econnect Germany – performance and evaluation of an electrically propelled minibus for public transportation

Barcelona, 18th of November 2013

Dipl.-Ing. Felix Töpler

Forschungsgesellschaft Kraftfahrwesen mbH Aachen
Agenda

• Introduction
• Test vehicles
• Test drive results
• Analysis of performance and energy costs
• Summary
Introduction

Project name: econnect Germany; predecessor project: Smartwheels
Model region: Aachen, Allgäu, Duisburg, Leipzig, Osnabrück, Sylt, Trier
Funded by: BMWi – Federal Ministry for Economics and Technology
Duration: January 2012 till December 2014
Topic: Information and Comunications Technology (ICT) for Electro mobility
Consortial leader: smartlab
Introduction

Urbanisation

Electromobility in public transport

No local emissions

Limited resources

Increasing energy prices

CO₂ Goals

High efficiency of electric traction systems
Introduction

Velocity [km/h]

- New York bus cycle
- NYCC Line 4
- Moskau bus cycle (Aachen)
- Line 3A (Aachen)
- Line 4 (Aachen)
- Line 5 (Aachen)
- Aachen - Eifel (Expressbus Line 63)

- Maximum velocity
- Average moving velocity

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
</tr>
<tr>
<td>70</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

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Agenda

- Introduction
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Test vehicles
Modification of the basic vehicle

- Rear battery
- Electric traction motor with reduction gear
- AC/DC converter
- Power Distribution Unit
- Front battery
- ECU
- DC/DC converter
- 230 V charger
- HV-DC charger socket
- 230 V charger

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## Test vehicles
### Comparison of diesel and electric bus

<table>
<thead>
<tr>
<th></th>
<th>Series vehicle</th>
<th>Electric prototype</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seats</td>
<td>12 + 1 (Driver)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stance</td>
<td>18</td>
<td>10 to 15</td>
<td></td>
</tr>
<tr>
<td>L x W x H</td>
<td>7700 x 1993 x 2845</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Max. Weight</td>
<td>5650</td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td>Motor power</td>
<td>120</td>
<td>150 (peak)</td>
<td>kW</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>80 (electronically limited)</td>
<td>78</td>
<td>km/h</td>
</tr>
<tr>
<td>Max. Torque (at rpm)</td>
<td>360 (1200 - 2400)</td>
<td>300 (0 - 4500)</td>
<td>Nm</td>
</tr>
<tr>
<td>Max. rpm</td>
<td>4000</td>
<td>12 500</td>
<td>rpm</td>
</tr>
<tr>
<td>Gearbox</td>
<td>6-speed automatic</td>
<td>Fixed planetary gearbox</td>
<td>-</td>
</tr>
<tr>
<td>Battery capacity (gross)</td>
<td>-</td>
<td>45</td>
<td>kWh</td>
</tr>
<tr>
<td>Usable SOC window</td>
<td>-</td>
<td>15 – 95</td>
<td>%</td>
</tr>
<tr>
<td>Peak discharging current</td>
<td>-</td>
<td>400</td>
<td>A</td>
</tr>
<tr>
<td>Peak charging current</td>
<td>-</td>
<td>160</td>
<td>A</td>
</tr>
<tr>
<td>Charging time @230 V (max. 3,6 kW)</td>
<td>-</td>
<td>12</td>
<td>h</td>
</tr>
<tr>
<td>Charging time @400 V DC (max. 64 kW)</td>
<td>-</td>
<td>ca. 0,5</td>
<td>h</td>
</tr>
<tr>
<td>Motortype</td>
<td>4-cylinder Diesel</td>
<td>Hybrid-synchron-motor</td>
<td>-</td>
</tr>
</tbody>
</table>
Agenda

• Introduction
• Test vehicles
• Test drive results
• Analysis of performance and energy costs
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Test drive results
Electric bus - Line 4

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Min. payload (300 kg)</th>
<th>max. payload (1500 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy demand</td>
<td>kWh/100km</td>
<td>41,4</td>
<td>60,2</td>
</tr>
<tr>
<td>Recuperation / Drive energy</td>
<td>-</td>
<td>0,20</td>
<td>0,19</td>
</tr>
<tr>
<td>Range with 35 kWh available</td>
<td>km</td>
<td>84,5</td>
<td>58</td>
</tr>
<tr>
<td>Charging time for 100 km</td>
<td>h</td>
<td>1,77</td>
<td>2,57</td>
</tr>
</tbody>
</table>

Charging time for 100 km with 26 kW charger

Ø-speed: 14,52 km/h
Cumulated altitude difference: 159 m
Test drive results
Electric bus - Line 63 (extra-urban express bus)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Min. payload (300 kg)</th>
<th>max. payload (1500 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy demand</td>
<td>kWh/100km</td>
<td>37,9 – 39,2</td>
<td>42,2 – 44,6</td>
</tr>
<tr>
<td>Recuperation / Drive energy</td>
<td>-</td>
<td>0,17</td>
<td>0,18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0,08 uphill; 0,26 downhill)</td>
<td>(0,07 uphill; 0,29 downhill)</td>
</tr>
<tr>
<td>Range with 35 kWh available energy</td>
<td>km</td>
<td>92,2</td>
<td>78,5</td>
</tr>
<tr>
<td>Charging time for 100 km with 26 kW charger</td>
<td>h</td>
<td>1,62</td>
<td>1,9</td>
</tr>
</tbody>
</table>

Ø-speed: 41,2 km/h
Cumulated altitude difference: 1000 m
Energy diagram for electric bus – Line 4
55.7 kWh / 100 km at battery; 61.9 kWh / 100 km at grid

- Charging station: 7735 Wh
- Battery: 773 Wh, 6962 Wh, 1744 Wh
- E-Motor + AC/DC: 7409 Wh
- Driving resistance (12.5 km; 0:56 h): 3260 Wh
- Recuperation: 106 Wh, 1992 Wh, 6459 Wh
- Generator + AC/DC: 1992 Wh, 2340 Wh
- Drivetrain, tires: 6459 Wh
- Mechanical brakes, friction losses: 634 Wh
- 12 V Netz: 867 Wh, 950 Wh
- DCDC: 14 Wh, 142 Wh, 106 Wh
- Power losses: 558 Wh, 14 Wh
Resulting energy demand (line 4)

Efficiencies battery ↔ E-Machine:
Driving $\eta = 83.1086\%$
Braking $\eta = 75.328\%$
Total $\eta = 81.0004\%$

Diagram showing energy demand with lines for E-Motor, E-Generator, Battery discharging, Battery charging, Battery total, and Auxiliaries.
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### Analysis of performance and energy costs

#### Overview

The charging power was 27 kW. It can be boosted up to almost 60 kW, which would half the needed charging time, but also increase the losses while charging.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>With minimal payload</th>
<th>With maximal payload</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bus line</strong></td>
<td></td>
<td>3 4 5 13 63 Ø</td>
<td>3 4 5 13 63 Ø</td>
</tr>
<tr>
<td><strong>Distance (ring or end-to-end)</strong></td>
<td>km</td>
<td>11,2 13,6 25 6,3 62 -</td>
<td>11,2 13,6 25 6,3 62 -</td>
</tr>
<tr>
<td><strong>Ø – Speed</strong></td>
<td>km/h</td>
<td>16,9 14,5 15,8 14,9 41,2 -</td>
<td>16,9 14,5 15,8 14,9 41,2 -</td>
</tr>
<tr>
<td><strong>Altitude difference (cumulated)</strong></td>
<td>m</td>
<td>132 159 268 80 1000 -</td>
<td>132 159 268 80 1000 -</td>
</tr>
<tr>
<td><strong>Ø – energy consumption at battery</strong></td>
<td>kWh/100km</td>
<td>41,3 45,7 40,2 42,3 38,6</td>
<td>57,1 60,2 52,5 60 43,4 54,6</td>
</tr>
<tr>
<td><strong>Ø – energy consumption at grid</strong></td>
<td>kWh/100km</td>
<td>45,4 50,3 44,2 46,5 42,5</td>
<td>62,8 66,2 57,8 66 47,7 60,1</td>
</tr>
<tr>
<td><strong>Recuperation / drive energy</strong></td>
<td>-</td>
<td>0,21 0,2 0,18 0,18 0,18</td>
<td>0,19 0,16 0,2 0,19 0,17 0,17 0,18</td>
</tr>
<tr>
<td><strong>Ø – range</strong></td>
<td>km</td>
<td>89,8 84,5 90,4 85,6 92,2</td>
<td>88,5 60 58 66,7 56,3 78,5 63,9</td>
</tr>
<tr>
<td><em><em>Ø – charging time</em> for 100 km</em>*</td>
<td>h</td>
<td>1,7 1,8 1,7 1,8 1,6</td>
<td>1,7 2,5 2,6 2,2 2,7 1,9 2,4</td>
</tr>
<tr>
<td><strong>Ø – Diesel consumption</strong></td>
<td>l/100km</td>
<td>16 16,2 16 17 14,5</td>
<td>15,9 22,5 20,6 19,4 21,4 16,9 20,2</td>
</tr>
</tbody>
</table>
## Energy costs for both vehicles for different price scenarios

### Electric bus

<table>
<thead>
<tr>
<th>Price scenario</th>
<th>Price for electricity [€/MWh]</th>
<th>Energy costs [€/100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (average EEX price in Germany and Austria)</td>
<td>37,71</td>
<td>1,73</td>
</tr>
<tr>
<td>Medium (Average price in EA-17 for industrial consumers, 500 – 2000 MWh/a)*</td>
<td>118</td>
<td>5,40</td>
</tr>
<tr>
<td>High (assumed price for scenario with high costs for electric energy)</td>
<td>400</td>
<td>18,32</td>
</tr>
</tbody>
</table>

*Prices for 2011

### Diesel bus

<table>
<thead>
<tr>
<th>Price scenario</th>
<th>Price for Diesel [€/l]</th>
<th>Energy costs [€/100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1,00</td>
<td>15,93</td>
</tr>
<tr>
<td>Medium</td>
<td>1,50</td>
<td>23,90</td>
</tr>
<tr>
<td>High</td>
<td>2,00</td>
<td>31,86</td>
</tr>
</tbody>
</table>

*Prices for 2011
Bandwidth of price scenarios for diesel and electric bus

Potential saving in energy costs: ~10 000 €
**CO₂ emissions for electric energy production and fossil fuels**

*assumed efficiency of nuclear powerplant: 33 %; energy demand for nuclear waste disposal is not included*

- **Specific equivalent CO₂ emissions in g/kWh**
  - Brown coal
  - Black coal
  - Natural gas
  - Photovoltaics
  - Biomass
  - Waterpower
  - Windpower
  - Nuclear power*
  - Solarthermal Power

- **CO₂ emissions in g / l fuel (kg for CNG)**
  - Diesel tank-to-wheel
  - Diesel W-T-W conventional oil
  - Diesel W-T-W shale oil
  - Biodiesel T-T-W
  - Biodiesel W-T-W
  - CNG T-T-W
  - CNG W-T-W

Sources: Bochum University; Institute of energy systems and economics; Verkehrsrundschau 51-52/2010
Comparison of CO₂ emissions from diesel and electric bus (well-to-wheel)

Minimal fuel consumption (minimal payload) & minimal CO₂ emissions well-to-wheel

Maximal fuel consumption (maximal payload) & maximal CO₂ emissions well-to-wheel

Diesel bus

Electric bus

Diesel W-T-W shale oil

Diesel W-T-W conv. oil

Brown coal

Black coal

Biodiesel W-T-W

EU-27

Natural Gas

Biomass

Photovoltaics

Renewable Energies (Wind & Water)

CO₂ emissions in g / km
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Summary

• The electric bus with a gross weight of 5.65 tons, a passenger capacity of 25 persons and a battery with a usable energy content of 35 kWh has a range of at least 60 km and maximum 95 km.

• With a DC highpower charger (ca. 25 kW) a charging time between 1,6 h and 2,7 h is necessary to recharge the battery for 100 km.

• The high efficiency of the electric drive train reduces the energy costs significantly, especially if the prices for energy are continuously rising.

• The CO\textsubscript{2} emissions can be significantly lowered by using electric traction systems.

• With the average CO\textsubscript{2} emissions in the EU made from electricity production the electric bus has emissions between 200 and 350 g CO\textsubscript{2} / km, while a diesel bus with fossil fuels from conventional oil-wells produces emissions between 440 and 640 g CO\textsubscript{2} / km.
Thank you for your attention!

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