Comparison of AWD vehicle powertrains

Authors: N. Holjevac, E. Sabbioni
Field of interest

- Vehicle and powertrain subsystems
- Powertrain architectures
- Modelling and simulation methods
- Multi-objective optimization
AWD powertrains

- AWD
  - driving performances
- electrified powertrains
  - energy consumption

EU average market share
- 5% in 2001
- 15% in 2016

Graph showing market share of vehicles with all-wheel drive from 2001 to 2016.
Methodological approach

- Modelling
- Optimization
- Results
- Conclusions
Methodological approach

- Modelling
- Optimization
- Results
- Conclusions
Modelling

- Vehicle: lumped parameters + lookup tables
- Internal Combustion Engine: 1D CFD
- Electric Motor: Electromagnetic FEM
Energy management strategy

- Gear shifting
- Power management
  - Axle power distribution
  - Hybrid operating modes

WLTP Driving Cycle

- HEV
- ICE 1.2 l
- Battery 30 kWh 165 Ah

Graz/Spielberg, May 9 to 10, 2019
Electrification & All-Wheel Drive Congress
Methodological approach

- Modelling
- Optimization
- Results
- Conclusions
Optimisation

Vehicle Level
- Specific vehicle
- AWD Class D

Subsystem Level
- Individual powertrain analysis

Components Level
- Design variables
### Design Variables

- Focus on powertrain subsystems
- Reduced set of subsystems main design variables

<table>
<thead>
<tr>
<th>Battery</th>
<th>Series cells</th>
<th>30,...,160(120*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parallel cells</td>
<td>10,...,70(50*)</td>
</tr>
<tr>
<td></td>
<td>Scaling factor</td>
<td>0,...,1</td>
</tr>
</tbody>
</table>

| ICE     | Bore/Stroke | 0.8,...,1.2     |
|---------| CR          | 9,...,13        |
|         | Bore [mm]   | 65,...,100      |
|         | Cylinders   | 3,4,6,8 (3,4**) |

<table>
<thead>
<tr>
<th>EM(GEN)</th>
<th>Type</th>
<th>PMSM,AIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM Power distribution (rear/front)</td>
<td>Current ratio (GEN/Battery)</td>
<td>0.1,...,0.9</td>
</tr>
<tr>
<td>GEN speed [rpm]</td>
<td>10000,...,20000</td>
<td></td>
</tr>
<tr>
<td>EMF speed [rpm]</td>
<td>10000,...,20000</td>
<td></td>
</tr>
<tr>
<td>EMR speed [rpm]</td>
<td>10000,...,20000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GearboxICE</th>
<th>Gears add</th>
<th>0,1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max gear ratio</td>
<td>3,...,5</td>
</tr>
<tr>
<td></td>
<td>Min gear ratio</td>
<td>0.4,...,0.9</td>
</tr>
<tr>
<td></td>
<td>type</td>
<td>MT,DCT,AT</td>
</tr>
<tr>
<td></td>
<td>Progression factor</td>
<td>0,...,1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GearboxEM</th>
<th>Max gear ratio</th>
<th>2,...,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front gears</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Rear gears</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

| Differential | Scaled gear ratio | 0.5,...,1.5 |
Objectives

- Consumption
- Range
- Emission
- Cost
- Dynamics
- Overtaking
- Consumer

Normalisation values [min-max]

Average consumer satisfaction based on: objectives fulfillment of common vehicle performances, off-road driving capabilities, cornering stability and optional components installation

\[
\text{Consumer} = \frac{1}{7} \left( \text{Consumption} \left[ \left[ \frac{6\text{–}10 \ \text{€}}{100\text{km}} \right] \right] + \text{Range} [400\text{–}500 \text{ km}] + \text{Emission} [100\text{–}150 \%] \\
+ \text{top speed} \left[ \left[ \frac{250\text{–}300 \ \text{km}}{\text{h}} \right] \right] + \text{0\–}100 \left[ \left[ \frac{\text{km}}{\text{h}} \right] \right] + \text{acceleration} [3\text{–}5 \text{ s}] + \text{Dynamics} \\
+ \text{Cost} [10\text{–}50 \text{ k€}] + \text{optional components} \times 5\% \\
+ \text{off–road} [30\text{–}40 \%] \times 5\% \\
+ \sqrt{\text{wheel steer angle} [\pm 10\text{–}0 \ ^\circ]} \times \text{roll stability} [0.1\text{–}0.5] \times 5\% \right)
\]
Methodological approach

- Modelling
- Optimization
- Results
- Conclusions
## Solution space frontiers

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>Cost</td>
</tr>
<tr>
<td>HEVp</td>
<td>Consumer, Trade-Off ICE-EV</td>
</tr>
<tr>
<td>HEVs</td>
<td>Trade-Off ICE-EV</td>
</tr>
<tr>
<td>BEV</td>
<td>Consumption, Dynamics</td>
</tr>
</tbody>
</table>

![Graphs showing the cost and dynamics of different powertrains: ICE, HEVp, HEVs, BEV](image_url)
Optimal design

Optimal design identified considering:

- Correlation coefficients
- Values range
- Distance from Utopia point (ideal optimal result)
Design variables analysis

\[
\text{Level of Hybridization} = \frac{P_{\text{Battery}}}{P_{\text{Battery}} + P_{\text{ICE}}}
\]

- HEVp more efficient energy flow in the powertrain
- Dynamics improvement with the level of hybridization related to electric power increase (favourable low-end torque of electric motors)
Design variables analysis

*Level of Hybridization (LoH)*

- Charge Sustaining Mode in WLTP driving cycle (CS Mode)
- Remarkable fuel consumption savings for LoH up to 40%
- LoH > 40% allows to further improve maximum achievable acceleration
Design variables analysis

Power Split = \frac{P_{EM,front}}{P_{EM,rear} + P_{EM,front}}

- Consumption optimal solution lies in the range 30-40%
- Dynamics optimal solution depends on powertrain layout, 30-40% for BEV and HEVs, 10-20% for HEVp (combustion engine on front axle)
Design variables analysis

- Power increase worsens consumption, the effect is less sensitive in HEV by optimally selecting the level of hybridization.

- Dynamics reaches a plateau value showing that further power increase doesn't provide relevant improvements in vehicle dynamics.
Methodological approach

- Modelling
- Optimization
- Results
- Conclusions
Conclusions

• Modelling
  □ detailed definition of the powertrain subsystems
  □ optimal energy management strategy

• Optimization
  □ problem definition
  □ design variables, objectives

• Results
  □ comparison of several powertrain architectures
  □ identification of optimal design solutions
  □ analysis of the main design variables
Thank you for the attention