Application of OpenTrack and OpenPowerNet for a Feasibility and Cost Effectiveness Study

Introduction of a Hybrid-trolleybus system in a large European city

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Work contents of the feasibility study

- **Market research regarding the state-of-the-art technology**

- **Technical design of the Traction Power Supply system**
  - Selection of **vehicle and propulsion technology** for vehicles charged while driving under consideration of line topology and density of traffic
  - **Rating of the vehicle propulsion systems**: traction power, auxiliary systems, traction motors, inverter, **battery**
  - Concept of **traction power and recharging infrastructure** considering the operation planing and the vehicle and propulsion technology for **three scenarios**
  - **Dimensioning of traction power and recharging infrastructure**: Rating and location of grid connection and feeding points as well as of the network structure: traction power substations, overhead line equipment, stationary recharging points; Verification with dynamic traction power simulation: Timetable, driving dynamics, power and energy demand
  - **Compilation of Bill of Quantity** for vehicles and facilities

- **Suggesting a scenario for implementation including scheduling**

- **Cost-effectiveness and sustainability compared to Diesel and Battery-electric-bus scenarios**
Methodology

Preparation of Traction Power Supply Simulation with

- Operation simulation software
- Traction Power Supply simulation software
- Simulations performed on the basis of iterative loops in terms of assessment of the required normative limits
- Identification of worst case scenario, comparison with the required normative limits
- Defining of electrical devices for adequate rating
Investigated Network

• Existing bus network of approx. 250 km network length, 14 bus lines
  – Dense bus traffic over the whole day
  – Long line lengths
  – High passenger load with expected increase

• The bus traffic shall be electrified to meet legal requirements regarding climate protection

• Not the whole network shall be electrified

→ Investigation of hybrid trolleybuses:
  → Conventional trolley buses equipped with energy storage
  → Hybrid trolleybuses are charged while moving under catenary
  → Less amount of catenary than for conventional trolley buses, in particular switches, crossings and curves
  → Smaller and lower mass of energy storage than for conventional battery buses
Investigated Network
Service frequency of bus operation

~250km Network length

Investigated Network (not to scale)
Service frequency of bus operation
Investigated Network
Service frequency of bus operation

Detail of investigated network, with service frequency (not to scale)

Buses per direction during peak hour
- 0...3 Buses
- 3...6 Buses
- 7...9 Buses
- 10...15 Buses
- 16...21 Buses
- 22...30 Buses
- 31...40 Buses
- More than 40 Buses

Buses per direction per day
- 77
- 6

Buses per direction during peak hour
- 136
- 102
- 238
- 596
- 960
- 997
- 242
- 250
- 553
- 303
- 247
- 93
- 139
- 85
- 218
- 19,5
- 37,5
- 18
- 12
- 8
- 6
- 6

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Scenarios and approach

Scenario 1: with high percentage of catenary wire
Scenario 2: minimised reduced catenary wire
Scenario 3: reduced catenary wire and reduced bus lines
→ two scenarios with minimised percentage of catenary wire developed

• The following analyses were performed:
  – minimum line voltage (EN 50163),
  – ability to recognise short-circuits within the TPS compared to maximum operational currents,
  – Load of electrical components versus load capabilities, and
  – Battery State of Charge (SoC) during operation and lifetime analysis

• Based on the simulation results, the design was optimised → analyses were repeated

• Iteration until all scenarios were approved for all outage scenarios
Scenario 2 with reduced catenary

Overview of Traction Power Supply, Scenario 2 with reduced catenary (not to scale)
Scenario 2 with reduced catenary

Detail from overview of Traction Power Supply,

Scenario 2 with reduced catenary

- Electrified
- Not Electrified
- Gap in Electrification (e.g. crossing)
- Gap bridged per parallel cable
- Single lanes with lane-wise coupling
- Traction Power Substation with feeder cables
- Short section with overhead line (recharge point)
- Points for orientation

Not to scale

Sectioning isolators not included in graphic
Input Data – Infrastructure

Example Screenshot of the infrastructure layout in OpenTrack
## Input Data – Rolling Stock

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Articulated Bus</th>
<th>Double-articulated Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Tare weight [t]</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Maximum permissible weight [t]</td>
<td>28</td>
<td>39</td>
</tr>
<tr>
<td>Seats</td>
<td>Standees 4P/m²</td>
<td>6P/m²</td>
</tr>
<tr>
<td>mech. traction power [kW]</td>
<td>240</td>
<td>280</td>
</tr>
<tr>
<td>max. auxiliary power[kW]</td>
<td>45</td>
<td>63</td>
</tr>
<tr>
<td>Recuperation possible</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Battery capacity [kWh]</td>
<td>app. 72</td>
<td></td>
</tr>
<tr>
<td>Battery type (cell chemistry)</td>
<td>lithium iron phosphate</td>
<td></td>
</tr>
<tr>
<td>Mean State of Charge ±Rate [%]</td>
<td>65 ±25</td>
<td></td>
</tr>
<tr>
<td>End of Life (Capacity in [%] or $R_i$)</td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>
Input Data – Courses and Timetable

Approx. 30% double-articulated buses

3488 Courses within the 24 h timetable

Example screenshot of the courses and timetable data in OpenTrack
Exemplary results

Voltage, Speed, and Battery State of Charge

One vehicle, 3 hours, different destinations

Catenary free section
Charging at standstill

72% SoC
Exemplary results

Voltage, Speed, and Battery State of Charge

One vehicle, 3 hours, different destinations

35% SoC
## Energy Consumption for different Scenarios

### Comparison of energy consumption

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario 1: All services / high percentage of electrification</th>
<th>Scenario 2: All services / reduced percentage of electrification</th>
<th>Scenario 3: Limited Services / reduced percentage of electrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performed kilometers</td>
<td>41.339 km</td>
<td>41.339 km</td>
<td>30.938 km</td>
</tr>
<tr>
<td>Daily energy consumption @ 33% auxiliary power</td>
<td>84 MWh</td>
<td>84 MWh</td>
<td>54 MWh</td>
</tr>
<tr>
<td>Daily energy consumption @ 75% auxiliary power</td>
<td>130 MWh</td>
<td>130 MWh</td>
<td>89 MWh</td>
</tr>
<tr>
<td>Annual energy consumption</td>
<td>38 GWh</td>
<td>38 GWh</td>
<td>25 GWh</td>
</tr>
<tr>
<td>Specific energy demand per bus</td>
<td>2,5 kWh / km</td>
<td>2,5 kWh / km</td>
<td>2,2 kWh / km</td>
</tr>
</tbody>
</table>

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**Note:**
- **Scenario 1** assumes all services with a high percentage of electrification.
- **Scenario 2** assumes all services with a reduced percentage of electrification.
- **Scenario 3** assumes limited services with a reduced percentage of electrification.
Environmental Effects

- **High CO₂ savings**

- **Additional advantages compared to diesel buses:**
  - Advantages of air pollution control (reduction of NOₓ)
  - Reduction of noise pollution

- **Assumption: power mix 2030**

- **CO₂ emissions not taken into account for infrastructure production**

<table>
<thead>
<tr>
<th></th>
<th>Diesel Charging</th>
<th>Depot Charging</th>
<th>Opportunity Charging</th>
<th>Scenarios 1 &amp; 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[t CO₂eq/a]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30,000</td>
<td>26.391</td>
<td>- 17.051</td>
<td>- 18.675</td>
<td>- 18.971</td>
</tr>
<tr>
<td>25,000</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>20,000</td>
<td>20.87</td>
<td>8.101</td>
<td>7.716</td>
<td>7.797</td>
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<tr>
<td>15,000</td>
<td>15.000</td>
<td>3.326</td>
<td>2.087</td>
<td>1.710</td>
</tr>
<tr>
<td>10,000</td>
<td>10.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5,000</td>
<td>5.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

- Emissions by operation
- Emissions during bus and battery production
- Emission savings
Economic efficiency comparison
Comparison of specific annuities

At the specific annuity, the profitability of the Hybrid-Trolleybusses is 10-20% higher than the other variants.
Summary of results

- Hybrid - trolleybus system for the chosen city is technically and economically feasible.
- A hybrid - trolleybus is especially advantageous where bus lines are concentrated and characterised by **high passenger numbers** and **long trip lengths**.
- Hybrid-trolleybuses combine trusted, proven, and reliable technology of conventional trolleybuses with modern battery storage technology → this allows **high-performant and reliable operation**.
- With an on-board energy storage, turns, crossings and other sections where electrification is complicated and expensive or unwanted for aesthetic reasons can be realised catenary-free → **Broadened flexibility for the best technical realisation of urban electrical infrastructure**.
- From economic point of view, the hybrid - trolleybus is an alternative to other electric bus technologies, with the additional possibility to operate bigger vehicles (e.g. double-articulated buses).
- **The comparison of specific annuities shows that it is worth in general to invest in electrical infrastructure for continuous storage loading and operating a bus system in case of dense headways and a high transportation quantity.**
Thank you for your attention!

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