Optimal dimensioning and control of HEV powertrains via convex optimization

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Outline

- Overview of electrified vehicles.
- Powertrain dimensioning problem.
- Methods.
- Powertrain model.
- Thermal states.
- Heuristic decisions.
- Example of sizing a double buffer PHEV bus.
- Future work.
Overview of electrified vehicles

William Morrison Electric Wagon, 1892.

The first HEV by Dr. Ferdinand Porsche, 1898.

Autotram, Fraunhofer, battery and ultracapacitor.

Opbrid, Umeå, 250kW charging.
Powertrain dimensioning problem

- Optimal powertrain sizing.
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- Electric machine (EM),
- Internal combustion engine (ICE).
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Sizing of energy buffer, Electric machine (EM), Internal combustion engine (ICE).

Charging opportunity

Bus line model described by demanded velocity and road gradient. Charging opportunities are shaded.
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Distribution, type, power of charging stations, traffic density.

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Minimize
- Operational and component cost.

Subject to (at each point of time):
- Driving cycle constraints;
- Charging infrastructure constraints;
- Powertrain components constraints;
- States equality constraints;
- Initial and final state constraints.

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- Heuristic algorithms.
- Dynamic programming.
- Convex optimization.
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- Dynamic programming.
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Do not guarantee optimality.

Based on optimal performance.

Nonlinear, non-convex, mixed-integer problems.

Computation time is exponential to the number of states.

Design parameters cannot be included in the optimization.

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Short computation time.

Computation time is polynomial to the number of states.

Design parameters can be included in the optimization.

Approximations to convexify the problem.

Heuristics for ICE start-stops, gear.
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Powertrain model

- **Series powertrain.**
- **Parallel powertrain.**
- **Series-parallel powertrain.**

- Quasi-static powertrain model.
- Battery SOC (and temperature states).
Internal combustion engine

Left plot: static efficiency map of the ICE. Right plot: power losses of the original ICE model and approximation with quadratic losses for several ICE speeds.

\[ P_{ICEloss} \approx a_0(\omega)\tau_{ICE}^2 + a_1(\omega)\tau_{ICE} + a_2(\omega)e_{on} \]

- A binary variable is needed for the engine on/of state.
Electric machine

Left plot: static efficiency map of the EM. Right plot: power losses of the original EM model and approximation with quadratic losses for several EM speeds.

\[ P_{EM\text{loss}} \approx b_0(\omega)\tau_{EM}^2 + b_1(\omega)\tau_{EM} + b_2(\omega) \]
Energy buffer

- Ultracapacitor or battery cells.
- Quadratic losses.
- Linear approximation of battery open circuit voltage.
- Double buffer system is supported.

\[ P_b = \left( u_i - R_i^2 \right) n \]

Model of the battery open circuit voltage and linear voltage-SOC approximation. Good fit is expected in the allowed SOC range represented by the shaded region.
Scaled ICE and EM models

- Torque, losses, mass, inertia and cost scale linearly.
- Speed limit and efficiency map do not change.

\[
P_f = s_{ICE} (\tau_{ICE, base} \omega + P_{ICEloss, base})
\]
\[
P_{EMel} = s_{EM} (\tau_{EM, base} \omega + P_{EMloss, base})
\]

Components’ losses are scaled linearly within the shaded region. The right plots show examples of scaled components with maximum allowed size.
Thermal states

- Thermal states are supported.
- Cooling supported if concave on electric power.
- With quadratic losses, prevention of overheating is allowed.
- Further studies needed for cold start scenarios.
- Example: temperature of a battery cell,

\[ C_{Tb} \dot{T}_b = \sum_j \frac{T_j - T_b}{RT_j} + R_i^2 - P_{cool}(P_{el}). \]
Heuristic decisions

- Heuristic decisions are needed for gear and engine on/off.
- Simple on/off heuristics give error $\leq 1\%$ for series powertrains.
- Error from on/off heuristics can be removed (based on Pontryagin’s maximum principle).
- Further studies needed for improving gear heuristics.
Example: sizing of a thermally constrained double buffer PHEV bus

- 3 sizing parameters (EGU, battery, ultracapacitor).
- 3 continuous states (SOC and ultracapacitor temperature).

Bus line with 7 charging stations (10 s charging).

Optimal operating points of the energy buffer.

Optimal temperature and SOC trajectories.

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**Results**

- With 7 chargers: Ultracapacitor (0.82 kWh), battery (4.1 kWh usable).
- With 1 charger: Ultracapacitor (0.5 kWh), battery (17.5 kWh usable), charging power of 120 kW.

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**Optimal operating points of the energy buffer.**

**Optimal temperature and SOC trajectories.**

**Charging opportunity**

- 0
  - 20
  - 40
  - 60
- Velocity [km/h] 0 10 20 30 40
- Gradient [%] −4 −2 0 2 4
- t [min] 20
- Charging opportunity

**Cell power [kW]**

- Ultracapacitor
  - 0 2 4 6
- Battery
  - 0 0.2 0.4 0.6

**SOC [%]**

- Battery
  - 0 20 40 60 80 100
- Ultracapacitor
  - −5 −3 −1 0 2 4

**Operating points (7 chargers)**

- Power bounds
- Efficiency \( \geq 90\% \)
- \( SOC_{min}, SOC_{max} \)

**Operating points (1 charger)**

- 7 chargers
- 1 charger
- 20
- 40
- 60
- 80
- 100
- Ultracapacitor temperature
- Ultracapacitor SOC
- Battery SOC

**Battery**

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Future work

- Construction of thermal models for all powertrain components, including passenger compartment.
- Convex modeling of fuel cells and flywheel hybrids.
- Investigation of hybrids with planetary gear, or CVT.
- Distributed computation for large problems (design of city infrastructure).
- More practical results (for varying and realistic prices, realistic driving cycles, infrastructure design, robustness and sensitivity study, etc).