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Joint Research Centre
EU-Commission
JRC Contribution to EVE IWG:
In-vehicle battery durability

E. Paffumi, M. De Gennaro

30th Meeting of the GRPE Informal Working Group on Electric Vehicles and the Environment (EVE)
April 8th-9th, 2019, Stockholm (Sweden)
Follow-up of the JRC activities for contribution to the EVE IWG under the “in-vehicle battery ageing” topic

Summary up to October 2018, i.e. what’s old:

• Finalization of the durability scenario analysis: chemistry formulation, battery architecture, vehicle technologies (BEV, PHEV);
• Different duty cycle representative of several EU geographic regions, ambient temperature or customer profiles;
• Several recharging behaviour
• Preliminary results of ambient temperature studies, i.e. warm and cold temperatures
• In-vehicle cross-validation of the model’s results against experimental data from Canada;
• Estimation of the Years needed to reach 90%; 80%; 70%; 60%; 50% capacity fade or 160,000 km
• Scientific paper on in-vehicle battery durability, copy of the modeling methodology, list of input/output parameters of in-vehicle battery durability module of JRC TEMA platform
Follow-up of the JRC activities for contribution to the EVE IWG under the “in-vehicle battery ageing” topic

January 2019, i.e. what’s old:

• Comparison between JRC TEMA in-vehicle battery durability predictions with Tesla data by Steinbuch M.*:
  - Data collected by users in Europe, Asia Pacific, USA, Canada
  - Remaining range estimates versus driven mileage
  - On average the batteries have 91% remaining capacity after 270,000 km

Follow-up of the JRC activities for contribution to the EVE IWG under the “in-vehicle battery ageing” topic

Current Status (April 2019), i.e. what’s new:

• Comparison between JRC TEMA in-vehicle battery durability predictions with Nissan data by Myall.*:
  ➢ Data collected by users in New Zealand
  ➢ 201 Nissan Leaf 24 kWh, 82 Nissan Leaf 30 kWh
  ➢ SOH estimates versus years
  ➢ Most (81%) of the sample are in private ownership and used for domestic travel, the other ones are part of fleets operated by companies.
  ➢ 3.1% per annum averaged rate of decline of 24 kWh Leafs
• Exploring the generalisation of the JRC TEMA model
• Extending the battery architecture selections in the model

Background information: Tesla Model S battery degradation data*

- The degradation data have been collected performing a full charge of the car and comparing the EPA rated range (in North America) or Typical range (in Europe and Asia/Pacific) to the range numbers the car displayed when it was new. For example, for the 85 kWh Model S85 variant, this is about 400 km typical range or 265 mi EPA rated range.
- To improve accuracy, the battery is rebalanced once a month, running it down to almost empty state of charge and then charge it at full.
- The data collected also include how many Supercharger visits were done, among other details such as frequency to empty or full battery SOC etc.

Background information: Nissan Leaf battery degradation data*

• The lithium-ion battery SoH is a value generated by the car's battery management system and outputted by the Nissan Consult 3 tool. Read using an OBDII adapter and the LeafSpy application.

• FliptheFleet: electric vehicle owners from throughout New Zealand sign up to provide monthly records on their cars’ distance travelled, efficiency, charging, patterns, and average speed.

• Over 620 electric vehicles contribute to data collection since 2016.

• Twenty-two models of electric vehicles provide monthly data, of which 73% are Nissan Leaf.

* https://flipthefleet.org/
Background information: JRC TEMA assumptions

• Calendar + Cycle ageing by using battery chemistry model:

• Recharge strategies adopted:
  ✓ Str. 3 = Night AC;
  ✓ Str. 5 = Long-Stop AC 3-phases;
  ✓ Str. 2 = Short-Stop Random DC;

• Both Modena and Amsterdam duty cycle and environmental temperature

• The capacity fade is calculated at the net of the capacity fade reserve (15%). i.e.:
  \[ Q_{\text{loss-total}} = Q_{\text{loss-calendar}} + Q_{\text{loss-cycle}} - \text{Reserve} \]
Summary of the logical passages

1. **Performance-based models**
   (validated on exp. at cell-level)

2. **3 vehicle reference architectures**
   (from cell-to-vehicle)

3. **Real-world Driving data**

4. **Durability Scenarios**
   (Yrs and/or km to EoL)

30th Meeting of the GRPE EVE IWG
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Data comparison: Tesla data

Night AC recharge – Modena Data

Night AC recharge – Amsterdam Data


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Data comparison: Nissan Leaf data - #4(NCM-LMO)

Night AC recharge – Modena Data

#4 NCM-LMO cell assumed; it might differ from the battery chemistry of the 24kWh Nissan Leaf data

Night AC recharge – Amsterdam Data


30th Meeting of the GRPE EVE IWG
April 8th-10th, 2019, Stockholm (Sweden)
## Generalising JRC TEMA in-vehicle battery durability model: is it possible?

### #1 Performance-based models
- **Predefined calendar and cycling models (Model 1 to Model 5)**
- **Fitting equations and parameters for calendar and cycling ageing?**

### #2 Vehicle reference architectures
- **Predefined reference architectures**
- **Customised: parameters? (still to check this possibility)**

### #3 Real-world Driving data
- **Predefined different EU duty cycle and recharging strategies**
- **Customised: average information (see table of inputs)**

### #4 Durability Scenarios
- **Predefined different vehicle technologies**
- **Predefined different recharging strategies**

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**30th Meeting of the GRPE EVE IWG**
April 8th-9th, 2019, Stockholm (Sweden)
Performance based models (SotA)

<table>
<thead>
<tr>
<th>Capacity fade</th>
<th>Power fade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calendar</td>
<td>Cycle</td>
</tr>
<tr>
<td>LiFePO$_4$</td>
<td>Sarasketa-Zabala et Al. (2013/14);</td>
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<tr>
<td>NCM + spinel Mn</td>
<td>Wang et Al. (2014);</td>
</tr>
<tr>
<td>NCM – LMO</td>
<td>-</td>
</tr>
</tbody>
</table>

Calendar + Cycle (4 Combinations):

- #1 (LiFePO$_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Wang et Al. (2011) model for cycle;
- #3 (NCM + Spinel Mn): Wang et Al. (2014) for calendar plus Wang et Al. (2014) for cycle;
Exploring JRC TEMA in-vehicle battery durability generalisation: example with the support of Norway

#1 Performance-based models (validated on exp. at cell-level)

- Fitting equations and parameters for calendar and cycling ageing
  - Calendar and cycling ageing cell test data, i.e. different T, SOC, C\text{rate}
  - Fitting of the data with Arrhenius type equations as for the performance based models already implemented:
    \[ Q_{\text{lossCal}}(\text{Days},T,SOC) = (A1*\exp(B1/T)*(A2)*\exp(B2*SOC))*\text{Days}^z \]
    \[ Q_{\text{lossCyc}}(\text{Ah},T,C\text{rate}) = A1*\exp((-A2 + A3*C\text{rate})/(R*T))*(\text{Ah})^z \]
  - Input to JRC TEMA in-vehicle battery durability model the fitting coefficients

- Testing data kindly provided by Norway: Hard carbon anode and NMC cathode
  - Preben J. S. Vie, Institute for Energy Technology, Norway, Understanding Ageing Mechanisms in Li-ion Batteries through in-situ Techniques, 2017
  - under suggestion by Sigve J Aasebø, Norwegian Public Roads Administration

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Generalizing JRC TEMA in-vehicle battery durability: non-linear least squares fitting calendar ageing data

\[ Q_{\text{lossCal}}(\text{Days}, T, \text{SOC}) = (A_1 \exp(B_1/T) \times (A_2) \exp(B_2 \times \text{SOC})) \times \text{Days}^z \]

Levenberg-Marquardt (LM) damped least-square algorithm in Least Absolute Residuals (LAR) formulation

*Preben J. S. Vie, Institute for Energy Technology, Norway, Understanding Ageing Mechanisms in Li-ion Batteries through in-situ Techniques, 2017
*Norwegian EV company Think
*Electrochimica Acta, 250 (2017), 228-237
Generalizing JRC TEMA in-vehicle battery durability: non-linear least squares fitting cycle ageing data

\[ Q_{\text{lossCyc}}(\text{Ah}, T, \text{C}_{\text{rate}}) = A1 \times \exp\left(\frac{-A2 + A3 \times \text{C}_{\text{rate}}}{(R \times T)}\right) \times (\text{Ah})^z \]

Levenberg-Marquardt (LM) damped least-square algorithm in Least Absolute Residuals (LAR) formulation
R-square: 0.7338

*Preben J. S. Vie, Institute for Energy Technology, Norway, Understanding Ageing Mechanisms in Li-ion Batteries through in-situ Techniques, 2017
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*Electrochimica Acta, 250 (2017), 228-237

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Implementation of the Performance based models into JRC TEMA (assumptions, 1/2)

TEMAT Structure

**Module 0**
Pre-Processor

**Module 1**
Statistical Mobility

- Hybrid/Electric Vehicles and Recharge Behavioral Models
- Modal-shift analysis
- Vehicles usability analysis and UF

**Module 2**
Statistical Mobility
- Calendar Ageing
- Cycle Ageing

**Module 3**
Vehicle energy demand analysis

**Module 4**
Infrastructure Design and V2G

**Module 5**
Driving, Evaporative and Cold-Start emissions module

**GIS & External System Interface**

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Two New Vehicle Electric Architectures (examples)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Battery Size [Wh]</th>
<th>Battery Shape</th>
<th>No. of Cells [#] and Type</th>
<th>Reference Voltage [V]</th>
<th>Electric Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV</td>
<td>16,000</td>
<td>T-shaped</td>
<td>192 – pouch</td>
<td>365</td>
<td>2P-96S</td>
</tr>
<tr>
<td>BEV 1</td>
<td>24,000</td>
<td>Parallelepiped</td>
<td>192 – pouch</td>
<td>360</td>
<td>48S-2P-2S</td>
</tr>
<tr>
<td>BEV 2</td>
<td>85,000</td>
<td>Flat</td>
<td>6,912 - cylindrical</td>
<td>345</td>
<td>16S-72P-6S</td>
</tr>
<tr>
<td>BEV 3</td>
<td>75,000</td>
<td>Flat</td>
<td>4,416 - cylindrical</td>
<td>345</td>
<td>4S-46P-23</td>
</tr>
<tr>
<td>BEV 4</td>
<td>95,000</td>
<td>Flat</td>
<td>432 – pouch</td>
<td>396</td>
<td>4P-108S</td>
</tr>
</tbody>
</table>

- Usable Energy at BoL [Wh]
- Usable Energy at EoL [Wh]
- Reserve [% of battery capacity]
- Energy consumption [Wh/km]

<table>
<thead>
<tr>
<th>T-shaped (PHEV)</th>
<th>12,000</th>
<th>9,600</th>
<th>25%</th>
<th>205</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallelepiped (BEV 1)</td>
<td>18,000</td>
<td>14,400</td>
<td>15%</td>
<td>210</td>
</tr>
<tr>
<td>Flat-shaped (BEV 2)</td>
<td>63,750</td>
<td>51,000</td>
<td>15%</td>
<td>235</td>
</tr>
<tr>
<td>Flat-shaped (BEV 3)</td>
<td>56,250</td>
<td>45,000</td>
<td>15%</td>
<td>180</td>
</tr>
<tr>
<td>Flat-shaped (BEV 2)</td>
<td>71,250</td>
<td>57,000</td>
<td>15%</td>
<td>262</td>
</tr>
</tbody>
</table>

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### Further Scenarios explored (EoL - tabulated)

<table>
<thead>
<tr>
<th>EoL @ 80% capacity fade</th>
<th>Li-ion NCM-LMO (2015)</th>
<th>Years Driving to Set Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV-1</td>
<td>Modena Prov.</td>
<td>9.7 ≥ 20 ≥ 20</td>
</tr>
<tr>
<td></td>
<td>Amsterdam Prov.</td>
<td>10.9 ≥ 20 ≥ 20</td>
</tr>
<tr>
<td></td>
<td>Brussels Prov.</td>
<td>10.8 ≥ 20 ≥ 20</td>
</tr>
<tr>
<td></td>
<td>Luxembourg Prov.</td>
<td>10.5 ≥ 20 ≥ 20</td>
</tr>
<tr>
<td></td>
<td>Paris Prov.</td>
<td>9.4 ≥ 20 ≥ 20</td>
</tr>
<tr>
<td>BEV-2</td>
<td>Modena Prov.</td>
<td>12.1 ≥ 20 ≥ 20</td>
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<tr>
<td>BEV-3</td>
<td>Modena Prov.</td>
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<td>11.9 ≥ 20 ≥ 20</td>
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<table>
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<tr>
<th>Recharge Strategy #1</th>
<th>NCM-LMO (2015)</th>
<th>Years Driving to Set Threshold</th>
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</tbody>
</table>

**Legend**
- EoL below 5.0 years;
- EoL above or equal to 5.0 and below 10.0 years;
- EoL above or equal to 10.0 years;
Hierarchical relation of the variables (tentative)

Level 1 (highest influence) → • Electrical architecture of the battery;
• Li-ion chemistry;

Level 2 (high influence) → • Driving pattern / mileage, i.e. time, SOC, DOD, Ah, C-rate;
• Environment temperature for the calendar ageing (No active BMS)

Level 3 (mid-to-low influence) → • Environment temperature on the cycling ageing if BMS active

Is the phenomenon fully comprehended? NO → More efforts needed
## Input/output of in-vehicle battery durability module of JRC TEMA platform

### Input to JRC TEMA

<table>
<thead>
<tr>
<th>General parameters</th>
<th>Environmental parameters</th>
<th>Duty cycle parameters</th>
<th>Charging data</th>
<th>Battery parameters</th>
</tr>
</thead>
</table>
| • Age of the car since manufacture [yrs]  
• Run-in km  
• Vehicle technology (BEV, PHEV)  
• EoL threshold for capacity fade and power fade | • Ambient temperature max and min for each month of the year [°C] | • Average number of trips per month  
• Average driven distance [km]  
• Average driving time [h]  
• Average driving speed [km/h]  
• Average energy consumption [Wh/km]  
• Average resting time without charging [h]  
• Average parking time [sec] | • Average recharging time [h]  
• Recharging power [kW]  
• Charging mode/level  
• Average number of recharge per month | • Battery chemistry  
• Battery architecture (no. of modules, no. of cells, cell voltage, cell current, series/parallel connection i.e. 48S-2P-2S etc.)  
• Reference battery voltage [V]  
• Battery capacity [Wh]  
• Battery reserve [%]  
• Average weighted battery temperature [°C]  
• Battery temperature min and max (BMS) [°C]  
• Average battery SoC min driving [%]  
• Average battery Delta SoC during charging [%]  
• Average battery SoC parking no charging [%] |

### Output from JRC TEMA

<table>
<thead>
<tr>
<th>HV battery chemistry</th>
<th>Capacity fade</th>
<th>Power fade</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Calendar</td>
<td>Cycle</td>
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<tr>
<td>LiFePO₄</td>
<td>Sarasketa-Zabala et al. (2013/14); Wang et Al. (2011); Sarasketa-Zabala et al. (2013); Sarasketa-Zabala et al. (2015);</td>
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Thank you for the attention

Q&A

Contacts Info:
EC DG JRC DIR-C ETC Sustainable Transport Unit
elena.paffumi@ec.europa.eu