mobility, logistics and automotive technology
Powertrain Design and Modelling for Light and Heavy Duty Vehicles
Part 1
Challenges for Electromobility
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>

x2 → x2 → x3 → x3
Average battery pack price
$ per kWh

2020 forecast
2030 forecast

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

2010 11 12 13 14 15 2016E

0 100 200 300 400 500 600 700 800 900 1,000

-77%

-160% p.a.

~530

CWIEME BERLIN
20-22 June 2017 Messe Berlin

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 (€)

Driving range (km)

- Nissan e-NV200 EVALIA 2016
- BMW i3 2016
- Citroën C-zero 2012
- Mitsubishi i-MiEV 2014
- Peugeot iOn 2016
- Volkswagen e-up 2016
- Mercedes-Benz A-Class 2015
- Kia S 2014
- VW e-Golf 2014
- Nissan Leaf Acenta 2013
- Tesla Model S 60 2016
- Tesla Model X 60D 2016
- Audi Q6 e-tron 2018
- Volkswagen e-Golf 2016
- Nissan Leaf Acenta 2013
- Tesla Model S 60 2016
- Audi Q6 e-tron 2018
- Opel Ampera-e 2017
- Renault Zoë ZE R90 2016
• **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 different vehicle models, including Ford Focus P, VW Golf D, Toyota Auris Hybrid HEV, Nissan Leaf BEV, BMW i3 PHEV, and VW Golf CNG. The chart breaks down costs into depreciation, vehicle registration tax, road tax, insurance, battery leasing, maintenance costs, tyre replacement, fuel or electricity costs, infrastructure, fines and parking fees, cost per km if 10000 km/year, and cost per km if 20000 km/year.]
Passenger cars – medium cars - subsidy
Company cars – premium cars
Consumer segmentation

- **Cost-balancer 35%**
  - Purchase price

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

- **Undisturbed driver 15%**
  - Fuelling time

- **Stylish traveller 29%**
  - Brand and travel cost
Subsidies for EVs (2016)

- Private persons

<table>
<thead>
<tr>
<th>Cataloguswaarde</th>
<th>Premie</th>
</tr>
</thead>
<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/Savaglen) - SAE paper 2009-01-1311
Garage and private parking per living unit

![Bar chart showing garage and private parking per living unit in Vlaanderen, Walonië, and Brussel. The chart indicates a higher percentage for Vlaanderen and Walonië compared to Brussel.](chart_url)
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
## Outline

- **Introduction of Powertrain topologies**
  - Modeling Approach
  - Co-design Framework for Powertrains
  - Case study: Electrified Buses
  - Conclusions and Future trend
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
Powertrain Topologies: BEVs (/SC)

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!!
Outline

- Introduction of Powertrain topologies
- Modeling Approach
- Co-design framework for Powertrains
- Case study: Electrified Buses
- Conclusions and Future trend
# Models Classification Criteria

## Transients consideration:
- Steady State
- Dynamic
- **Quasi-static**

## Calculation Direction
- Forward
- Backward
- Backward-Forward

## Model Representation
- **Structural**
- **Functional**

## Causality
- **Causal**
- Non-causal

Source: A. Bouscayrol (2010)
Modeling Approach

- Positive Power Flow
- Calculation Direction
  - Backward approach
  - Forward approach

Calculation Direction

Low fidelity models
Medium fidelity models
High fidelity models

⇒ Given Driving Cycle = Vehicle speed
⇒ Vehicle speed is controlled by driver
Modeling Approach: Fidelity

Low fidelity models

- Medium fidelity models

High fidelity models

- Time step: 0.5s – 1s
- Time step < ms

- Detailed efficiency map of components
- No transients

Motor Drive & Motor
$\eta(T,\omega)$

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

- 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.
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)
- 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
- Engine
- Clutch
- Engaged gear
- Wheel torque, power setpoint
- EMS
- Energy management strategy
- Driver
- Driving cycle: speed setpoint
- Driving cycle: speed setpoint
- EMS set point
- $T_{em}$ set point
- $T_{e}$ set point
- EM
Modeling Approach: “Backward” for HEV

- Vehicle speed: Driving cycle
- Wheel torque, power setpoint
- EMS
- Battery energy consumption
- Engine
- Fuel tank
- Battery
- Wheel torque, power setpoint
- Trm set point
- Tice set point
- Fuel consumption
- Vehicle
- Electric motor
- Engine
- Battery
Modeling Approach: “Forward” for HEV

Powertrain model

Reference speed

High Level Control

Driver model/Speed controller

Energy Management Strategy

ICE Ref. Torque

REF gear ratio

REF Braking Torque

Actual speed

SOC, SoH, etc.

SoC

SoH

Desired torque

E Motors Ref Torque

REF Ref Torque

Actual speed
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)
Outline

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

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

Nested Approach

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

Iterative Approach

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

Simultaneous Approach

Topology

Sizing + Control → Optimal Sizing & Control
Outline

- Introduction of Powertrain topologies
- Modeling Approach
- Co-design framework for Powertrains
- Case study: Electrified Buses
- Conclusions and Future trend
Case Study: Electrified Buses in Brussel

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
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 → 3kW (Assumption)
Case Study: Bus Line 86: Battery sizing

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

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

Overnight Charging: Battery Size (kWh)

- NMC 20Ah: 180 kWh
- LFP 45Ah: 185 kWh
Case Study: Bus Line 17: Battery sizing

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

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

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

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

- Opportunity charging: 200 kW @ both terminals
- Charging time: 7mins
- Energy Cons. → ~ 2.97 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
Outline

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

Contacts

Omar Hegazy
Omar.hegazy@vub.ac.be
+3226292992

Thierry Coosemans
Thierry.Coosemans@vub.be
+3226293767