Working Paper No. **HDH-10-04**
(10th HDH meeting, 05 June 2012)

RESEARCH PROGRAM ON AN EMISSIONS TEST PROCEDURE FOR HEAVY DUTY HYBRIDS (HDH)

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WP3: Non-electric HDHs

Jonas Fredriksson
Department of Signals and Systems
Chalmers University of Technology
Gothenburg, Sweden

Content

- **Introduction** - Work package 3
- **WT 3-1:** Technology overview and selection of scope
- **WT 3-2:** Development of HIL elements for non-electrical hybrid systems/components
- **WT 3-3:** Test methods for input data to non-electric component models
- **WT 3-4:** Definition of control signals
- **WT 3-5:** Alignment with HILS for HEV and verification
- **Summary**

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

3. Extension of HILS to non-electrical hybrids, which are currently not covered by Kokujikan No.281.

To May 2012 the following WP is to be carried out.

- Overview of possible other types of hybrids of interests and issues for HILS testing will be investigated. Information gathering. Proposal of which non-electric hybrids to include in the HILS method.
- Evaluate, using software models and simulation the possibilities of using HILS for assessment of quality factors of these hybrids.

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-1: Technology overview and selection of scope

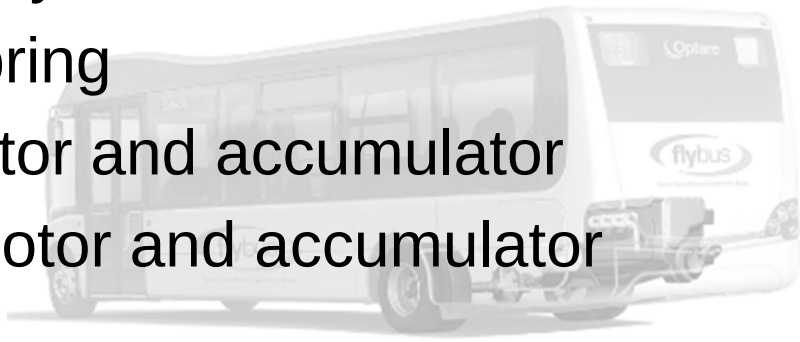
- Detailed analysis on what non-electric hybrid systems/components to be included in the HILS method. Review of non-electric hybrid topologies proposed in the literature, by OEMs and others. Review of non-electric components, such as flywheels, accumulators etc, used in non-electric powertrains proposed in the literature, by OEM and others. Together with OEMs and other partners decide which topologies that should be covered. Meetings with OEMs, will be co-planned with TU Graz and TU Wien in relation to WP 1-4 (TU Graz and TU Wien offer).

- The preliminary result is a list of non-electric powertrain topologies and a list of components that needs to be modeled.

Hybrid Powertrain Principles

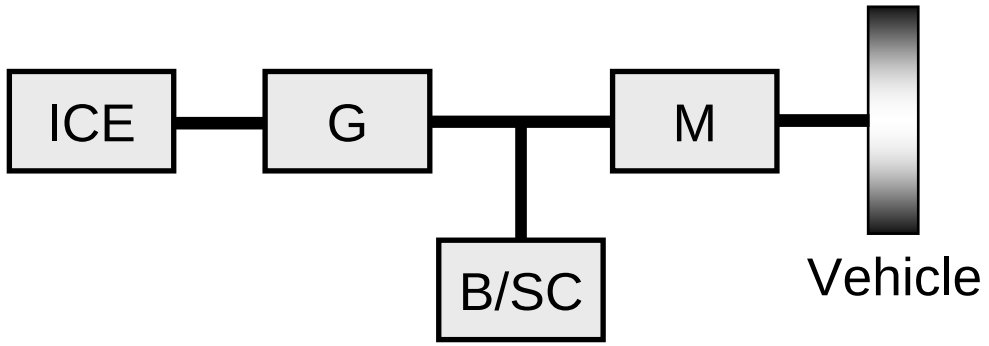
Energy, converter and storage

- Electrochemical, generator/motor and battery
- Electrostatic, generator/motor and supercapacitor
- Electromagnetic, generator/motor and superconductor coil
- Kinetic, CVT and flywheel
- Kinetic, motor/generator and flywheel
- Potential, CVT and torsion spring
- Potential, hydraulic pump/motor and accumulator
- Potential, pneumatic pump/motor and accumulator

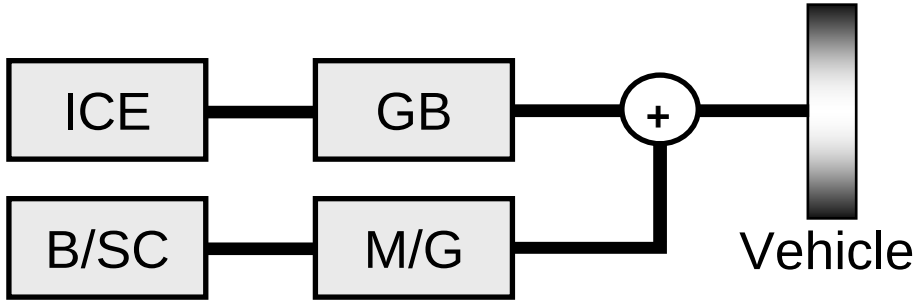


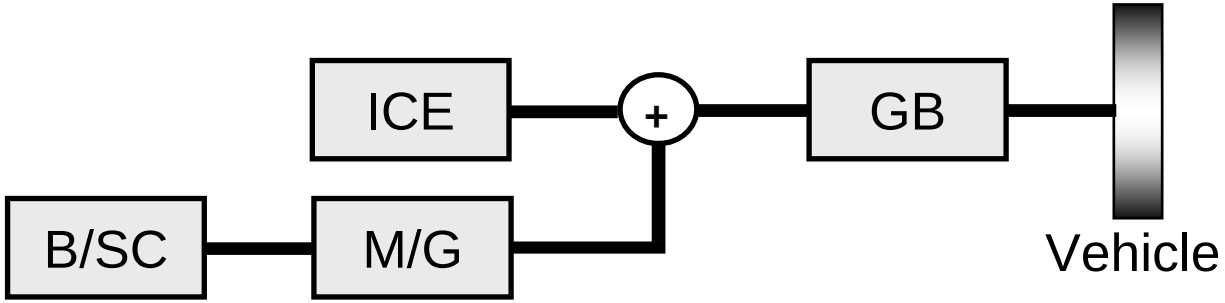
Hybrid Powertrain Topologies

Series powertrain:



Parallel powertrain:

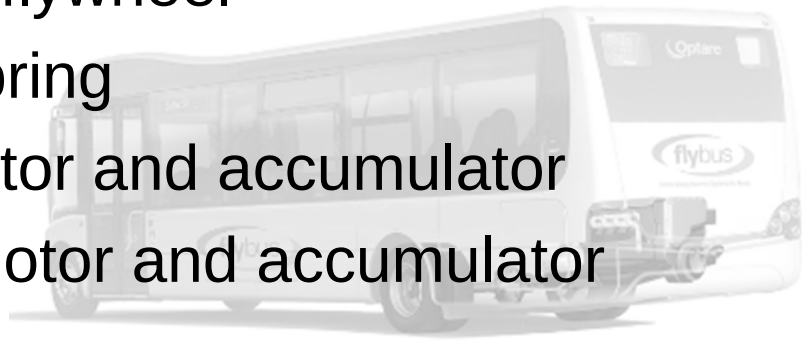




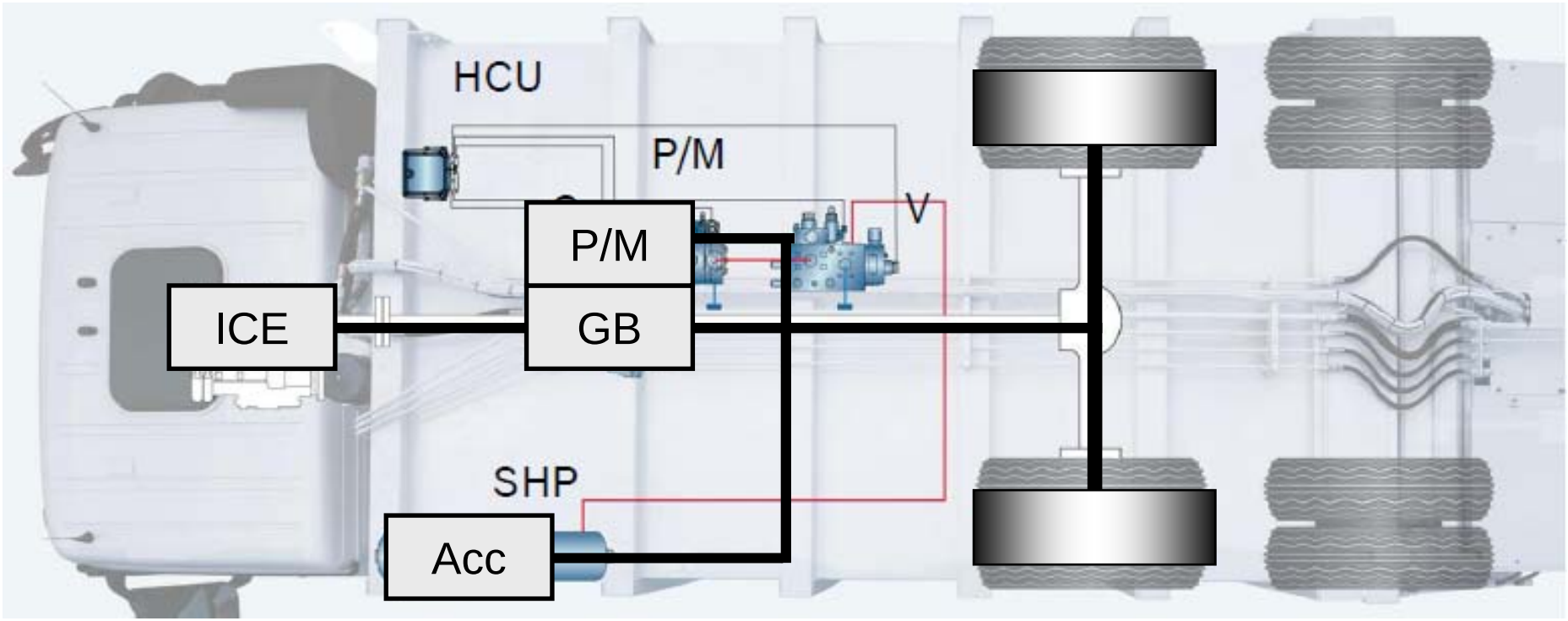
Hybrid Powertrain Principles

Energy, converter and storage

- Electrochemical, generator/motor and battery
- Electrostatic, generator/motor and supercapacitor
- Electromagnetic, generator/motor and superconductor coil
- Kinetic, CVT and flywheel
- Kinetic, motor/generator and flywheel
- Potential, CVT and torsion spring
- Potential, hydraulic pump/motor and accumulator
- Potential, pneumatic pump/motor and accumulator



Hydraulic pump/motor and accumulator

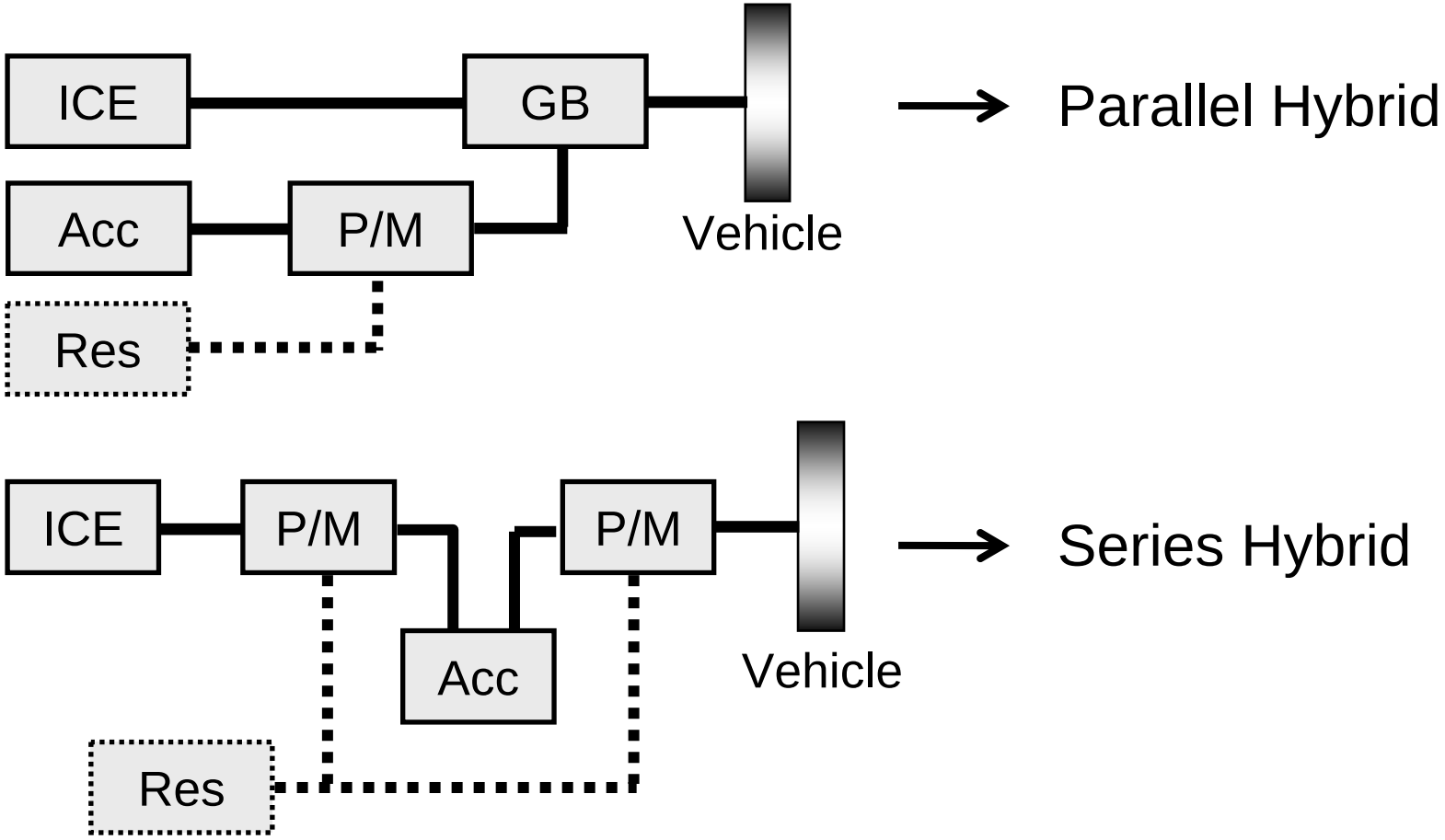


Vehicle

Rexroth HRB

Hydraulic pump/motor and accumulator

- Energy storage: Potential energy

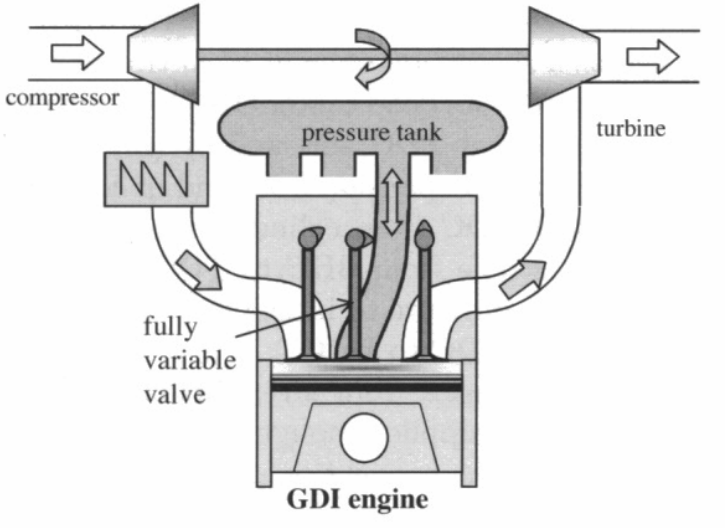


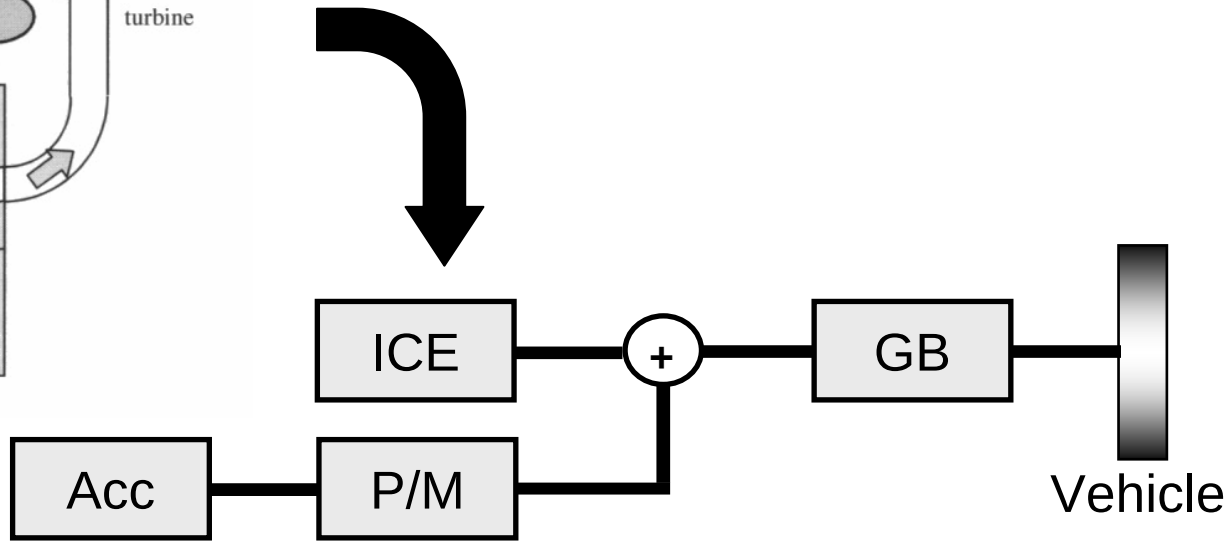
Hydraulic pump/motor and accumulator

- Ford F150 and F350 Hydraulic Hybrid (Parallel)
- Eaton, Hydraulic Launch Assist (Parallel and Series)
- NRG Dynamix (Parallel and Series)
- Innas, Netherlands, (Series)
- Parker, Runwise system, (Parallel and Series)
- Bosch Rexroth, HRB (Parallel and series)
- Poclain Hydraulics, ADDIDRIVE Assist (Series, addon to non-driven wheels)

Pneumatic pump/motor and accumulator

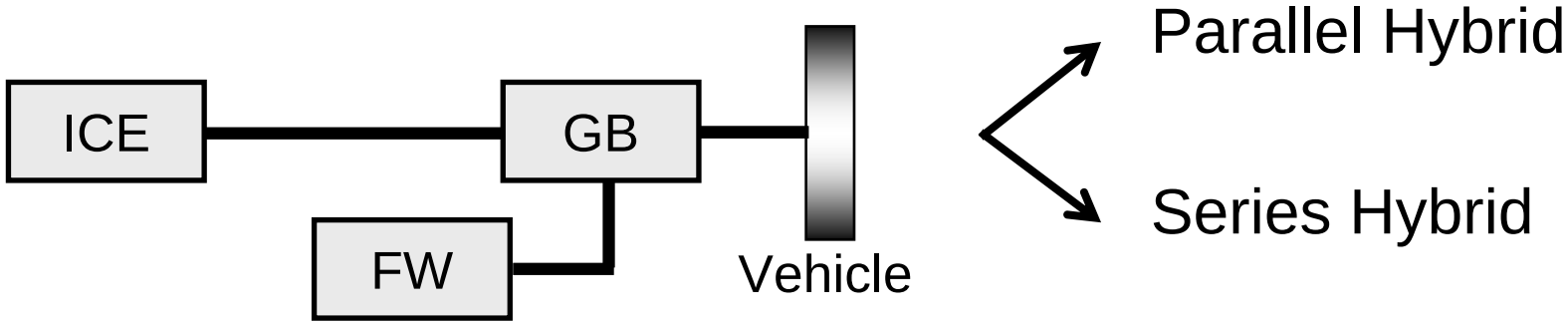
- Energy storage: Potential energy
  - Principle could be similar as for hydraulic hybrids
- Alternative: Hybrid engine concept:



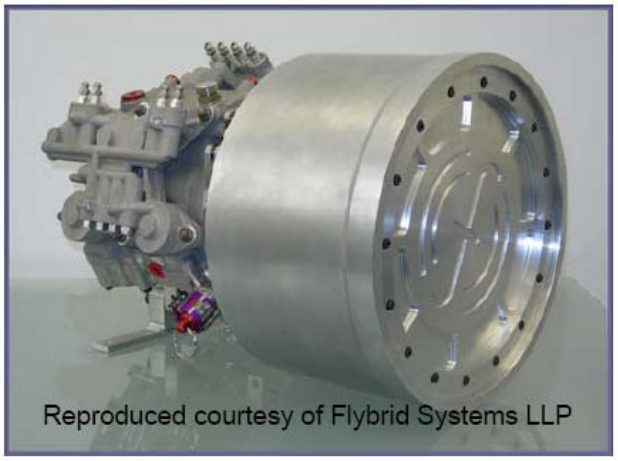


CVT and flywheel

- Energy Storage: Kinetic energy

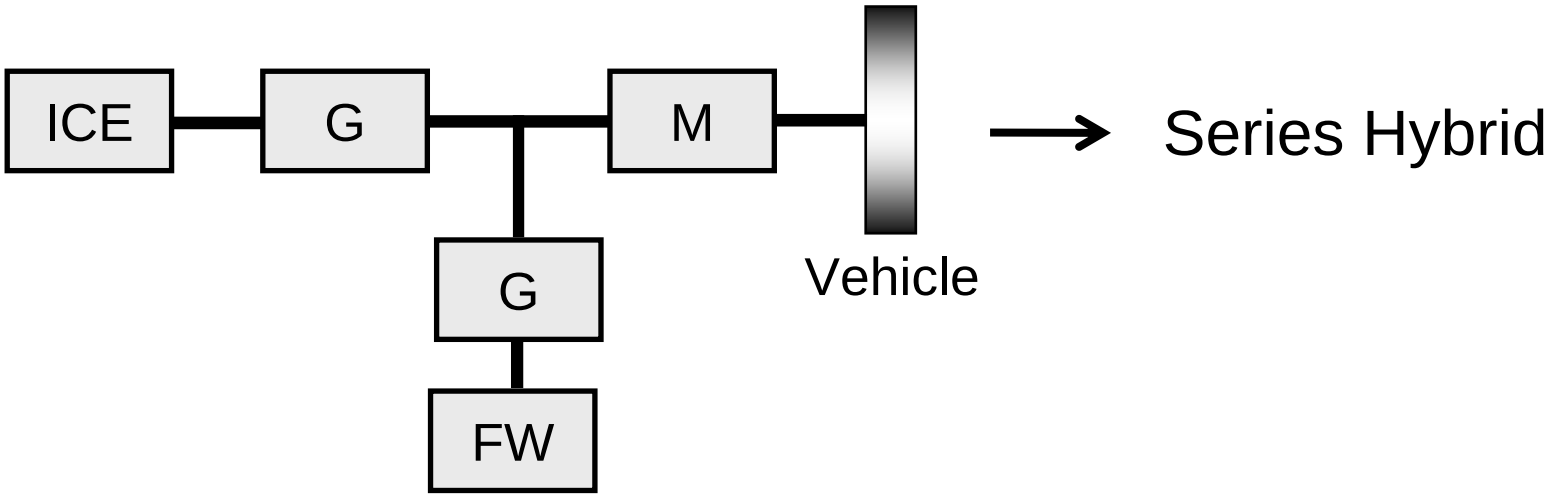


- Examples:
  - Formula 1
  - Flybrid
  - Torotrack for city bus



Motor/generator and flywheel

- Energy storage: Kinetic energy



- Examples:
  - PhD thesis from Uppsala University, Sweden

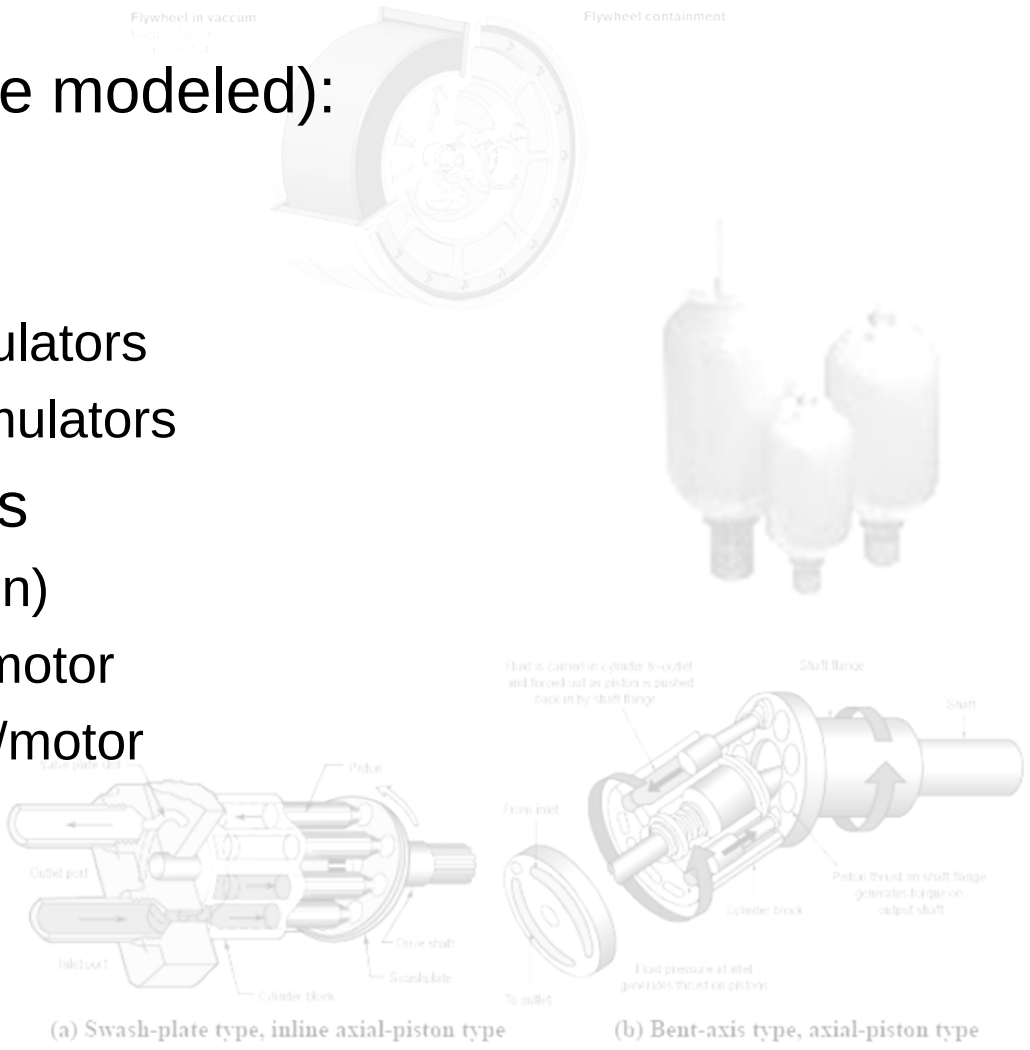
Results

- Non-electric hybrid powertrain topologies (concepts) fits well into the same categories as for electric hybrid powertrains:
  - Series powertrain topologies
  - Parallel powertrain topologies
  - Split powertrain topologies

- Interesting non-electric powertrain concepts:
  - CVT and flywheel
  - Motor/generator and flywheel
  - Hydraulic or (pneumatic) pump/motor and accumulator

Results

- Component list (to be modeled):
  - Energy storages:
    - Flywheel
    - Hydraulic accumulators
    - Pneumatic accumulators
  - Energy converters
    - CVT (transmission)
    - Hydraulic pump/motor
    - Pneumatic pump/motor



Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-2: Development of HIL elements for non-electrical hybrid systems/components

- Based on the list of topologies and components in WP 3-1, develop simple, representative mathematical models of the different powertrain components, such as actuators and energy buffers. The models will be implemented in a simulation software. All models will be documented.

- The result is a set of simulation models of non-electric powertrain components, which are suitable to use in a HILS setup.

The most important part is the model structure, the input-output signals, not the model equations.

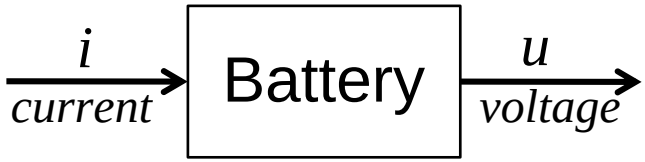
Energy storages

- Flywheel
- Accumulators

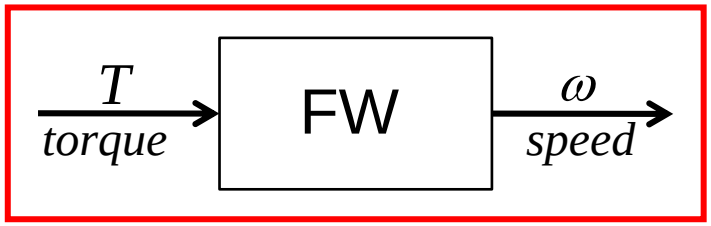
Notice the similarity to the electric energy storage used in Kokujikan No 281.

Flywheel

Electric battery:



Flywheel:



State-of-Charge

$$C\frac{dSOC}{dt} = -i$$

$$u = u_{OCV}(SOC) - Ri$$

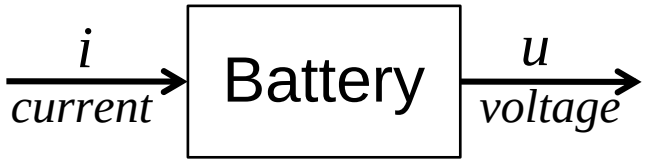
$$J\frac{d\omega}{dt} = -T - T_{loss}(\omega)$$

losses

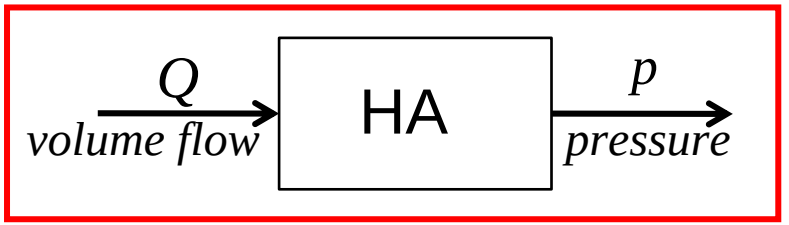
$T_{loss}(\omega)$ - Lookup table

Accumulator

Electric battery:



Accumulator:



State-of-Charge

$$C\frac{dSOC}{dt} = -i$$

$$u = u_{OCV}(SOC) - Ri$$

$$\frac{dV_g}{dt} = Q$$ (mass balance)

losses

Temperature

$$p_g = \frac{m_g R_g \vartheta_g(t)}{V_g(t)}$$ (ideal gas law)

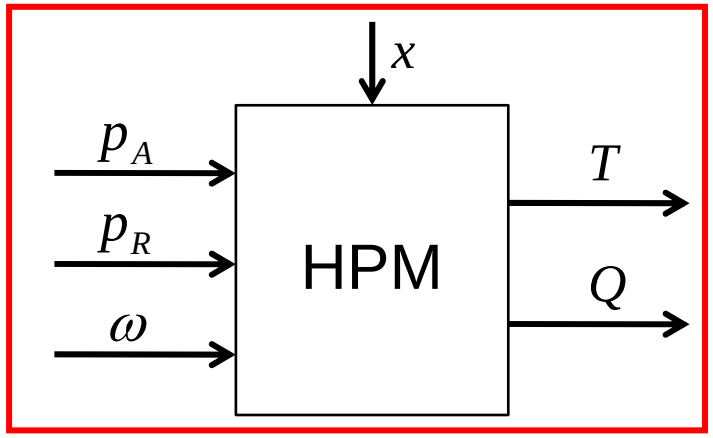
$$m_g c_v \frac{d\vartheta_g}{dt} = -\frac{m_g R_g \vartheta_g(t)}{V_g(t)} Q - hA_w(\vartheta_g - \vartheta_w)$$

(energy balance)

Energy converters

- Hydraulic pump/motor
- CVT

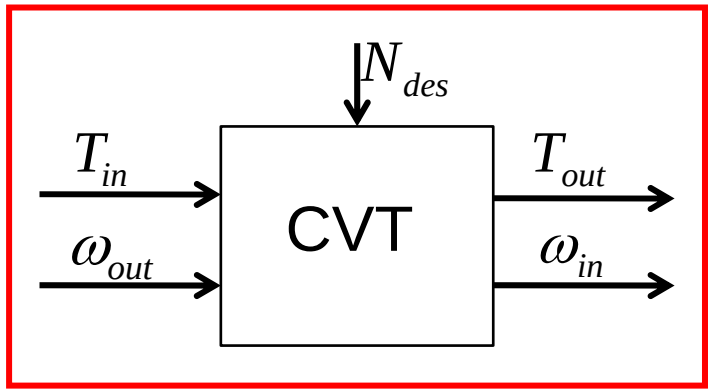
Hydraulic Pump/Motor



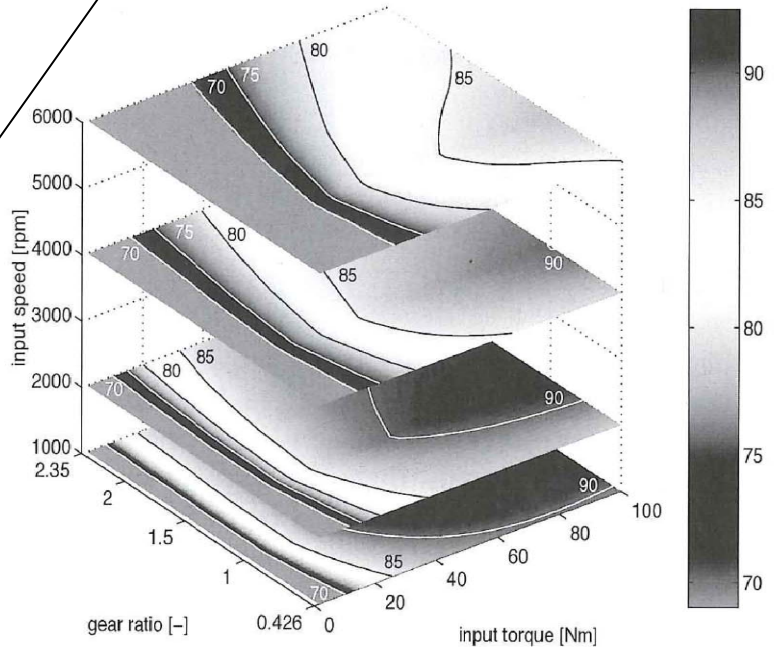
	Pump:	Motor:
Volumetric flow rate:	$Q = \eta_v x D \omega$	$Q = x D \omega / \eta_v$
Torque:	$T = \eta_t x D (p_A - p_R)$	$T = x D (p_A - p_R) / \eta_t$
Efficiencies:	$\eta_v = f(x, p_A, p_R, \omega)$	$\eta_t = f(x, p_A, p_R, \omega)$

Lookup table

CVT



Lookup table



Torque: $T_{out} = NT_{in}\eta$

Efficiency: $\eta = f(\omega_{out}, T_{in}, N)$

Speed: $\omega_{in} = N\omega_{outt}$

Gear ratio: $\frac{dN}{dt} = -\frac{1}{T}(N - N_{des})$

Results

- Model structure for non-electric powertrain components
- Representative mathematical models are developed for:
  - Flywheel
  - Accumulator
  - Pump/Motor
  - CVT
- MATLAB/Simulink implementation

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-3: Test methods for input data to non-electric component models

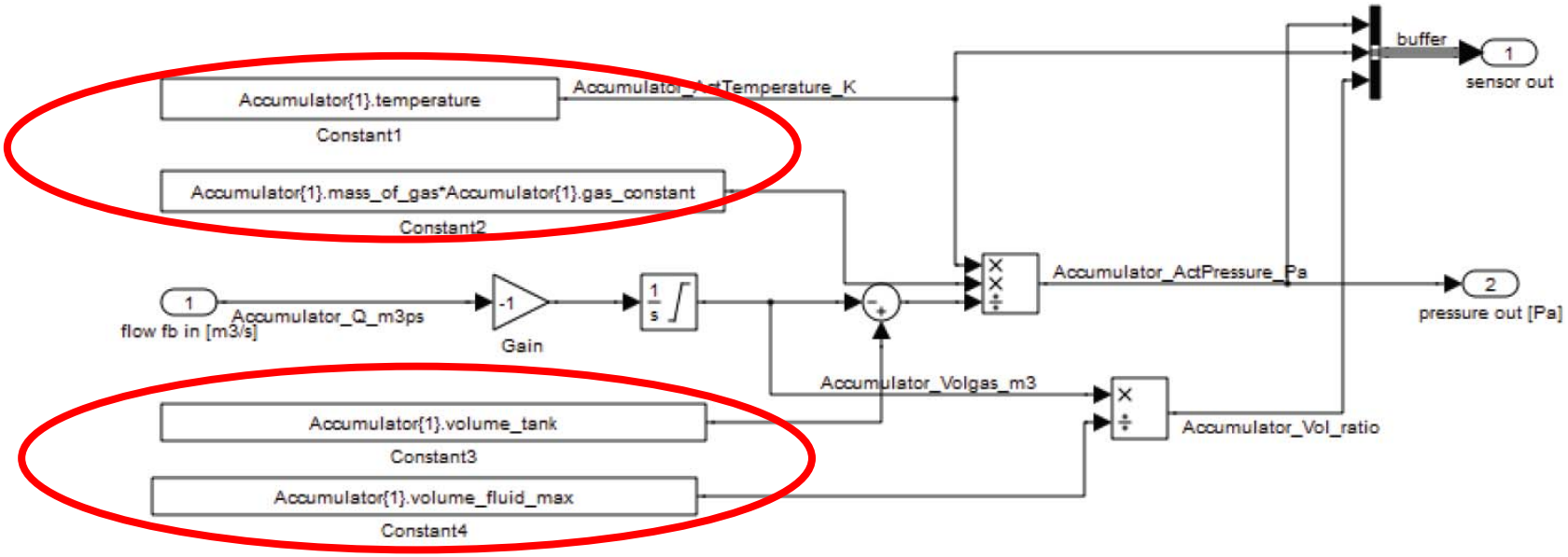
- In this workpackage, specifications on parameters that need to be determined in order to use the components modeled in WP 3-2 will be written. A feasibility study on how or if the parameters can be determined from experiments will also be conducted. Depending on the feasibility study, modifications on the component modeling might be necessary.

- The deliverable is the specification of the component's parameters.

Results

- Mathematical models are developed for:
  - Flywheel
  - Accumulator
  - Pump/Motor
  - CVT
- MATLAB/Simulink implementation

Results



Description	Name in model	Unit
Gas temperature	Accumulator{1}.temperature	K
Gas mass	Accumulator{1}.mass_of_gas	kg
Gas constant	Accumulator{1}.gas_constant	J/kgK
Accumulator volume	Accumulator{1}.volume_tank	m^3
Maximum fluid volume	Accumulator{1}.volume_fluid_max	m^3
Initial volume of gas	Accumulator{1}.volume_init	m^3

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

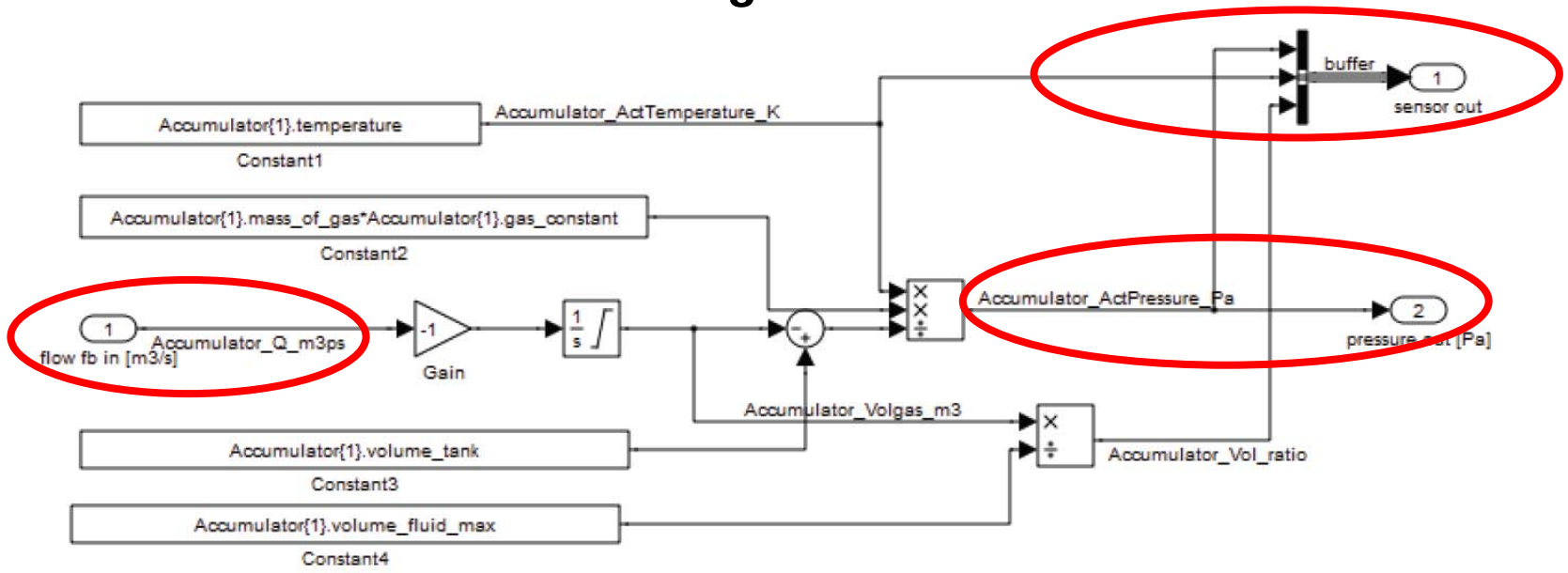
WT 3-4: Definition of control signals

- Based on the non-electric component models and also available components on the market today determine which control signals and sensor signals are necessary/available. Analysis for a standard interface connecting the hardware (HDH ECU) with the HILS software. Identifying the modifications needed to get non-electric hybrid components into the HILS method. This work will be in collaboration with WP 1, see TU Graz and TU Wien offer.

- The result is a list of input and output signals to and from the non-electric components.

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-4: Definition of control signals



- Names need to be standardized
  - Suggestion: (`Component_description_unit`)

Results

Model	Input/Output	Symbol	Meaning of signal	Unit
Flywheel	Input-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	m3/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

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-5: Alignment with HILS for HEV and verification

- Review of the HILS method to understand what modifications are needed to get the new components into the method. Hypothesis: No major modifications is needed, the non-electric components/subsystems have the same purpose as the electric components/subsystems. Verification of hypothesis.

- Result: Hypothesis is verified or suggestion on modification of method.

Development of Emissions and CO2 Test Procedure for Heavy Duty Hybrid Vehicles

WT 3-5: Alignment with HILS for HEV and verification

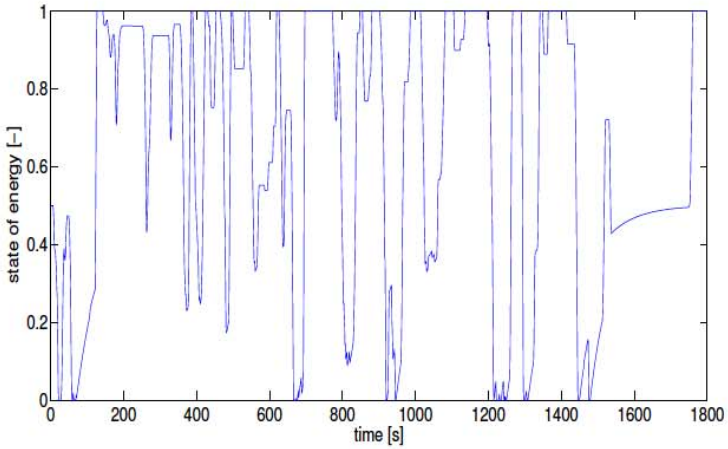
- Topologies – OK
- Model structures/mathematical models – more or less “plug ‘n play”
- Control interface – OK
- Component testing for obtaining model parameters – needs to be regulated in a regulation

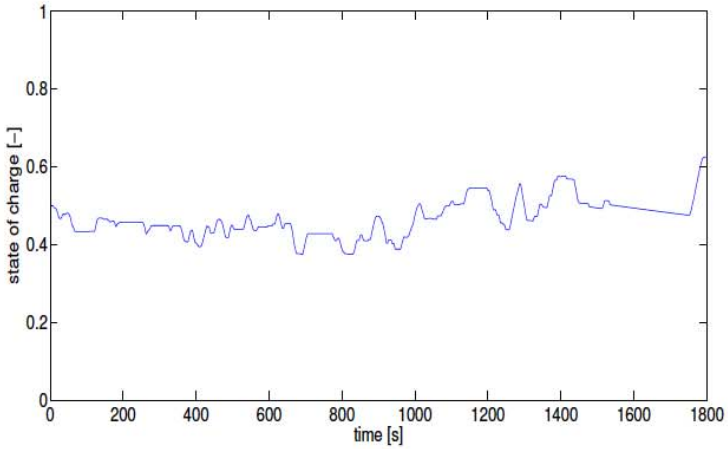
Simulation results

Hybrid hydrualic vehicle

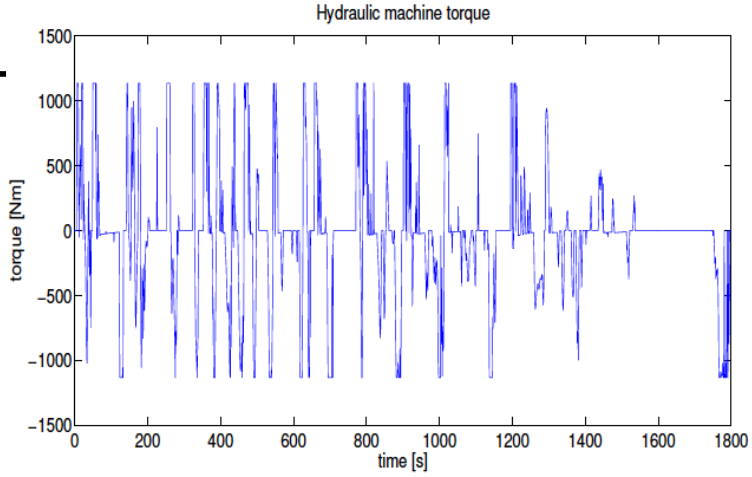
Hybrid electric vehicle

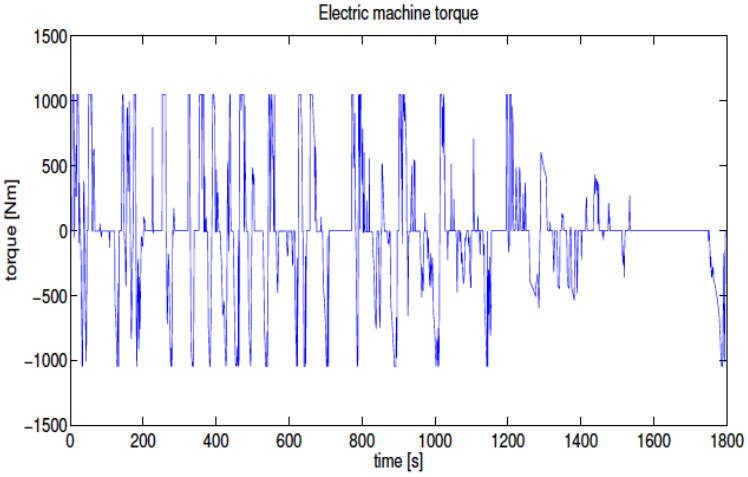
Energy level





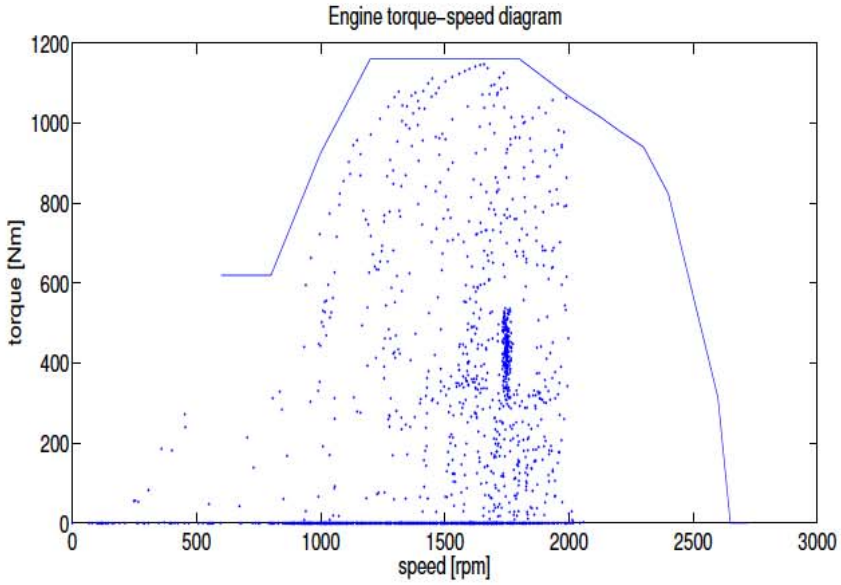
Converter torque



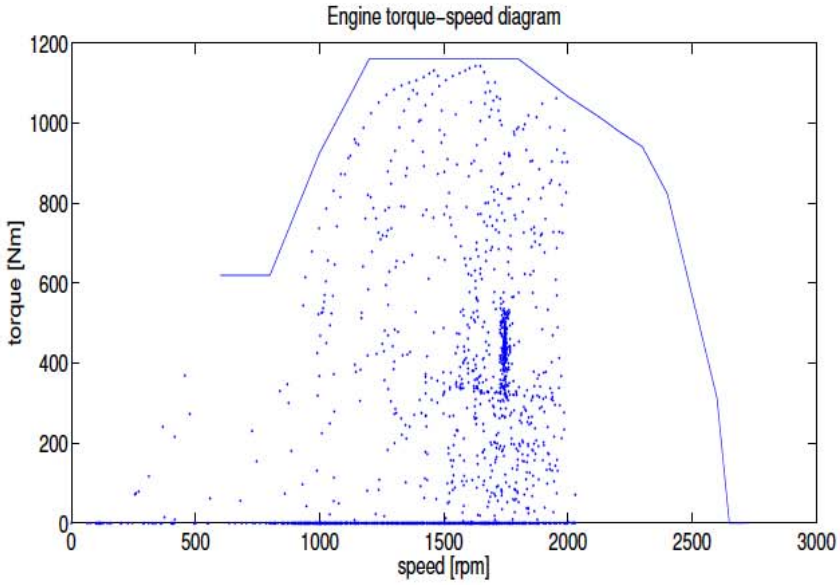


Simulation results

Hybrid hydrualic vehicle



Hybrid electric vehicle



Summary

- WT 3-1:
  - Non-electric hybrid powertrain topologies (concepts) fits well into the same categories as for electric hybrid powertrains

  → HILS should be possible for non-electric HDHs

- WT 3-2:
  - Model structures/Mathematical models for:
    - Flywheel
    - Accumulator
    - Pump/Motor
    - CVT

  → Similar model structures as proposed in Kokujikan No. 281

Summary

- WT 3-3:
  - Parameters specified for:
    - Flywheel
    - Accumulator → Working on getting
    - Pump/Motor relevant data
    - CVT
- WT 3-4:
  - I/O:s identified → Needs standardization
- WT 3-5:
  - No major changes in Kokujikan No 281 needed to include non-electric hybrid powertrains

Thanks for your attention!

Contact information

Jonas Fredriksson
Department of Signals and Systems
Chalmers University of Technology

jonas.fredriksson@chalmers.se
+46-31-772 1359