Electrification of Urban Public Transportation Networks
1) Electrification of public transportation networks
   - What is the motivation?

2) Electric bus fleets for public transportation
   - What are typical urban network requirements?

3) Battery integration for fleet requirements
   - How should a battery be designed?
Motivation: current & future regulatory policy
Climate constraint > energy constraint in urgency

CO$_2$ amount “available”

Additional CO$_2$ amount “tolerable” until 2050

Drivers for electrification of public transportation

1) Climate change mitigation policy

2) Urbanization*

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>7.3 bil.</td>
<td>9.7 bil.</td>
</tr>
<tr>
<td>% pop. cities</td>
<td>54 %</td>
<td>66 %</td>
</tr>
</tbody>
</table>

3) Low cost Li-ion battery forecast**

4) Particulate matter concentration (incl. Volatile Organic Compounds)

*Sources: UN, 2015;  **Navigant
Impact of diesel emissions
European regulatory policy on transit vehicles

Fig.: Particles entering the human body (size in μm). Source: EMBARQ, 2012

Fig.: Euro emissions standards for transit vehicles (g/km). Source: EMBARQ, 2012

<table>
<thead>
<tr>
<th>Emission Standards</th>
<th>Date</th>
<th>CO</th>
<th>THC</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro I</td>
<td>1992</td>
<td>8.1</td>
<td>1.98</td>
<td>14.4</td>
<td>0.648</td>
</tr>
<tr>
<td>Euro II</td>
<td>1998</td>
<td>7.2</td>
<td>1.98</td>
<td>12.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Euro III</td>
<td>2000</td>
<td>3.78</td>
<td>1.188</td>
<td>9</td>
<td>0.18</td>
</tr>
<tr>
<td>Euro IV</td>
<td>2005</td>
<td>2.7</td>
<td>0.828</td>
<td>6.3</td>
<td>0.036</td>
</tr>
<tr>
<td>Euro V</td>
<td>2008</td>
<td>2.7</td>
<td>0.828</td>
<td>3.6</td>
<td>0.036</td>
</tr>
<tr>
<td>EEV</td>
<td></td>
<td>2.7</td>
<td>0.45</td>
<td>3.6</td>
<td>0.036</td>
</tr>
<tr>
<td>Euro VI</td>
<td>2013</td>
<td>2.7</td>
<td>0.234</td>
<td>0.72</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Outline

1) Electrification of public transportation networks
   - What is the motivation?

2) Electric bus fleets for public transportation
   - What are typical urban network requirements?

3) Battery integration for fleet requirements
   - How should a battery be designed?
Requirements - network

- Buses can be used on any line.
- Planned for traffic & population growth over >50 years (urbanization).
- **Buses are never late (rush hour!)**

Partial view of Zürich public transportation network (Source: Zürcher Verkehrsverbund)
Requirements - line

- Must be exception ready. (e.g. traffic, car blocks bus stop, etc)
- **Buses are never late (rush hour!)**
  - At terminals, buses often turn around and keep going
  - No or little time for terminal charging

Terminal vs. “opportunity” charging

- Terminal charge (e.g. 100 kW for 0-5 min)
- Opportunity charge (e.g. 600 kW for 20s)
Requirements - electric bus

- Do everything the diesel bus did*
- Sufficient power (kW)
- Sufficient energy (kWh) for all use cases:
  - ~1 kWh/km for driving
  - ~2 kWh/km for heating / cooling
- For end of life of battery
- Reserve capacity for exceptions

→ Sufficient battery AND terminals needed

*except the local emissions…
Requirements - electric bus

- Fully automatic Energy Transfer System
- Water-cooled battery pack
- Water-cooled Traction converter
- Two-axles drive powered by water-cooled traction motors

Example: – TOSA electric bus in Geneva, CH
Requirements - battery

- Lifetime of 5-10 years
- Design driven by mitigation of risks – BMS, thermal management, cell type, etc
- Sufficient energy
- Sufficient charging power → also in cold weather and at end of life.

Outcome: use of Li-ion battery with thermal management and high charging power.

Design the battery & infrastructure for the network, line, and bus.
Outline

1) Electrification of public transportation networks
   - What is the motivation?

2) Electric bus fleets for public transportation
   - What are typical urban network requirements?

3) Battery integration for fleet requirements
   - How should a battery be designed?
Battery aging estimation
How to quickly estimate all these aging processes?

- Aging by chemical / physical degradation (e.g. graphite - left).
- OEMs must handle battery aging to specify product lifetime

→ How to predict aging in a bus?

**Fig.: Aging at graphitic anode.**
*Source: Vetter et al. (PSI), JPS, 2005*
Battery Model

Electrical

Load (kW) & temp. (°C) → Joule heating → cell temp.

ΔQ, ΔIR

SoC profile

Aging

Cell temp.

Thermal

ΔQ, ΔIR

SoC profile

Capacity (Ah)

Relative IR [%]

Change in capacity (Ah) & resistance (Ω)

© ABB
May 2, 2016 | Slide 14
Heat transfer coefficient (HTC*) impact on aging

Battery model demonstrating cooling impact

*HTC = heat transfer coefficient in W/m²K experienced at the side walls of a prismatic cell →
Battery design
Necessity of thermal management

- Cell design & Li-ion anode/cathode chemistry also key.
- Thermal management seen to be essential to ensure reliability, as seen in modelling work and in general operation concept (below).

Diagram:
- Power Limits
- Desired Operating Temperature
- Limiting power to reduced T increase and degradation
- Sluggish Electrochemistry
- Rated Power
- Degradation
- Dictates power capability through cold cranking
- 15°C, 35°C
- Also limits the electric driving range

Source: Kandler Smith, NREL Milestone Report, 2008
Conclusions

Electrification of public transportation networks

1) Regulations guided by climate change & air quality policies.

2) Design infrastructure for the network, line, and bus.

3) Battery thermal management ensures reliability.
Outlook
Other routes to electrification of public transportation

- **Subway breaking energy recuperation** in Warsaw (PL) for Metro Line 2 with 7 underground substations with supercapacitors: [ABB Press Release – 2016-03-09](#).

- **Electric hybrid bus fleet** in Namur (BE) – fast-charging stations and small diesel engines to reduce battery size & backup capacity: [ABB Press Release – 2016-02-25](#).

Power and productivity for a better world™