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JRC Contribution to EVE IWG:
In-vehicle battery durability

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30th Meeting of the GRPE Informal
Working Group on Electric Vehicles
and the Environment (EVE)

April 8th-9th, 2019, Stockholm (Sweden)

European
Commission

Presentation Summary (1/3)

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:

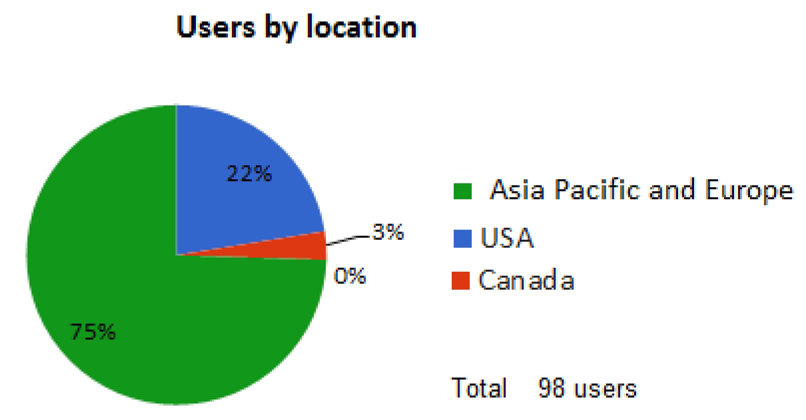
- Finalization of the durability scenario analysis: chemistry formulation, battery architecture, vehicle technologies (BEV, PHEV);
- Different duty cycle representative of several EU geographic regions, ambient temperature or customer profiles;
- Several recharging behaviour
- Preliminary results of 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

Presentation Summary (2/3)

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



*Technical University Eindhoven, May2018, https://steinbuch.wordpress.com/2015/01/24/tesla-model-s-battery-degradation-data

Presentation Summary (3/3)

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

*Myall, Dima Ivanov, Walter Larason, Mark Nixon, Henrik Moller, Preprints, 2018, doi:10.20944/preprints201803.0122.v1

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.

*Steinbuch M. Technical University Eindhoven, May2018, https://steinbuch.wordpress.com/2015/01/24/tesla-model-s-battery-degradation-data

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.

* Myall, Dima Ivanov, Walter Larason, Mark Nixon, Henrik Moller, Preprints, 2018, doi:10.20944/preprints201803.0122.v1

* https://flipthefleet.org/

Background information: JRC TEMA assumptions

- Calendar + Cycle ageing by using battery chemistry model:

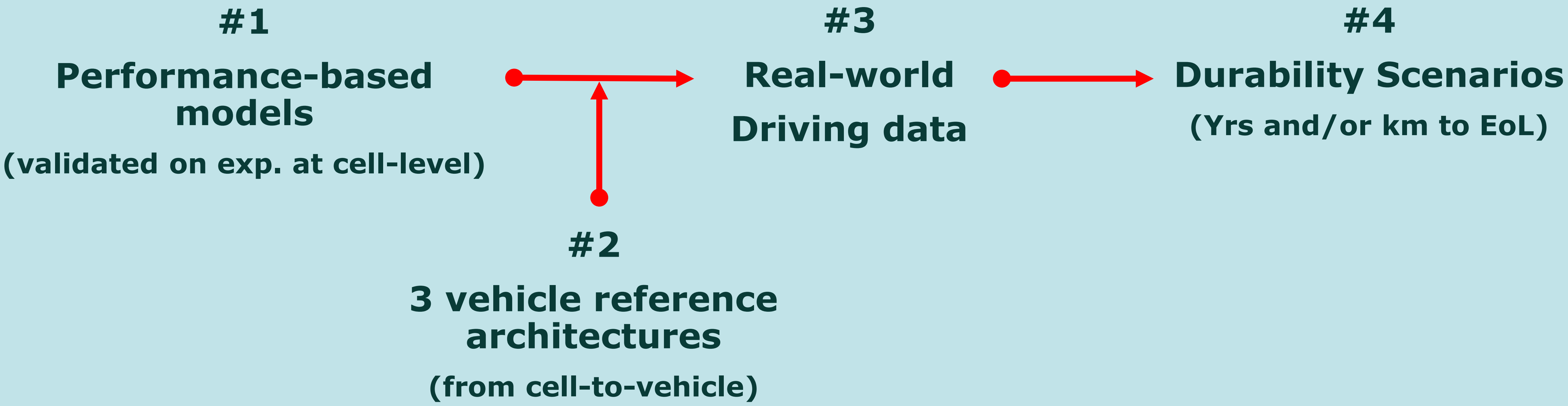
#4 (NCM-LMO): Wang et Al. (2014) for calendar plus Cordoba-Arenas et Al. (2015) for cycle;

- 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.: $Q_{loss\text{-}total} = Q_{loss\text{-}calendar} + Q_{loss\text{-}cycle}$ - 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

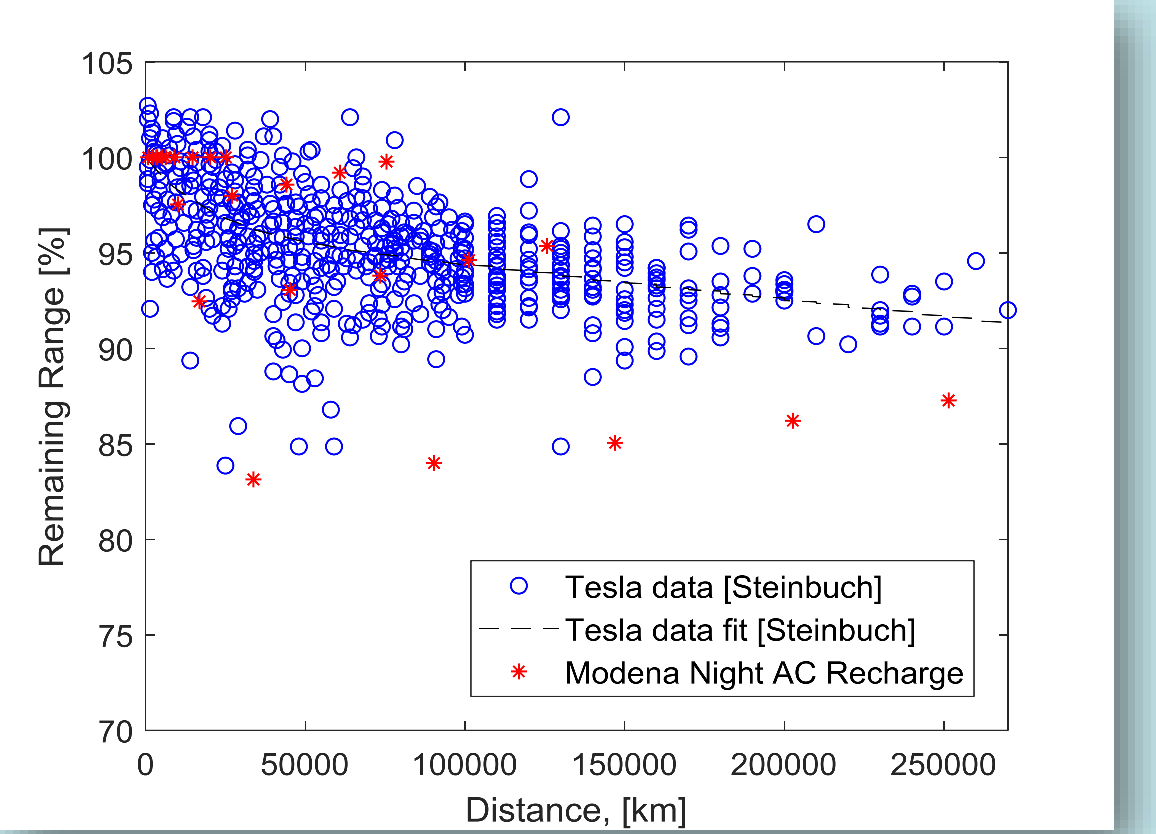
Driving data

#4

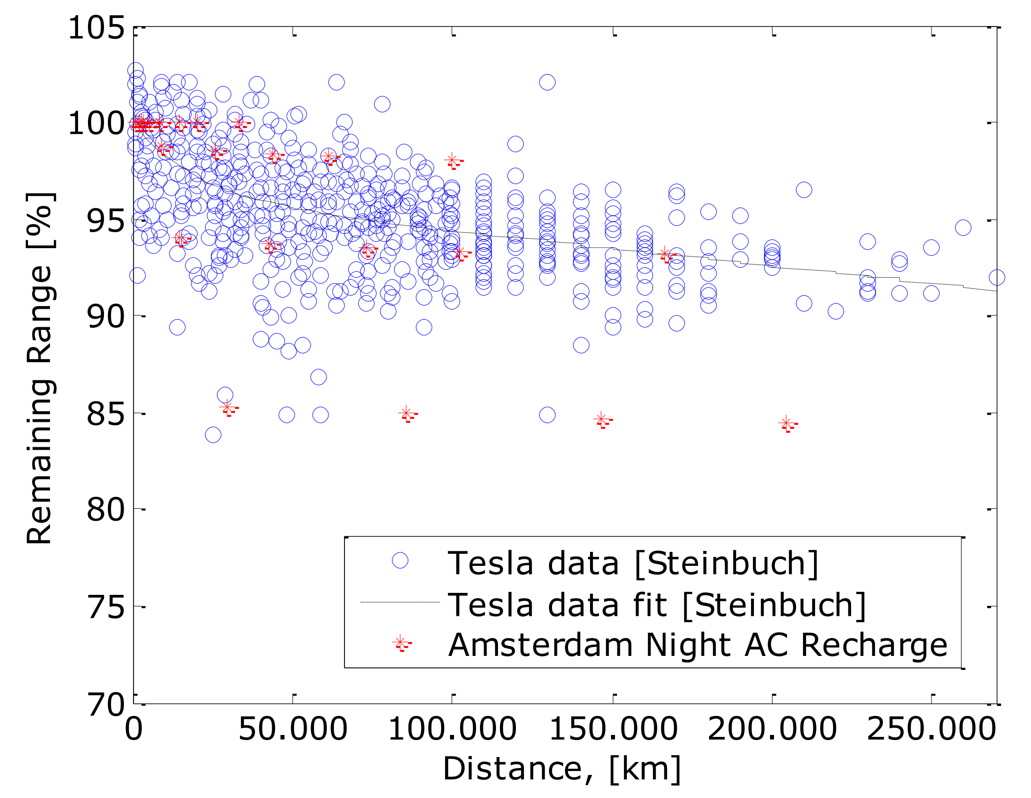
Durability Scenarios

(Yrs and/or km to EoL)

Data comparison: Tesla data



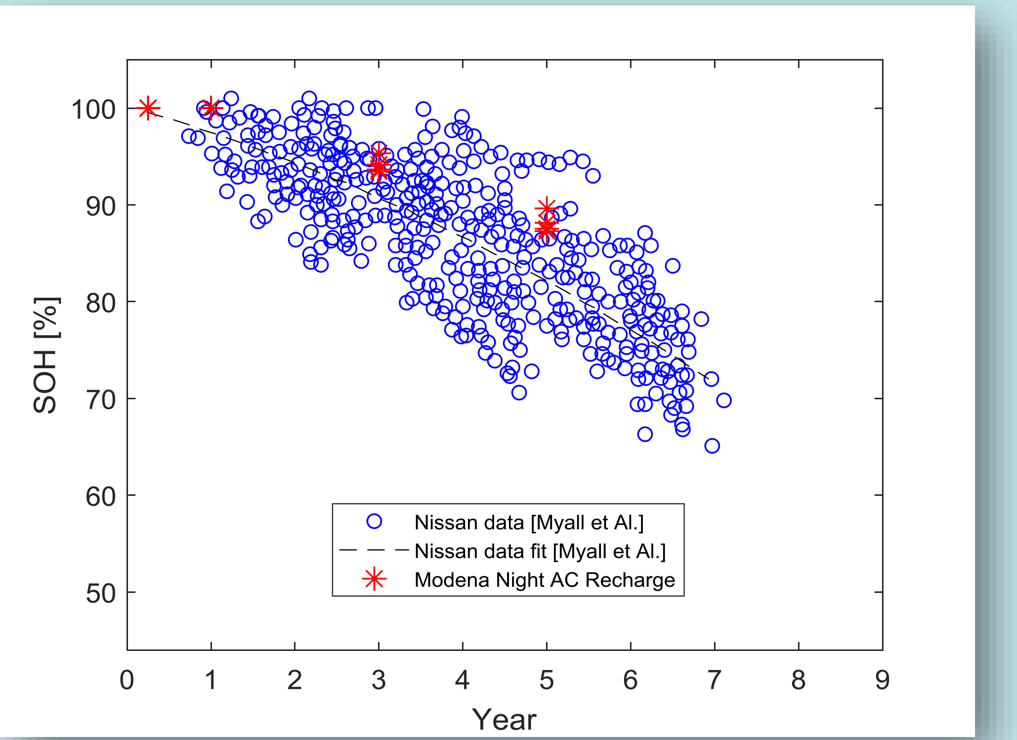
Night AC recharge – Modena Data

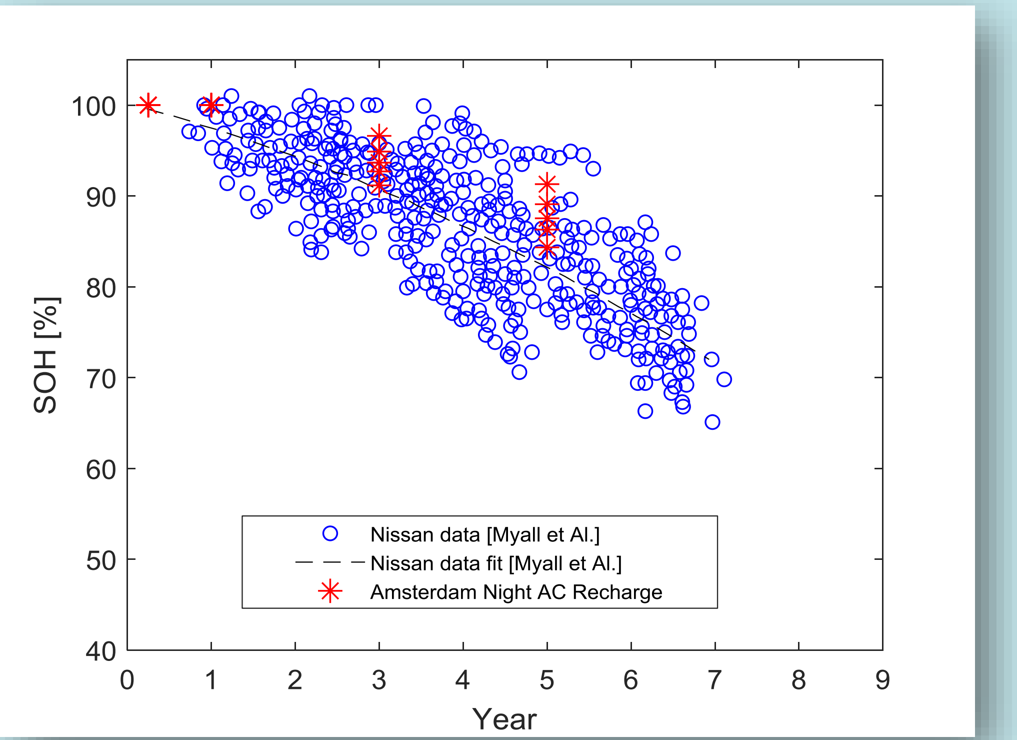


Night AC recharge – Amsterdam Data

*Technical University Eindhoven, May2018, https://steinbuch.wordpress.com/2015/01/24/tesla-model-s-battery-degradation-data

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





Night AC recharge – Modena Data

Night AC recharge – Amsterdam Data

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

*Myall, Dima Ivanov, Walter Larason, Mark Nixon, Henrik Moller, Preprints, 2018, doi:10.20944/preprints201803.0122.v1

Generalising JRC TEMA in-vehicle battery durability model: is it possible?

#1

Performance-based models

(validated on exp. at cell-level)

Predefined calendar and cycling models (Model 1 to Model 5)

Fitting equations and parameters for calendar and cycling ageing ?

#2

Vehicle reference architectures

(from cell-to-vehicle)

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

(Yrs and/or km to EoL)

Predefined different vehicle technologies

Predefined different recharging strategies

Performance based models (SotA)

	Capacity fade		Power fade	
	Calendar	Cycle	Calendar	Cycle
LiFePO$_4$	Sarasketa-Zabala et Al. (2013/14);	Wang et Al. (2011); Sarasketa-Zabala et Al. (2013); Sarasketa-Zabala et Al. (2015);	Sarasketa-Zabala et Al. (2013);	
NCM + spinel Mn	Wang et Al. (2014);		-	-
NCM – LMO	-	Cordoba-Arenas et Al. (2014);	-	Cordoba-Arenas et Al. (2015);

Calendar + Cycle (4 Combinations):

- **#1 (LiFePO$_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Wang et Al. (2011) model for cycle;**
- **#2 (LiFePO$_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Sarasketa-Zabala et Al. (2015) model for cycle;**
- **#3 (NCM + Spinel Mn): Wang et Al. (2014) for calendar plus Wang et Al. (2014) for cycle;**
- **#4 (NCM-LMO): Wang et Al. (2014) for calendar plus Cordoba-Arenas et Al. (2015) 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_{rate}
- Fitting of the data with Arrhenius type equations as for the performance based models already implemented:
  - $Q_{lossCal}(Days,T,SOC) = (A1*exp(B1/T)*(A2)*exp(B2*SOC))*Days^z$
  - $Q_{lossCyc}(Ah,T,C_{rate}) = A1 * exp((-A2 + A3 * C_{rate}) / (R * T)) * (Ah)^z$
- 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
- Egil Mollestad, Zero Emission Maritime solutions ZEM AS (https://www.zemenergy.com)
- under suggestion by Sigve J Aasebø, Norwegian Public Roads Administration

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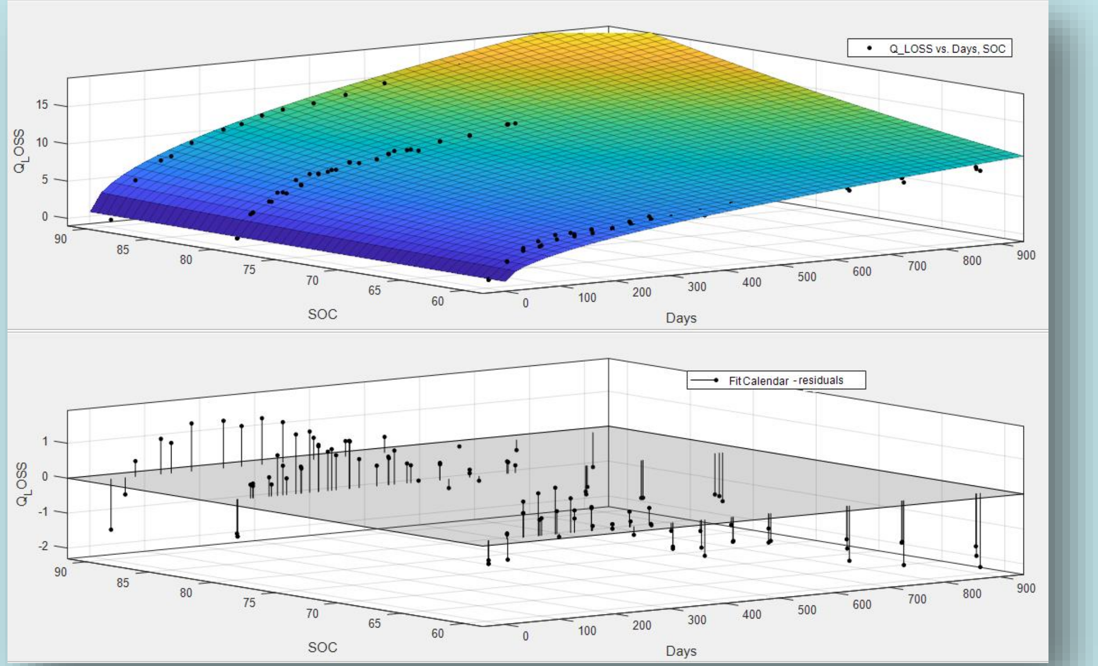
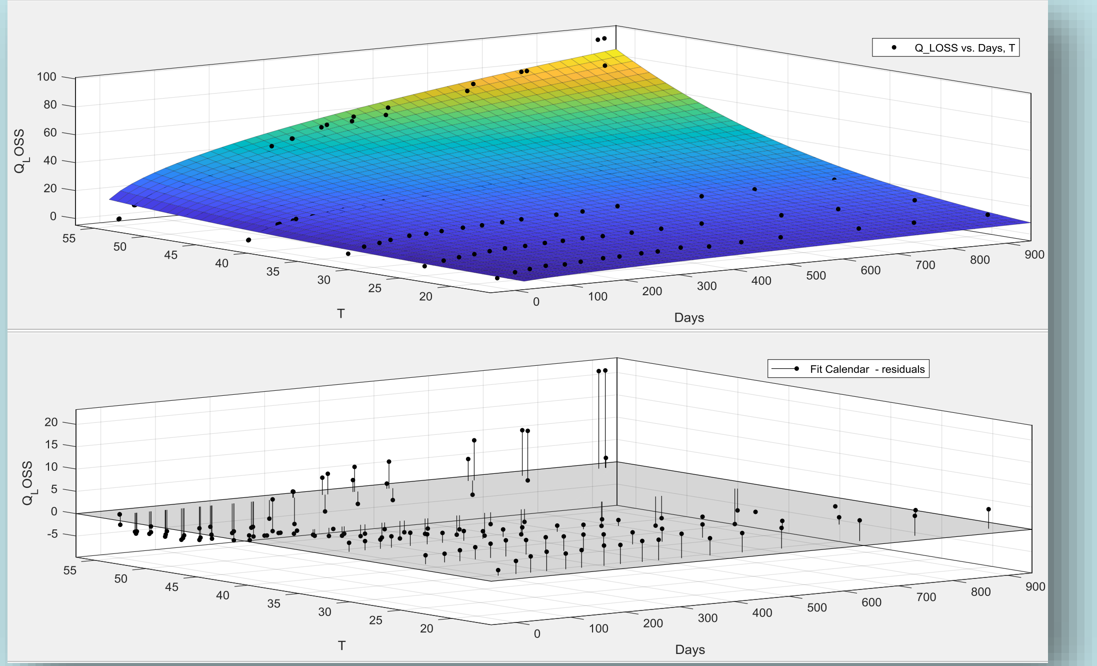
Generalizing JRC TEMA in-vehicle battery durability: non-linear least squares fitting calendar ageing data

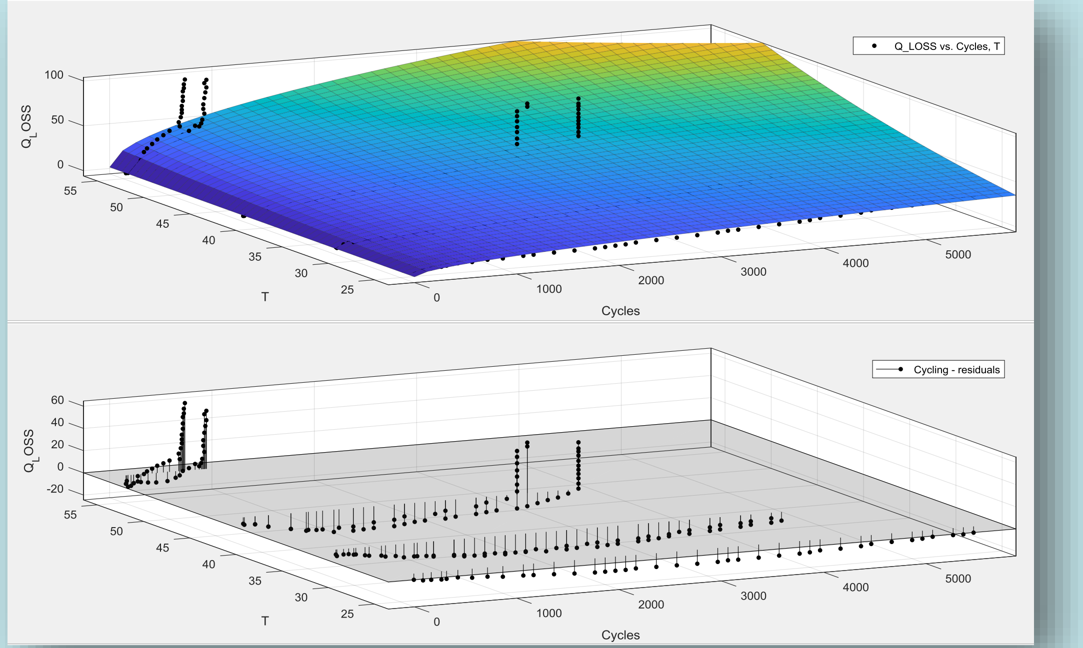




$Q_{lossCal}$(Days,T,SOC) = (A1*exp(B1/T)*(A2)*exp(B2*SOC))*Days^z
Levenberg-Marquardt (LM) damped least-square algorithm in Least Absolute Residuals (LAR) formulation

*Preben J. S. Vie, Institute for Energy Technology, Norway, Understanding Ageing Mechanisms in Li-ion Batteries through in-situ Techniques, 2017
*Egil Mollestad, ZEM AS, https://www.zemenergy.com
*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



$Q_{lossCyc}(Ah,T, C_{rate}) = A1 * \exp((-A2 + A3*C_{rate}) / (R * T)) * (Ah)^z$

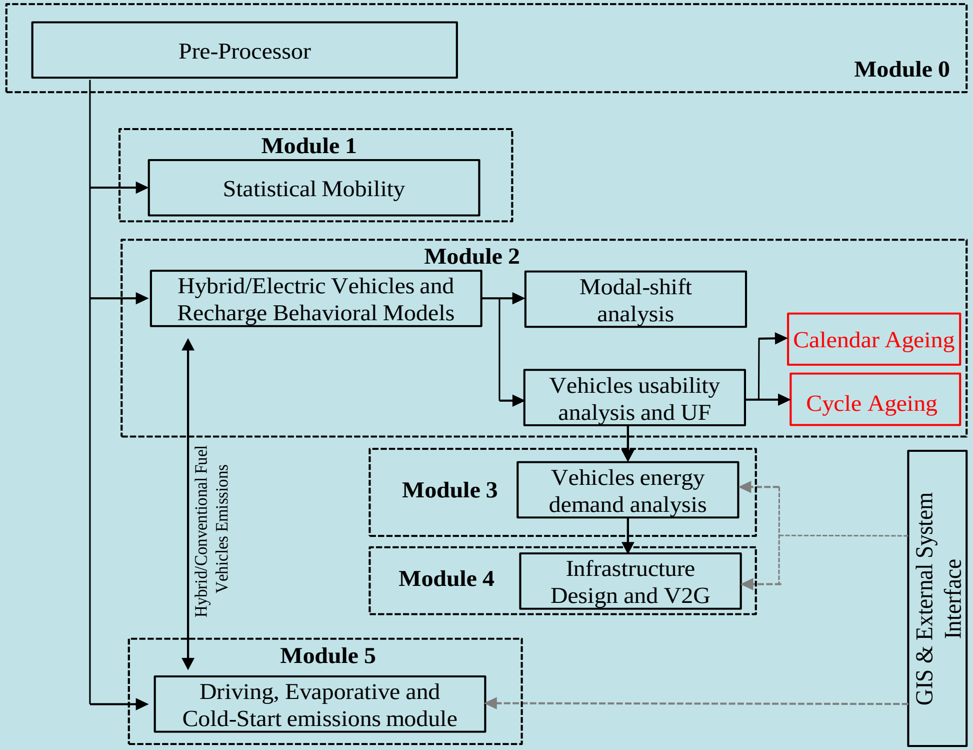
Levenberg-Marquardt (LM) damped least-square algorithm in Least Absolute Residuals (LAR) formulation

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
*Egil Mollestad, ZEM AS, https://www.zemenergy.com
*Norwegian EV company Think
*Electrochimica Acta, 250 (2017), 228-237

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

TEMA Structure



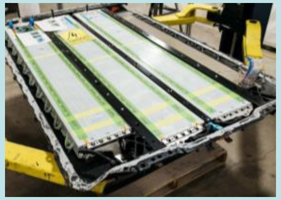
Two New Vehicle Electric Architectures (examples)

PHEV

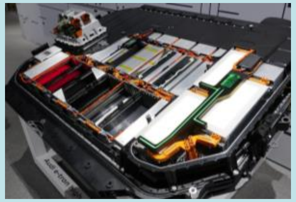
BEV 1

BEV 2

BEV 3



BEV 4



	Vehicle Type	Battery Size [Wh]	Battery Shape	No. of Cells [#] and Type	Reference Voltage [V]	Electric Architecture
T-Shaped	PHEV	16,000	T-shaped	192 – pouch	365	2P-96S
Parallelepiped	BEV 1	24,000	Parallelepiped	192 – pouch	360	48S-2P-2S
Flat-shaped	BEV 2	85,000	Flat	6,912 - cylindrical	345	16S-72P-6S
Flat-shaped	BEV 3	75,000	Flat	4,416 - cylindrical	345	4S-46P-23|25S
Flat-shaped	BEV 4	95,000	Flat	432 – pouch	396	4P-108S

	Usable Energy at BoL [Wh]	Usable Energy at EoL [Wh]	Reserve [% of battery capacity]	Energy consumption [Wh/km]
T-shaped (PHEV)	12,000	9,600	25%	205
Parallelepiped (BEV 1)	18,000	14,400	15%	210
Flat-shaped (BEV 2)	63,750	51,000	15%	235
Flat-shaped (BEV 3)	56,250	45,000	15%	180
Flat-shaped (BEV 2)	71,250	57,000	15%	262

Further Scenarios explored (EoL - tabulated)

EoL @ 80% capacity fade Li-Ion NCM-LMO (2015) Years Driving to Set Threshold				0 - 500 km/month			500 – 1,000 km/month			1,000 -1,500 km/month			1,500 – 2,000 km/month			2,000+ km/month		
				Years to EoL	Years to 100,000 km	Years to 160,000 km	Years to EoL	Years to 100,000 km	Years to 160,000 km	Years to EoL	Years to 100,000 km	Years to 160,000 km	Years to EoL	Years to 100,000 km	Years to 160,000 km	Years to EoL	Years to 100,000 km	Years to 160,000 km
Recharge Strategy #1	BEV-1	Modena Prov.	NCM-LMO (2015)	9.7	≥ 20	≥ 20	8.6	12.8	≥ 20	8.2	7.9	12.6		-			-	
		Amsterdam Prov.		10.9	≥ 20	≥ 20	9.1	11.6	18.6	8.2	6.9	11	7.5	4.9	7.8	6.7	3.4	5.4
		Brussels Prov.		10.8	≥ 20	≥ 20	9.1	12.7	≥ 20	8.2	6.9	11	7.6	4.8	7.7	7.2	3.7	5.9
		Luxembourg Prov.		10.5	≥ 20	≥ 20	9	11.6	18.5	8.1	7	11.2	7.5	5	7.9	6.8	3.4	5.4
		Paris Prov.		9.4	≥ 20	≥ 20	8.2	11.1	17.9	7.4	6.8	10.8	6.8	4.8	7.7	5.9	2.6	4.2
	BEV-2	Modena Prov.		12.1	≥ 20	≥ 20	12.7	11.2	17.9	13.6	6.9	11	14.7	5	8.1	16.1	3.9	6.3
		Amsterdam Prov.		13.9	≥ 20	≥ 20	13.7	11.6	18.6	13.6	6.9	11	13.5	4.9	7.8	13.3	3.4	5.4
		Brussels Prov.		13.4	≥ 20	≥ 20	13.4	12.6	≥ 20	13.4	6.9	11	13.7	4.8	7.7	13.7	3.7	5.9
		Luxembourg Prov.		13.4	≥ 20	≥ 20	13.4	11.6	18.5	13.4	7	11.1	13.2	4.9	7.9	13.3	3.4	5.4
		Paris Prov.		12	≥ 20	≥ 20	12	11.2	17.9	12	6.8	10.8	11.9	4.8	7.7	11.8	2.6	4.2
	BEV-3	Modena Prov.		19.1	≥ 20	≥ 20	18.6	11.0	17.6	18.3	6.7	10.8	18.1	4.8	7.7	17.8	2.9	4.6
		Amsterdam Prov.		13.8	≥ 20	≥ 20	13.5	11.6	18.6	13.4	6.9	11.0	13.2	4.9	7.8	13.0	3.4	5.4
		Brussels Prov.		13.3	≥ 20	≥ 20	13.2	12.7	≥ 20	13.2	6.9	11.0	13.5	4.8	7.7	13.5	3.7	5.9
		Luxembourg Prov.		≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20
		Paris Prov.		11.9	≥ 20	≥ 20	11.8	11.2	17.9	11.8	6.8	10.8	11.7	4.8	7.7	11.6	2.6	4.2
Rech. Str. #2	BEV-1	Modena Prov.	NCM-LMO (2015)	9.3	≥ 20	≥ 20	7.9	11.7	18.7	7.1	7.1	11.4	6.6	5.1	8.1	6.2	3.7	6
		Amsterdam Prov.		10.9	≥ 20	≥ 20	8.9	11.6	18.8	7.9	6.9	11	7.2	4.9	7.8	6.5	3.4	5.4
		Brussels Prov.		10.8	≥ 20	≥ 20	8.8	12.7	≥ 20	7.8	6.9	11	7.4	4.8	7.7	6.9	3.7	5.9
		Luxembourg Prov.		10.4	≥ 20	≥ 20	8.7	11.6	18.6	7.8	7	11.1	7.1	4.9	7.9	6.5	3.4	5.4
		Paris Prov.		9.3	≥ 20	≥ 20	7.9	11.3	18	7.1	6.8	10.8	6.6	4.8	7.7	5.6	2.6	4.2
	BEV-2	Modena Prov.		11.6	≥ 20	≥ 20	11.4	11	17.7	11.3	6.8	10.8	11.2	4.8	7.7	11.2	3.4	5.4
		Amsterdam Prov.		13.7	≥ 20	≥ 20	13.2	11.7	18.7	12.9	6.9	11.0	12.8	4.9	7.8	12.6	3.4	5.4
		Brussels Prov.		13.2	≥ 20	≥ 20	12.8	12.7	≥ 20	12.7	6.9	11.0	13.1	4.8	7.7	13.2	3.7	5.9
		Luxembourg Prov.		13.1	≥ 20	≥ 20	12.8	11.6	18.6	12.6	7	11.1	12.5	4.9	7.9	12.4	3.4	5.4
		Paris Prov.		11.8	≥ 20	≥ 20	11.5	11.3	18.1	11.4	6.8	10.8	11.3	4.8	7.7	11.3	2.6	4.2
	BEV-3	Modena Prov.		19.0	≥ 20	≥ 20	18.5	11.0	17.6	18.2	6.7	10.8	18.0	4.8	7.7	17.7	2.9	4.6
		Amsterdam Prov.		13.7	≥ 20	≥ 20	13.1	11.7	18.8	12.8	6.9	11.0	12.6	4.9	7.8	12.4	3.4	5.4
		Brussels Prov.		13.1	≥ 20	≥ 20	12.6	12.7	≥ 20	12.5	6.9	11.0	12.9	4.8	7.7	12.9	3.7	5.9
		Luxembourg Prov.		≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20
		Paris Prov.		11.7	≥ 20	≥ 20	11.4	11.3	18.0	11.2	6.8	10.84	11.1	4.8	7.7	11.0	2.6	4.2

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
General parameters	• Age of the car since manufacture [yrs] • Run-in km • Vehicle technology (BEV, PHEV) • EoL threshold for capacity fade and power fade
Environmental parameters	• Ambient temperature max and min for each month of the year [°C]
Duty cycle parameters	• 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]
Charging data	• Average recharging time [h] • Recharging power [kW] • Charging mode/level • Average number of recharge per month
Battery parameters	• 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 [%]

HV battery chemistry	**Output from JRC TEMA**			
	Capacity fade		**Power fade**	
	Calendar	Cycle	Calendar	Cycle
$LiFePO_4$	Sarasketa-Zabala et Al. (2013/14);	Wang et Al. (2011); Sarasketa-Zabala et Al. (2013); Sarasketa-Zabala et Al. (2015);	Sarasketa-Zabala et Al. (2013);	
NCM + Spinel Mn	Wang et Al. (2014);		-	-
NCM – LMO	-	Cordoba-Arenas et Al. (2014);	-	Cordoba-Arenas et Al. (2015);

Thank you for the attention

Q&A

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