tables by Neural Networks to reduce the size of the real time code without generating computational overhead.

In automotive every day use the Modelica/Dymola environment has proved to be a useful tool.

References

[1] dSPACE: http//www.dspace.de

[2] Dymola: Dymola User Manual, Version 5.3a. Dynasim AB, http://www.dynasim.se, 2004

[3] Heywood, J.: Internal Combustion Engine Fundamentals. McGraw-Hill, Inc., 1988

[4] Meir, F., Bertram, M., Christ, T.,Reuss, H.-C., Morawietz, L., Büchner, S.: Energiemanagement des elektrischen Bordnetzes im Kraftfahrzeug - Werkzeuge der Funktionsentwicklung. Proceedings of the VDE Congress, Berlin, 2004

[5] Krug, C.: Ein Beitrag zur dynamischen Modellierung des Verbrennungsmotors für Ausgaben der Echtzeit-Simulation. München, Germany, PhD thesis, Department of Car-electornics and electrics, Dresden University of Technology, 2003

[6] Verein Deutscher Ingenieure: VDI-Wärmeatlas. Springer Verlag, 2002