HIGH PERFORMANCE TRACTION BATTERIES FOR ELECTRIC BUSES AND TRAMS

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Head of Engineering Bus & Rail
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PRIMOVE ... making cities quieter, cleaner and more attractive

Complete
One-stop shop that delivers turnkey system solution for true e-mobility

Practical
Small and compact products for easy maintenance and higher passenger capacity

Invisible
No cables, wires or plugs for more attractive cities

Quiet
No noise or vibrations for better passenger comfort

Clean
No emissions, carbon or noxious gases for healthier cities

Energy efficient
Fast charging and minimized energy loss for reduced operating costs

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Requirement Definition
Challenges for battery development (compared to automotive)

- **Charging time**: 30 min to 8 hours / 10 minutes / 30 s
- **Quantity**: 1,000,000 till 2020? / 1 to 20 busses/trams per line
- **EOL Performance**: Weak defined range / Specific operation
- **Mileage**: ~15,000 km/year / 40,000 – 120,000 km/year
- **Typical Integration**: In vehicle / Roof (heat, sun, rain)
- **Weight**: Vehicle opt. for e-car / Limitations on axle load
- **User acceptance**: Driver opted for E-car / Driver & passenger not
- **Off-time handling**: Parked in garage / Heated depot, Outside
- **Variant handling**: Car specific battery / Modular battery
- **Safety**: … no compromise!
High performance traction batteries
Requirement definition bus - vehicle consumption and range

~ 1,5 kWh/km x 200 km:
- useable energy > 300 kWh => battery weight 3 - 4 tons
- Goal full day operation without spare buses
- High-power opportunity charging on en-route stops
- Small high power batteries for low weight and initial investment

Energy reserve to cover minimum one round trip
High performance traction batteries
Requirement definition tram - vehicle consumption and range

More limiting boundaries apply for trams

- Timetable information defines performance requirements
- Climate boundaries define AUX Power supply and energy need
  - > 55% energy need defined by AUX consumption
  - ~ 33% consumed by HVAC System
- Vehicle layout defines mechanical boundaries
  - Roof space envelope limited
  - Vehicle weight limits

~ 6 kWh/km at full AUX

- Travelling distance and recharging spots need to be selected carefully
- Minimum reduction of performance compared to catenary
  - High-power density required
  - Small high power batteries for low weight
- Energy reserve to cover emergency and redundancy cases

Roof arrangement with traction battery
Operational concept planning
System design and optimisation process

Analyse operational properties

Identify power consumption

Charging concept & battery size determination

System simulation (battery, charging station)

Optimisation

Final operation concept

Determine life cycle costs

Verify timetable and system

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High performance traction batteries
Battery development – modular platform approach

Standardized approach
- One Cell: nNMC for high energy, power density and safety
- Two different module configurations in the same package
- Two different battery pack formats for two major applications: road and rail
- Battery packs can be connected in series or in parallel
- Many different configurations are possible!

Plug and play with other PRIMOVE / BT components
- Standardized architecture towards traction system or DC/DC

Thermally insulated enclosure, liquid cooled
- Decoupling of performance from ambient temperature influences

Verified according to international standards
- Both for road and rail applications
  - e.g. IEC 61508, ECE R100 rev2

2 kWh Module 22 V / 44 V

49 kWh System 532 V (2 x 24.5 kWh) including TCU

30 kWh Pack 220 V / 330 V
High performance traction batteries
Battery development - power and cooling performance

Power demand (example 60 kWh battery):
- 200 kW high power charging at 3.3 °C
- Max. Continuous RMS currents: 2.6 °C
- Loss estimation:
  - Begin of Life: ~4 kW (2C)
  - End of Life: ~8 kW (2C)
➢ Task: Ensure same performance at end of life

Thermal Conditioning:
- Cooling: enables battery to deliver full performance in all climatic and operational conditions
- Preheating: required to enable fast charging
- Lifetime: battery conditioning required to maximise the battery lifetime

Specification:
- 8 kW cooling power
- 500 W heating power
- 1500 – 3000 l/h coolant flow rate
High performance traction batteries
Battery development - safety and testing

Testing activities:
- Electrical performance
- Thermal performance
- System operation
- Cell ageing (external)
- Cell/system abuse (external)

   Full Scale System Power Lab

   leads to aging prediction

   Nail Penetration, Crush, Overcharge, Short Circuit,
   Shock and vibration,
   UN Transportation, Fire resistance,

Functional safety approach with TÜV (IEC 61508):
- Hazardous situation identified and assessed
- Safety integrity level is defined (SiL)
- Components and systems designed and tested accordingly
- SW functions assessed by independent external assessor

Fire resistance acc. to EN45545
Shock and vibration test acc. IEC61373
High performance traction batteries
Project data analysis - real world profiles gathered by remote data access

Project Brunswick - 18m e-bus, 90 kWh battery - 250 km @ 25 December 2016

Missing charge due to limited end stop time

End stop charging

<table>
<thead>
<tr>
<th>Date</th>
<th>Distance travelled [km]</th>
<th>Driving time [hh:mm:ss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.12.2016</td>
<td>180.1</td>
<td>15:50:03</td>
</tr>
<tr>
<td>27.12.2016</td>
<td>230.0</td>
<td>18:38:07</td>
</tr>
<tr>
<td>25.12.2016</td>
<td>247.5</td>
<td>20:54:17</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>973.9</strong></td>
<td><strong>88:32:13</strong></td>
</tr>
</tbody>
</table>

Ambient: min. Temperature 6°C, max. Temperature 9°C

Up to 250 km/d or 23h/d operation supported by the system
High performance traction batteries
Project data analysis - real world profiles gathered by remote data access

**Project Nanjing** - 32 m tram, 96 kWh battery – 45°C ambient operation @ 15 August 2016

- One round trip
- Ambient at 45°C
- Vehicle parked with HVAC on

**Full operation at max. environmental temperature**
**Enough reserve for unplanned stops and energy need**
Record setting in CFO travelling distance:
41.6 km Inner City operation without recharging
- Empty vehicle
- 41.6 km operation only out of the traction battery
- Average speed 25 km/h

Full usage of AUX (up to 100 kW) reduced distance to app. 12 km

Vehicle is operated as driving school
Approval from TAB BW for operation in CFO simulation mode
Additional experience on automated operation
## High performance traction batteries
### Project overview and findings

<table>
<thead>
<tr>
<th>Start of operation</th>
<th>Project</th>
<th>PRIMOVE charging equipment</th>
<th>Bus / tram</th>
<th>Mileage</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/2013</td>
<td>Brunswick L19, 12 km</td>
<td>3x End Station 2x En-Route 1x Depot</td>
<td>4x18 m, 1x12 m</td>
<td>&gt; 235 tkm</td>
<td>&gt; 200 km per day, up to 700 kWh per day in winter (18 m)</td>
</tr>
<tr>
<td>08/2015</td>
<td>Berlin L304, 12 km</td>
<td>2x End Station 1x Depot</td>
<td>4x12 m</td>
<td>&gt; 151 tkm</td>
<td>good performance after fixed HV system issues</td>
</tr>
<tr>
<td>06/2015</td>
<td>Mannheim L63, 9 km</td>
<td>2x End Station 2x En-Route</td>
<td>2x12 m</td>
<td>&gt; 96 tkm</td>
<td>Extreme short end station times, complete PRIMOVE package</td>
</tr>
<tr>
<td>08/2014</td>
<td>RNV Test vehicle</td>
<td>None / Conductive charging</td>
<td>1x32 m</td>
<td>&gt; 20 tkm</td>
<td>Record setting CFO distance 41.6 km TAB approval for CFO operation</td>
</tr>
<tr>
<td>08/2014</td>
<td>Nanjing Hexi</td>
<td>None / Conductive charging</td>
<td>8x32 m</td>
<td>&gt; 500 tkm</td>
<td>First Li-Ion battery system in commercial operation on LRV</td>
</tr>
<tr>
<td>10/2016</td>
<td>Nanjing Qilin</td>
<td>None / Conductive charging</td>
<td>7x32 m</td>
<td>&lt; 10 tkm</td>
<td></td>
</tr>
</tbody>
</table>
Developed with focus on high power applications

- Inductive / conductive opportunity charging
- Allowing for energy reserve during operation

Delivered to 3 bus projects and one tram project

Reliable performance on >1,000,000 km
- Minor replacement of auxiliary components only

Project findings:

- Technology is ready for daily operation also in rail applications
- In field lifetime still to be proven, but tendency shows very positive signs

Battery sizing and charging station distributions depend on route and operational conditions

- Individual planning and TCO optimisation crucial for success

Spread out of standardised approach towards other Bombardier vehicles

- Battery electric multiple unit (BEMU)
PRIMOVE true e-mobility Get in contact with us...

www.primove.com

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Motivation

PRIMOVE – Electric Bus Equipment Portfolio

- Battery system
- Power converter
- Drives
- Pick-up
- Vehicle detection
- Onboard sending device
- Wayside electrical installation
- Charging slab
Thank you!

www.primove.bombardier.com
PRIMOVE wireless charging – proven in service

Commercial projects

- Brunswick
  - Circular bus line
  - 5 e-buses

- Bruges
  - City centre bus line
  - 3 e-buses

- Mannheim
  - Inner-city bus line
  - 2 e-buses

- Berlin
  - Inner-city bus line
  - 4 e-buses

Development projects

- Lommel
  - Inductive charging tests
  - e-bus + e-car

- Mannheim
  - Static & dynamic charging tests
  - e-bus, e-truck, e-van

- Augsburg
  - Static & dynamic charging tests
  - Tram, e-bus, van

- Total driven distance: >300,000 km
- Total charge cycles ca.: 90,000
PRIMOVE e-bus – example: Mannheim, Germany

In passenger service since June 2015

PRIMOVE scope:
- PRIMOVE charging 200
- PRIMOVE battery 60
- PRIMOVE propulsion

Vehicles:
- 2 x HESS Swiss PRIMOVE
PRIMOVE e-bus – example: Mannheim, Germany

100% e-mobility on demanding city route

- **Bus line 63**
  - Journey time: 34 minutes
  - Journey time in %: 85%
  - Headway: 20 minutes (weekday), 30 minutes (weekend)

- **Charging stations**
  - Charging time: 4 approx. 2 minutes

- **End stops**
  - Charging time: 2 approx. 5 minutes

- **Depot**
  - Charging time: 1 up to 15 minutes

- **Bus stops (total)**
  - 22 (roundtrip)

- **Number of e-buses**
  - 2
PRIMOVE tram – example: Nanjing, China

In passenger service since July 2014

PRIMOVE scope:
- 30 x PRIMOVE li-ion battery systems, 98 kWh per vehicle

Vehicles:
- 15 x low-floor trams based on BOMBARDIER FLEXITY 2
- Recharging via Pantograph during normal dwell times
First commercially operated CFO trams with compact PRIMOVE batteries

**Hexi line**
- 8 km
- 26 min
- approx. 7 min
- 13
- approx. 45 s

**Qilin line**
- 9 km
- 21 min
- approx. 7 min
- 13
- approx. 45 s

**End stops**
- Charging time
- 2
- approx. 10 min
- 1
- up to 45 s

**Depot**
- Charging time
- Numbers of vehicles
- 8
- 7

**Nanjing**