

Working Paper No. HDH-11-04-Rev1e  
(11th HDH meeting, 10 to 12 October 2012)

# GRPE-HDH Research Project

11<sup>th</sup> meeting of the GRPE informal group on heavy duty hybrids (HDH)

## Report of the Institutes on validation phase 1



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# Content

- › Working tasks in current validation phase 1 (until mid-year 2013)
  - › Deliverables
  - › Current results
  - › Timetables and milestones
  - › Required manufacturer input
- › Outlook on validation phase 2

## Validation phase 1 overview

- › **Task 1)** Adaptation of the Japanese HILS Simulator for serial hybrid
  - › 7 sub-tasks where we are currently working on
- › **Task 2)** Adaptation of the HILS Simulator for parallel hybrid
  - › 4 sub-tasks officially starting this month
  - › Due to intersections with task 1 already began earlier
- › **Task 3)** Report on test procedure and adaptations
  - › 3 sub-tasks ending on schedule in June 2013

## Task 1.1)

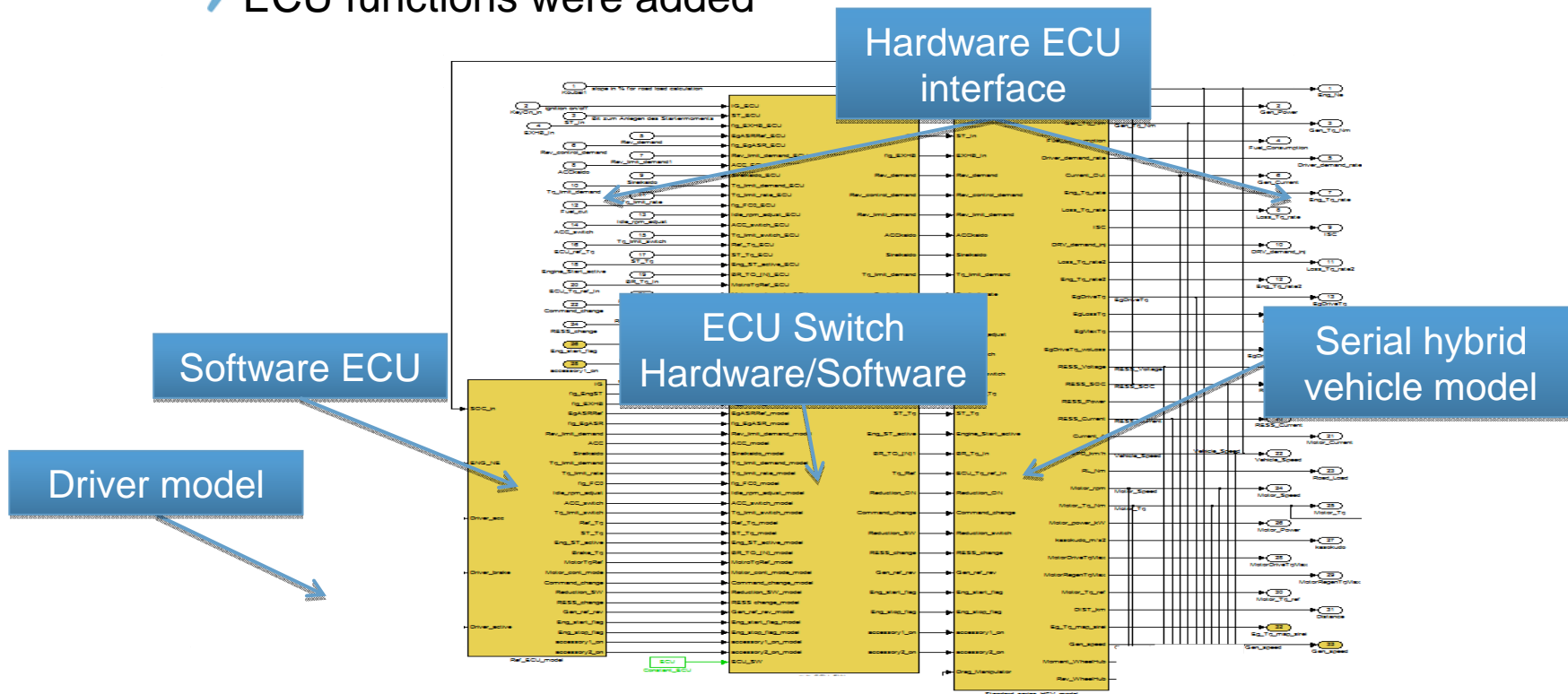
- Deliverables

- › **Set up a serial HDH in the simulator with the ECU as software in the loop as basis for further programming and software development**
  - › Basic serial hybrid model was provided by JARI
  - › ECU control strategy with different ICE operation points was added
  - › Driver model running the model with a vehicle speed cycle as input

## Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

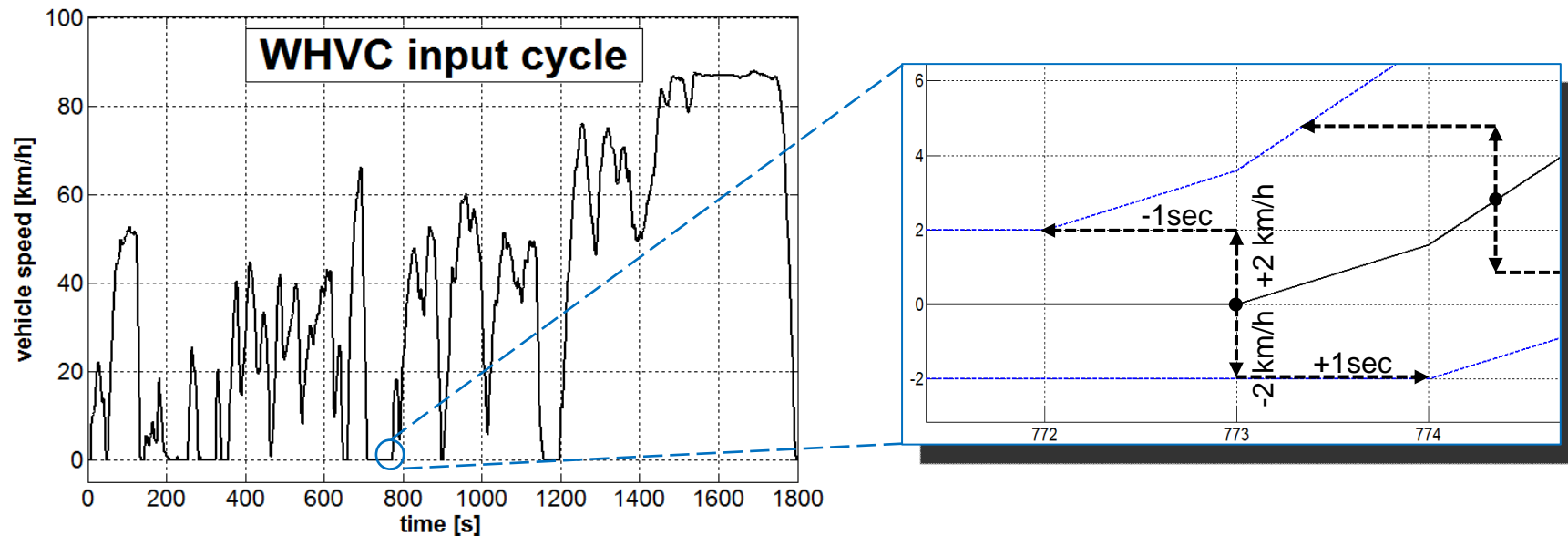
- › Basic serial hybrid model was provided by JARI
- › ECU functions were added



## Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

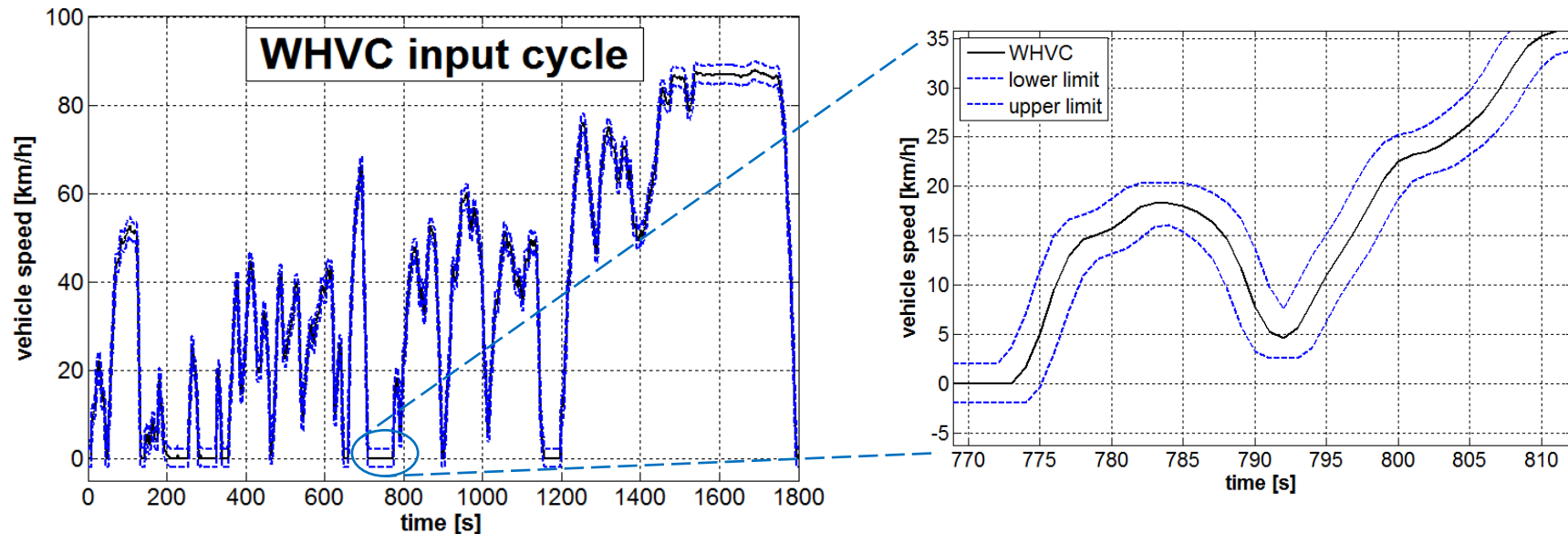
- › Driver model running the model with a vehicle speed cycle as input
  - › Vehicle cycle input is needed at the driver model
  - › Tolerances have to be specified
  - › Tolerance cycles are calculated automatically in MATLAB



## Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

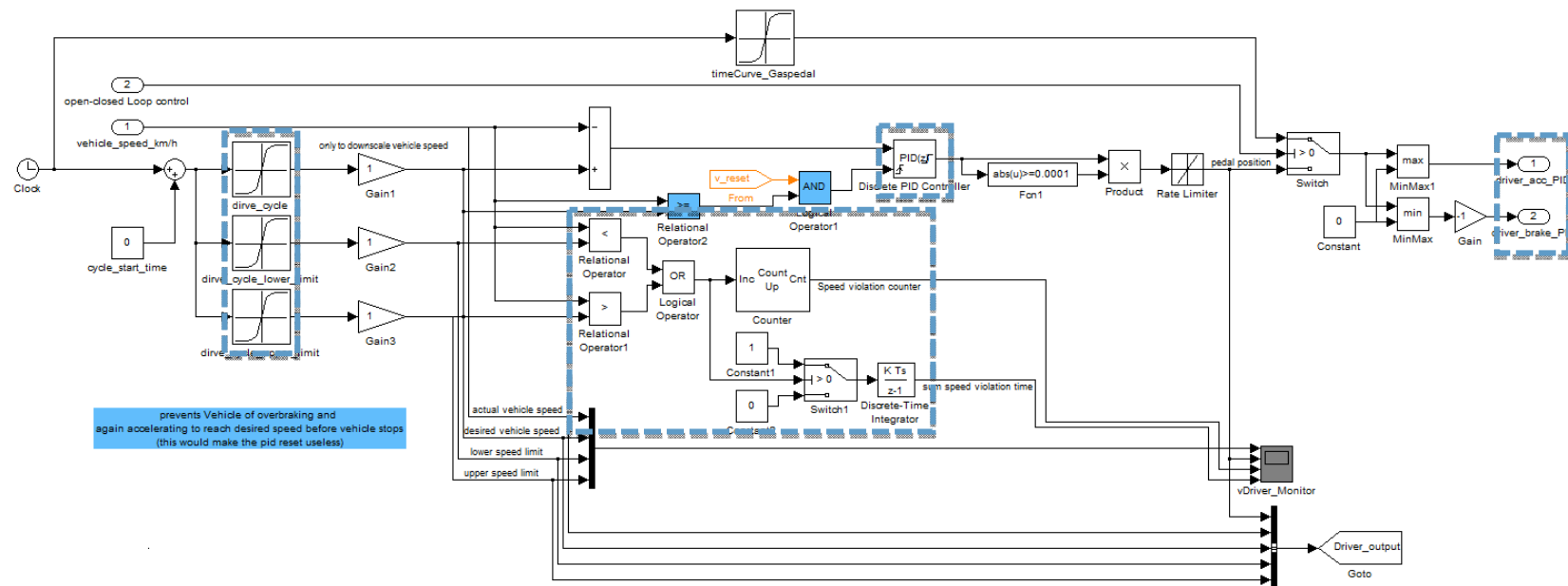
- › Driver model running the model with a vehicle speed cycle as input
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# Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

- Driver model running the model with a vehicle speed cycle as input
  - PID Controller
  - Cycle reference tables
  - Watchdog system



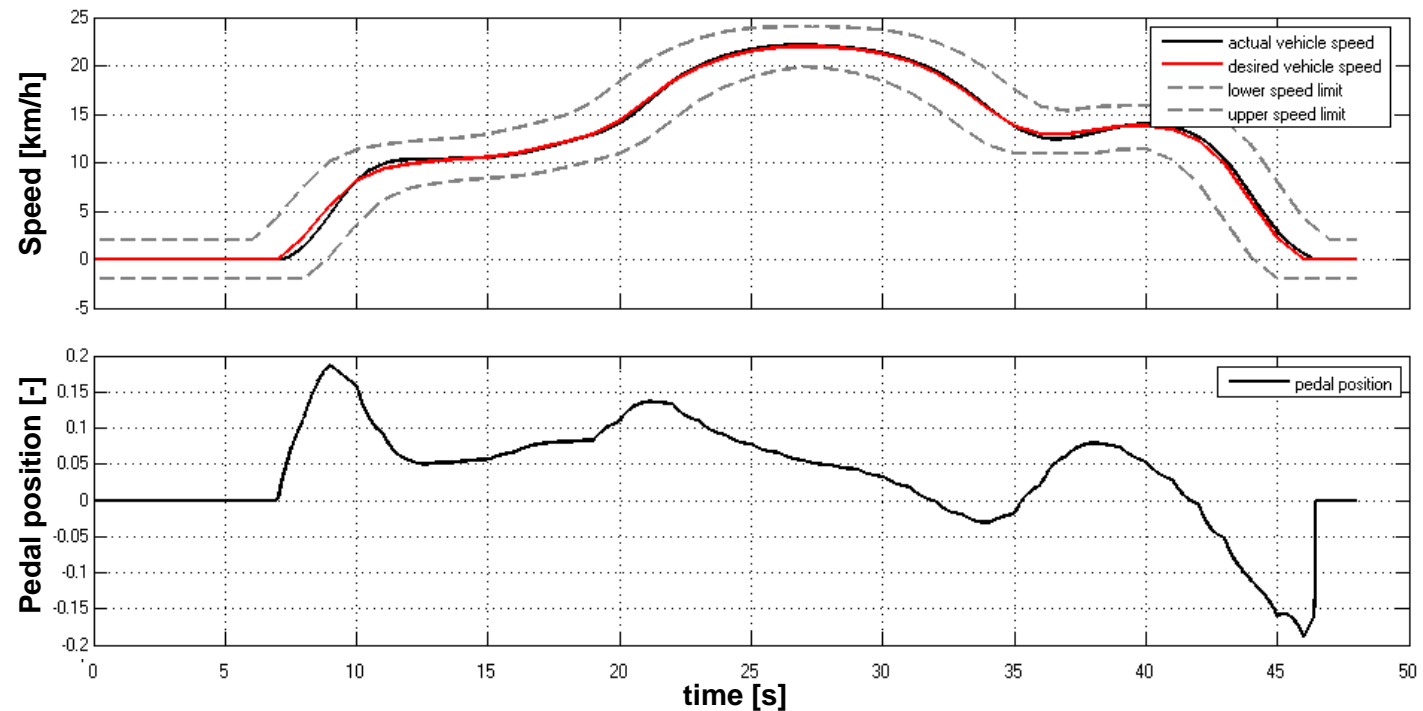


## Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

### › Simulation results

- › Input: vehicle cycle + permitted tolerances + ICE operation strategy
- › Output: ICE torque- and speed cycle, tolerance cycle violation

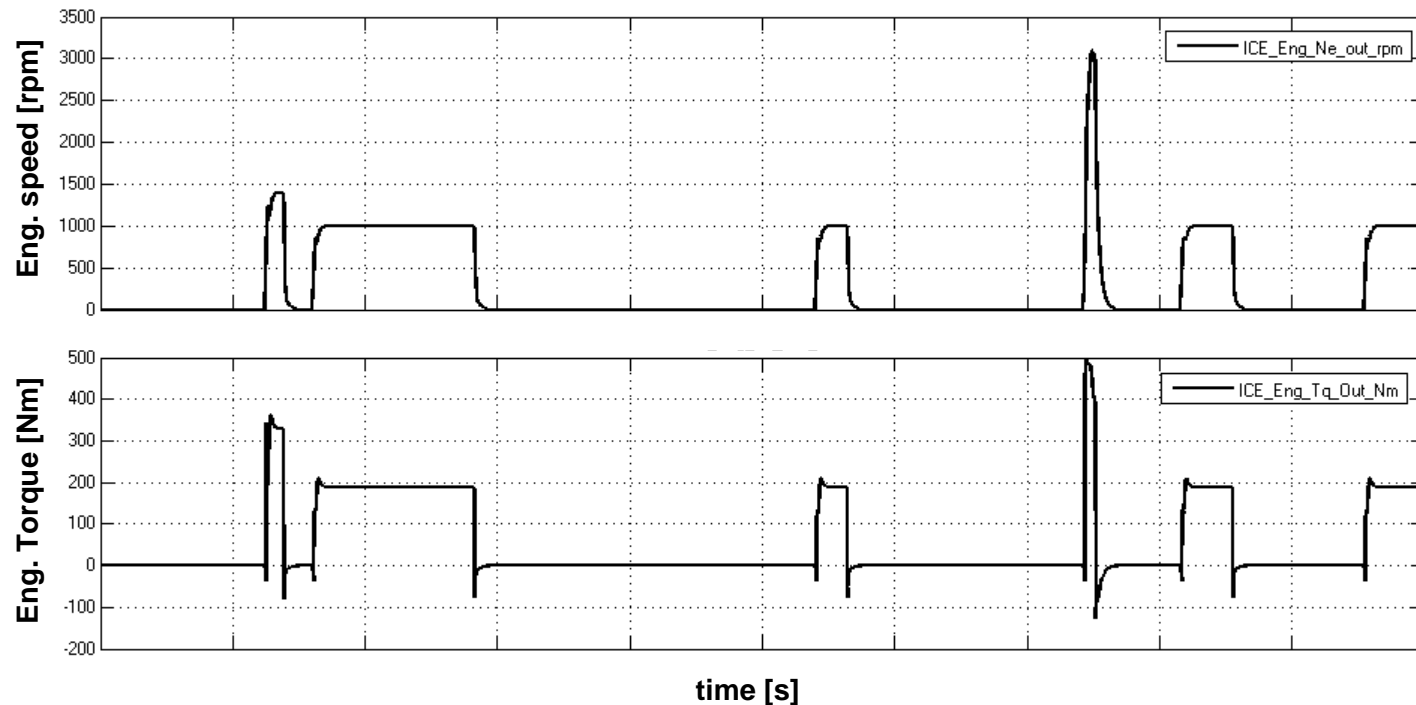


## Task 1.1)

Set up a serial HDH in the simulator with the ECU as software in the loop

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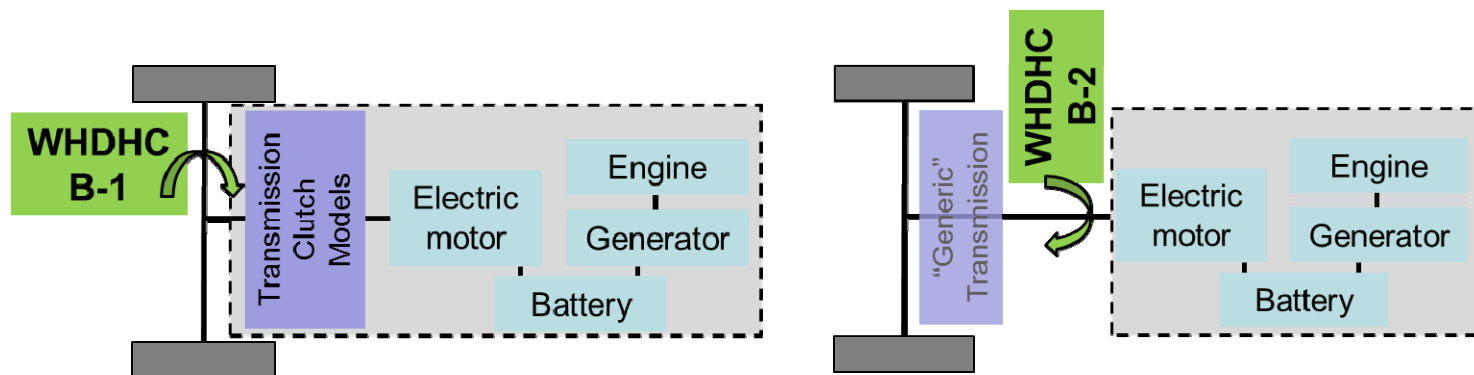


## **General preface concerning driving cycles from the previous project phase (linked to current Task 1.2)**

- ▶ The final worldwide HILS method should be – as far as reasonable - in agreement with the test procedure for conventional engines
- ▶ The review of vehicle related data resulted in power demand cycles at the power pack shaft which are similar to the test cycle for conventional engines (WHTC)
- ▶ This makes the type approval of a hybrid power pack generally more comparable to conventional combustion engines
- ▶ To allow for charging of a hybrid vehicle's RESS (rechargeable energy storage system) during phases of deceleration, a corresponding negative power course for mechanical braking was added in the existing motoring phases of the WHTC

## General preface concerning driving cycles from the previous project phase (linked to current Task 1.2)

- › There are three different options for the realisation of the developed World Heavy Duty Hybrid Cycle (WHDHC)
  - › B-1) power cycle at the wheel hubs (with WHVC as speed signal)
  - › B-2) power cycle at the power pack shaft (with original engine speed signal acc. to WHTC method / WHVC as speed signal)
  - › B-3) vehicle speed cycle WHVC



## Task 1.2)

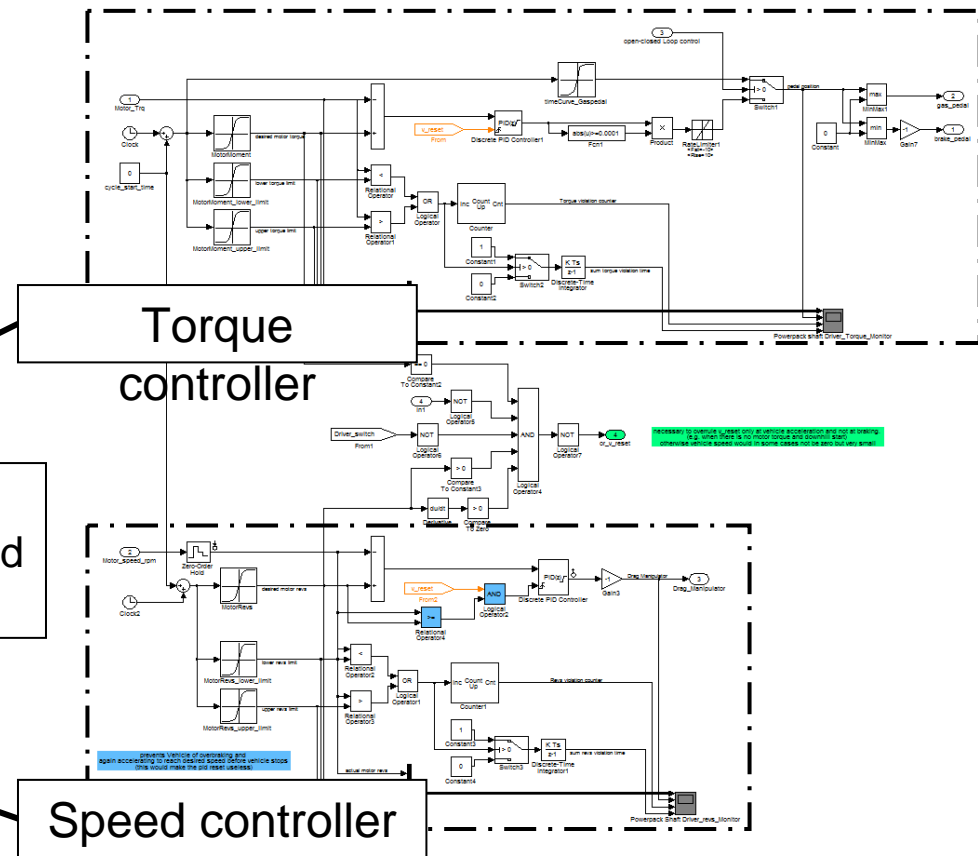
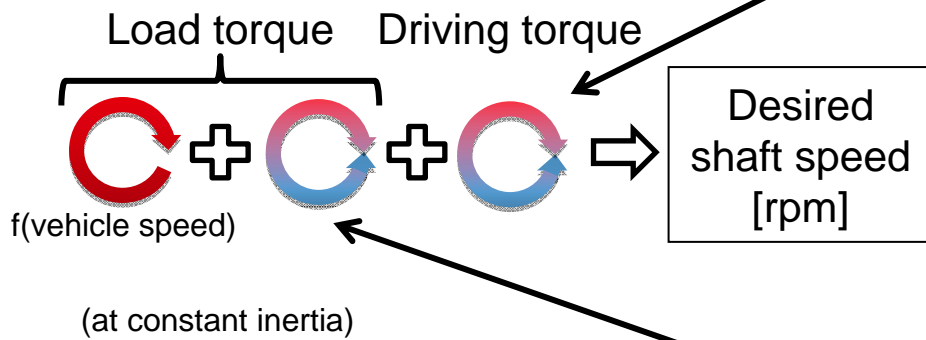
- Deliverables

- › **Elaborate a driver model which allows to run the simulator with test cycles consisting on power and rpm at the wheel hub and at the power pack shaft**
  - › 2 different driver models for power cycle input
    - › 2 PID Controllers per driver model needed
    - › Cycle reference tables
    - › Watchdog system

# Task 1.2)

Elaborate a driver model for power cycles at the hub and at the power pack shaft

- Example: power pack shaft driver
  - Torque controller  
controlling driving torque
  - Speed controller  
controlling load torque



## Task 1.1) + 1.2)

### - Summary

- › Driver models are able to run serial hybrid powertrains
  - › Monitoring system detects faulty or undesired system reactions
  - › Function check with different input cycles and vehicles
- › Differences between the 3 driving cycle inputs (vehicle speed, power at hub/shaft) are currently under investigation
- › PID control parameter variation for different vehicle configuration
  - › Seems to be a moderate effort for accurate results within tolerances
  - › Too aggressive control parameters may lead to erratic engine operation
- › To run parallel hybrid powertrains the driver models have to be adapted in the upcoming task 2 (starting this month)
  - › Functions for shifting gears and actuating the clutch have to be added

## Task 1.3)

- Deliverables

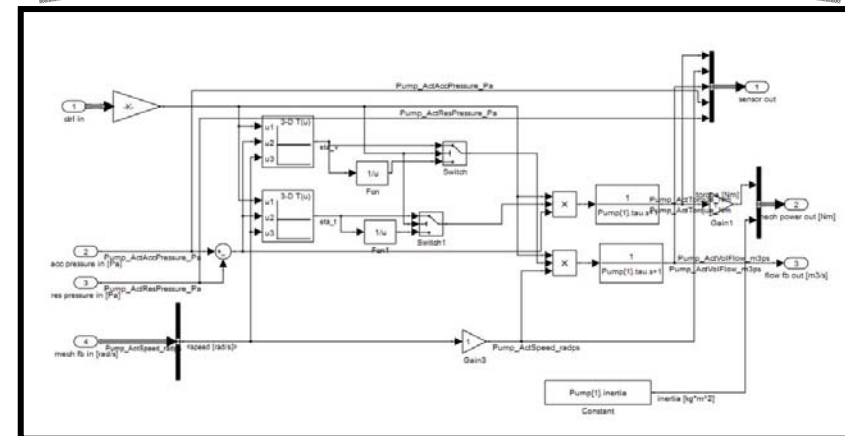
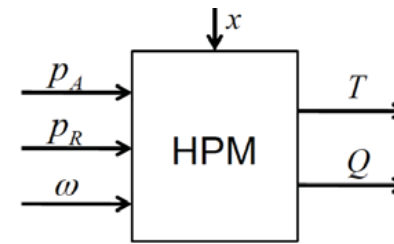
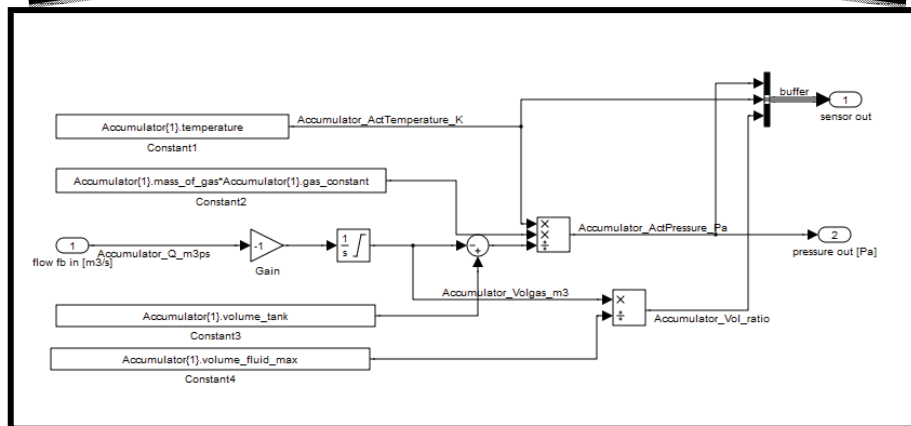
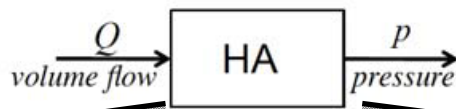
- › **Extend the Simulator with a library for non-electric components (as defined in part one of the project)**
  - › The result is a set of simulation models of non-electric powertrain components, which are suitable to use in a HILS setup.
  - › Non-electric hybrid powertrain topologies (concepts) fits well into the same categories as for electric hybrid powertrains
  - › Interesting non-electric powertrain concepts:
    - › CVT and flywheel
    - › Motor/generator and flywheel
    - › Hydraulic or (pneumatic) pump/motor and accumulator



# Task 1.3)

Simulation models for non-electric powertrain components

- ▶ Mathematical models are developed for:
  - ▶ Flywheel
  - ▶ Accumulator
  - ▶ Pump/Motor
  - ▶ CVT



## Task 1.3)

- Summary

- › Mathematical models for non-electric components are available in MATLAB/Simulink
  - › Simple models suitable for HILS
  - › Input and output signals are defined

Model	Input/Output	Symbol	Meaning of signal	Unit
Flywheel	Input-1	Flywheel_ActSpeed_radps	Speed of flywheel	rad/s
	Output-1	Flywheel_ActSpeed_radps	Speed of flywheel	rad/s
CVT	Input-1	CVT_ActGearNumber	Actual gear number	-
	Input-3	CVT_ActSpeedOut_radps	Outgoing speed from CVT	rad/s
	Input-4	CVT_ActSpeedIn_radps	Ingoing speed to CVT	rad/s
	Output-1	CVT_CmdGearNumber	Commanded gear number	-
Accumulator	Input-1	Accumulator_ActPressure_Pa	Pressure in accumulator	Pa
	Input-2	Accumulator_ActTemperature_K	Temperature in accumulator	K
Pump/Motor	Input-1	Pump_ActTorque_Nm	Actual pump/motor torque	Nm
	Input-2	Pump_ActSpeed_radps	Actual pump/motor speed	rad/s
	Input-3	Pump_ActVolFlow_m3ps	Actual pump/motor volume flow	m <sup>3</sup> /s
	Input-4	Pump_ActAccPressure_Pa	Actual accumulator pressure	Pa
	Input-5	Pump_ActResPressure_Pa	Actual reservoir pressure	Pa
	Output-1	Pump_RefSpeed_radps	Reference speed	rad/s
	Output-2	Pump_CmdRefSwitch_B	Switch between torque or speed control	0/1
	Output-3	Pump_RefTorque_Nm	Reference torque	Nm

- › Models not implemented in the Simulator yet (Japanese open-source model)

## Task 1.4)

- Deliverables

- › **Meetings with OEM's and stakeholders to discuss relevant components to be included in a first version of the GTR-HILS model as basis for tasks 1.5 and 1.6**
- › Input of the Institutes
  - › List with already available components
  - › List with signals at the ECU-Hardware interface of the model
- › Dialogue and manufacturer input is needed
  - › Provided lists should be a basis for discussion
  - › Also component test methods have to be reviewed with manufacturers
  - › Meeting at the beginning of Nov. in Stuttgart is aimed
  - › If we get no input we can only rely on the information from the Japanese model (will not be sufficient)

## Task 1.5)

- Deliverables

- › **Extend the Simulator with a library for power pack components not yet included in the Japanese HILS model**
  - › Components are modelled according to the manufacturers input in task 1.4
  - › Currently a planetary gearbox is offered and already under development
    - › Will most likely be used for parallel hybrids in task 2
    - › Planetary gearbox models without inertias and losses already implemented in the library
    - › Models considering gear inertias and losses under development
    - › Manufacturer input is needed for component testing methods and available model input parameters (e.g. how efficiencies are specified)

## Task 1.5)

- Extend the Simulator with a library for power pack components

› Planetary gearbox for power split

› 3 basic models are provided in the library

› Gearbox output at:

› Sun gear

› Ring gear

› Planet gear carrier

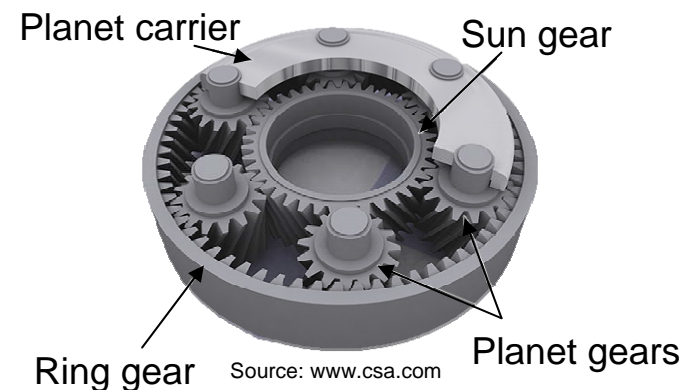
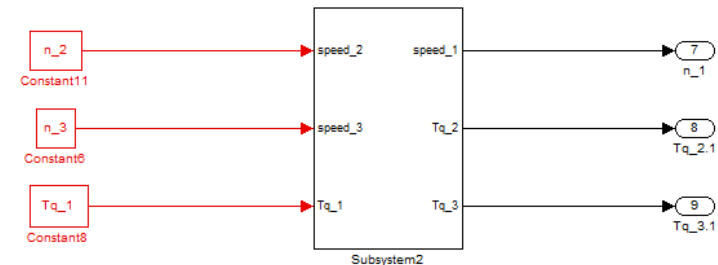
› Models require:

› Gear tooth numbers

› Component inertias

› Gear efficiencies (S-P,P-R)

› Validation through other software  
(GT-Suite, Dymola)



## Task 1.6)

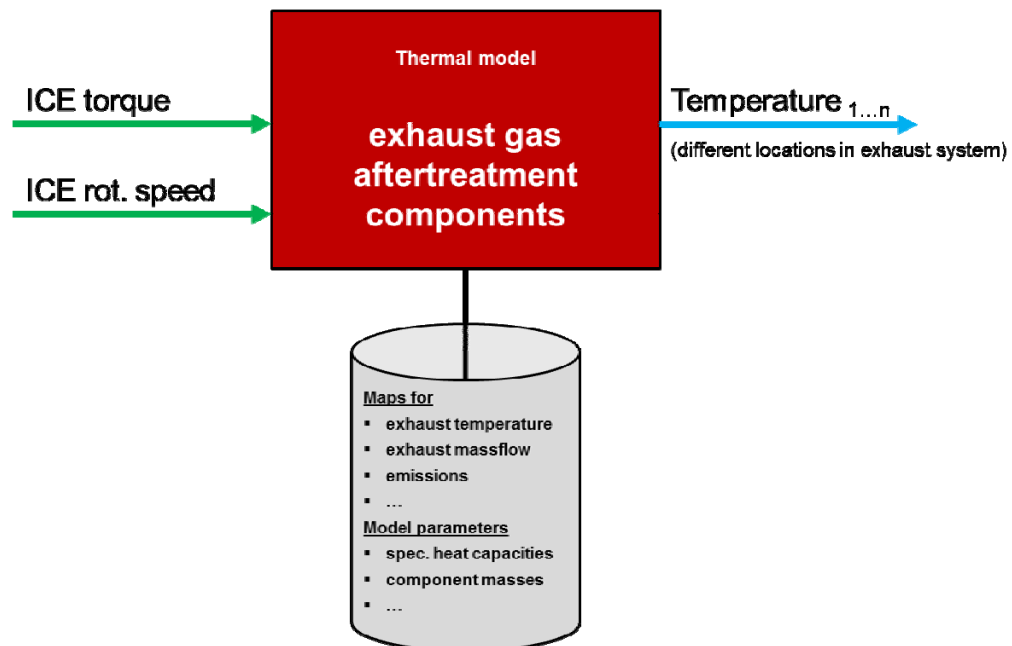
- Deliverables

- › **Extend the GTR-HILS Simulator with thermal models for exhaust gas aftertreatment components, coolant, lube oil, battery and electric motor**
- › In previous project phase it was decided that HDH will have to undergo a cold start test similar to the conventional ICEs
- › HDH ECUs will need plausible information on the temperature levels of all relevant components to select the correct operation strategies
- › Simple thermal models with generic input parameters are being developed / adapted and integrated into the HILS simulator

## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

- › **Thermal models for exhaust gas aftertreatment components**
  - › implemented in Simulink
  - › validation with existing measurement data finished
  - › ready to be linked to the main Simulink model

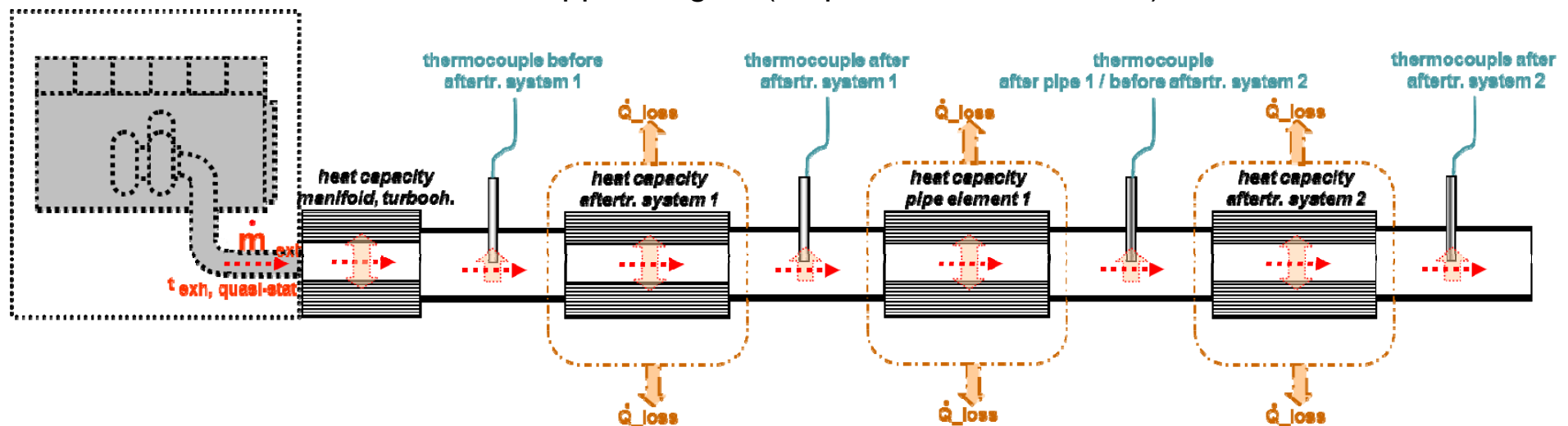


## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal models for exhaust gas aftertreatment components

- › 2 separate aftertreatment systems (i.e. DOC/POC and SCR) modeled
- › 0-dimensional heat capacities
- › Heat transfer between exhaust gas and heat capacities: convection (turb. / lam.)
- › Catalyst: heat input through chemical reactions (conversion rate maps)
- › Cooldown of stopped engine (empiric cool down curve)



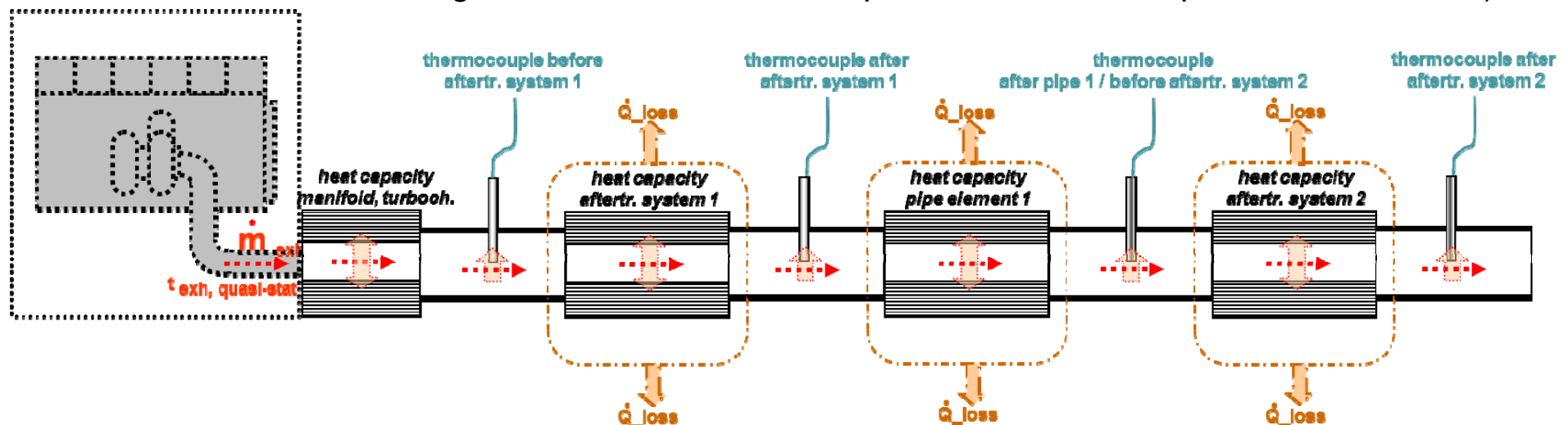


## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal models for exhaust gas aftertreatment components

- › Heat transfer between heat capacities and environment: convection, radiation
- › Heat conduction between masses neglected (effect much smaller than 0-d model accuracy)
- › Thermal behavior of thermocouples included (essential to provide realistic sensor signals for ECU and for comparison of model output with meas. data)

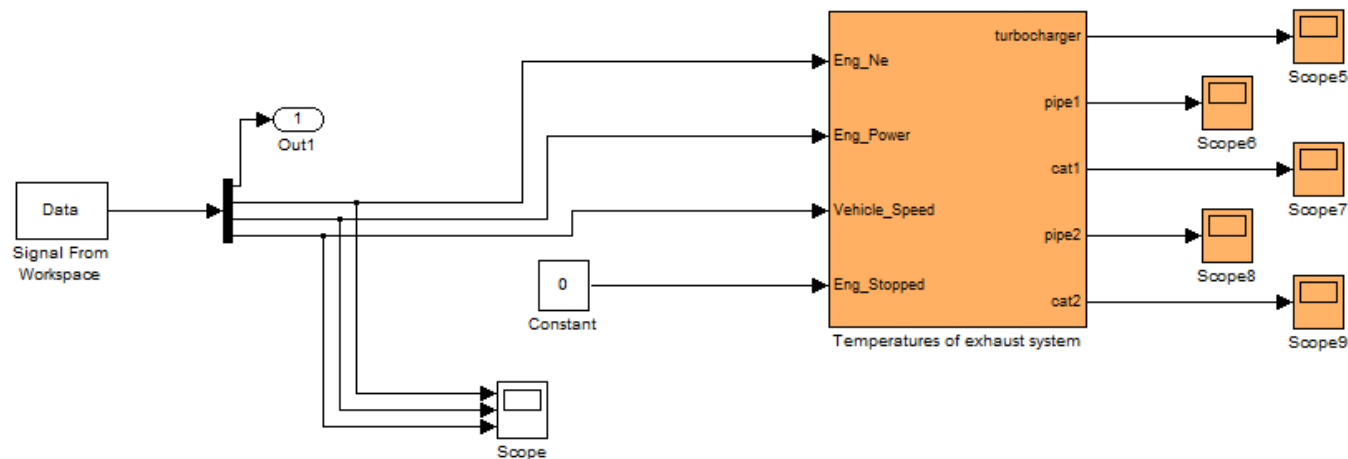


## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal models for exhaust gas aftertreatment components

- › Input signals: engine speed, power, vehicle speed, engine status
- › Maps: exhaust gas temp after turbocharger, exhaust gas massflow, lambda, emissions, conversion rates in catalyst
- › Input parameters: masses, start temperatures, heat capacities, heat transfer coefficients, lengths & diameters of pipe sections



# Task 1.6)

Extend the GTR-HILS Simulator with thermal models

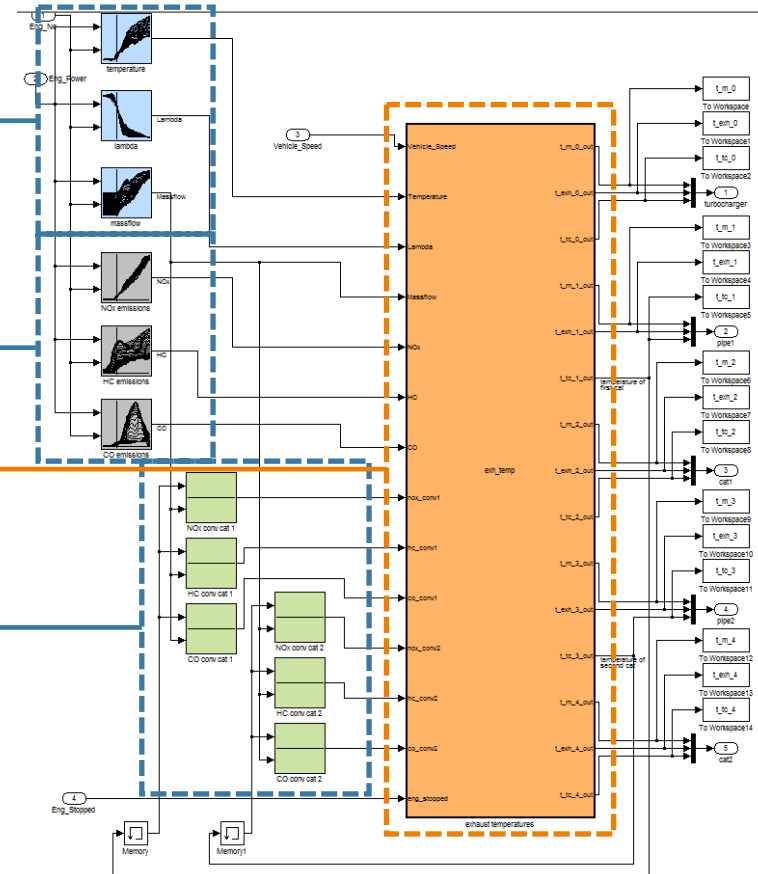
## Thermal models for exhaust gas aftertreatment components

maps for temperature exh. out, lambda, massflow

maps for emissions

Calculations in MATLAB code

maps for conversion rates of catalyst

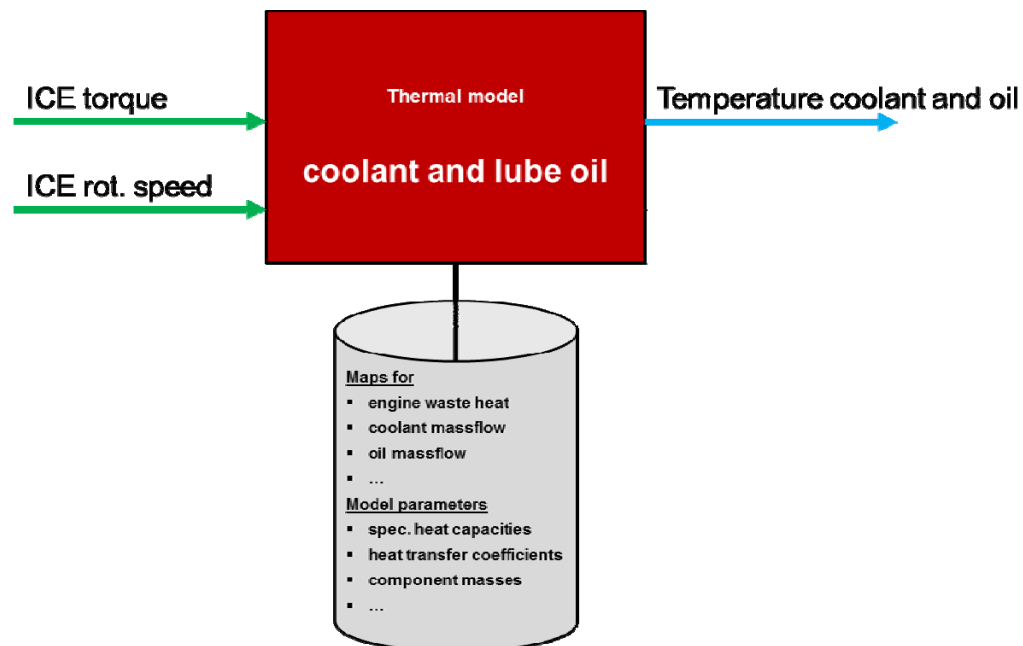


## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal model for coolant and lube oil

- › implemented in Simulink
- › measurements on engine testbed for parameterization of model currently running
- › needs to be adapted, parameterized and validated with measurement data



## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### Thermal model for coolant and lube oil (exemplarily for coolant)

- › Cooling circuit divided into 2 cells
- › 0-dimensional heat capacities for ICE & cooler
- › 4 equations:

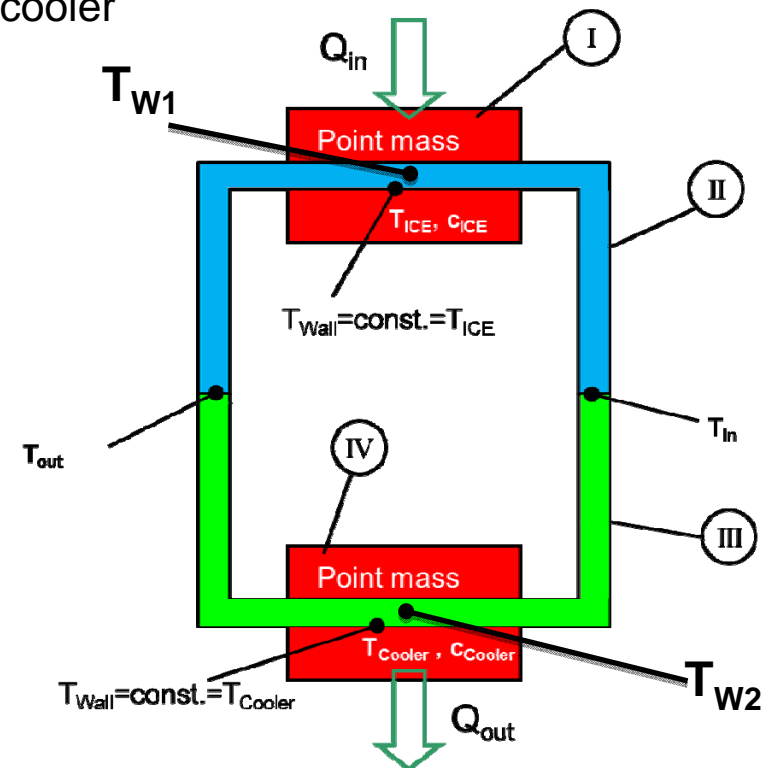
$$(I) \quad c_{ICE} \cdot m_{ICE} \cdot \frac{dT_{ICE}}{dt} = \dot{Q}_{in} - \alpha_{W1} \cdot A_{W1} \cdot (T_{ICE} - T_{W1})$$

$$(II) \quad c_W \cdot m_{W1} \cdot \frac{dT_{W1}}{dt} = \alpha_{W1} \cdot A_{W1} \cdot (T_{ICE} - T_{W1}) - c_W \cdot \dot{m} \cdot (T_{W1} - T_{W2})$$

$$(III) \quad c_W \cdot m_{W2} \cdot \frac{dT_{W2}}{dt} = c_W \cdot \dot{m} \cdot (T_{W1} - T_{W2}) + \alpha_{W2} \cdot A_{W2} \cdot (T_C - T_{W2})$$

$$(IV) \quad c_C \cdot m_C \cdot \frac{dT_C}{dt} = -\alpha_{W2} \cdot A_{W2} \cdot (T_C - T_{W2}) + \alpha_{Air} \cdot A_{Air} \cdot (T_{Amb} - T_C)$$

**Open:** simulate engine test conditions with constant  $T_{cooler}$   
 Or vehicle conditions with variable  $\alpha_{Air}$



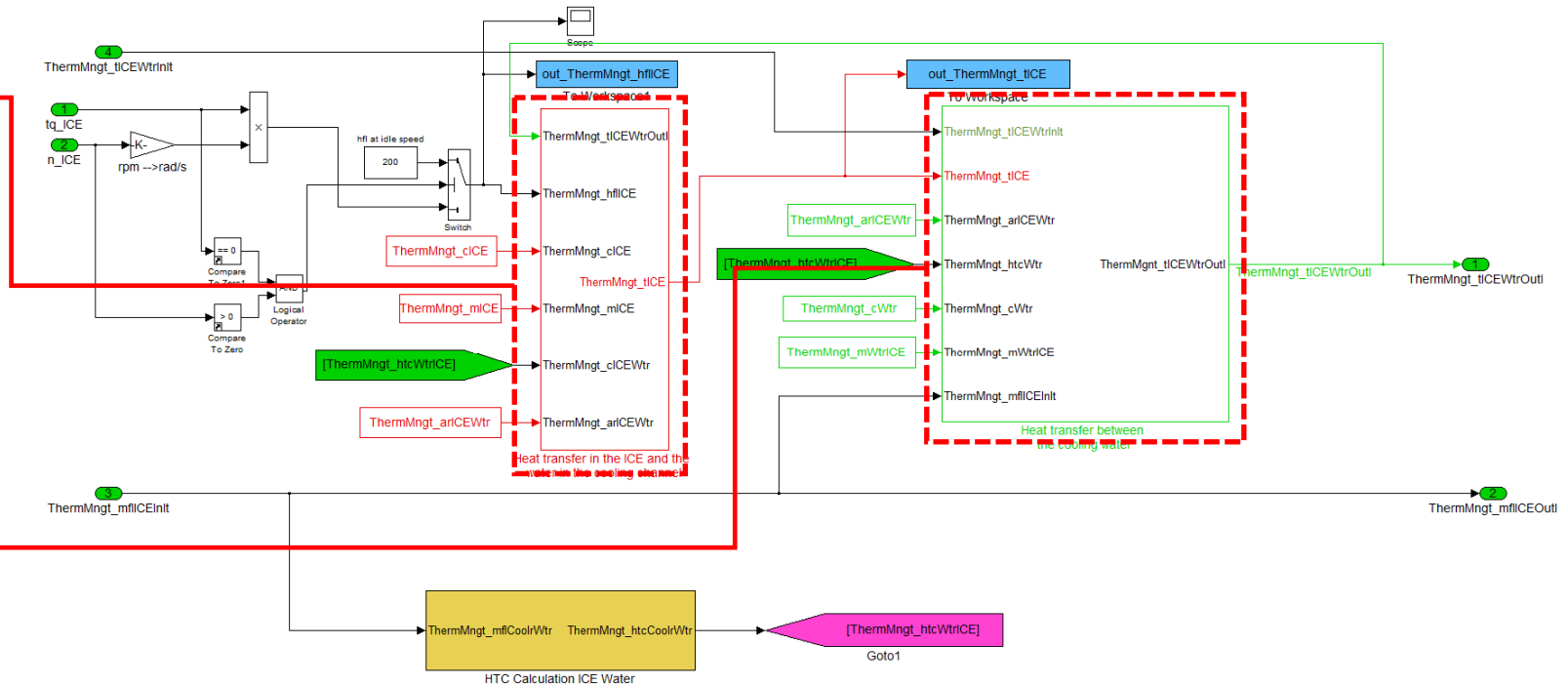
# Task 1.6)

Extend the GTR-HILS Simulator with thermal models

- ▶ Thermal model for coolant and lube oil (exemplarily for coolant)
  - ▶ Heat transfer part 1 (from ICE to cooling water)

ICE thermal management submodel

Heat transfer between ICE and cooling water



# Task 1.6)

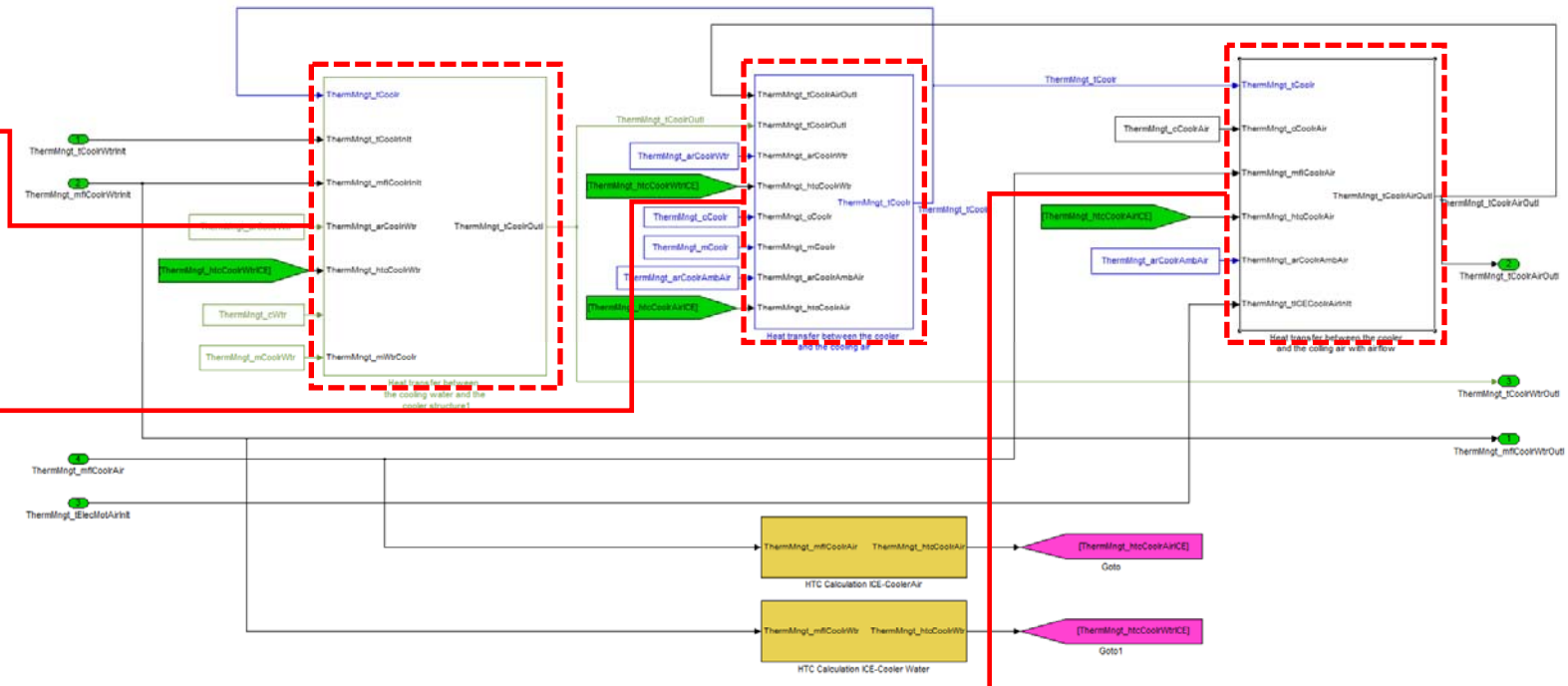
Extend the GTR-HILS Simulator with thermal models

- ▶ Thermal model for coolant and lube oil (exemplarily for coolant)
  - ▶ Heat transfer part 2 (from cooling water to ambient air)

Heat transfer between cooling water and cooler structure

Heat transfer between cooler structure and ambient air (no amb. air flow)

Heat transfer depending on ambient air flow due to vehicle speed

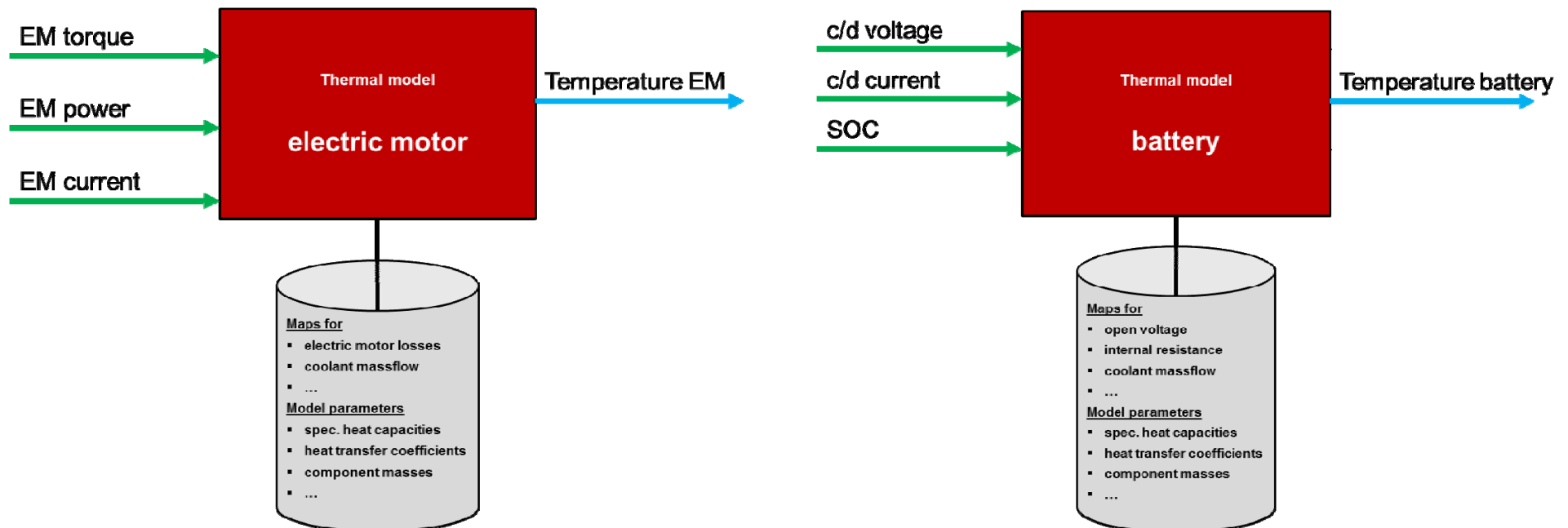


## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal models for battery and electric motor

- › under preparation in cooperation with Institute of Electrical Measurement and Measurement Signal Processing at TUG
- › OEM input and validation data needed





## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal model for electric storage device

#### › From Kokujiikan No. 281:

› Actual state of charge - coulomb counting:  $SOC = SOC_{initial} - \int_0^t \frac{I}{C_{nominal} \times 3600} dt \times 100$

› Calculation of the electrical power:  $P = V_s I = (V_o - R_i I) I$

#### › Required Extensions to calculate battery and fluid temperatures:

› Adding a time dependence (time constant) for the current/voltage behavior

› Adding a thermal model of the battery pack

› Calculation of the power loss and in combination with the thermal battery pack model calculation of the temperatures

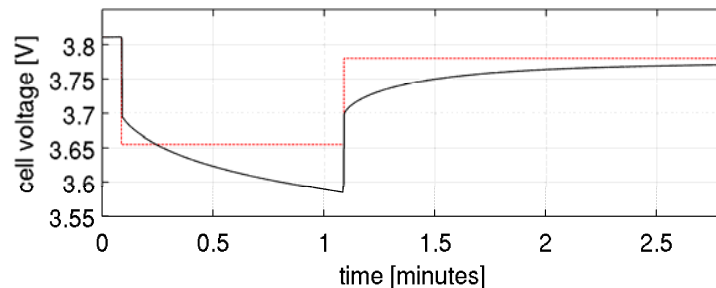
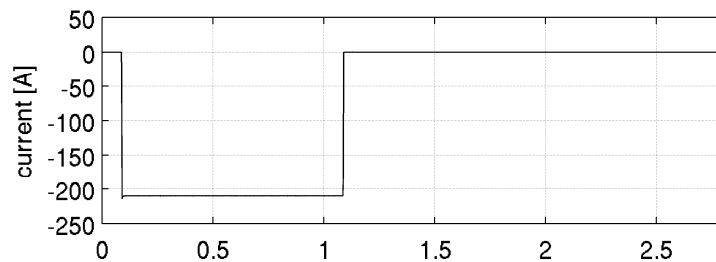
## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal model for electric storage device

#### › Time dependence of current / voltage behavior

- › Measured voltage behavior due to a rectangular current pulse (commercial 70Ah Kokam LiPoly cell)



- › Time dependence is required for a better estimation of the power loss
- › Parameter estimation: Almost the same measurements as described in Kokujikan No. 281 but different data analysis needed.

- No time dependent model as shown in Kokujikan No. 281  
- Time dependent model

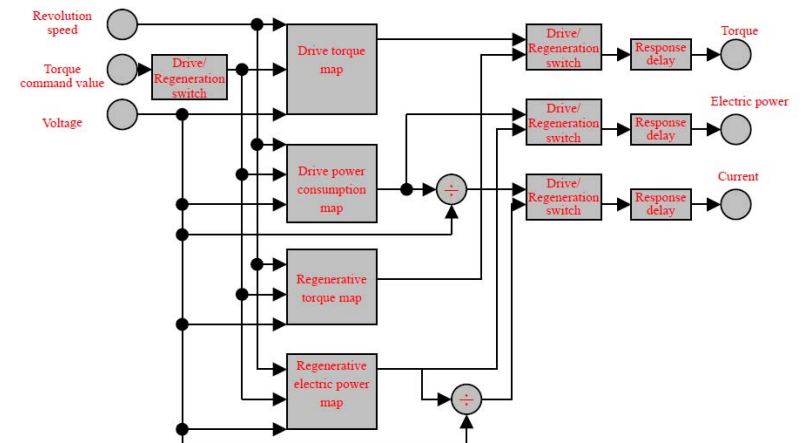
## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal model for electric motor

#### › From Kokujiikan No. 281:

- › Model calculates torque, electric power and current in dependence of revolution speed, voltage and torque demand



#### › Required Extensions to calculate motor, controller and fluid temperatures:

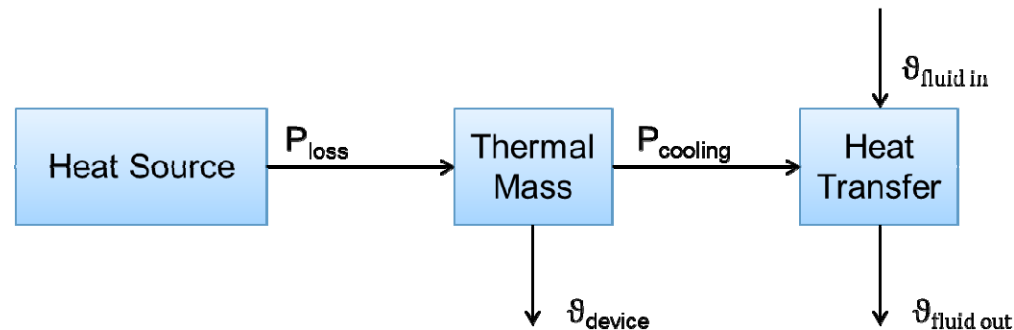
- › Separation of power losses for EM and controller (leading also to individual power consumption maps for the motor and controller)
- › Adding thermal models of motor and controller
- › Combining the calculated power losses and the thermal models calculation of the corresponding temperatures

## Task 1.6)

Extend the GTR-HILS Simulator with thermal models

### › Thermal model for one component (battery, motor, controller)

- › Thermal mass is considered as a point mass
- › Heat transfer is modeled by a constant heat transfer coefficient
- › Pressure drop for fluid flow is stored in a lookup table



- › Parameter estimation: Same measurements as described in Kokujikan No. 281 but additional measurement between controller and motor is needed.

## Task 1.7)

- Deliverables

- › **Simulation runs and validation of basic functions**
  - › Simple control strategy for model validation (including vehicle-, driver-, thermal- and non-electric models)
    - › With regard to validation phase 2, models of later on tested vehicles should be used for validation here
    - › Largely realistic control strategy would be favourable
  - › Different input data will be used
    - › Generic values
    - › Measurement data from institutes
    - › Measurement data from manufacturers if available

# Validation phase 1 overview

## Task 1) Adaptation of the Japanese HILS Simulator for serial hybrid

### › Timetable and milestones

- › Task 1.1) and 1.2) serial hybrid model with different driver models are completed
- › Task 1.3) modelling non-electric components is finalized, overall model-implementation deferred with regard to validation phase 2
- › Task 1.5) and 1.6) modelling of components and thermal models is planned to end in November to have enough time for overall model validation which should start in December
- › Task 1 report to ACEA at the end of February

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1 SILS for serial hybrid												
1,1 Set up a serial HDH as SILS												
1,2 Adapt driver model												
1,3 Library for non electric com												
1,4 Meetings with OEM's and stakeholders												
1,5 Library for new power pack components												
1,6 Thermal models												
1,7 Simulation runs and validation												

## Validation phase 1 overview

- › **Task 1)** Adaptation of the Japanese HILS Simulator for serial hybrid
  - › 7 sub-tasks where we are currently working on
- › **Task 2)** Adaptation of the HILS Simulator for parallel hybrid
  - › 4 sub-tasks officially starting this month
  - › Due to intersections with task 1 already began earlier
- › **Task 3)** Report on test procedure and adaptations
  - › 3 sub-tasks ending on schedule in June 2013

## Task 2.1)

- Deliverables

› Meetings with OEM's and stakeholders

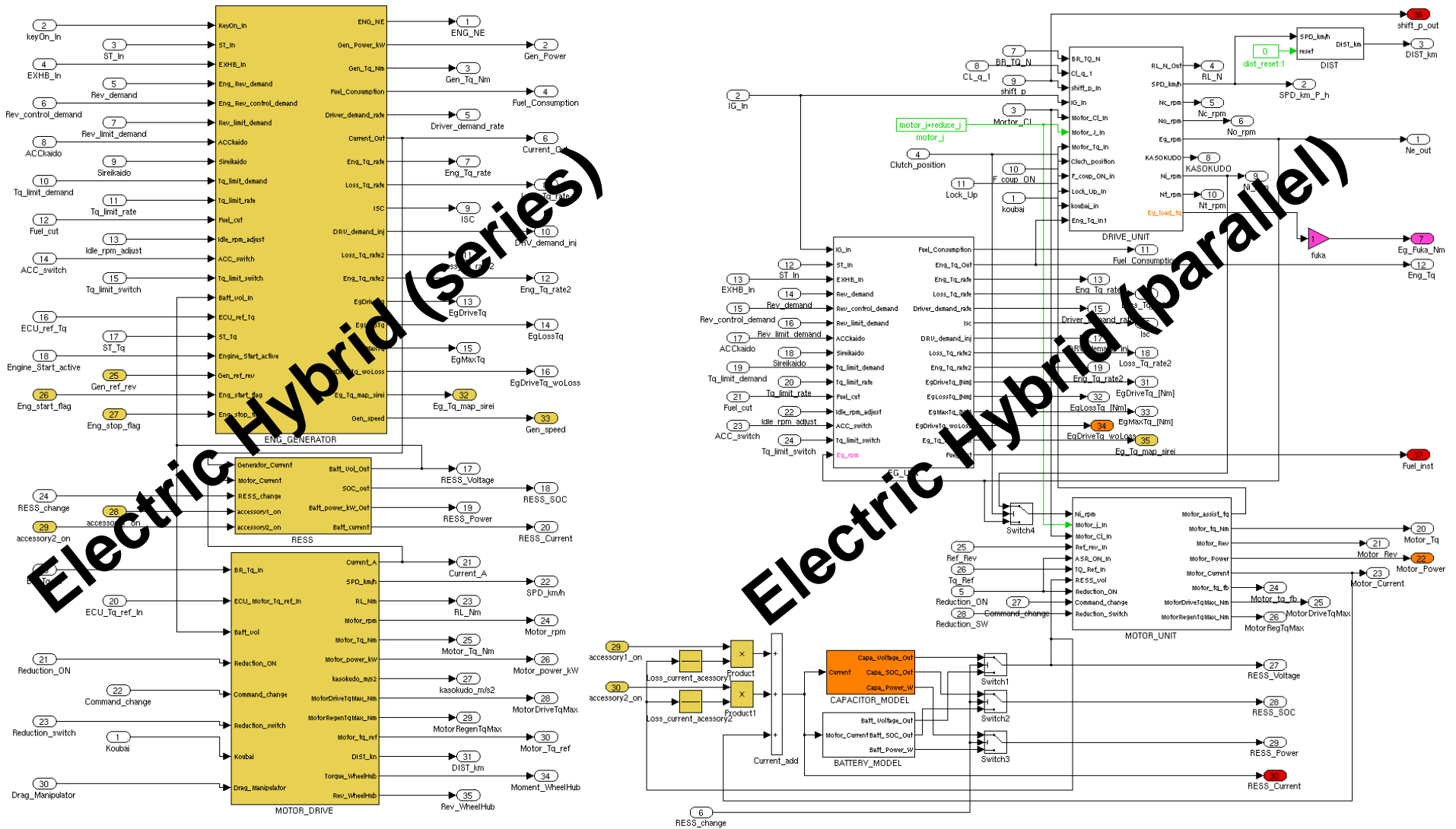
› See Task 1.4



## Task 2.2)

- Discussion point

- › **Set up a data bus system in the model to allow various combinations of engines, gear boxes and storage systems**
  
- › Difficult in the current model to setup a data bus system
  - › Components are represented in different ways in the two vehicle models
  - › Components are lumped in different ways
  - › There might be a need to restructure the models



## Task 2.2)

- Discussion point

- › **Set up a data bus system in the model to allow various combinations of engines, gear boxes and storage systems**
  
- › Bring up the question (“who is the owner of the model in the end”)
  - › Who is responsible for structure, who for components;  
Are these different persons/authorities?  
-> model will never be “plug&play”
  
- › Manufacturers should be able to bring in their own submodels, we can only provide a minimum of signals that are needed

## Task 2.3)

- Discussion point

### › Adapt the Software to simulate a parallel HDH

- › Would be good if we know which drivetrain topologies we will have in validation phase 2 (to prepare parallel and serial HDH models)
- › Task 2 already starting
- › In need of control strategy? Depend on topology!
- › Idea of control strategy! Is this acceptable for doing simulations?

## Task 2.3)

- Deliverables

- › **Adapt the Software to simulate a parallel HDH**
  - › In need of control strategy? Depend on topology!
  - › Idea of control strategy! Is this acceptable for doing simulations?

*The control strategy is to use the electric machine below a certain speed and the combustion engine above that. If energy level stored in the accumulator is lower than a certain value, the electric machine is used as generator and is then driven either by the engine or purely by the kinetic energy of the vehicle. The electric machine is used for braking the vehicle when possible, if the brake torque is not enough then the mechanical brakes are used as well. The electric machine is also used for power assist when the desired torque, interpreted from the accelerator pedal position, is larger than the combustion engine can deliver.*

## Task 2.4)

- Deliverables

- › **Simulation runs and validation of basic functions, including the functions from task 1**
  - › See Task 1.7)
    - › Generic data or measurement data of institutes or manufacturers will be used
  - › Depending on vehicles in validation phase 2
    - › Provided simulation models have to be specified
    - › Models for all possible combinations of library components will not be provided

# Validation phase 1 overview

## Task 2) Adaptation of the HILS Simulator for parallel hybrid

### › Timetable and milestones

- › Task 2.2) the model structure and the further proceeding has to be discussed at earliest
- › Task 2.3) control strategy proposal has to be discussed
- › Task 2.4) available vehicles in validation phase have to be specified

		Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
2	Adaptation of SILS for parallel hybrid												
2,1	Meetings with OEM's and stakeholders												
2,2	Set up a data bus system in the model												
2,3	Adapt the Software to parallel HDH												
2,4	Simulation runs and validation												

## Validation phase 1 overview

- › **Task 1)** Adaptation of the Japanese HILS Simulator for serial hybrid
  - › 7 sub-tasks where we are currently working on
- › **Task 2)** Adaptation of the HILS Simulator for parallel hybrid
  - › 4 sub-tasks officially starting this month
  - › Due to intersections with task 1 already began earlier
- › **Task 3)** Report on test procedure and adaptations
  - › 3 sub-tasks ending on schedule in June 2013



## Task 3.1)

- Deliverables

- › **Report on test procedure and user manual for software**
  - › Component testing procedure
  - › Application of the HILS simulator
  - › Validation procedure of the HILS setup
  - › User manual for the software
- › Reports can only be on schedule if we agree to keep working with the current HILS model structure

## Task 3.2)

- Deliverables

- › **Provide the interface system for real ECU's**
  - › Depending on manufacturer input in task 1.4) the ECU model interface will be standardized
  - › If individual vehicles in validation phase 2 request additional signals they will be made available at the interface to run the HILS system
  - › How to handle multiple ECU's has to be discussed
    - › Manufacturer input on quantity and required signals is needed

## Task 3.3)

- Deliverables & comments

- › **Adaptations and improvements on the methods for component testing, test cycle definition and simulation method according to demands of industry and Commission**
- › For eventual adaptation and improvement of methods suggested by the HDH group, two weeks of work is reserved
- › Maybe transient model behaviour will get a topic
  - › Currently transfer functions and time constants are used (e.g. for ICE torque buildup)
  - › Not clear how they are specified in the component test methods
  - › Effort tuning the time constants can not be estimated today, at earliest possible in validation phase 2



## Outlook on validation phase 2 (from spring 2013)

- › Validation phase 2 influences current work
  - › Certain points have to be clarified at earliest (see previous slides)
  - › Still an open question is who will work on validation phase 2 and which vehicles will be tested
    - › We will not provide vehicle models which are not used in validation phase 2
    - › We propose to leave the non-electric components outside the model in the library and focus on modelling vehicle structures tested in validation phase 2

# THANK YOU FOR YOUR ATTENTION!



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