mobility, logistics and automotive technology
Powertrain Design and Modelling for Light and Heavy Duty Vehicles
Part 1
Challenges for Electromobility
20%
57% NOx – 25% PM
1 Billion Euro’s per Day for import of Oil in Europe
Top 3 Barriers for EVs

- High purchase cost
- Limited driving range
- Limited charging infrastructure
## Specific Energy (Wh/kg)

<table>
<thead>
<tr>
<th></th>
<th>Lead</th>
<th>Nickel</th>
<th>Lithium</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
</table>

The energy density increases by x2 for Nickel to Lithium, and by x3 for both Lead and 2030 compared to 2020.
Average battery pack price
$ per kWh

US, EU, and China electric vehicle sales¹
Units, thousands

1 Plug-in hybrid electric vehicles and battery electric vehicles; excludes low-speed vehicles and hybrid electric vehicles without a plug
2 Includes Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, and the UK
3 Extrapolated based on Q1-Q3 2016 IHS data and assuming continued growth in all three markets in Q4

SOURCE: IHS, Bloomberg, New Energy Finance
Market evolution

Purchase price (€) vs. Driving range (km)

- Tesla model X 60, 2016
- Tesla model S 60, 2016
- Audi Q6 e-tron, 2018
- Opel Ampera-e, 2017
- Renault Zoë ZE R90, 2016
- VW e-Golf, 2014
- Nissan Leaf Acenta, 2013
- VW e-up, 2016
- Peugeot iOn, 2016
- Mitsubishi i-MiEV, 2014
- Citroën C-zero, 2012
- BMW i3, 2016
- Nissan e-NV200 EVALIA, 2016

mobi
• Partners: AVERE, VUB, TNO, POLIS, TOBANIA
• Period: 2015-2017

http://www.eafo.eu
TCO methodology

- **Financial costs**
  - Purchase price
  - Registration tax
  - Governmental supports
  - Opportunity cost
  - Depreciation cost

- **Fuel operating costs**
  - Fuel cost (electricity)
  - Taxes on fuel

- **Non-fuel operating costs**
  - Taxation
  - Insurance
  - Technical control
  - Tyres
  - Maintenance
Passenger cars – medium cars

![Bar chart showing the total cost of ownership and cost per kilometer for various medium cars. The chart includes categories such as depreciation, vehicle registration tax, road tax, insurance, battery leasing, maintenance costs, fuel or electricity costs, infrastructure, fines and parking fees.](image-url)
Passenger cars – medium cars - subsidy
Company cars – premium cars
Consumer segmentation

- **Price-focused buyer (20%)**
  - Purchase price

- **Cost-balancer (35%)**

- **Stylish traveller (29%)**
  - Brand and travel cost

- **Undisturbed driver (16%)**
  - Fuelling time
Subsidies for EVs (2016)

- Private persons

<table>
<thead>
<tr>
<th>Cataloguswaarde</th>
<th>Premie</th>
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<tbody>
<tr>
<td>&lt; 31.000 euro</td>
<td>5.000 euro</td>
</tr>
<tr>
<td>31.000 euro – 40.999,99 euro</td>
<td>4.500 euro</td>
</tr>
<tr>
<td>41.000 euro – 60.999,99 euro</td>
<td>3.000 euro</td>
</tr>
<tr>
<td>&gt; 61.000 euro</td>
<td>2.500 euro</td>
</tr>
</tbody>
</table>

- 120% tax reduction for companies
Infrastructure needs
Where is your car during one week?

Source of Data - 2001 National Household Travel Survey;
GM Data Analysis (Tate/Savaglin) - SAE paper 2009-01-1311
Garage and private parking per living unit

- Vlaanderen: 60.00%
- Walonië: 50.00%
- Brussel: 10.00%
Intelligent roll-out of infrastructure
Charging Infrastructure Location: Fast Chargers
Dynamic Inductive Charging
Part 2
Powertrain Co-design
Outline

- Introduction of Powertrain topologies
- Modeling Approach
- Co-design Framework for Powertrains
- Case study: Electrified Buses
- Conclusions and Future trend
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Powertrain Topologies: Hybrid EV

Hybrid Electric Vehicle (HEV)
- Series-HEV
  - Extended-Range
- Parallel-HEV
  - Pretransmission
  - Posttransmission
  - Through-the-road (TtR)
- Series-parallel HEV
  - Complex-HEV
- Plug-in HEV (PHEV)

All-Electric Vehicle (AEV)
- Battery-based HESS
  - Bat/SC
- Fuelcell-based HESS
  - FC/Bat
  - FC/SC
  - FC/Bat/SC

FC: Fuel Cell; Bat: Battery; SC: Supercapacitor
Powertrain Topologies: Hybrid EV

Parallel HEV

Series-Parallel HEV
Powertrain Topologies: Hybrid EV

Hybridization:

- will reduce the fuel consumption
- will improve the energy efficiency
- will add one or more degree of freedom in the control strategy
- will improve the dynamic performance
- will minimize the emissions

Compared with ICE vehicle
Advantages of Battery (High Energy) /SC or High Power Battery

- Improve the battery lifetime
- More energy efficiency
- High dynamic performance
- Advanced DC/DC converter (i.e. MPC) with high efficiency (up to 96% thanks to WBG technology)
  - More compactness
  - High reliability

HE: High Energy; HP: High power; WBG: Wide-Bandgap semiconductors
**Powertrain Topologies: FCHEVs**

→ **Disadvantages of FCEV**
  - Low dynamic response (during starting & transient)
  - High cost and size
  - No ability to recover the braking energy

Wide range of powertrains topologies or Architectures & Sizing

Generic optimization problem !!

Source: VUB (Hegazy, 2012): FCHEV based on MPC
Outline

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## Models Classification Criteria

<table>
<thead>
<tr>
<th>Transients consideration:</th>
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</thead>
<tbody>
<tr>
<td>- Steady State</td>
</tr>
<tr>
<td>- Dynamic</td>
</tr>
<tr>
<td>- <strong>Quasi-static</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculation Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Forward</td>
</tr>
<tr>
<td>- Backward</td>
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<tr>
<td>- Backward-Forward</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- <strong>Structural</strong></td>
</tr>
<tr>
<td>- <strong>Functional</strong></td>
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<thead>
<tr>
<th>Causality</th>
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<tbody>
<tr>
<td>- <strong>Causal</strong></td>
</tr>
<tr>
<td>- Non-causal</td>
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</tbody>
</table>

*Source: A. Bouscayrol (2010)*
Modeling Approach

Positive Power Flow

Calculation Direction

Backward approach

→ Given Driving Cycle
   = Vehicle speed

Positive Power Flow

Calculation Direction

Forward approach

→ Vehicle speed is controlled by driver

Low fidelity models
Medium fidelity models
High fidelity models
Modeling Approach: Fidelity

**Low fidelity models**

- Time step: 0.5s – 1s
- Detailed efficiency map of components
- No transients

**Medium fidelity models**

- Dynamic models of components
  - Transients are considered;
  - Low-level control of the power electronics (i.e. the cutting frequency);
  - Dynamic D-q model and control.

**High fidelity models**

- Time step < ms

Mathematical equations:

\[
I_{md} = \frac{T_m \omega}{V_{DC} \eta(T, \omega)}
\]

- Motor Drive
- Motor Drive
- Motor
- Motor Drive & Motor
- Motor & Motor

Symbols:

- \(V_{DC}\) (DC Voltage)
- \(I_{md}\) (Motor Drive Current)
- \(T_{REF}\) (Reference Torque)
- \(T_{REAL}\) (Real Torque)
- \(I_m\) (Motor Current)
- \(I_{md}\) (Motor Drive Current)
- \(\eta(T, \omega)\) (Efficiency)
- \(\omega\) (Angular Speed)
- \(T\) (Torque)
- \(T_{REF}\) (Reference Torque)
- \(T_{REAL}\) (Real Torque)
- \(\eta\) (Efficiency)
- \(\omega\) (Angular Speed)

Equation:

\[
I_m = I_{md} \frac{T_m \omega}{V_{DC} \eta(T, \omega)}
\]
Powertrain Topologies: EMS

- **Rule-based**
  - Deterministic
    - Thermostat (on/off)
    - Power follower
    - Frequency-based
    - Optimal working condition
  - Fuzzy logic
    - Conventional FL
    - Predictive FL
    - Adaptive FL

- **Optimization-based**
  - Off-line
    - Direct (Dynamic Programming)
    - Indirect (Pontryagin Minimization Principle)
    - Derivative-free (DIRECT, SA, GA, PSO)
    - Gradient (SQP, QP)
    - Other (Game theory)
  - On-line
    - Equivalent Consumption Minimization Strategy
    - Model Predictive Control

- **Learning-based**
  - Support Vector Machine
  - Reinforcement learning
  - Artificial neural network

Modeling Approach: “Forward” for HEV

Battery energy consumption

Battery

Electric motor

Gear box

Vehicle

Fuel consumption

Fuel tank

Engine

Clutch

Energy management strategy

EMS

Wheel torque, power setpoint

Driving cycle: speed setpoint

Engaged gear

Engine speed set point $T_{\text{e}}$ set point

Electric machine power set point $T_{\text{EM}}$ set point

Driver

Fuel consumption

Battery energy consumption
Modeling Approach: “Backward” for HEV

Vehicle speed: Driving cycle

Vehicle

Wheel torque, power setpoint

EMS

Electric motor

Battery energy consumption

Battery

Battery energy consumption

Engine

Fuel consumption

Fuel tank
Modeling Approach: “Forward” for HEV
Modeling Approach: Backward-forward (SHEV)

For HEVs, EVs, PHEVs: on-road Light and Heavy Duty

LFM: Low Fidelity Models; Medium Fidelity Models; High Fidelity Models
Powertrain: Modeling and EMS

SHEV: An example → On/Off Strategy

Source: R. Barrero (2012)
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Co-design Framework for PTs

- Powertrain Topology Selection (HEVs, PHEVs, FCHEVs, EVs, etc.).
- Layout component optimization (i.e. ICE, battery, Electric Machine, power electronics, CVT, EVT, auxiliaries, etc.).
- Technology Selection (i.e. battery chemistry, ICE, electric machines, etc.).
- Optimal sizing (i.e. kWh for battery (Ah?), ICE Power (kW), EM (kW), gearbox (kW), etc.).
- Optimal power sharing: i.e. between ICE & battery.
- Fuel consumption minimization.
- Optimal charging strategy (especially for electric buses):
  - Considering the battery lifetime and limitations;
  - Charging power and time.
Co-design Framework for PTs

- **Sequential Approach**
  - Environment
  - Optimal Sizing (i.e. Technology) → Optimal Control

- **Nested Approach**
  - Environment
  - Optimal Sizing (i.e. Technology) → Optimal Control

- **Iterative Approach**
  - Environment
  - Optimal Sizing (i.e. Technology) → Optimal Control

- **Simultaneous Approach**
  - Environment
  - Optimal Sizing & Control
  - Topology
  - Sizing + Control
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Case Study: Electrified Buses in Brussels

Standard Diesel Bus: 12m

Articulated Diesel Bus: 18m
Case Study: Bus Lines and Requirements

Bus Line 86: Feeder bus → 12m Standard Bus
- Overnight Charging
- 12hr Autonomy

Bus Line 48: Trunk Line → 18m Articulated Bus
- Opportunity Charging

Bus Line 17: Neighborhood bus → 12m standard Bus
- Overnight Charging
- 12hr Autonomy

CC3

Pantograph up to 450 kW
Case Study: Bus Lines and Design Considerations

Expected Outcome of the Co-design Framework

- Battery technology (i.e. NMC, LFP, LTO, etc.)
- Energy consumption (kWh/km)
- Battery Pack Voltage (V)
- Charging power (kW)
- Charging time (min)

→ Design Considerations

- Road Characteristics
- Battery Aging
- Charging Scenarios (Overnight or OPPch)
- Bus Schedule
- Bus Autonomy
- Auxiliaries

Iterative Approach

Optimal Sizing (i.e. Technology) → Optimal Control

Environment
Case Study: E-Bus Architecture

→ High Voltage Battery → 600-750V
Case Study: Bus Line 86: Battery sizing

- Back-Forth Driving Cycle
- LFP battery (45Ah)/700
- Aux. Power $\rightarrow$ 3kW (Assumption)
Case Study: Bus Line 86: Battery sizing

- Autonomy = 12hr
- DoD: 90%
- LFP (45Ah)
- Energy Cons. → \(\sim 1.8\) kWh/km
Case Study: Charging Power

- Overnight charging: 40kW
- Charging time: 4hr15min

![Graph showing overnight charging battery size comparison between NMC 20Ah (180 kWh) and LFP 45Ah (185 kWh).]
Case Study: Bus Line 17: Battery sizing

- Back-Forth Driving Cycle
- NMC battery (20Ah)/700 V
- Aux. Power → 3kW
Case Study: Bus Line 17: Battery sizing

- Autonomy = 12hr
- DoD: 90%
- NMC (20Ah)
- Average Aux. power → 3kW
- Battery size: 265kWh for 210 km

- Overnight charging: 60kW
- Charging time: 4hr30mins
- Energy Cons. → ~ 1.3 kWh/km
Case Study: Bus Line 48: Battery sizing

• Back-Forth Driving Cycle
• LTO battery (60Ah)/600 V
• Average Aux. Power → 3kW
Case Study: Bus Line 48: OPPch

- Opportunity charging: 200 kW @ both terminals
- Charging time: 7mins
- Energy Cons. $\rightarrow \sim 2.97 \text{ kWh/km}$
Case Study: Summary

<table>
<thead>
<tr>
<th>Bus Line</th>
<th>Energy (kWh/km)</th>
<th>Charging Scenario</th>
<th>Charging time</th>
</tr>
</thead>
<tbody>
<tr>
<td>L 86</td>
<td>1.8 kWh/km (LFP)</td>
<td>OverNCharg: 40kW</td>
<td>4hr 15min</td>
</tr>
<tr>
<td>L 17</td>
<td>1.3 kWh/km (NMC)</td>
<td>OverNCharg: 60 kW</td>
<td>4 hr 30min</td>
</tr>
<tr>
<td>L 48</td>
<td>2.97 kWh/km (LTO)</td>
<td>OPPCharg.: 200 kW</td>
<td>7min</td>
</tr>
</tbody>
</table>

- One charging Infra for L48 bus line could be integrated into Tram 3 or 4
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Conclusions

- Co-design framework is an enabler tool for optimal design and control towards minimum TCO.
- Average auxiliary power has significant impact on bus energy consumption.
- LTO is the best option for Opportunity Charging thanks to its high charging current. However, the cost will be one of the key challenges.
Future Trends

- Real integration of Opportunity charging into DC Tram/Metro network.
- Vehicle-to-Grid (V2G) Systems towards smart grid and smart home.
- On-road Opportunity Charging up to 600 kW.
Thank you for your attention

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