Electrification of city bus transport: An overview and SOLEZ-gained experience

Presenter: Prof. Joško Deur, Ph.D.
A WIDER CONCEPT OF SMART CITIES

➢ Basic share characteristics of (larger) cities till 2025

- **TERRITORY**
  - 2%

- **PEOPLE**
  - 50%

- **GDP**
  - 70%

- **ENERGY**
  - 75%

➢ Basic Smart City functionalities

- **E mobility**
- **Connected parking**
- **Connected public transport**
- **Smart Grid**
- **The Internet of things**
- **Autonomous cars**

+ Car sharing

Vrste električnih vozila (EV)

Hibridno električno vozilo (HEV)

Utično hibridno električno vozilo (PHEV)

EV evolucija

Baterijsko električno vozilo (BEV)

Električno vozilo proširenog dometa (EREV)
Hibridno električno vozilo (HEV)

Utično hibridno električno vozilo (PHEV)

Baterijsko električno vozilo (BEV)

EV evolucija

Segment | Market share (segment / total sales)
---|---
HEVs 2020 up to Oct. | 335k / 8.4m ~3.9%
PHEV Q1-Q3 2020 | ~4.1%
BEV Q1-Q3 2020 | ~4.9%
BEV+PHEV, Q1-Q3 2020 | ~772k/8.472m --> ~9.1%
Toyota HEVs share, Q1-Q3 2020 | 62% (JATO Dynamics)

"Toyota's command of the technology has pushed the hybrid share of its overall European sales to 62 percent, up from 20 percent in 2014, according to JATO. Sister brand Lexus counts on hybrids for 94 percent of its European sales."
ELECTRIC VEHICLES

ADVANTAGES

- Virtually zero emissions of CO2 and pollutants
- 5-10 times lower energy cost (approx. saving of 1000-1500 EUR/year for C-class passenger car) and 50% lower maintenance costs
- Support to power utility system (via smart charging)
- Lower noise pollution, particularly at low velocities
- Much faster powertrain response – fun-to-drive
- Higher level of vehicle dynamics stability due to better front/rear mass balance and lower CoG (battery influence)
- Higher comfort level: e.g. better thermal comfort due to preheating/precooling while parked/charged
- High level of informatization and connectivity
Otklanjanje nedostataka (domet, cijena, vrijeme punjenja)

Izvorni podaci: B. Witkamp (AVERE), CIVITAS FORUM, Ljubljana, listopad 2015.

“There’s a cost gap of about $12,000 between electric vehicles and internal-combustion-engine vehicles today (small to mid-size car segments). Our analysis shows that EVs have potential to reach cost parity by around 2025.” McKinsey & Company 2019

Chevrolet Bolt: 55 Pre-Production Cars Made And Exceeding 200 Mile Range Target (2015)

- 300+ km range (EPA): 2016 – 2018, $30 – 40k
  
  2020, Chevrolet Bolt 400+ km (EPA)

- Audi R8 e-tron, 2016, 450 km, 92 kWh, discontinued
- Audi Q6 e-SUV Audi e-Tron 55 quattro, 436 km (WLTP)
- BMW i5, 2019 i5 cancelled? iX3 in 2021, 460 km (WLTP)
- Jaguar (SUV) I-Pace since 2018, 470 km (WLTP)
- Landrover After 2021
- Porsche 717 Taycan launched in 2020, 495 km (WLTP)
- Volkswagen (500 km range by 2020) ID.3 launched in 2020, 550 km (WLTP)

Audi says its E-tron Quattro, planned for 2018, will be able to charge at 150 kW, and Porsche says its Mission-E concept can handle 300 kW (Tesla’s Superchargers, the fastest publicly available today, deliver up to 135 kW at some locations).

... Porsche Taycan omogućava i snagu punjenja od 350 kW (do 80%)
ELECTRIC BUS TYPES
EXAMPLE OF VOLVO 7900 SERIES: HEV AND BEV TYPES

Volvo 7900 series (Hybrid/HEV, ElectricHybrid/PHEV, Electric/BEV)

BEV-TYPE BUS

➢ E-bus (150 kWh battery, 1500 kg)
➢ Energy consumption: 12 kWh per route (cycles)
➢ DUB-pre-study: One charging per night (slow) and one daily charging (fast)

BEV-TYPE BUS

➢ HEV-bus (1.2 kWh battery)
➢ Paralell HEV drive: ICE-240 HP, EM-70 kW nominal, 120 kW max.

HEV-TYPE BUS

I-Shift AT2412E gearbox 12 gears

D5K240 diesel engine
918Nm, 173kW, 240Hp
Euro 6 Compatible

Battery
Li-ion
Fe Phosphate

Power electronics
Electric Motor Drive
(EMD)

Electrical machine
generator/motor
800Nm, 120kW
1200Nm, 150kW for Artic
ELECTRIC BUS TYPES
EXAMPLE OF VOLVO 7900 SERIES: PHEV TYPE

PHEV-TYPE BUS

➢ PHEV-bus (19 kWh battery; ~ 7 km in full electric mode - eco zone)
➢ Paralell HEV drive: ICE - 240 HP, EM -150 kW max.
➢ Fast charging: max. power 150 kW (6 min, at end station, using pantograph)
CHARGING INFRASTRUCTURE
PROJECTED EXAMPLES OF DUBROVNIK AND ŽILINA

Use of trolleybus grid for fast charging of e-buses (applicable to Žilina)

Use of e-bus fast charging power station as a city e-mobility hub (applicable to Dubrovnik)
AN OVERVIEW OF SOLEZ-DEVELOPED TOOL

ORGANISATIONAL STRUCTURE OF THE SOFTWARE APPLICATION

- Application is made as a set of software modules written in Python & C++.
- All modules share the same database.

1. **DPPM** (Data Post-processing Module)
   Tool for post-processing and analysis of recorded driving cycles.

2. **EBSM** (E-bus Simulation Module)
   Tool for simulation of various bus models (e.g. conventional, hybrid and electric ones).

3. **COM** (Charging Optimisation Module)
   Tool for electric vehicle (EV) fleet charging optimisation.

4. **TEAM** (Techno-Economic Analysis Module)
   Tool for techno-economic analysis related to the replacement of conventional vehicle fleet with electric one.
The software tool is designed having in mind **transferability** to other cities/FUAs (it is **database** driven).

Includes **Data Management Module** for greater **flexibility** (bus model definition, station locations, etc.)
Target cities for SOLEZ pilots

Žilina (DPMŽ)  

Dubrovnik (Libertas)
PILOT ACTIVITIES
OVERALL APPROACH

Necessary steps:

Step 1
• Equipping bus fleets with GPS/GPRS tracking modules (fast tracking, 1 sec sampling time)

Step 2
• Driving cycle data collection (24 h/day for 1 year).

Step 3
• Application of developed ICT tools to collected data (DPPM, EBSM, COM & TEAM).

Step 4
• A detailed techno-economic analysis for city bus transport electrification (TCO of EV fleet, and corresponding infrastructural costs)

Data included:

<table>
<thead>
<tr>
<th>Label</th>
<th>ZIL</th>
<th>DUB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timestamp</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Coordinates (lat, lon)</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Altitude</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Engine state</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Total mileage</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Fuel consumed</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Engine RPM</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Accelerator pedal position</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Engine temperature</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Engine load</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Vehicle weight</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Clutch/break switch</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Ambient air temperature</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Selected/current gear</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
PILOT ACTIVITIES
STATUS OF PILOT ACTIVITIES

- Total of 25 buses (15 ZIL + 10 DUB) are equipped with GPS/GPRS tracking equipment.
- Driving cycle data were processed by the developed ICT tools in order to acquire the most suitable city bus transport electrification configurations for target cities and calculate the electrification cost.

**Data recording started on:**
- **01/03/2018!**
- **01/10/2018!**

- **5x Solaris Urbino 12**
- **10x Karosa**
- **10x MAN Lion’s City**

**GPS Portal employee connecting the tracking device on bus chassis (ZIL)**

**STM Eagle units built in buses (DUB)**

**ZOOM**
**PILOT ACTIVITIES**
**DPPM - RESULTS OF STATISTICAL ANALYSES**

### Proportions of buses parking times

#### ZIL

**Daily parking ratios:**
- **Depot:** ≈ 60%
- **Endstations:** ≈ 5%
- **Other locations:** ≈ 10%
- **Driving:** ≈ 25%

*Cheap & efficient slow charging at depot would be appropriate!*

#### DUB

**Daily parking ratios:**
- **Depot:** ≈ 30%
- **Endstations:** ≈ 25%
- **Other locations:** ≈ 5%
- **Driving:** ≈ 40%

*Fast charging at endstations would be appropriate!*

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**Time period:**
- 01/10/2018 – 01/03/2019
- Fleet of 10 buses

**Day no. [-]**

**Percentage of time being parked [%]**

**Parking duration [min]**

- **Depot**
- **Endstations**
- **Other locations**
- **Driving**
PILOT ACTIVITIES
COM - CHARGING SYSTEM OPTIMISATIONS

Considered scenarios

<table>
<thead>
<tr>
<th>DUB</th>
<th>ZIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Considered charging station locations</td>
<td>Selected endstations</td>
</tr>
<tr>
<td>Charging power (PHEV / BEV)</td>
<td>150 / 300 [kW]</td>
</tr>
<tr>
<td>Battery capacity for BEV</td>
<td>76 kWh</td>
</tr>
</tbody>
</table>

➢ EBSM simulations were performed for fleets of Conventional (CONV), Hybrid (HEV), Plug-In Hybrid (PHEV) and Battery (BEV) electric buses

➢ Repetitive simulations in COM module gave an optimal number of charging stations

- Depot
- Charging station/spot

Taking cooperation forward
PILOT ACTIVITIES
COM - FUEL CONSUMPTIONS FOR DIFFERENT FLEET TYPES

Fuel consumption per fleet type

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Fuel consumption [L]</th>
<th>Fleet</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONV</strong></td>
<td>212486.0 (ref)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HEV</strong></td>
<td>105507.0 (-50.3%)</td>
<td>15</td>
<td>01/04/2018 - 01/03/2019</td>
</tr>
<tr>
<td><strong>PHEV</strong></td>
<td>96372.3 (-54.6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BEV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Relative fuel consumptions:
- HEV vs CONV: ≈ 50% lower
- PHEV vs CONV: ≈ 55% lower

High proportion of driving in CS mode for PHEV (≈70%)!
Due to lack of chargers at endstations (uneconomical / impractical) and short stays of buses at charging spots located in city centre

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Fuel consumption [L]</th>
<th>Fleet</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONV</strong></td>
<td>145294.9 (ref)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HEV</strong></td>
<td>73625.0 (-49.3%)</td>
<td>10</td>
<td>01/10/2018 - 01/03/2019</td>
</tr>
<tr>
<td><strong>PHEV</strong></td>
<td>43119.7 (-68.9%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BEV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Relative fuel consumptions:
- HEV vs CONV: ≈50% lower
- PHEV vs CONV: ≈70% lower

High proportion of driving in CD mode for PHEV (≈75%)!

CS mode = (battery) charge sustaining mode; CD mode = charge depleting mode
PILOT ACTIVITIES
COM - SAVINGS OF CO2 EMISSIONS FOR DIFFERENT FLEET TYPES

Emissions of CO2 (well-to-wheel)

**ZIL**
- HEV: ≈ 50% lower
- PHEV: ≈ 45% to 55% lower
- BEV: ≈ 40% to 95% lower

**DUB**
- HEV: ≈ 50% lower
- PHEV: ≈ 30% to 65% lower
- BEV: ≈ 30% to 90% lower

**Approx. emissions:**
- Diesel: 2.64 g/L
- Coal: 1.00 g/kWh
- Natural Gas: 0.45 g/kWh
- Renewables: 0.10 g/kWh

**Time periods:**
- Fleet of 15 buses: 01/04/2018 - 01/03/2019
- Fleet of 10 buses: 01/10/2018 - 01/03/2019
PILOT ACTIVITIES
TEAM - SETUP FOR TECHNO-ECONOMIC ANALYSES

Considered TCO scenarios:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Buses no.</th>
<th>Reserve buses no. (BEV only)</th>
<th>Battery replacement</th>
<th>Random sampling</th>
<th>Lift of BEV electricity consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DUB: 10</td>
<td>0</td>
<td>Not included</td>
<td>No</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>ZIL: 15</td>
<td>0</td>
<td>Not included</td>
<td>Yes</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>DUB: 10</td>
<td>1</td>
<td>Not included</td>
<td>No</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>DUB: 10</td>
<td>1</td>
<td>Included</td>
<td>No</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>DUB: 10</td>
<td>1</td>
<td>Included</td>
<td>No</td>
<td>40%</td>
</tr>
<tr>
<td>6</td>
<td>DUB: 10</td>
<td>1</td>
<td>Included</td>
<td>No</td>
<td>100%</td>
</tr>
</tbody>
</table>

Main costs components:

<table>
<thead>
<tr>
<th></th>
<th>ZIL (on-board charger) [EUR]</th>
<th>DUB (off-board charger) [EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONV</td>
<td>240,000</td>
<td>240,000</td>
</tr>
<tr>
<td>HEV</td>
<td>400,000</td>
<td>400,000</td>
</tr>
<tr>
<td>PHEV</td>
<td>470,000</td>
<td>420,000</td>
</tr>
<tr>
<td>BEV</td>
<td>545,000</td>
<td>495,000</td>
</tr>
</tbody>
</table>

Bus types: Volvo 7900 series
Fuel price [€/L]: 1.0243 €/L
Electricity prices (HT, LT): 0.1215/0.1084 [€/kWh]
Battery lifetime: 6 years

Infrastructure:
- Fast charging station (150 kW - PHEV): $45,000 (PS) + $80,000 = $125,000
- Fast charging station (300 kW - BEV): $45,000 (PS) + $120,000 = $165,000
- Battery replacement costs (every 6 years): HEV: $15,000; PHEV: $25,000; BEV: $80,000

Electricity consumption may be higher than simulated due to high summer temperatures and seasonal tourist peaks!

Buses service life: 12 years
Loan period (buses + stations): 7 years

Note: Maintenance, insurance & registration costs for BEV, PHEV, HEV are 40%, 20% and 15% lower than CONV, respectively (BEV → 90% less moving parts than CONV, reduced CO2 emissions)

DUB Case unless otherwise stated
PILOT ACTIVITIES
TEAM - TIME PROGRESS OF TCO FOR DUB & ZIL FLEETS

<table>
<thead>
<tr>
<th>Fleet type</th>
<th>Total cost of ownership [mil. €]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DUB (ref)</td>
</tr>
<tr>
<td>CONV</td>
<td>9.3 (-12.8%)</td>
</tr>
<tr>
<td>HEV</td>
<td>8.1 (+3.8%)</td>
</tr>
<tr>
<td>PHEV</td>
<td>9.0 (-3.8%)</td>
</tr>
<tr>
<td>BEV</td>
<td>10.1 (+8.6%)</td>
</tr>
</tbody>
</table>

Main reasons for higher TCO in case of ZIL:
- Lower exploitation of buses while compared to DUB case
- Higher price of PHEV & BEV buses due to integrated on-board chargers
PILOT ACTIVITIES
TEAM - TCO SENSITIVITY WITH RESPECT TO DIFFERENT SCENARIOS

Base scenario

“Worst case” scenarios

40% higher electricity consumption

100% higher electricity consumption

Battery replacement

Battery replacement

Battery replacement

Battery replacement

Random sampling

+1 reserve bus

+1 reserve bus

+1 reserve bus

+1 reserve bus

DUB

BEV vs CONV

-11.9%

-12.5%

-4.5%

+8.6%

+14.4%

+23%
PILOT ACTIVITIES
TEAM - SHARES OF INDIVIDUAL COSTS FOR DIFFERENT FLEET TYPES

- Energy = fuel & electricity cost
- RMI = registration, maintenance & insurance cost

Cost ratios for different type of fleets

**CONV**
- Buses: 61.4%
- Energy: 25.9%
- Battery: 12.7%

**HEV**
- Buses: 49.4%
- Energy: 35.7%
- RMI: 12.6%
- Battery: 12.4%

**PHEV**
- Buses: 27.2%
- Energy: 46.8%
- Battery: 10.6%

**BEV**
- Buses: 53.5%
- Energy: 13.2%
- Battery: 12.1%
- RMI: 7.7%
- Infrastructure: 13.5%

Energy costs exceed buses purchase & RMI costs

- Highest costs for buses, battery replacement and associated charging infrastructure
  - Paid off with highest savings in energy costs

Lower energy costs but higher bus prices (400 k€ vs. 240 k€)
CONCLUSION REMARKS

- It has been shown that hybridisation/electrification of the existing (Diesel) fleet can reduce overall fuel consumption by up to 50% in the case of HEV, 70% in the case of PHEV and virtually 100% in the case of BEV; and thus achieve significant savings in CO2 emissions: up to 50% in case of HEV, 65% in case of PHEV and 95% in case of BEV.

- An optimal charging system configuration for DUB (10 buses fleet) is considered to be the one consisting of (BEV or PHEV) buses with lower battery capacity (e.g. Volvo 7900 Electric; 76 kWh) and fast chargers located at 7 most pronounced endstations (including depot), while ZIL (15 buses fleet) requires BEV buses with higher battery capacity (e.g. 250 kWh) and on-board chargers connected to trolleybus grid, along with the ability to charge at 4 charging spots in city center (due to the multitude of trolleybus lines that pass through the city center).

- Finally, results of techno-economic analyses have shown that the profitability of investment in the fleet electrification can be viable, and it depends mostly on degree of fleet exploitation → the greater the exploitation, the more it will be saved on energy (i.e. fuel & electricity).

- The SOLEZ developed ICT tool has been proven through the two pilots, and it is made to be transferable to other cities.
Thank you for your attention

Looking forward to future cooperation

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