EMOTH
The E-Mobility Library of OTH Regensburg

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Abstract

The importance of E-Mobility is rapidly increasing, not only for private vehicle traffic but also for public transport. In and around Regensburg, Germany there are a lot of automotive companies. Therefore E-Mobility is an important topic in the curriculum of several courses of study at the East-Bavarian Technical University of Applied Sciences Regensburg (OTH).

One Master of Applied Research student at OTH has chosen the topic to develop an open-source simulation tool for electric vehicles – the EMOTH Library – based on Modelica and to refine several aspects of the library during the one and a half year of the master course.

After one semester, the basic version of the library is available and will be presented in this paper.

Keywords: e-mobility, electric vehicle, modular vehicle model, energy consumption, real driving cycle, driving performance.

1 Introduction

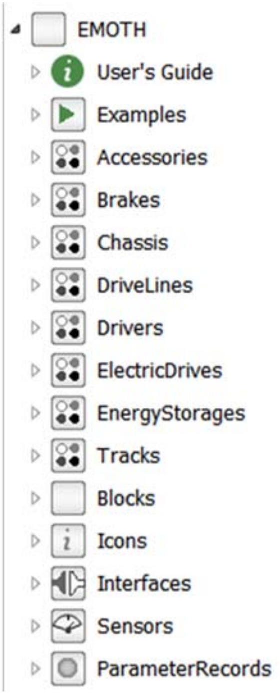
The City of Regensburg decided to purchase E-buses to serve the old part of the town to decrease emissions and noise pollution in this area visited by many tourists per year. Moreover, the City of Regensburg maintains an E-Mobility Cluster to provide a platform for collaboration between local automotive companies and educational institutions. One project of this cluster is allowed to utilize one of the above mentioned buses for field tests of newly developed components, also offering the possibility to gather measurement data during real driving cycles.

OTH Regensburg joined that cluster and plans to provide an open-source simulation tool based on Modelica to review new components of the electrical drive train in an early stage of development: the EMOTH-Library. This project also permits to validate simulation results against measurements during real driving cycles.

Of course there are several simulation tools for electric vehicles available, also based on Modelica, but we found only commercial available libraries. The drawback of commercial tools is the invest hurdle for the cluster partners and the fact that it might be not that easy to take components out from a commercial library and improve them to match the specific needs.

The library is based on Modelica and the VehicleInterfaces Library offered by the Modelica Association ([1], [2]). Following the structure and the templates of the VehicleInterfaces Library has the advantage that components can easily be exchanged without having any troubles with the interface definition. A big advantage of the VehicleInterfaces Library is the fact that there are one-dimensional rotational and translational mechanical connectors predefined in the templates as well as three-dimensional mechanical connectors. In the basic version, only one-dimensional effects have been taken into account. During the remaining two semesters of the master course, the basic models available now have to be refined to meet certain requirements, e.g. to enable changing the vehicle’s mass at bus stops due to exchange of passengers.

2 Structure and Components of the Library



EMOTH
- User's Guide
- Examples
- Accessories
- Brakes
- Chassis
- DriveLines
- Drivers
- ElectricDrives
- EnergyStorages
- Tracks
- Blocks
- Icons
- Interfaces
- Sensors
- ParameterRecords

Figure 1 Structure of the EMOTH Library

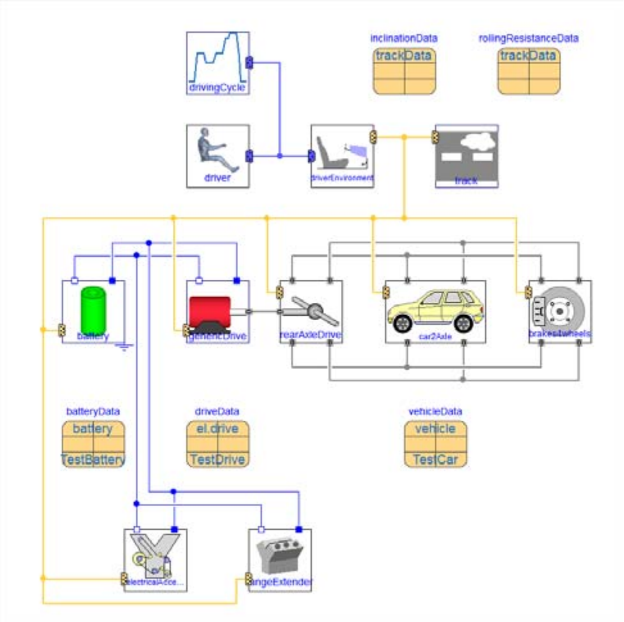


Figure 2 Components used in a complete model

Figure 1 depicts the structure of the EMOTH Library, Figure 2 shows a complete model with all components described in the following sections.

2.1 Chassis

The central component is the chassis (here a car with 2 axles) containing:

- the mass of the car including passengers
- the four wheels with their inertia
- the driving resistances
- connectors of the four half axles
- measurements feeding relevant signals to the bus

According to literature (e.g. [3], [4], [5]) the driving resistances consist of:

- drag resistance according to (1), dependent on relative speed of vehicle with respect to surrounding air,
- rolling resistance dependent on sine of inclination angle γ according to (2),
- inclination resistance according to (3) dependent on cosine of inclination angle γ.

$$F_D = c_W A \rho_A \frac{(v - v_A)^2}{2} \quad (1)$$

$$F_R = c_R m g \cos(\gamma) \quad (2)$$

$$F_I = m g \sin(\gamma) \quad (3)$$

c_W … coefficient of drag resistance
A … front cross section of vehicle
ρ_A … density of air
v … vehicle speed
v_A … longitudinal wind speed
c_R … coefficient of rolling resistance
m … total vehicle mass
g … gravitational constant

The wheels are taken as ideal wheels from Modelica.Mechanics.Rotational, but can easily be exchanged against more sophisticated models.

Since energy consumption is one of the most important aspects of the planned investigations, a one dimensional model of the mass and the rotating wheels is implemented, taking only longitudinal acceleration and velocity into account.

2.2 Brakes

In the first version, the brakes are built with the brake model from Modelica.Mechanics.Rotational. A simple controller distributes the brake signal to left and right wheel at front and rear axle. Each brake produces its own braking torque respectively force, according to the parameterization which allows to specify the braking force distribution between front and rear axle.

Driver assistance functions like antiskid braking can be implemented in a more sophisticated controller.

2.3 Drive Line

The drive line model contains the gear box, either with fixed ratio or with gear selection by the driver environment, and a simple model of the differential.

2.4 Electric Drive

The electric drive represents the motor, the power electronics and control. Since a correct parameterized current controlled drive can be represented by a second order block (see [6]), the desired torque is calculated from the throttle signal (in the range 0...1), taking field weakening into account. Throttle signal = 1 is interpreted as maximum torque available at the actual speed. Maximum torque depends on break-down torque of the motor and maximum current of the power electronics. The actual torque is fed to the motor's inertia and the flange, which is connected to the drive line.

Taking losses respectively efficiency of the motor and the power electronics into account, an ideal power converter draws the corresponding current from the DC power connection, taking actual DC voltage into account.

This simplified generic drive model ensures a maximum of simulation performance and can be easily improved by using more sophisticated models of motor, power electronics and control.

2.5 Energy Storage

In the first version, the battery is simplified as constant DC voltage and an inner resistance. However, the calculation of relevant signals – especially the state of charge (SOC) – is already implemented. A more sophisticated battery model, taking into account the SOC – dependent no-load voltage and the transient behavior of the batteries terminal voltage as an answer to non-constant DC currents, is planned to be implemented in a following development phase.

2.6 Electrical Accessories

Electrical accessories, especially heating and cooling, have significant impact on energy consumption of an electric vehicle. In order to obtain realistic simulation results for the batteries state of charge, the power consumption of the accessories can be defined either constant or by a signal input from measurements over a real driving cycle.

2.7 Range Extender

Range extenders are common practice to increase range without increasing the batteries capacity which in turn means rising mass. In most cases they are a small combustion engine driven at an optimal point of operation, which drives an electric generator charging the battery.

The implemented range extender allows to specify constant charging power and state of charge limits for switching the range extender on and off.

2.8 Track

The track model defines the inclination and the road surface with respect to actual position of the vehicle along the track, either given by a constant value or interpolated from a table. The user has the choice how to extrapolate the table data if the vehicle’s position leaves the range of the table definition:

- Hold the first / last point
- Extrapolation using the last two points
- Periodic repetition
- Extrapolation triggers an error.

Periodic repetition allows to define a closed loop, where the vehicle drives as many rounds as desired.

To be able to check the definition of inclination, especially on a closed loop track, the calculation of actual altitude is included. Longitudinal position and velocity of the vehicle is defined along the inclined track.

Additionally, longitudinal wind speed can be given either as a constant or by an input signal from an external table, containing measured data.

2.9 Driver Environment

The driver environment provides the signals that a driver could read from a dashboard to the driver interface. To have a maximum of flexibility, either a throttle and brake model (section 2.10) or a driver model (section 2.11) following the desired driving cycle can be connected to the driver interface.

The throttle and brake commands read from the driver interface are fed to the recuperation controller. The recuperation controller decides upon active braking using the electric drive and charging the battery (recuperation), or using the mechanical brake system, or to distribute desired braking force between the two alternatives. The user can switch off recuperation.

The first implementation of the recuperation strategy is a very simple one:

- if recuperation is not switched off and
- if the batteries SOC is not above an upper limit and
- vehicle speed is above a lower limit

throttle and brake command (torque demand < 0 means braking) are fed to the electric drive, otherwise throttle signal is sent to the electric drive and brake signal is sent to the mechanical brake system.

2.10 Throttle and Brake

To be able to perform simple experiments, a throttle and brake block has been implemented. Like a human driver, the user can command throttle and brake separately. The commands can be given either by constants or by signal inputs. Additionally, the user can demand to move either forwards or backwards along the defined track (section 2.8).

2.11 Driver

The driver model tries to mimic a human driver. A human driver will watch the environment and the state of the vehicle. The decision somehow is based on a preview of the environment. To take that into account, the driver reads from the driving cycle the reference speed and a preview of the future reference speed. The preview time can be chosen to define the driver’s behavior.

Based on his decision, the driver will make his mind of accelerating or braking the vehicle, with some delay representing the human response time. This is modeled by a PI-controller, fed by the difference of preview reference speed and a prediction of actual speed:

$$\epsilon_v(t) = v_{Ref}\left(t + t_{pre}\right) - \left(v(t) + a(t) \cdot t_{pre}\right) \qquad (4)$$

2.12 Driving Cycle

The driving cycle is defined with table data as reference speed versus time. The user is able to define his own driving cycle, or choose one of the following predefined driving cycles:

UDC	urban driving cycle
EUDC	extra-urban driving cycle
NEDC	new European driving cycle

If simulation shall last longer than the time span defined by the driving cycle, one of the following choices can be taken:

- Hold the first / last point
- Extrapolation using the last two points
- Periodic repetition
- Extrapolation triggers an error.

The user can decide whether to terminate the simulation after a specified number of repetitions of the driving cycle, or to drive until another termination condition is met, e.g. empty battery (SOC below minimum SOC).

2.13 Optional Thermal Connectors

All components have optional thermal connectors that can be switched on or off with the Boolean parameter includeHeatPort. In case includeHeatPort = true, the user has to connect an external thermal model representing the thermal behavior of the complete vehicle. This allows to develop and investigate the thermal management system.

Components with optional thermal connector:

- brake system
- drive line
- electric drive (motor and power electronics)
- battery (energy storage)

It has been decided that the chassis model has no thermal connector because the energy to overcome inclination resistance is converted rather to potential energy than to thermal energy; energy consumption due to drag resistance and rolling resistance is dissipated to heat, but the heat is generated at the exterior envelope of the vehicle and is most likely not taken into account for thermal management.

However, the power consumptions of driving resistances are fed as signals to the bus, allowing to analyze the power sinks of the biggest influence on energy consumption.

2.14 Bus Concept

According to the concept, all components communicate via their own sub-bus. All sub-buses are collected in the central control bus. This concept eases the distribution of signals through the whole vehicle architecture.

For the communication between the driver and the driver environment, a separate bus called driver interface is implemented.

2.15 Parameterization of the Models

As shown in Figure 1, the parameterization is managed in a flexible way by records:

- vehicleData
- inclinationData and rollingResistanceData
- driveData
- batteryData

VehicleData not only contains vehicle parameters like mass, front cross section, wheel radius and inertia, but also the parameters of the driveline and the brakes.

InclinationData and rollingResistaneData define inclination and rollingResistance with respect to the position along the track. The user can give constant values or a table definition.

DriveData summarizes the parameters of the motor, the power electronics and the control.

BatteryData gathers the parameters of the energy storage.

The modular concept allows to define independently a track with inclination and road surface, a vehicle and to try different designs of the drive and / or the battery.

3 Simulation Results

For testing the library components, the parameters summarized in Table 1 have been estimated. The drive parameters are shown in Table 2, the parameters of the battery in Table 3.

Table 1. Vehicle parameters

Vehicle mass	$1500\,kg$
Desired acceleration/deceleration	$5\,\frac{m}{s^2}$
Front brake : Rear brake force	$50:50$
Front cross section	$2\,m^2$
Drag coefficient	$0{,}5$
Wheel radius	$0{,}3\,m$
Wheel inertia	$0.25\,kg \cdot m^2$
Gear ratio	$1:5$
Gear efficiency	85 %
Efficiency of differential	95 %

Table 2. Drive parameters

Base speed	4500 rpm
Nominal torque	250 Nm
Efficiency	90 %
Breakdown torque	1000 Nm
Maximum torque	500 Nm
Substitute time constant	5 ms
Inertia	$0.1\,\mathrm{kg} \cdot \mathrm{m}^2$

Table 3. Battery parameters

Nominal DC voltage	$400\,V$
Inner resistance	$50\ m\Omega$
Nominal Charge	$100\,A \cdot h$
Minimum SOC	0.1

For the first test, the rolling resistance coefficient was set as $c_R = 0.02$ and inclination of the track was set to 0. The electrical accessories have been estimated with a constant power consumption of $5000\,W$, and a range extender with a constant power generation of $6000\,W$. The range extender is started if SOC falls below 40% and is stopped if SOC rises above 80%. Recuperation is chosen for braking if SOC falls below 98%.

The driving cycle has been chosen to meet the NEDC (New European Driving Cycle) shown in Figure 3. Additionally, Figure 3 shows the actual vehicle speed which proves that the vehicle can follow the desired driving cycle nearly perfect.

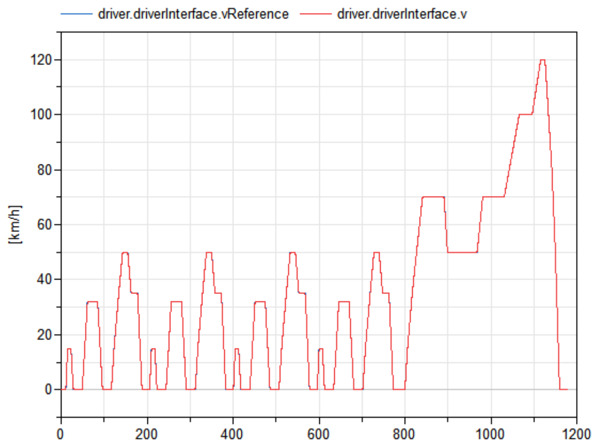


Figure 3 NEDC New European Driving Cycle

The DC power consumption during one cycle is shown in Figure 4, the development of the state of charge in Figure 5. Note that the range extender is not yet started during that cycle since SOC is high enough.

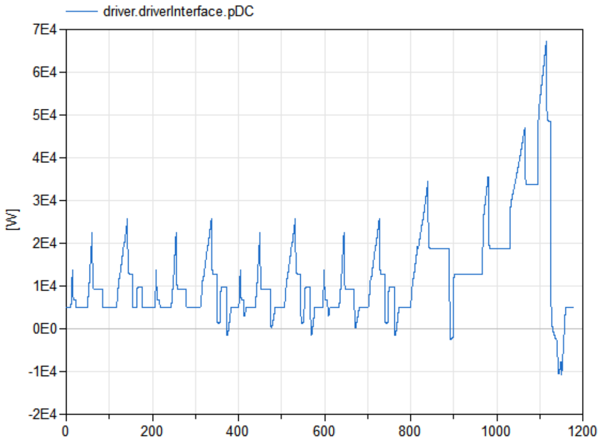


Figure 4 DC power consumption during NEDC

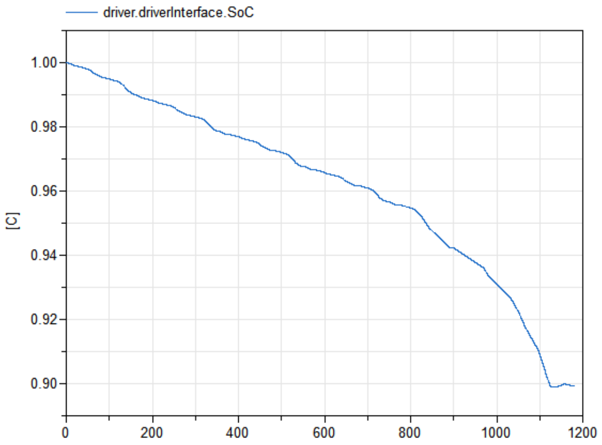


Figure 5 SOC during NEDC

On a notebook with Intel Core i7 processor at 2.3 GHz, 8 GB RAM, Windows 7 64 bit, using Dymola 2017 FD01 64 bit the simulation of the 1180 s cycle took 6 s which shows pretty good performance.

Subsequently, the NEDC was repeated until the battery was exhausted. Figure 6 shows that the range extender gets started at 7021.3 s when SOC falls below 0.4, the battery is discharged slower than before. In Figure 7 the vehicle position is depicted. It can be seen that the battery is exhausted after 14096 s reaching 131.25 km.

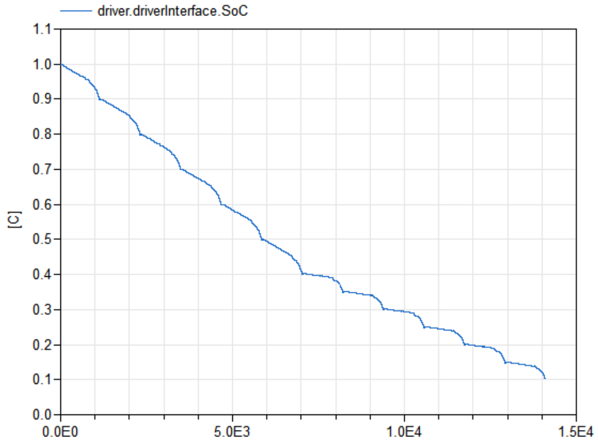


Figure 6 SOC during repeated NEDC

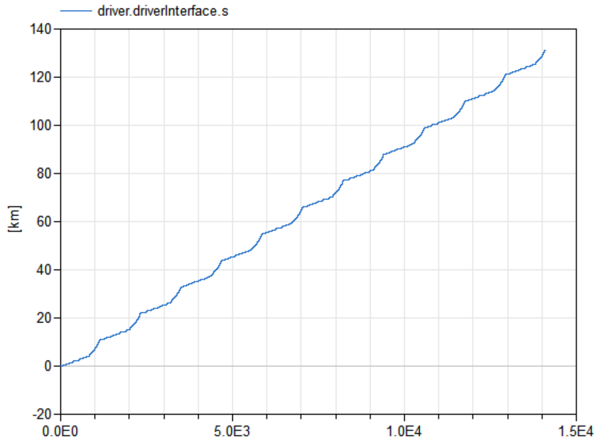


Figure 7 Vehicle position during repeated NEDC

The third experiment investigates acceleration and maximum speed with the chosen electric drive by setting a reference speed rising from standstill to 250 $\frac{km}{h}$ in 1 s. Of course, the vehicle cannot follow this reference speed but requires maximum torque from the drive. Figure 8 proves that a maximum speed of slightly above 225 $\frac{km}{h}$ can be achieved. Acceleration from standstill to 100 $\frac{km}{h}$ takes approximately 6.8 s. Of course the drive may not be operated continuously at maximum torque, a thermal protection function would reduce throttle signal to avoid overheating of the motor and the motor electronics.

Figure 9 reveals both limits of field weakening: During the first phase, torque of the motor remains constant, and DC power consumption rises linearly with speed. After exceeding the first limit, DC power consumption remains constant with respect to speed as torque is lowered reciprocal to speed. When the reference torque exceeds breakdown torque of the motor dependent on speed, torque has to be reduced more than reciprocal to speed and DC power consumption is reduced, too.

Of course driving with maximum torque respectively maximum power, Figure 10 confirms that the battery gets discharged much quicker than in the previous example.

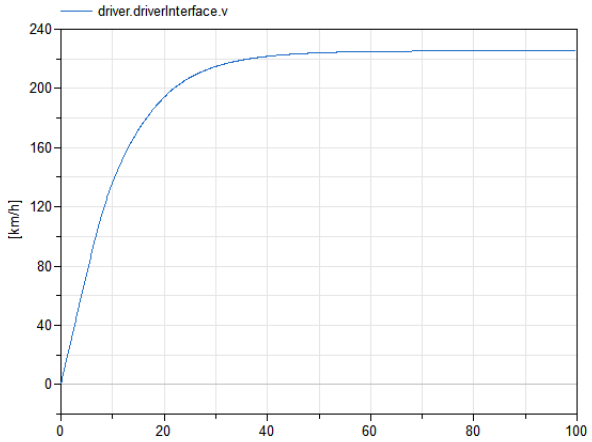


Figure 8 Maximum acceleration and maximum speed

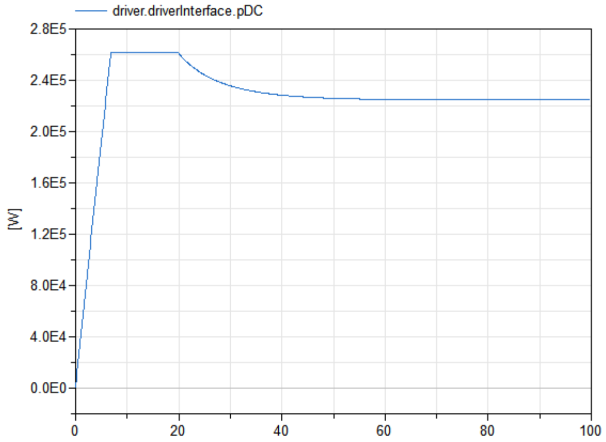


Figure 9 Maximum DC power

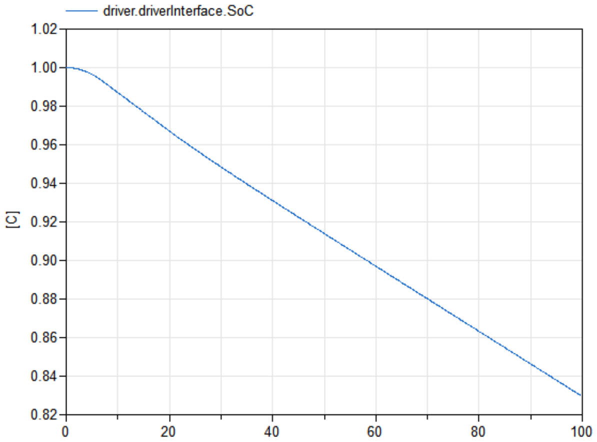


Figure 10 SOC at maximum torque / power

4 Conclusions and Outlook

During the first semester of the three semester Master of Applied Research course the EMOTH Library based on the Modelica Vehicle Interfaces Library has been developed. The library shall provide a flexible framework for longitudinal simulations of electric vehicles to investigate energy consumption during a defined driving cycle including accessories and range extenders as well as the ability of the vehicle to follow the desired driving cycle with prescribed acceleration and deceleration.

For the project members of the E-Mobility Cluster Regensburg it is possible to test new components in an early design stage in the context of the full vehicle.

Up to now, full vehicle models based on the components of the library with estimated but realistic vehicle parameters have been tested successfully with Dymola 2017 FD01. Since the library is conformant to the Modelica Language Specification, it should be possible to run the examples in other Modelica tools, too. In a first test using OpenModelica 1.11 beta 3 the model translates but during simulation errors occur which have to be investigated.

During the following two semesters it is planned to gather the necessary parameters of both the E-bus “EMIL” of Regensburg as well as the E-Smart designed by the Faculty of Electrical Engineering and Information Technology of OTH Regensburg. With these parameters, the results of simulations following real driving cycles shall be validated against measurements. Furthermore, several components of the library shall be refined and improved, such as the electric drive and the battery / energy storage.

It is planned to make the library public available under the Modelica License 2.

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