Smart solutions for urban and regional mobility in Europe
Brno Exhibition Centre, June 6, 2019.

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

University of Zagreb

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

ELECTRIC VEHICLES

TYPES OF ELECTRIC VEHICLES

Hybrid Electric Vehicle (HEV)

Plug-in Hybrid Electric Vehicle (PHEV)

Battery Electric Vehicle (BEV)

Extended Range Electric Vehicle (EREV)

EV evolution
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
ELECTRIC VEHICLES
HANDLING DISADVANTAGES (RANGE, PRICE, CHARGING TIME)

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

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

FEV luxury cars ("Tesla fighters")
- Audi R8 e-tron, 2016, 450 km, 92 kWh;
- Audi Q6 e-SUV
- BMW i5, 2019
- Jaguar (SUV)
- Landrover
- Porsche 717
- Volkswagen (500 km range by 2020)

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).

Electric Cars To Cost Same As, Or Less Than ICE Within A Decade

Deutsche Bank, Dec 2014

Source: B. Witkamp (AVERE), CIVITAS FORUM, Ljubljana, October 2015.
**ELECTRIC BUS TYPES**

**EXAMPLE OF VOLVO 7900 SERIES: HEV AND BEV TYPES**

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

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**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)

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**HEV-TYPE BUS**

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

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**Battery**

- Li-ion
- Fe Phosphate

**Power electronics**

- Electric Motor Drive (EMD)

**Electrical machine generator/motor**

- 800Nm, 120kW
- 1200Nm, 150kW for Artic

**D5K240 diesel engine**

- 918Nm, 173kW, 240Hp
- Euro 6 Compatible

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**I-Shift AT2412E**

- gearbox 12 gears

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**TAKING COOPERATION FORWARD**
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)
➢ Parallell 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.

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**APPLICATION STRUCTURE**

**DATABASE**

- **DATA POST-PROCESSING MODULE (DPPM)**
- **VEHICLE FLEET SIMULATION MODULE (VFSM)**
- **TECHNO-ECONOMIC ANALYSIS MODULE (TEAM)**
- **CHARGING OPTIMISATION MODULE (COM)**
- **DATA MANAGEMENT MODULE (DMM)**

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**APPLICATION**

**INTERREG CENTRAL EUROPE**

SOLEZ

**EUROPEAN UNION**

**INTERREG CENTRAL EUROPE**

SOLEZ
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>
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.

**Solaris Urbino 12**

**Karosa**

**MAN Lion’s City**

**Data recording started on:**

- **Solaris Urbino 12**: 01/03/2018!
- **Karosa**: 01/03/2018!
- **MAN Lion’s City**: 01/10/2018!

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

**ZOOM**

**STM Eagle units built in buses (DUB)**
Proportions of buses parking times

**ZIL**

- **Time period:** 01/04/2018 – 01/03/2019
- **Fleet of 15 buses**
- **Depot:** ≈ 60%
- **Endstations:** ≈ 5%
- **Other locations:** ≈ 10%
- **Driving:** ≈ 25%

*Endstations considers the stations located at Žilina centre!*

Cheap & efficient slow charging at depot would be appropriate!

**DUB**

- **Time period:** 01/10/2018 – 01/03/2019
- **Fleet of 10 buses**
- **Depot:** ≈ 30%
- **Endstations:** ≈ 25%
- **Other locations:** ≈ 5%
- **Driving:** ≈ 40%

Fast charging at endstations would be appropriate!
## PILOT ACTIVITIES

**COM - CHARGING SYSTEM OPTIMISATIONS**

### Considered scenarios

**DUB**

- 7 charging stations + depot
- 1 reserve bus (sporadically needed)

**ZIL**

- 4 charging spots + depot
- 1 reserve bus (regularly needed)

<table>
<thead>
<tr>
<th>Considered charging station locations</th>
<th>DUB</th>
<th>ZIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected endstations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selected stations in the city centre ring</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Charging power (PHEV / BEV)**
  - 150 / 300 [kW]
  - 150 / 300 [kW]

- **Battery capacity for BEV**
  - 76 kWh
  - 250 kWh

- **ESBM 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

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**TAking Cooperation Forward**
PILOT ACTIVITIES
COM - FUEL CONSUMPTIONS FOR DIFFERENT FLEET TYPES

Fuel consumption per fleet type

**ZIL**
- **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

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

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

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BEV: zero fuel consumption

**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
PILOT ACTIVITIES

COM - DAILY FUEL & ELECTRICITY CONSUMPTIONS FOR DIFFERENT BUS TYPES

Distributions of fuel & electricity consumption per bus per day

**DUB**

Energy consumption (average):
- CONV: 106.2 L/day
- HEV: 53.8 L/day
- PHEV: 33 L/day + 106 kWh/day
- BEV: 195.9 kWh/day

Buses rest in depot only for a few hours, and cross 300 km/bus per day on average!

**ZIL**

Energy consumption (average):
- CONV: 42.3 L/day
- HEV: 21 L/day
- PHEV: 19.2 L/day + 11.1 kWh/day
- BEV: 66.8 kWh/day

Buses are resting at depot significantly longer than in the case of DUB, and cross 110 km/bus per day on average!
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

### 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></td>
<td>1</td>
<td>Not included</td>
<td>No</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
<td>Included</td>
<td>No</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1</td>
<td>Included</td>
<td>No</td>
<td>40%</td>
</tr>
<tr>
<td>6</td>
<td></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

**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 €

**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)
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>DUB</td>
<td>ZIL</td>
</tr>
<tr>
<td>CONV</td>
<td>9.3 (ref)</td>
</tr>
<tr>
<td>HEV</td>
<td>8.1 (-12.8%)</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

-11.9%  -12.5%  -4.5%  +8.6%  +14.4%  +23%

Base scenario

„Worst case” scenarios

40% higher electricity consumption
100% higher electricity consumption

Battery replacement
Battery replacement
Battery replacement

Random sampling
+1 reserve bus
+1 reserve bus
+1 reserve bus
+1 reserve bus
+1 reserve bus
**PILOT ACTIVITIES**

TEAM - SHARES OF INDIVIDUAL COSTS FOR DIFFERENT FLEET TYPES

### Cost ratios for different type of fleets

**CONV**
- 61.4%
- 12.7%
- 25.9%

**HEV**
- 35.7%
- 2.6%
- 12.4%

**PHEV**
- 27.2%
- 3.9%
- 10.6%
- 11.6%

**BEV**
- 53.5%
- 13.2%
- 12.1%
- 7.7%
- 13.5%

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

**DUB Scenario 4**

- Energy costs exceed buses purchase & RMI costs
- Lower energy costs but higher bus prices (400 k€ vs. 240 k€)
- Highest costs for buses, battery replacement and associated charging infrastructure
- Paid off with highest savings in energy costs
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.
Looking forward to future cooperation
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