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MODEL OF A NEW POWERTRAIN CONCEPT BASED ON THE INTEGRATION OF ELECTRIC GENERATION, ENERGY RECOVERY AND STORAGE

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Emilio Navarro Peris
Alex Rinaldi
IIE

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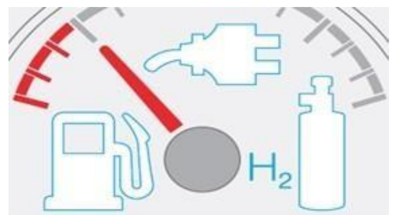
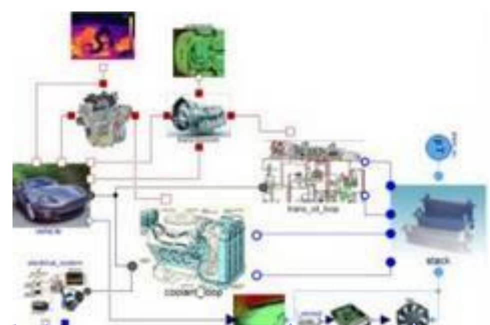
Motivation





To support research and enhance a better future:

SEVENTH FRAMEWORK PROGRAMME

GASTone is one of the project that belongs to the FP7-transport

Concept and Objectives

- **The main goal of the Project is the development of a new powertrain concept based on the integration of:**

$\eta > 50\,\%$

At vehicle level

Concept and objectives

- **This target will be mainly reached based on the following three streams:**

  (1) The **energy recovery** from the exhaust gases heat with a cascade approach thanks to the adoption of an advanced thermoelectric generator and a turbo-generator.

  (2) The integration of a smart kinetic energy recovery system to substitute the alternator and generate electricity during decelerations **improving the efficiency of the engine**.

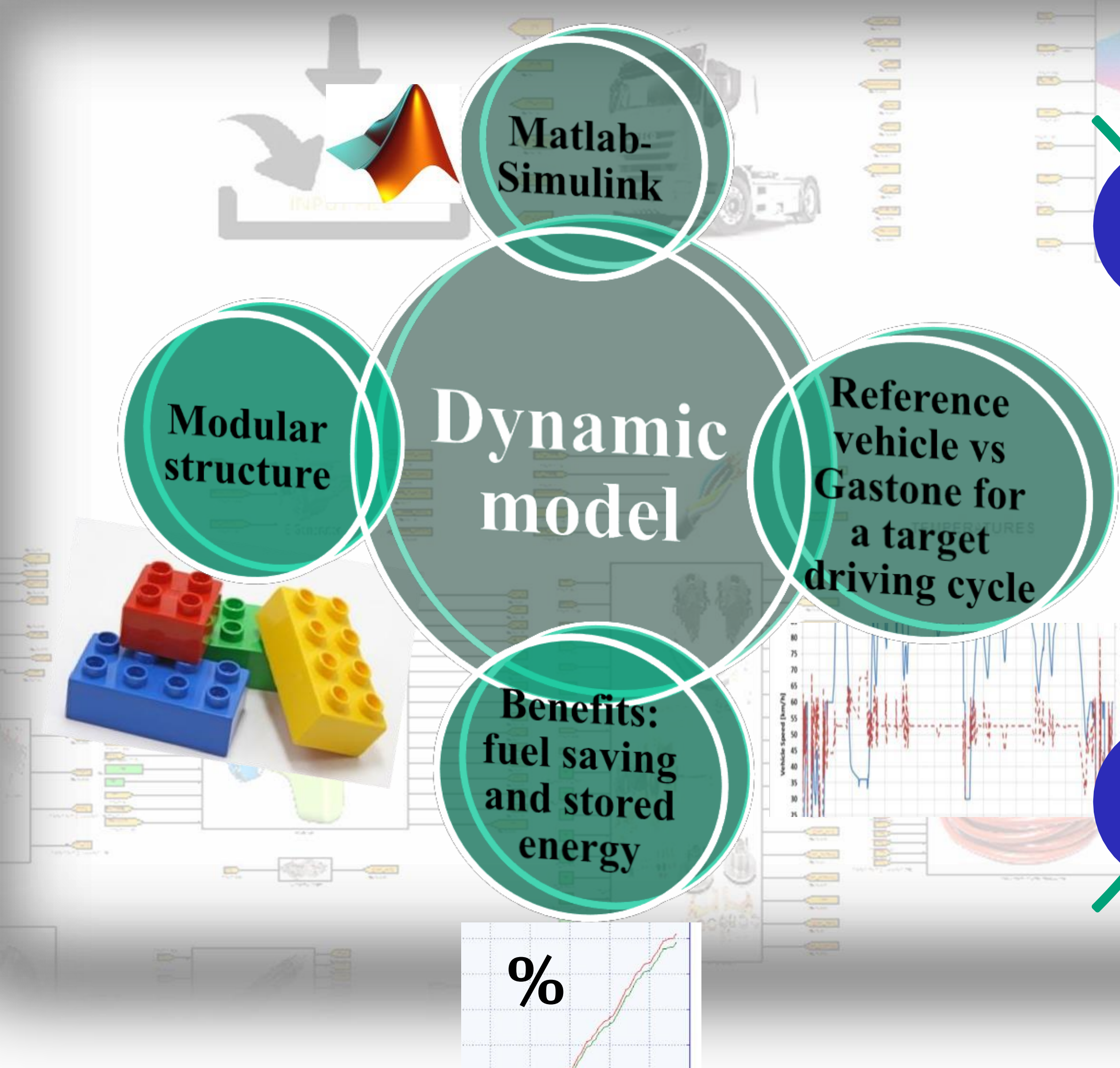
  (3) The **electrification and control of the main auxiliaries** (coolant pump, oil pump, auxiliary e-supercharger and air conditioning compressor) by using the produced electric energy.

- **The system includes sizing and development of an appropriate energy storage system as well as the adoption of electrified auxiliaries.**

- **To optimize and evaluate the integration of the whole system and the control strategy, a dynamic model has been developed.**

- **The project results will be demonstrated at bench level while the benefits of the control strategies will be evaluated at vehicle level thanks to advanced dynamics models.**

Dynamic model



Target of the model:

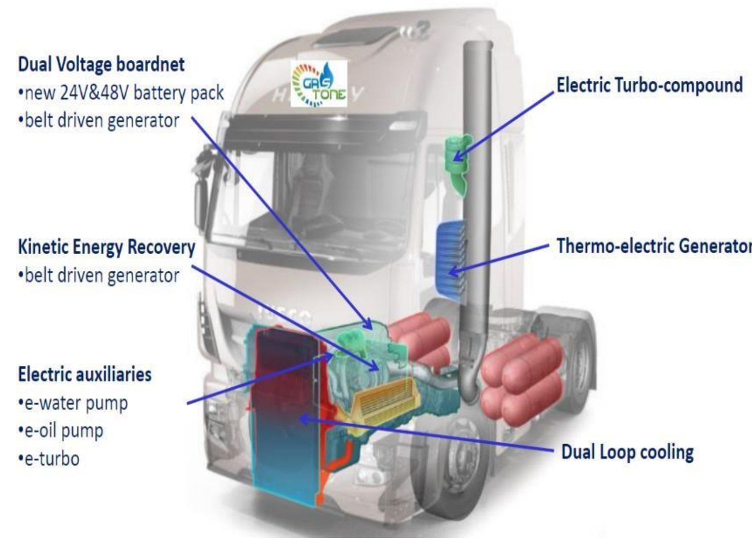
- Estimate the total fuel consumption over the driving cycle
- Estimate the energy balance of the system: Production vs consumption
- Estimate the temperatures and pressures in each relevant point
- Comparison between the reference vehicle and the Gastone concept

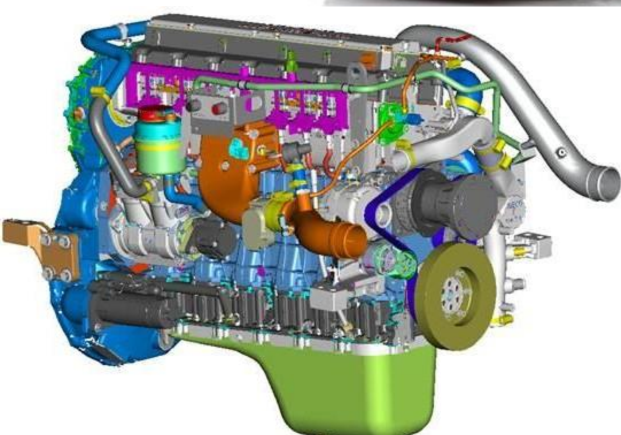
Engine Description

REFERENCE VEHICLE: the reference vehicle is ***IVECO STRALIS CNG MY2014***, the reference engine is ***Cursor8 CNG Euro VI*** and the experimental data for it is given by one of the partners.

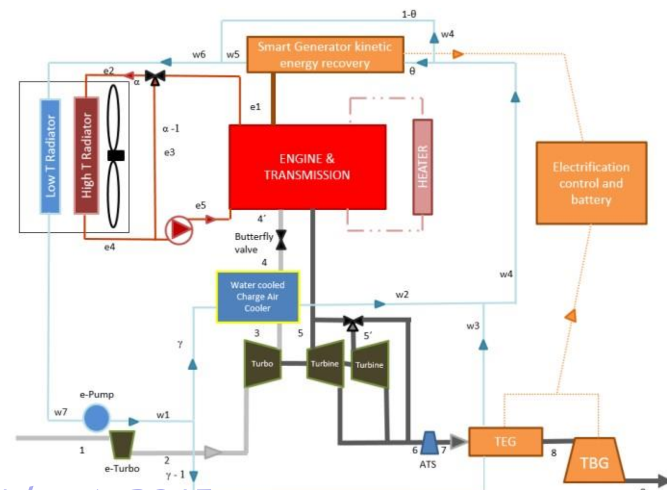
VS.

GASTONE CONCEPT:



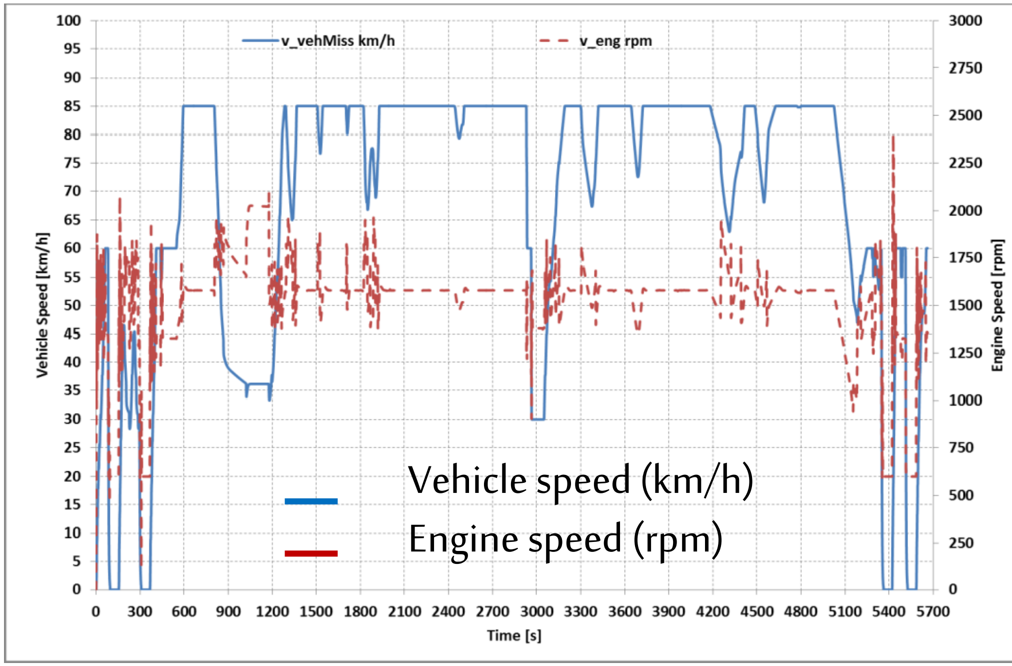


- ***Model:*** *AT440S33T/P CNG*
- ***Vehicle:*** *Tractor 4x2 Artic (UG4T)*
- ***Cabin:*** *AT*
- ***Weight:*** *44 t*
- ***Gear box*** *mechanical ZF (16 speed)*
- ***Mission:*** *road (Long haulage deliveries)*
- ***Engine:*** *Cursor8 L6 CNG Euro VI*
- ***Power and Torque:*** *243kW - 330 HP - 1.300 Nm*
- ***Differential gear ratio:*** *1:3.7 (default Euro VI)*
- ***Wheel (default Euro VI):*** *295/80R22.5*

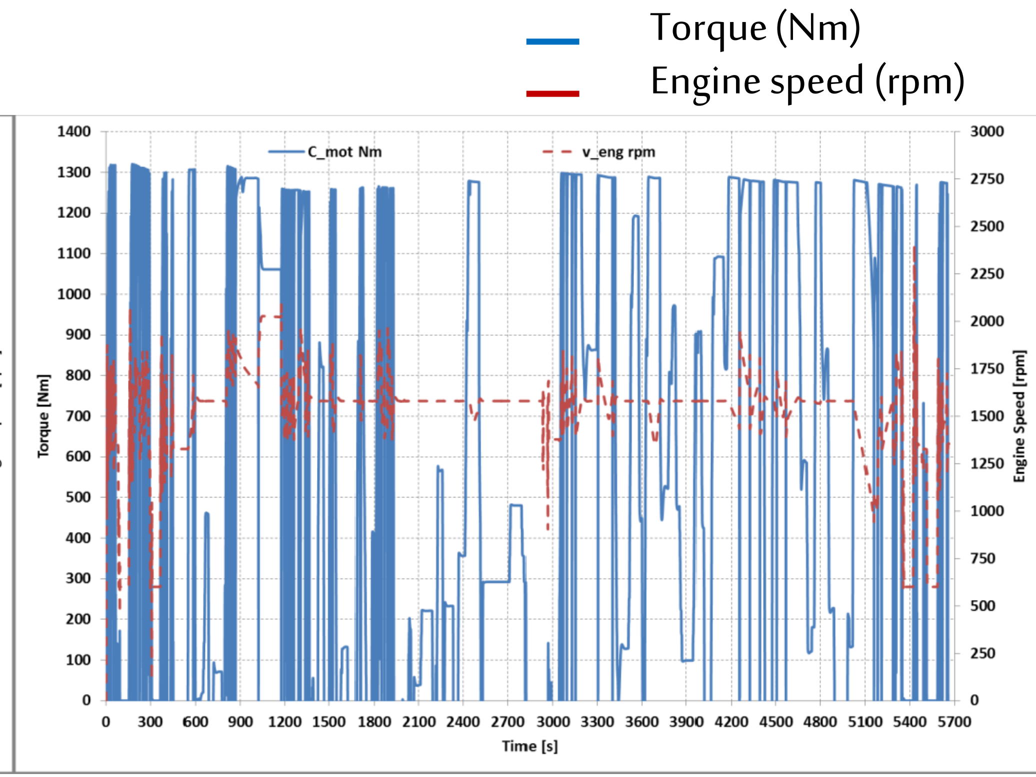


Reference driving cycle: ACEA cycle

- The reference mission is the ACEA long haul and its duration is 5662 seconds.



Vehicle Speed Profile



Torque Profile

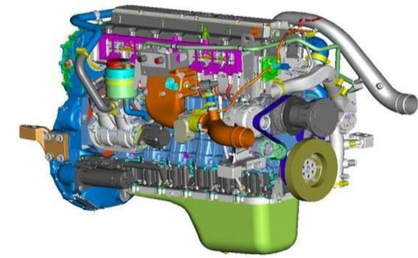
Engine

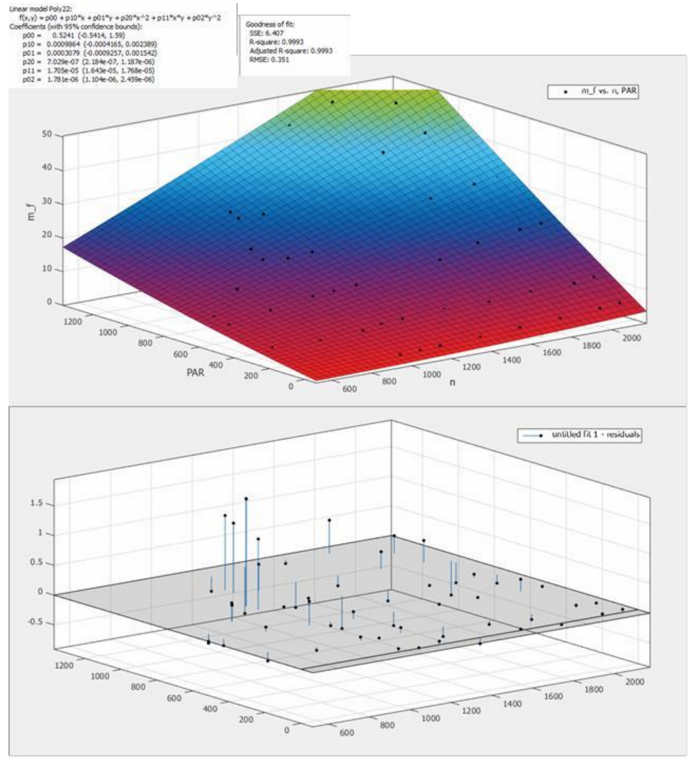
The engine has been modeled based on real data for the "reference vehicle".

The torque and the engine speed in each of the cycle points are the inputs: $\phi_i = \phi_i(n, M)$

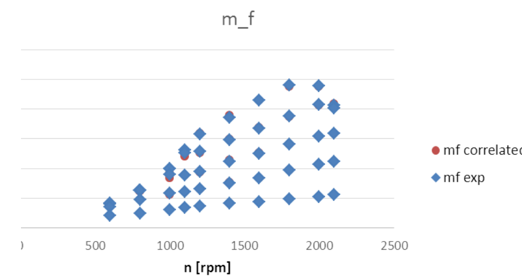
While the outputs are:

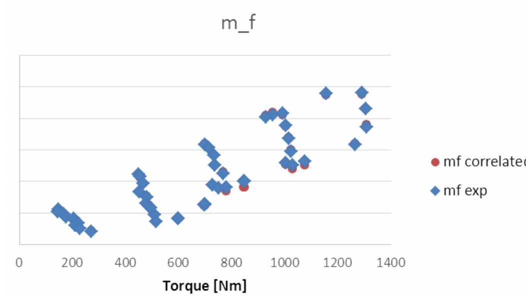
- Mechanical Power [kW]
- Fuel mass flow rate [kg/s]
- Air mass flow rate [kg/s]
- Total engine power
- The heat loss to exhausted gas [kW]
- Heat loss to ambient [kW]
- Q disipated by the radiator
- Heat transfer removed by the AC
- Exhaust temperature
- Temperature after the ATS



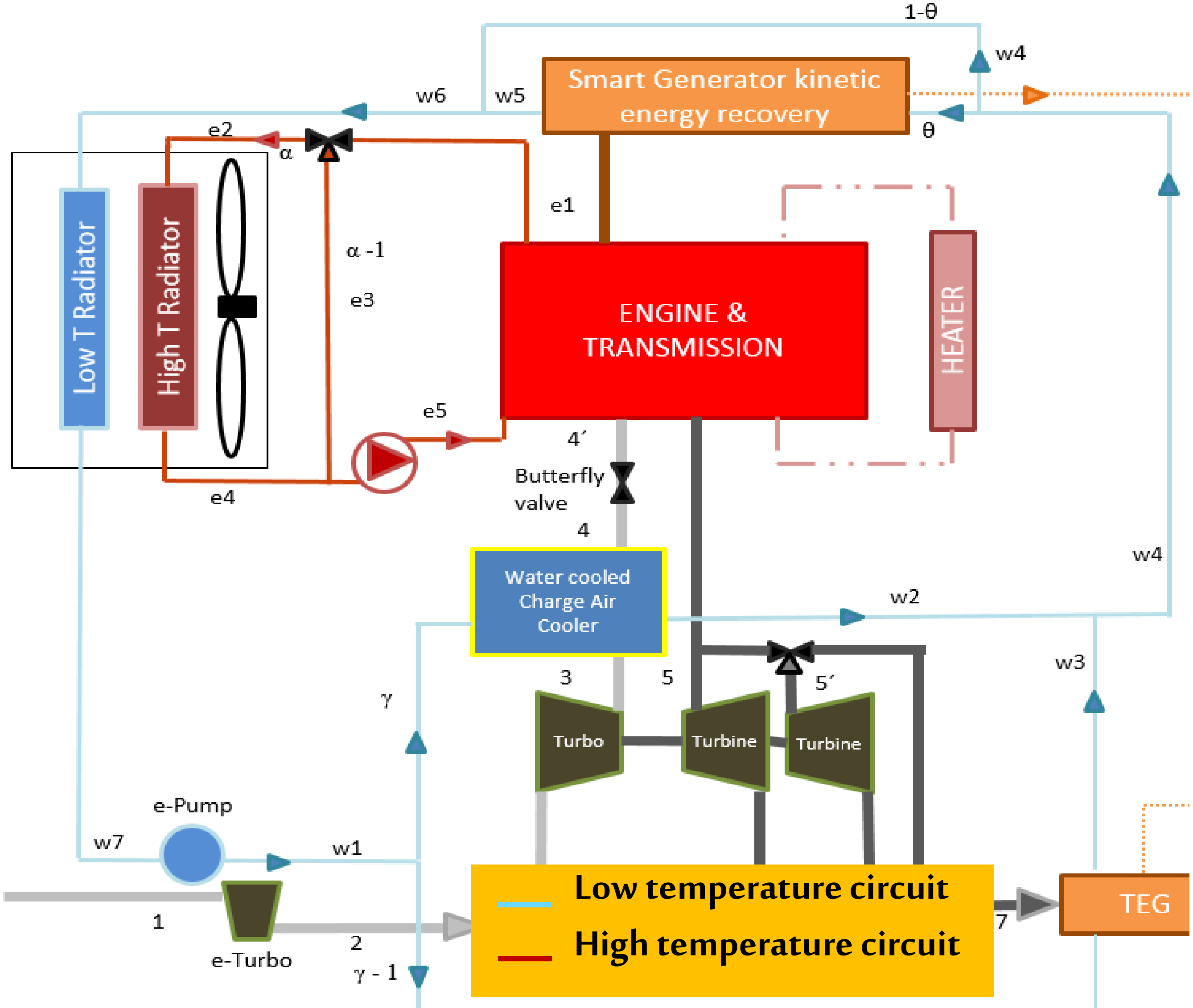


mf (Torque, n)





Low and high temperature water circuits



Models:

-WCAC (heat transfer and pressure drop)

-TEG (Heat transfer, electric production, pressure drop)

- KER (Electric production, pressure drop)

-LTR (Heat transfer, pressure drop)

- HTR (Heat transfer,pressure drop)

Radiators model

The following methodology has been used:

LTR,HTR and IC

Effectiveness model

$$\varepsilon^* = \varepsilon_s = \frac{Q}{C_{min} \cdot (T_{air\_in} - T_{w\_in})}$$

$$\varepsilon = 1 - \exp\left[\frac{NTU^{0.22} \cdot (\exp[-C^* \cdot NTU^{0.78}] - 1)}{C^*}\right]$$

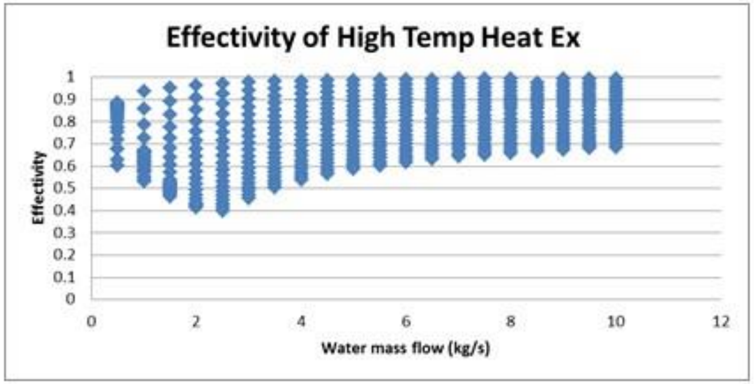
$$NTU = \frac{UA}{c_{p,air} \cdot \dot{m}_{air}} \qquad C^* = \frac{C_{min}}{C_{max}} = \frac{c_{p,air} \cdot \dot{m}_{air}}{c_{p,w} \cdot \dot{m}_w}$$

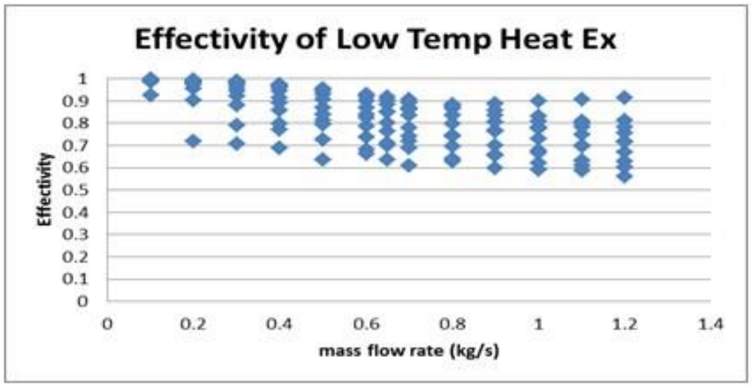
ESDU 86018, Effectiveness – NTU Relationships for the Design and Performance Evaluation of Two-Stream Heat Exchangers (1991); Engineering Science Data Unit 86018 with amendment A, July 1991, pp. 92–107, ESDU International plc, London.

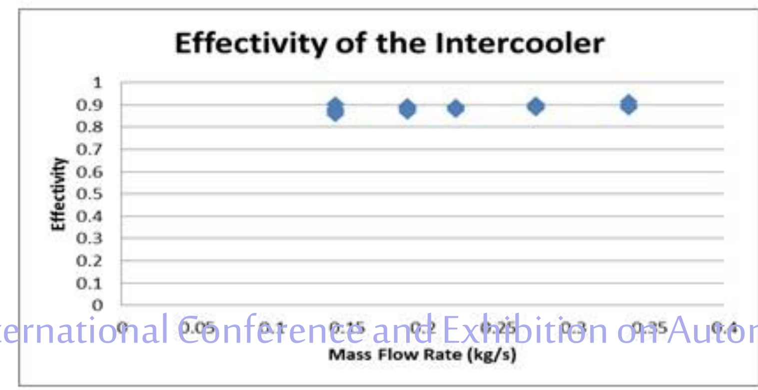
$$UA = \frac{1}{\frac{1}{h_i \cdot A_i} + \frac{1}{h_e \cdot (A_w + \eta A_f)_e}}$$

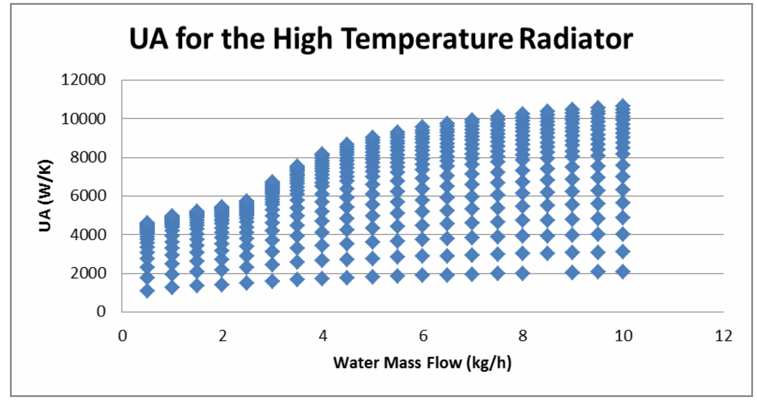
$$UA = \frac{1}{\frac{1}{K_1 \cdot \dot{m}_w^{n1}} + \frac{1}{K_2 \cdot \dot{m}_{air}^{n2}}}$$

Heat exchangers model (Heat Exchange)









$$UA = \frac{1}{\frac{1}{K_1 \cdot \dot{m}_w^{n1}} + \frac{1}{K_2 \cdot \dot{m}_{air}^{n2}}}$$

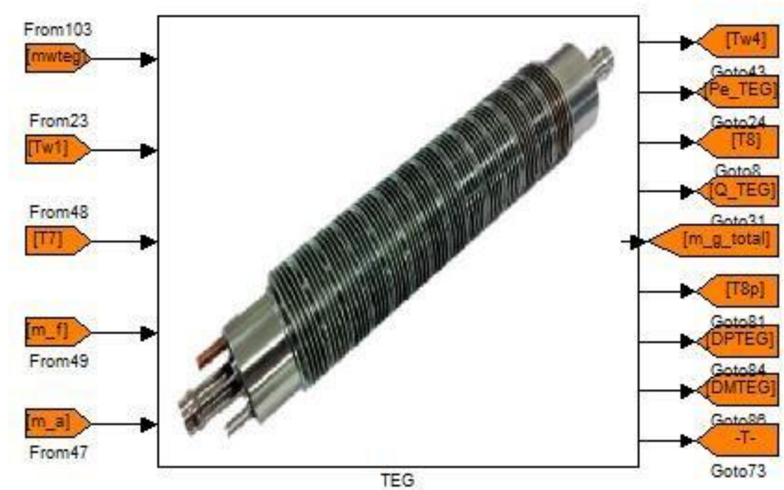
Constant	Radiator high temperature circuit Laminar/Turbulent		Low temperature circuit	Intercooler
K1	7940	5241	16587	9141449.7
n1	0.22	0.76	0.52	0.3
K2	3639	4435	4105	2887.9
n2	0.67	0.76	0.68	1.1

Error in effectiveness is lower than 2% for all the cases

Thermoelectric Generator (TEG)

Inputs

- Water mass flow rate
- Water inlet Temperature
- Gas inlet temperature
- Fuel mass flow rate
- Air mass flow rate



Outputs

- Back-pressure
- Water pressure drop
- Water outlet Temperature
- Gas oulet temperature
- Heat transfer
- Power production

Low temperature water circuit

TEG-Thermal problem

- The value of UA can be estimated from the experimental data as:

$$UA = \frac{Q}{DMLT} \rightarrow UA = f(m_{hg}, T_{hg}, T_w) = 0.0018 m_{hg}^{0.1062} + 4.2703 \cdot 10^{-7} T_{hg} + 9.9135 \cdot 10^{-7} T_w$$

$$NTU = \frac{UA}{mCp_{min}}$$

$$C_r = \frac{mCp_{min}}{mCp_{max}}$$

Effectiveness correlation for cross flow heat exchangers:

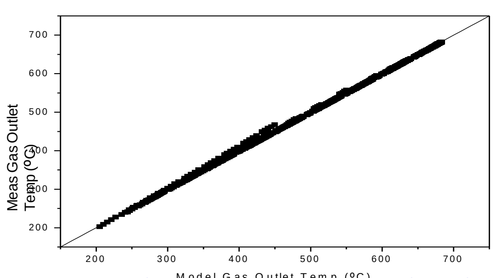
$$\varepsilon = 1 - \exp\left(\frac{1}{C_r}\left(NTU^{0.22}\left(\exp(-C_r NTU^{0.78}) - 1\right)\right)\right)$$

$$Q = \varepsilon m Cp_{min}(T_{hgin} - T_{win})$$

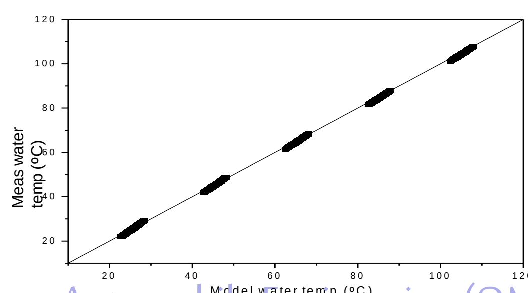
$$T_{wout} = \frac{Q}{mCp_w} + T_{win}$$

$$T_{hgout} = T_{hgin} - \frac{Q}{mCp_{hg}}$$

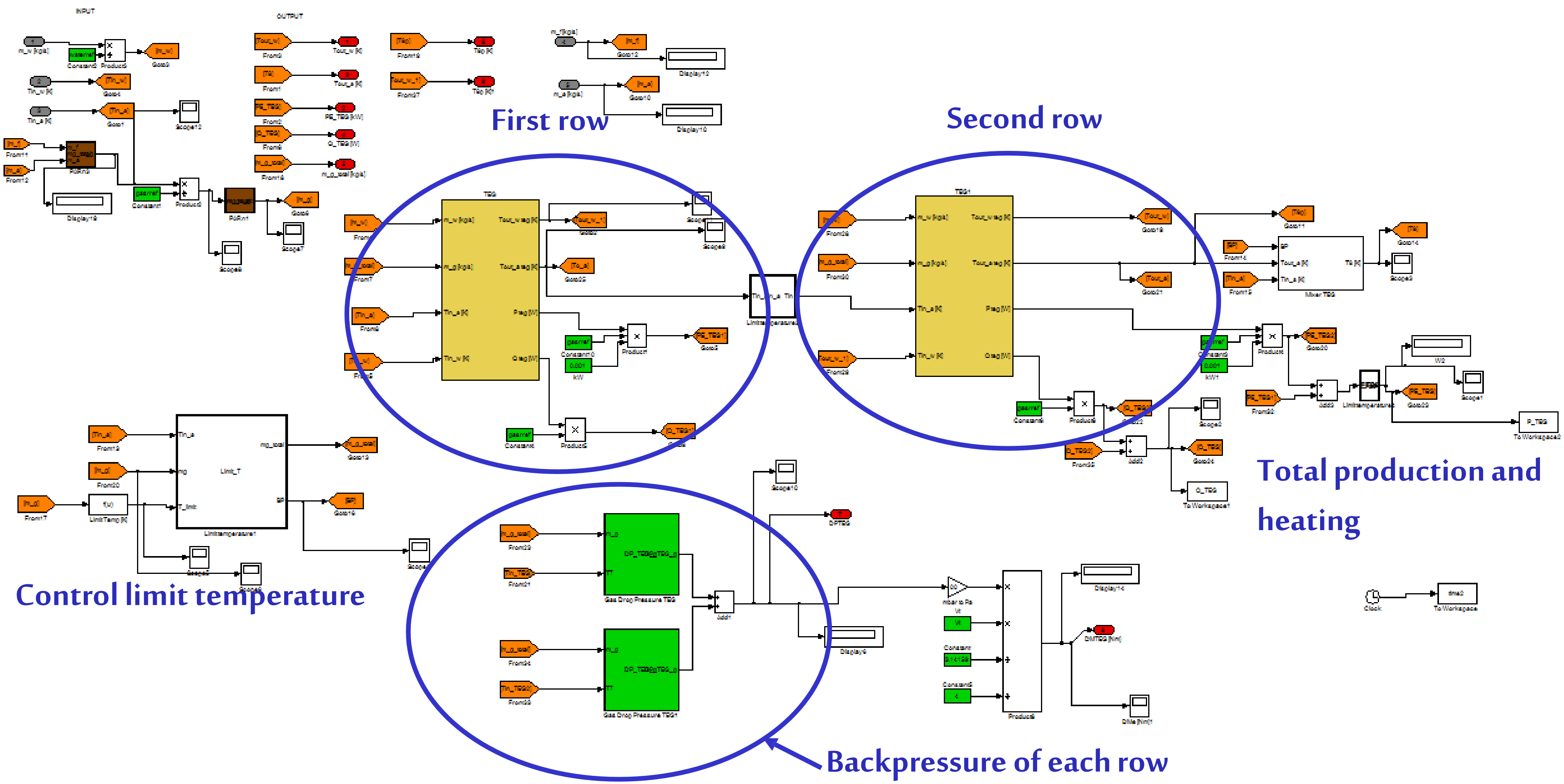
Hot Gas outlet temperature



Water outlet temperature



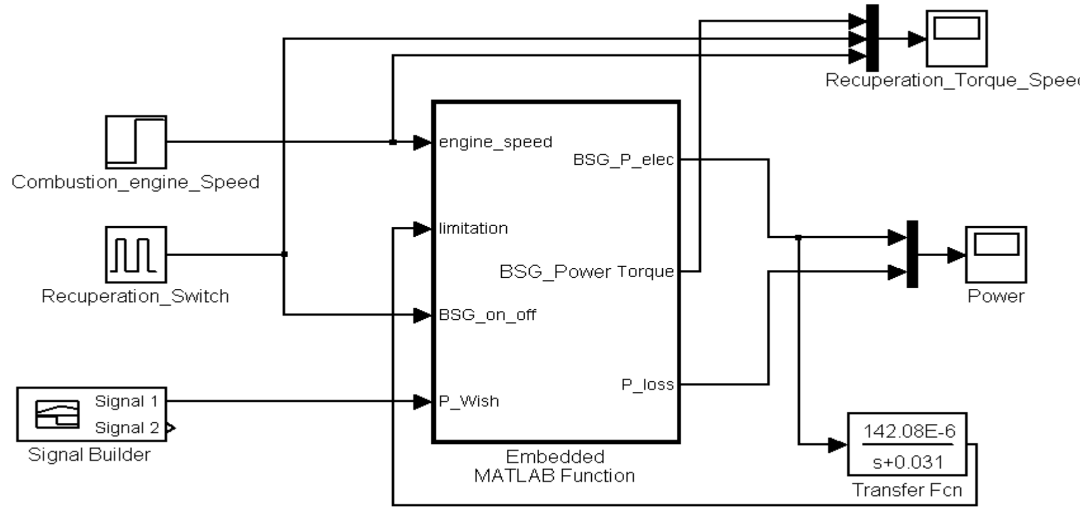
TEG-model


First row
Second row
Total production and heating
Control limit temperature
Backpressure of each row

Kinetic Energy Recovery System-KER

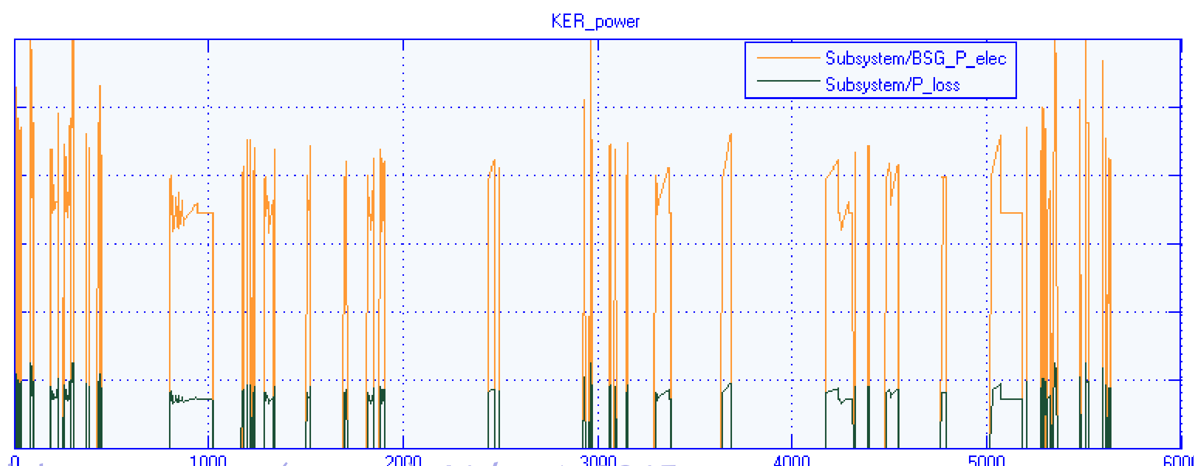
Inputs

- Engine speed
- Deceleration periods
- Electric demand

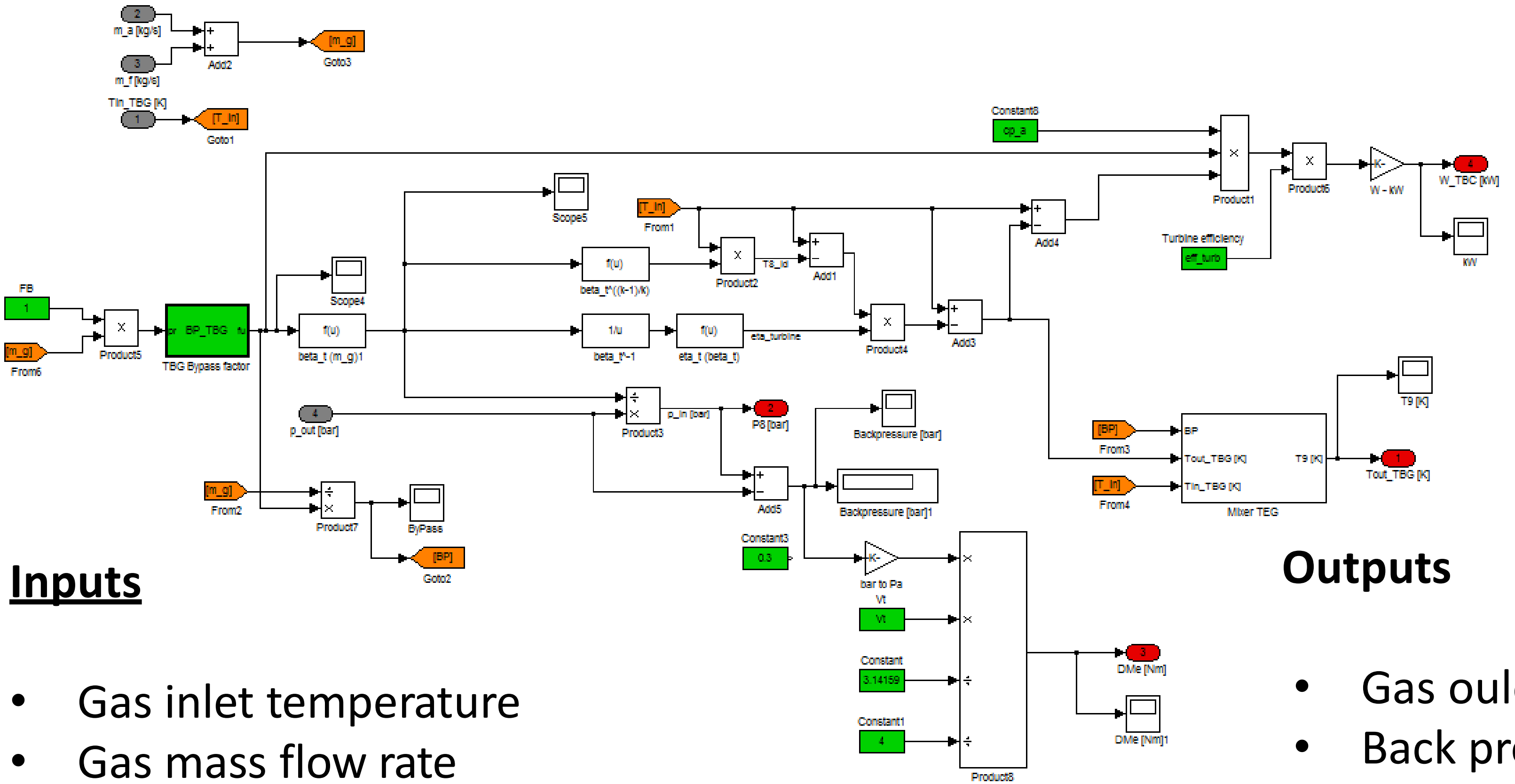


Outputs

- Electric production
- Torque increase
- Heat loss



Turbogenerator: TBG



Inputs

- Gas inlet temperature
- Gas mass flow rate
- Oulet pressure

Outputs

- Gas oulet temperature
- Back pressure
- Inlet pressure
- Electric generation

TBG-modeling

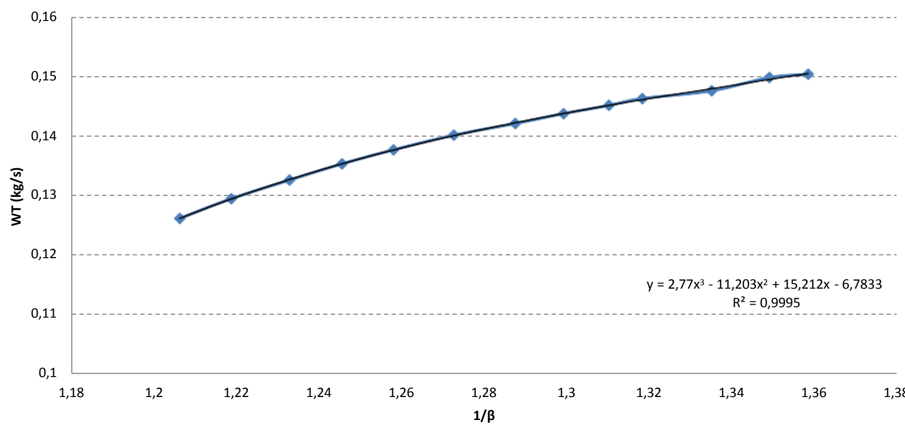
Methodology: The TBG is modeled based on the turbine equations and the correlations has been found from experimental data.

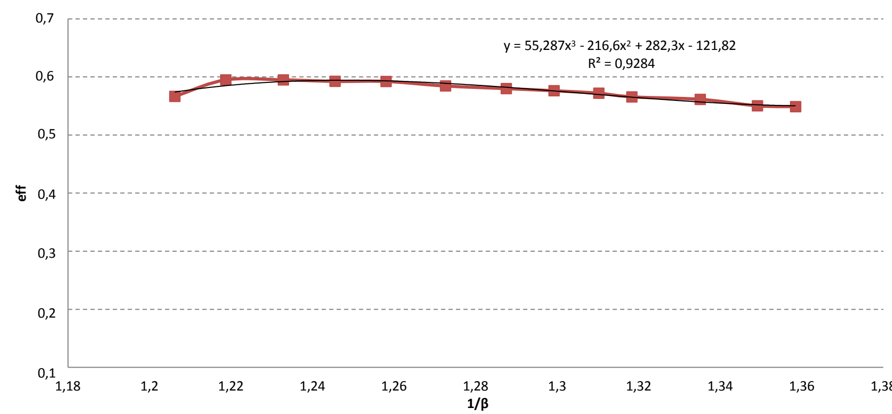
$$\beta_t = \frac{p_8}{p_7} = 1 - 1.839 \cdot m_g + 15.31 \cdot m_g^2 - 93.48 \cdot m_g^3$$

$$T_8 = T_7 \cdot \left[1 - \eta_t \left(1 - \beta_t^{\frac{k-1}{k}} \right) \right]$$

$$W_{TBC} = \dot{m}_g c_{p,a} (T_7 - T_8)$$

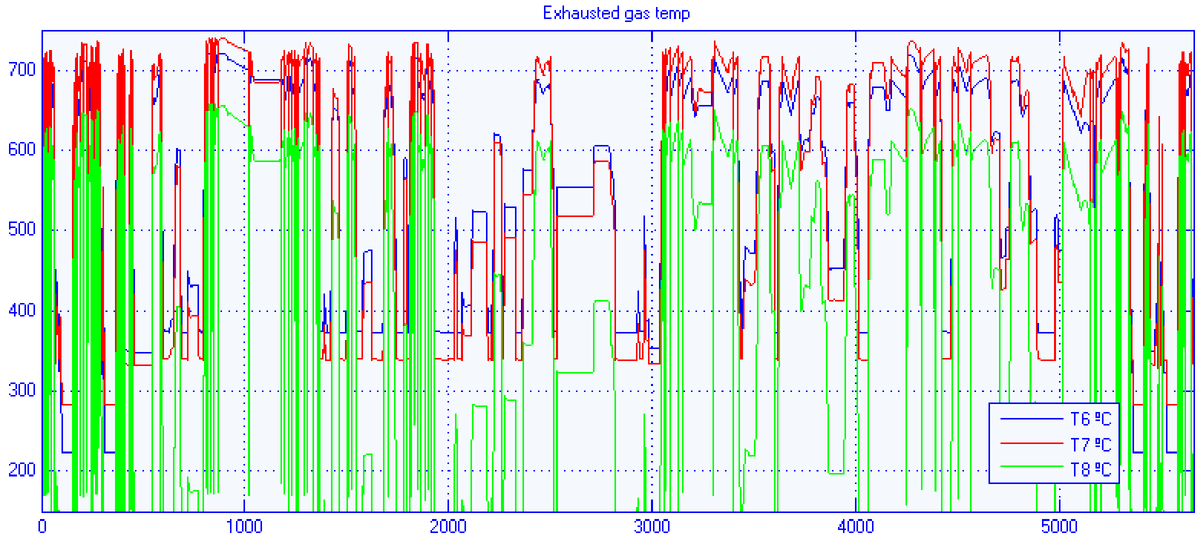
k=1.391

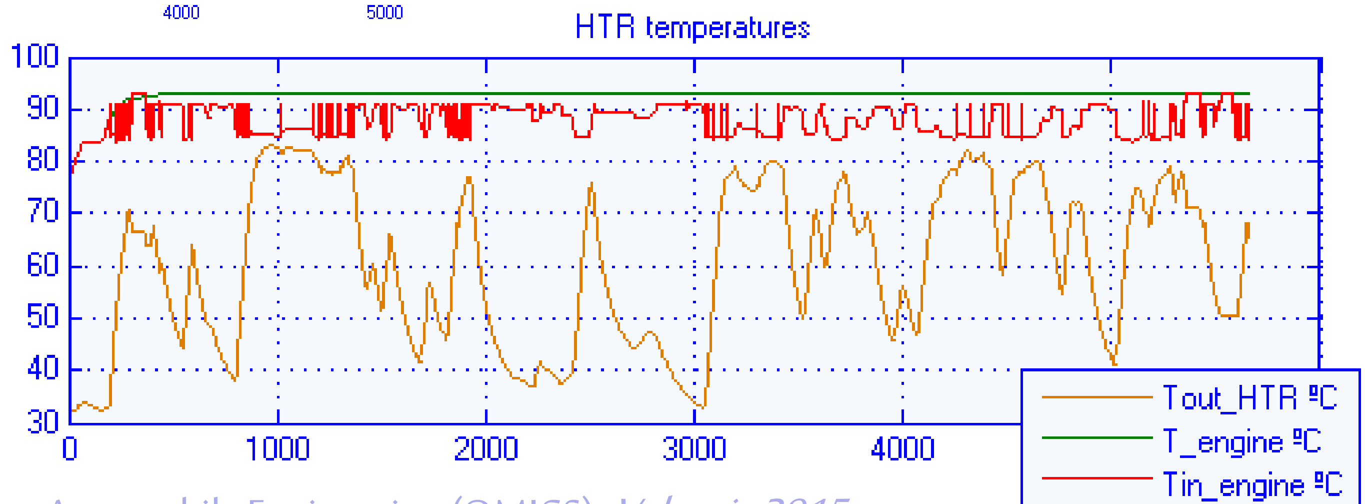




Results

Temperature at different points of the ACEA cycle for the powertrain

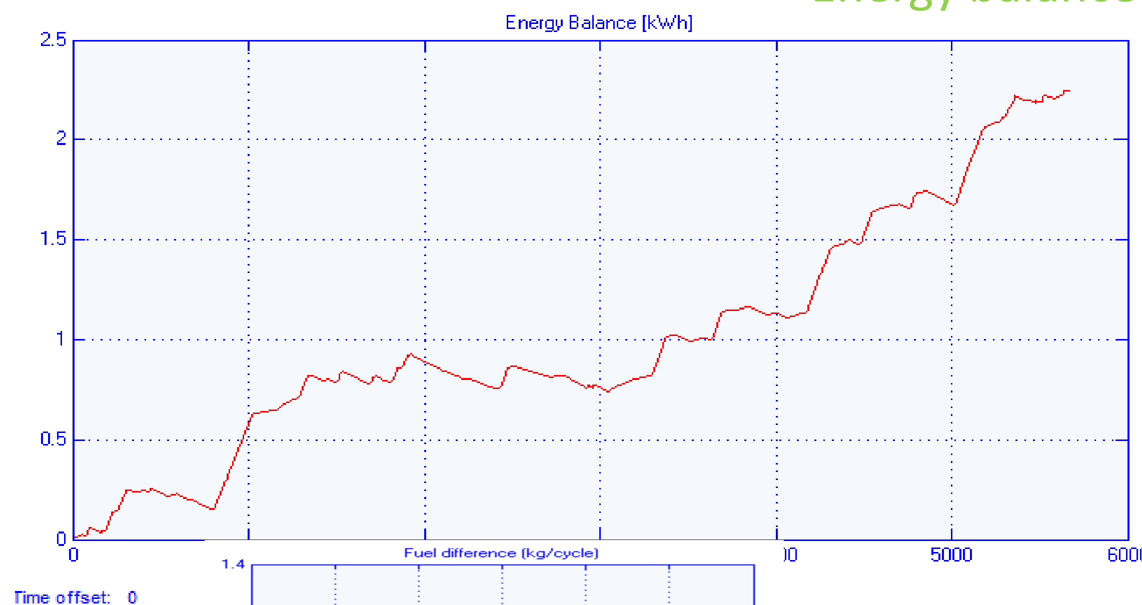


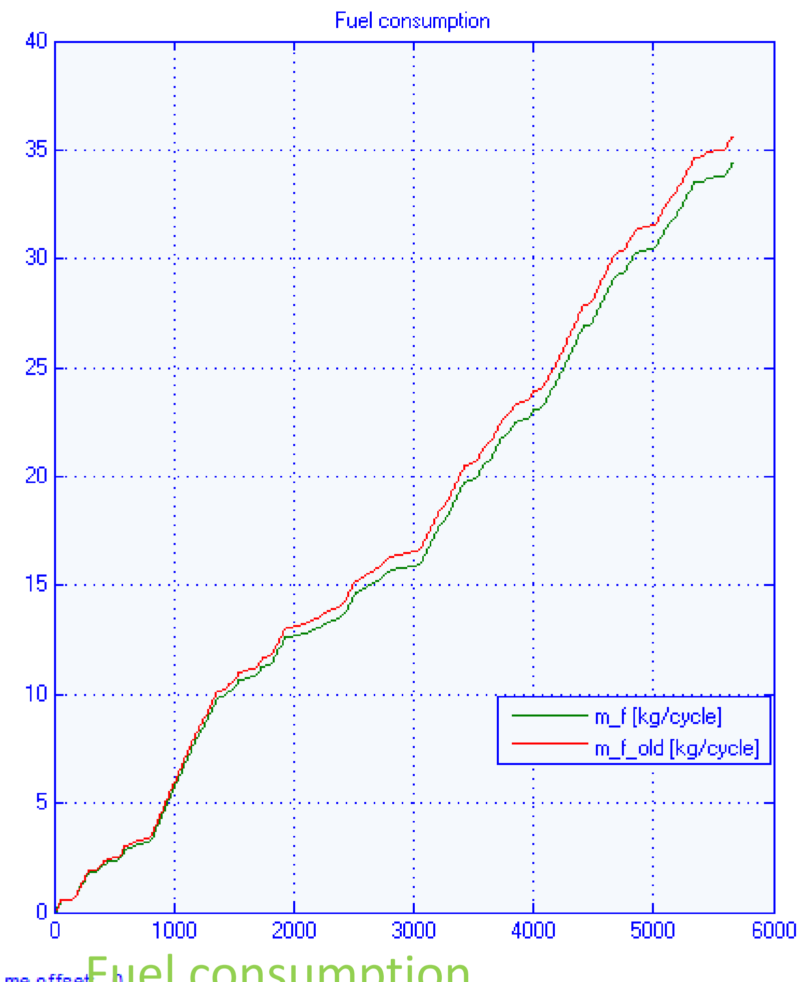


Results

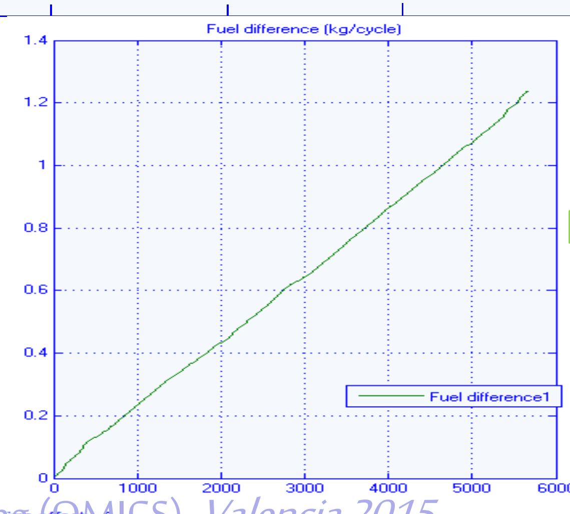
Fuel consumption comparison between the Gastone concept and the reference vehicle

Energy balance





Fuel consumption



Fuel difference

Model preliminary results

Nominal point

	Electric energy (kWh)	Average Power (kW)
TEG	0.7094	0.4562
KER	-	-
TBG	2.113	1.3944
Total produced	2.8224	1.8506
Total consumed	2.6888	1.7096
Stored energy	0.1344	-
Fuel saved	1.99%	

Cycle time 5662sec

ACEA driving cycle

	Electric energy (kWh)	Average Power (kW)
TEG	0.7962	0.5062
KER	2.4620	1.5653
TBG	1.6990	1.0802
Total produced	4.9572	3.1496
Total consumed	2.6888	1.7096
Stored energy	2.2684	-
Fuel saved	3.472%	

Results strongly depend on the components perfomance and sytem management.

Model expected results

Definition of the thermal characteristics (temperature, pressure) at any point of the system.

The possibility of the comparison between different control strategies.

The study of the influence of changes in different parameters under an overall point of view as well as at the subsystem level.

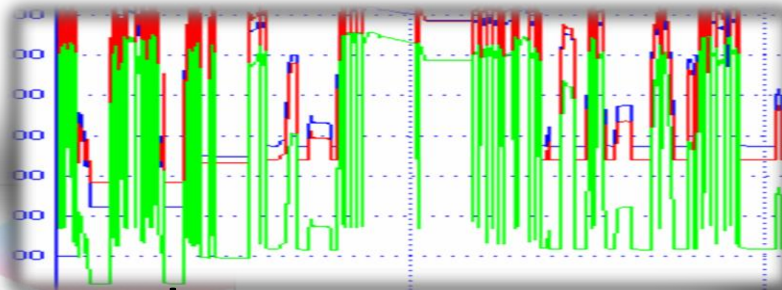
Flexibility in the considered components.

The benefit measured in terms of fuel saving and stored energy.

Optimization of the electric energy production (energy stored and production out of the deceleration periods).

The possible study for different driving cycles.

Conclusions



- **The model is successfully working as the temperature and pressure conditions can be seen.**

- **It is possible to define and evaluate different control strategies.**

- **The models of the components are already developed and waiting for validation.**

- **Currently, we are defining the size and the specifications of the components.**

- **After the collection of the data, the auxiliaries will be electrified and an optimal control strategy will be investigated.**

Thank you very much for your attention!