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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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IIE
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• Motivation
• Concept and Objectives
• Engine description
• Driving cycle
• Modelling
• Results
• Project timing and next steps
• Conclusions
Motivation

To support research and enhance a better future:

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:

  - Energy recovery and storage
  - System control strategies

\[ \eta > 50\% \]

At vehicle level

Natural Gas engine
Electric generation

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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

Matlab-Simulink

Modular structure

Reference vehicle vs Gastone for a target driving cycle

Benefits: fuel saving and stored energy

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

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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.

GASTONE CONCEPT:

- **Model**: AT440S33T/P CNG
- **Vehicle**: Tractor 4x2 Artic (UG4T)
- **Cabin**: AT
- **Weight**: 44 t
- **Gear box**: mechanical 2F (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

- **Vehicle speed (km/h)**
- **Engine speed (rpm)**

### Torque Profile

- Torque (Nm)
- Engine speed (rpm)
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

\( mf (\text{Torque}, n) \)
**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:

Effectiveness model

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

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

\[ NTU = \frac{UA}{C_{p\_air} \cdot \dot{m}_{air}} \]

\[ C^* = \frac{C_{min}}{C_{max}} = \frac{C_{p\_air} \cdot \dot{m}_{air}}{C_{p\_w} \cdot \dot{m}_{w}} \]

\[ UA = \frac{1}{h_i \cdot A_i} + \frac{1}{h_s \cdot (A_w + \eta A_f)} \]

Heat exchangers model (Heat Exchange)

Effectivity of High Temp Heat Ex

Effectivity of Low Temp Heat Ex

Effectivity of the Intercooler

UA for the High Temperature Radiator

\[
UA = \frac{1}{\frac{1}{K_1 \cdot m_w^{n1}} + \frac{1}{K_2 \cdot m_{air}^{n2}}}
\]

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

<table>
<thead>
<tr>
<th>Constant</th>
<th>Radiator high temperature circuit Laminar/Turbulent</th>
<th>Low temperature circuit</th>
<th>Intercooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_1)</td>
<td>7940</td>
<td>5241</td>
<td>16587</td>
</tr>
<tr>
<td>(n_1)</td>
<td>0.22</td>
<td>0.76</td>
<td>0.52</td>
</tr>
<tr>
<td>(K_2)</td>
<td>3639</td>
<td>4435</td>
<td>4105</td>
</tr>
<tr>
<td>(n_2)</td>
<td>0.67</td>
<td>0.76</td>
<td>0.68</td>
</tr>
</tbody>
</table>
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 outlet temperature
- Heat transfer
- Power production
Low temperature water circuit

TEG-Thermal problem

• The value of $U_A$ can be estimated from the experimental data as:

\[
U_A = \frac{Q}{DMLT}
\]

\[
UA = f(m_{hg}, T_{hg}, T_w) = 0.0018m_{hg}^{0.1062} + 4.2703 \cdot 10^{-7} T_{hg} + 9.9135 \cdot 10^{-7} T_w
\]

\[
NTU = \frac{UA}{m C_p \min}
\]

\[
C_r = \frac{\max}{m C_p \min}
\]

Effectiveness correlation for cross flow heat exchangers:

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

\[
Q = \varepsilon m C_p \min (T_{hg in} - T_{win})
\]

\[
T_{wout} = \frac{Q}{m C_p_w} + T_{win}
\]

\[
T_{hg out} = T_{hg in} - \frac{Q}{m C_p_{hg}}
\]
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
- Outlet pressure

Outputs

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

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

\[
\beta_t = \frac{P_8}{P_7} = 1 - 1.839 \cdot m_g + 15.31 \cdot m_g^2 - 93.48 \cdot m_g^3
\]

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

\[
W_{TBC} = m_g c_{p,a} (T_7 - T_8)
\]

\[k = 1.391\]
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 difference

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# Model preliminary results

## Nominal point

<table>
<thead>
<tr>
<th></th>
<th>Electric energy (kWh)</th>
<th>Average Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG</td>
<td>0.7094</td>
<td>0.4562</td>
</tr>
<tr>
<td>KER</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TBG</td>
<td>2.113</td>
<td>1.3944</td>
</tr>
<tr>
<td>Total produced</td>
<td>2.8224</td>
<td>1.8506</td>
</tr>
<tr>
<td>Total consumed</td>
<td>2.6888</td>
<td>1.7096</td>
</tr>
<tr>
<td>Stored energy</td>
<td>0.1344</td>
<td>-</td>
</tr>
<tr>
<td>Fuel saved</td>
<td></td>
<td>1.99%</td>
</tr>
</tbody>
</table>

## ACEA driving cycle

<table>
<thead>
<tr>
<th></th>
<th>Electric energy (kWh)</th>
<th>Average Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEG</td>
<td>0.7962</td>
<td>0.5062</td>
</tr>
<tr>
<td>KER</td>
<td>2.4620</td>
<td>1.5653</td>
</tr>
<tr>
<td>TBG</td>
<td>1.6990</td>
<td>1.0802</td>
</tr>
<tr>
<td>Total produced</td>
<td>4.9572</td>
<td>3.1496</td>
</tr>
<tr>
<td>Total consumed</td>
<td>2.6888</td>
<td>1.7096</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.2684</td>
<td>-</td>
</tr>
<tr>
<td>Fuel saved</td>
<td></td>
<td>3.472%</td>
</tr>
</tbody>
</table>

Cycle time 5662sec

Results strongly depend on the components performance and system management.

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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.

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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.
MODEL Of A New Powertrain Concept Based On The Integration Of Electric Generation, Energy Recovery AND Storage

Thank you very much for your attention!