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JRC Contribution to EVE IWG:

In-vehicle battery durability

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28th Meeting of the GRPE Informal
Working Group on Electric Vehicles
and the Environment (EVE)

October 16th-18th, 2018, Ottawa (Canada)

Presentation Summary (1/2)

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

Summary up to June 2018, i.e. **what's old**:

- Finalisation of the durability scenario analysis: chemistry formulation, battery architecture, vehicle technologies (BEV, PHEV);
- In-vehicle cross-validation of the model's results against experimental data from Canada;
- Development of further scenarios for in-vehicle battery durability: 2 additional BEVs (i.e. A-segment + D-segment SUV);
- Estimation of the Years needed to reach 90% ; 80% ; 70% ; 60% ; 50% capacity fade
- 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 (2/2)

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

Current Status (June-October 2018), i.e. **what's new**:

- Development of further scenarios for in-vehicle battery durability:
 - duty cycle representative of other EU geographic regions, ambient temperature or customer profiles;
 - Preliminary results of ambient temperature studies, i.e. warm and cold temperatures

Performance based models (SotA)

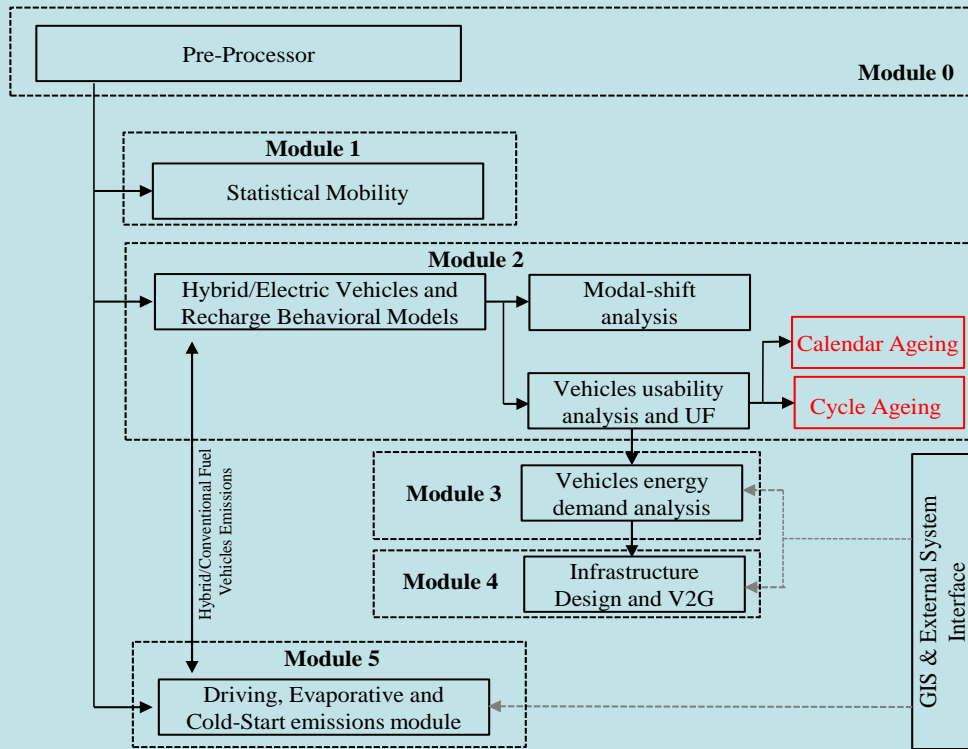
	Capacity fade		Power fade	
	Calendar	Cycle	Calendar	Cycle
LiFePO₄	Sarasketa-Zabala et Al. (2013/14);	Wang et Al. (2011); Sarasketa-Zabala et Al. (2013);	Sarasketa-Zabala et Al. (2013);	
		Sarasketa-Zabala et Al. (2015);		
NCM + spinel Mn	Wang et Al. (2014);		-	-
NCM – LMO	-	Cordoba-Arenas et Al. (2014);	-	Cordoba-Arenas et Al. (2015);

Calendar + Cycle (4 Combinations):

- #1 (LiFePO₄): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Wang et Al. (2011) model for cycle;
- #2 (LiFePO₄): 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;

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

TEMA Structure



Vehicle Electric Architecture (examples)

PHEV



BEV 1



BEV 2



	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

	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%	265

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

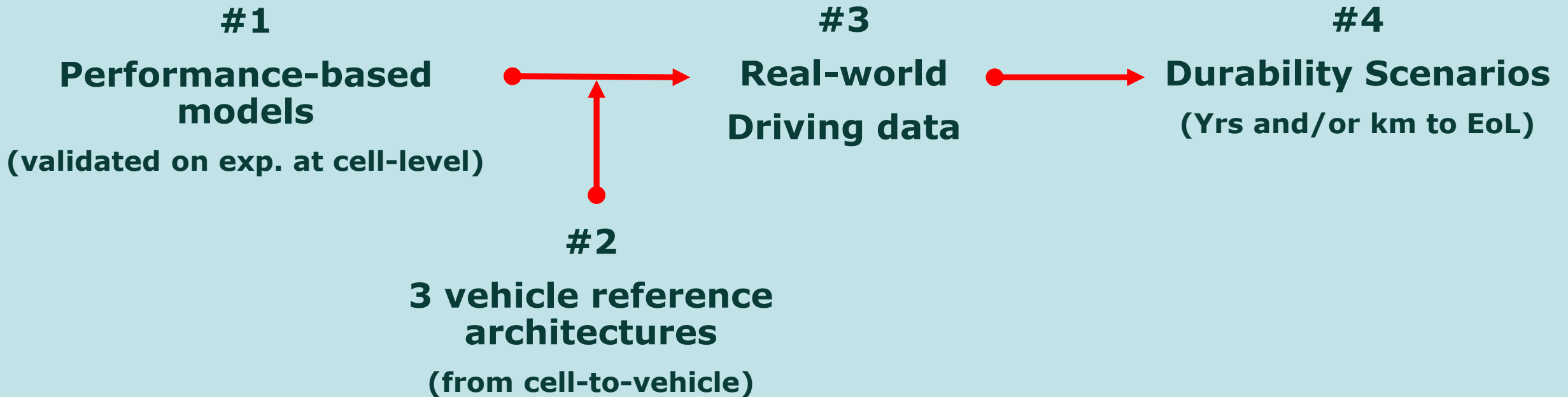
The models have been implemented by adopting the following assumptions:

- the calendar and cycle capacity fades are calculated at cell level (uniform ageing assumption);
- the model assumes average quantities in the reference period per each vehicle for DOD, C-rate, Ah-throughput and temperature;
- DOD and temperature are assumed equal to the battery values, consistently with the uniform fade assumption, whilst the C-rate and Ah-throughput are scaled from the battery level down to the cell;
- the battery temperature is regulated by the BMS between 22 °C and 27 °C during the driving and recharging phases (cycle capacity fade modelling), whilst it assumes the ambient temperature in the parking phase (calendar capacity fade modelling);
- The model capacity fade is calculated at the net of the capacity fade reserve. i.e.:

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

- 5 recharge strategies adopted:
 - ✓ Str. 1 = Long Stop Random AC;
 - ✓ Str. 2 = Short-Stop Random DC;
 - ✓ Str. 3 = Night AC - Str. 4 = Smart AC;
 - ✓ Str. 5 = Long-Stop AC 3-phases;
- 5 vehicle segments:
 - ✓ B-segment BEV
 - ✓ D-segment premium BEV
 - ✓ D segment PHEV
 - ✓ 2 additional BEVs (i.e. A-segment + D-segment SUV)

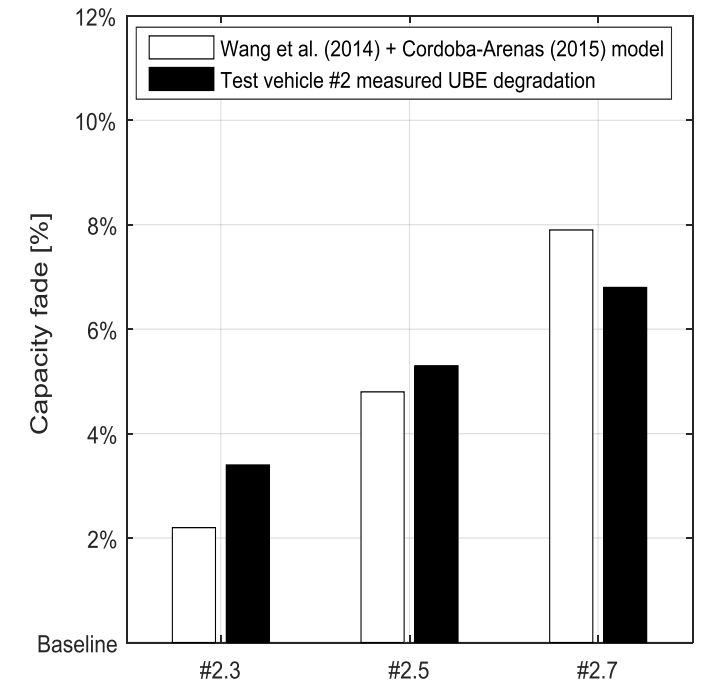
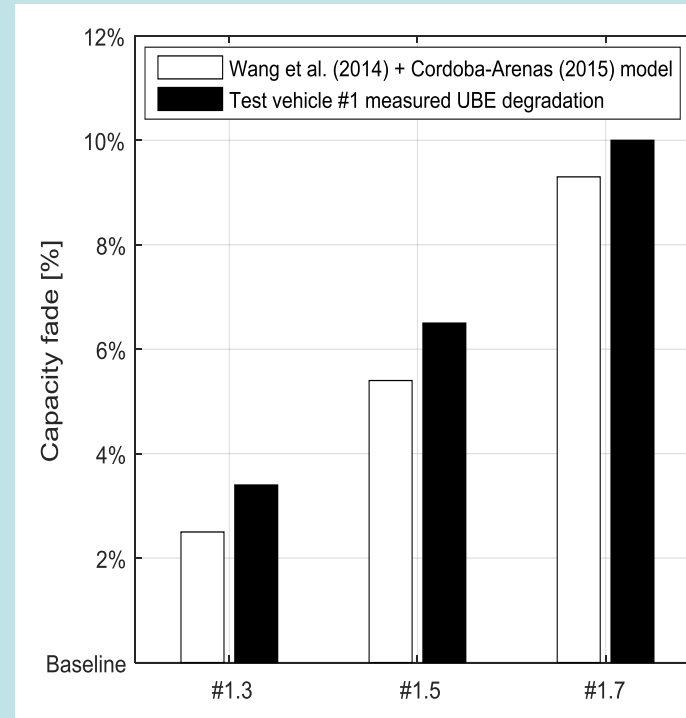
Summary of the logical passages



Experimental data from Canada (Validation)

In-vehicle validation of the models (assumptions):

- Uniform T, DoD, C-rate and Ah-throughput;
- T, DoD @ battery level;
- C-rate and Ah-throughput @ cell level;
- $Q_{\text{loss-total}} = Q_{\text{loss-cal.}} + Q_{\text{loss-cycle}} - \text{Reserve}(10\%)$;
- NCM-LMO model (closer to real LEAF chemistry i.e. LiMn_2O_4 with LiNiO_2)



The results have been presented at the EVS 31&EVTeC 2018, Kobe, Japan and will be described in the scientific paper “Capacity fade of Lithium-ion automotive batteries under real-world use conditions”, Submitted in Feb. 2018

Further Scenarios explored

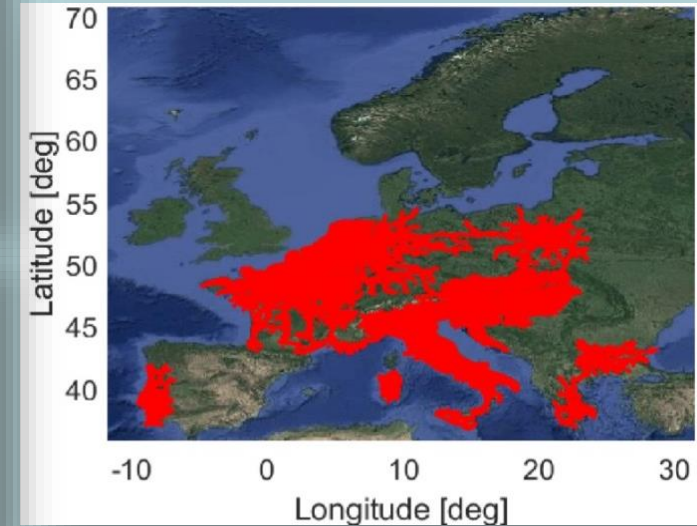
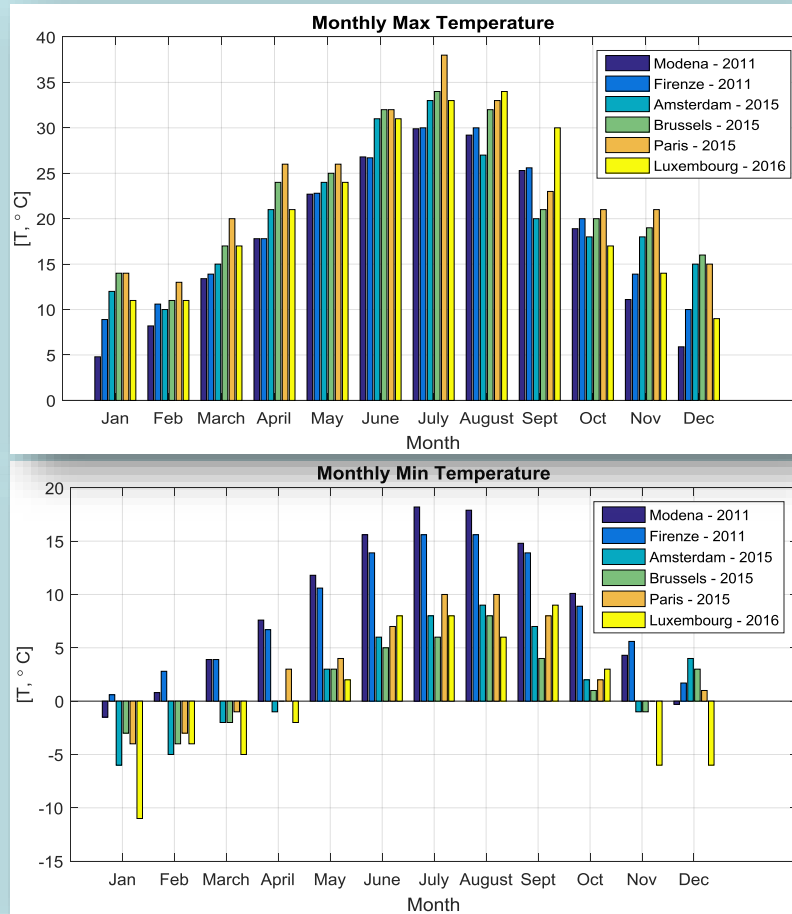
Scenarios presented in June 2018, EVE 27th, include:

- Different duty cycle representative of more EU geographic areas; additional databases included in the analysis;
- Analysis of the BEV1, BEV2 and PHEV1 vehicles:
 - Focus on NCM-LMO chemistry;
 - 5 recharge strategies per 5 user bins (as before);
 - Estimates of the Years needed to reach 80% capacity fade, 100,000km and 160,000km.

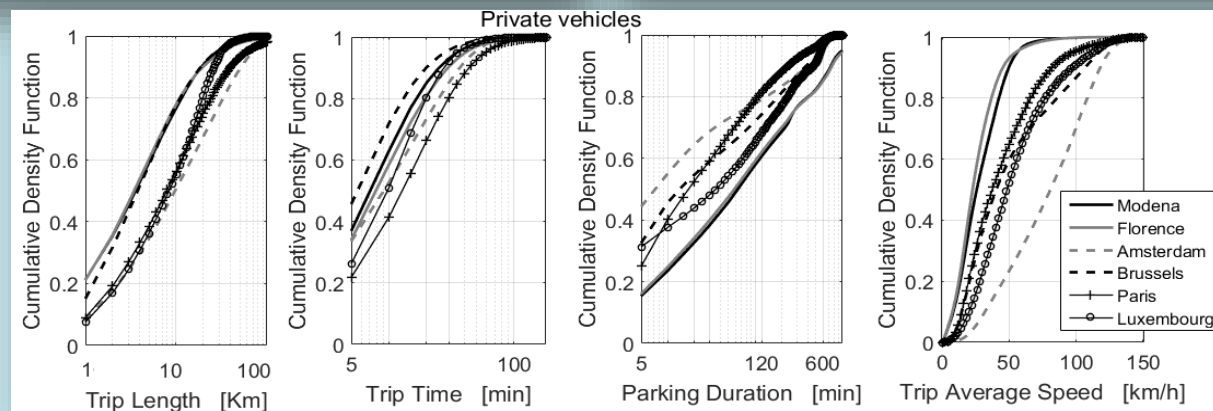
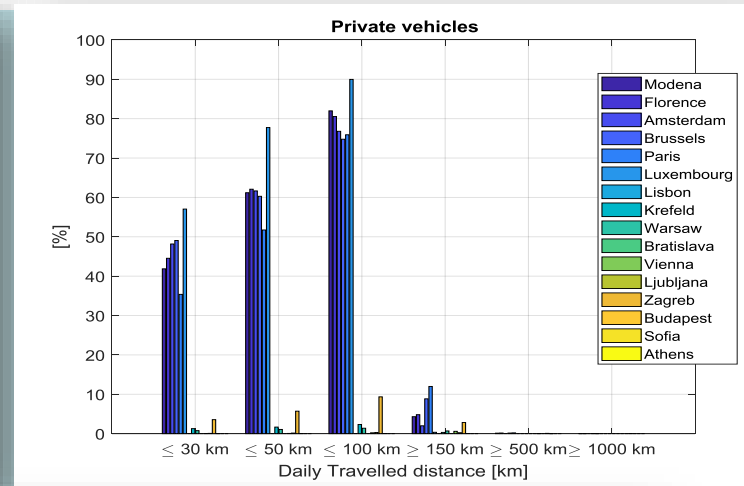
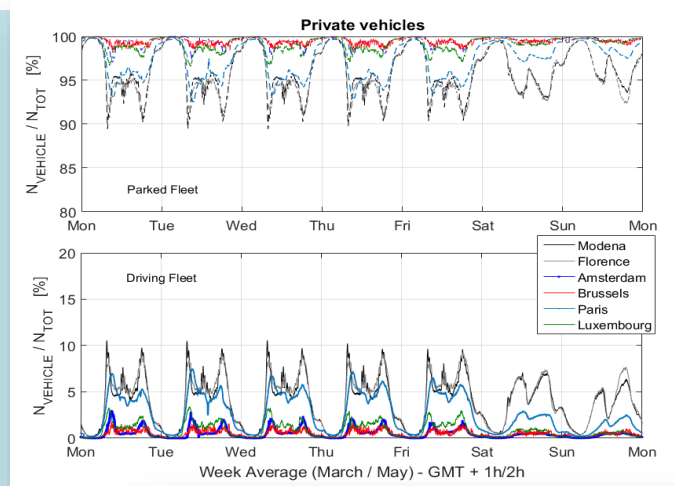
EU-wide extension of the activity data

		No. of days [#]	No. of vehicles [#]	Records [·10 ⁶]	Trips [·10 ⁶]	Total trips lengths [km·10 ⁶]	No. of trip per day (mean) [#]	Trip length [km] (mean)	Daily driven distance (mean) [km]	
Private Vehicles	Province of Modena	31	16,263	16.00	1.9	14.98	6.6	7.8	51.9	
	Province of Florence	31	12,478	32.01	2.6	20.66	6.4	8.0	51.3	
	Province of Amsterdam	7	197,756	466.28	1.1	19.86	1.9	19.7	37.2	
	Province of Brussels	14	96,802	277.05	1.1	11.21	7.9	7.7	55.2	
	Province of Paris	7	171,220	963.27	2.3	38.39	4.2	17.0	71.7	
	Province of Luxembourg	7	14,090	24.33	0.08	1.0	2.5	11.9	30.1	
Commercial Vehicles	Province of Lisbon	7	7,522	66.16	0.16	2.48	5.8	15.0	86.1	
	Province of Krefeld	7	4,160	22.11	0.01	0.97	1.7	88.8	151.7	
	Province of Warsaw	7	862	3.79	0.003	0.16	2.4	51.8	124.3	
	Province of Bratislava	7	18,296	23.08	0.04	1.0	1.5	22.9	35.0	
	Province of Vienna	7	9,943	49.44	0.06	2.14	13.8	37.9	134.2	
	Province of Ljubljana	7	11,616	95.77	0.08	4.04	3.4	45.3	148.6	
	Province of Zagreb	7	12,036	91.66	0.15	3.79	4.6	24.3	104.6	
	Province of Budapest	7	32,410	320.45	0.32	14.10	4.1	44.1	179.0	
	Province of Sofia	7	11,368	79.60	0.20	3.28	5.4	16.4	87.4	
	Province of Athens	7	15,366	42.09	0.13	1.49	4.9	11.0	53.9	
	TOTAL		632,186	2.57·10³	10.19	139.57				
	TOTAL (private)		506,105	1.77·10³	8.56	101.87				
	TOTAL (commercial)		126,081	0.80·10³	1.63	37.70				

*From Octo Telematics
 †From BeMobile



Mobility Behaviour Private Vehicles



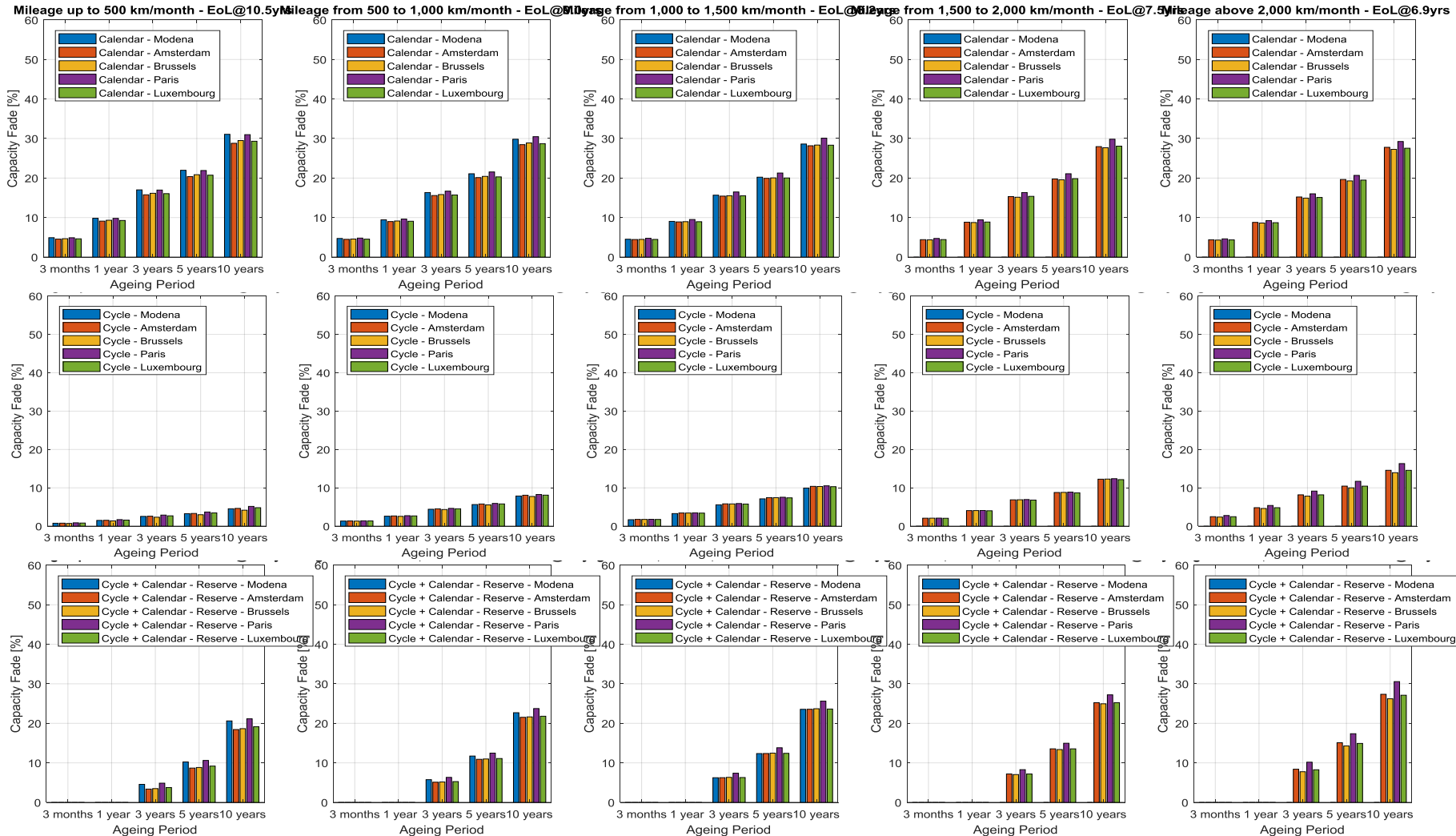
Further Scenarios (capacity fade – visualisation)

BEV 1 + Recharge Strategy 1- Li-Ion NCM-LMO (2015)

Calendar Ageing

Cycle Ageing

Calendar + Cycle Ageing - Reserve



October 16th-18th, 2018, Ottawa (Canada)

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	PHEV-1	Modena Prov.	NCM-LMO (2015)	16.5	≥ 20	≥ 20	14.6	14.2	≥ 20	-	-	-	-	-	-	-		
		Amsterdam Prov.		18.3	≥ 20	≥ 20	15.3	11.6	18.6	13.7	6.9	11	12.5	4.9	7.8	11.3	3.4	5.4
		Brussels Prov.		18	≥ 20	≥ 20	15.2	12.6	≥ 20	13.6	6.9	11	12.8	4.8	7.7	12.1	3.7	5.9
		Luxembourg Prov.		17.5	≥ 20	≥ 20	15	11.5	18.4	13.6	7	11.1	12.6	5	7.9	11.4	3.4	5.4
		Paris Prov.		15.6	≥ 20	≥ 20	13.6	11.2	17.9	12.4	6.8	10.8	11.4	4.8	7.7	9.8	2.6	4.2
	BEV-1	Modena Prov.		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
Recharge Strategy #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	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	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
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;																		

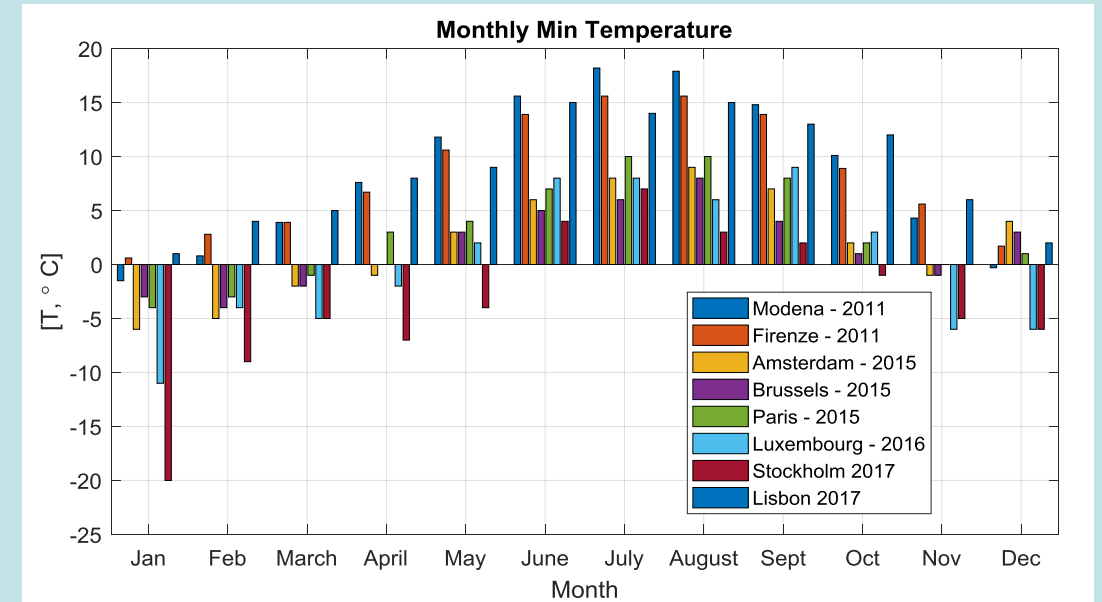
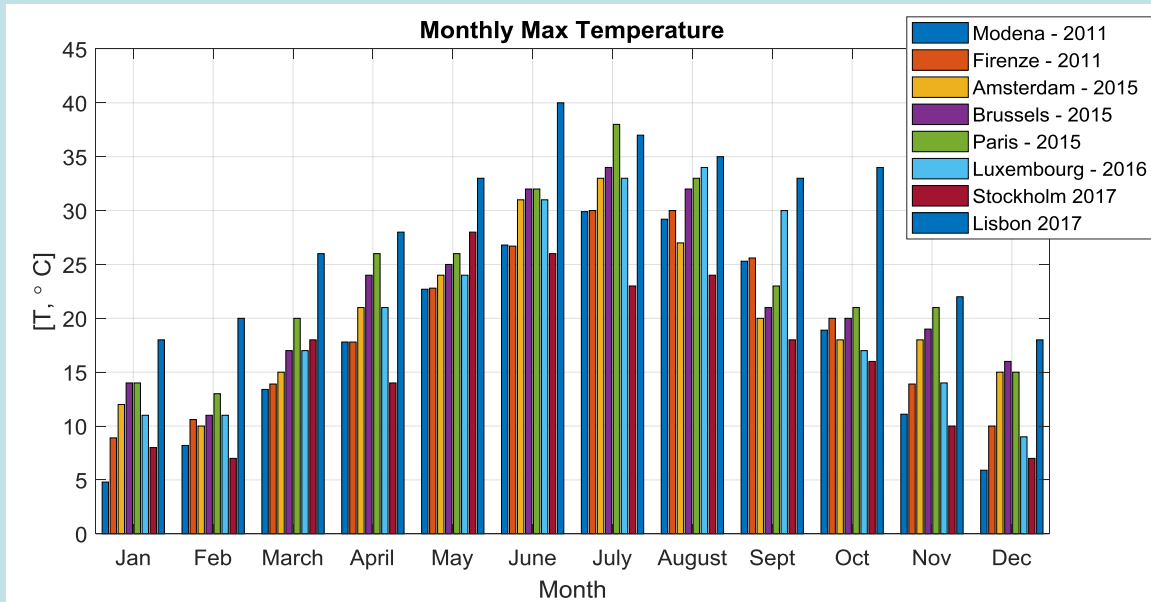
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Further Scenarios explored

New scenarios include:

- Warm and cold ambient temperatures, i.e. Lisbon and Stockholm 2017 temperatures, keeping the same driving duty cycle of Modena province;
- Analysis of the BEV1 and BEV2 vehicles:
 - Focus on NCM-LMO chemistry;
 - 5 recharge strategies per 5 user bins (as before);
 - Increase of the energy consumption due to the usage of the HVAC system +15% due to the cabin cooling, +35% due to the cabin heating;
 - Estimates of the Years needed to reach 80% capacity fade, 100,000km and 160,000km.

Environmental temperature variation



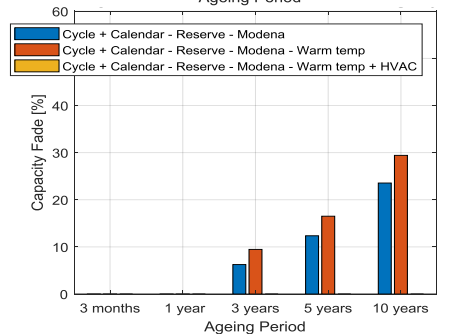
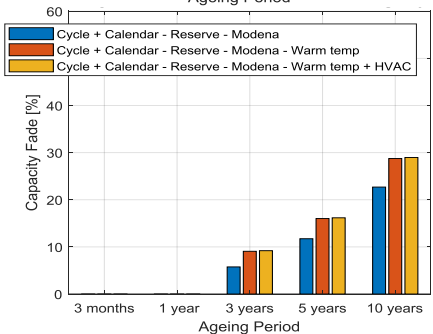
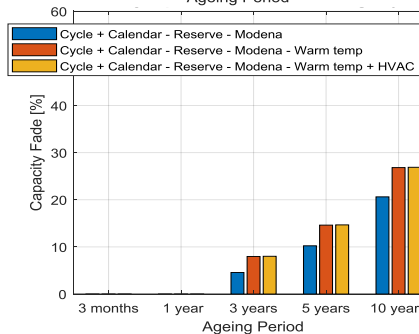
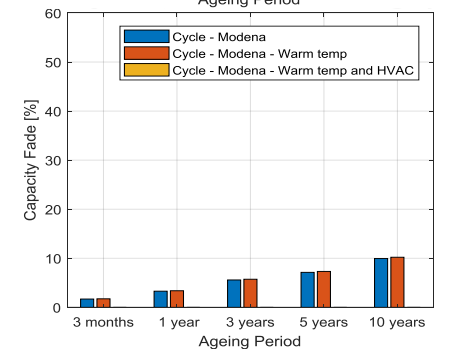
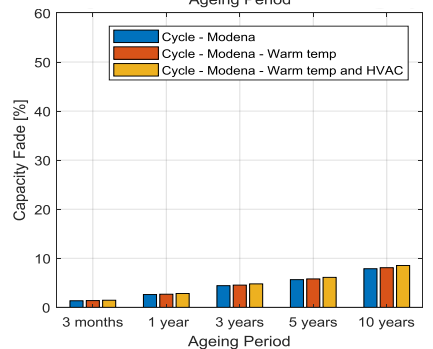
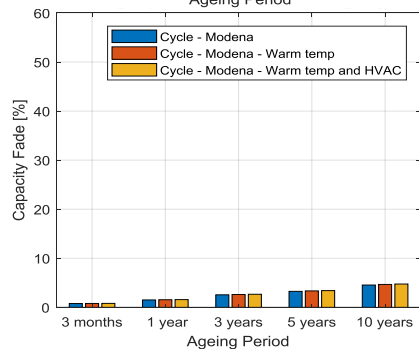
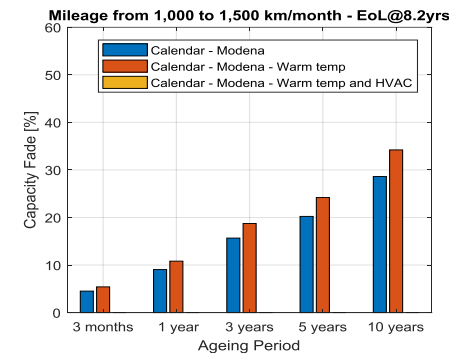
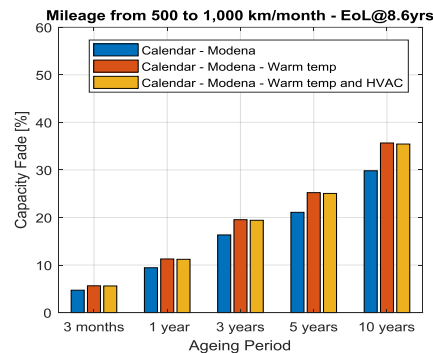
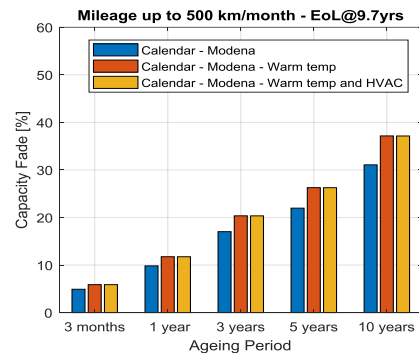
Further Scenarios (capacity fade – visualisation)

BEV 1 + Recharge Strategy 1 - Li-Ion NCM-LMO (2015)

Calendar
Ageing

Cycle
Ageing

Calendar
+Cycle
Ageing -
Reserve



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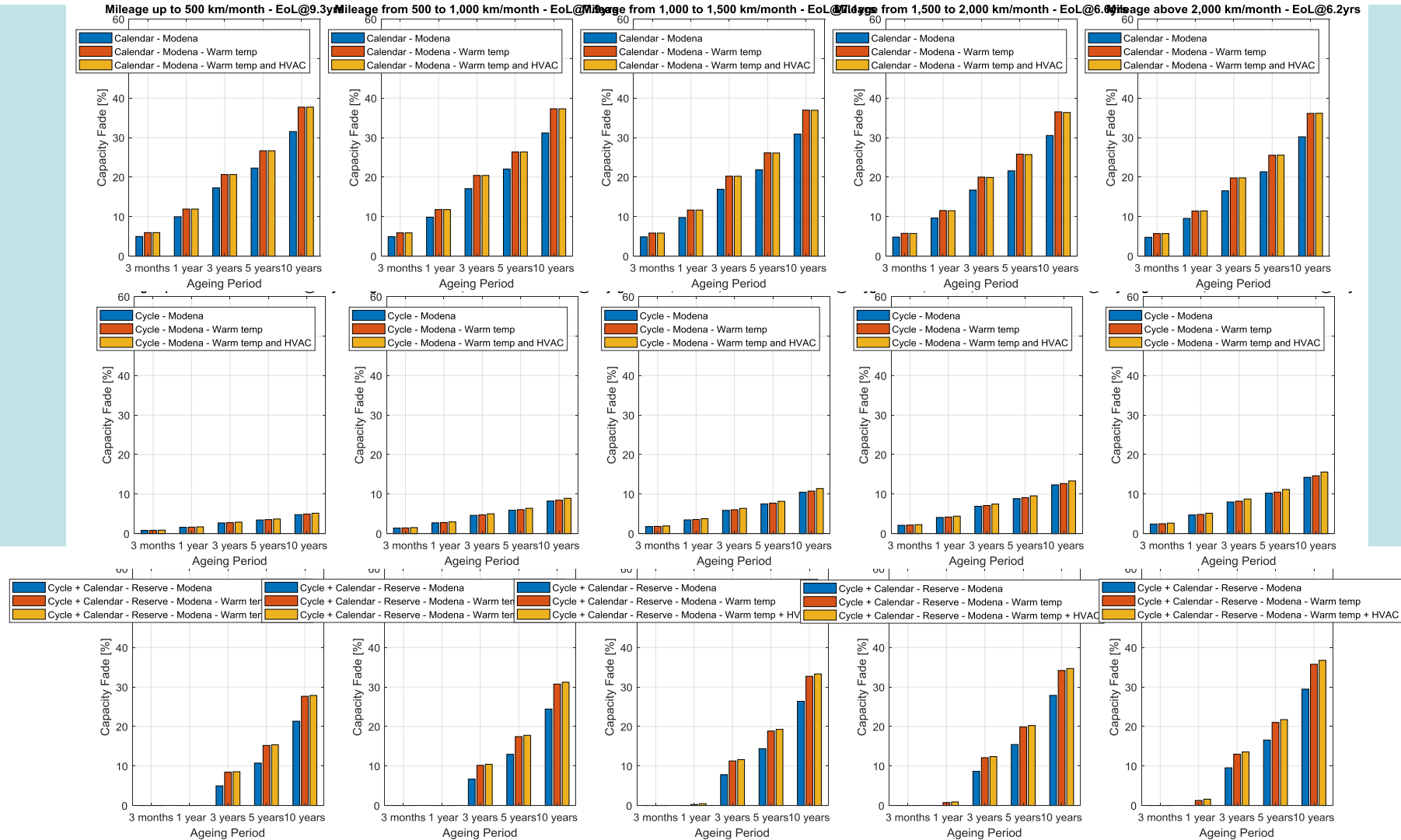
Further Scenarios (capacity fade – visualisation)

BEV 1 + Recharge Strategy 2 - Li-Ion NCM-LMO (2015)

Calendar Ageing

Cycle Ageing

Calendar + Cycle Ageing - Reserve



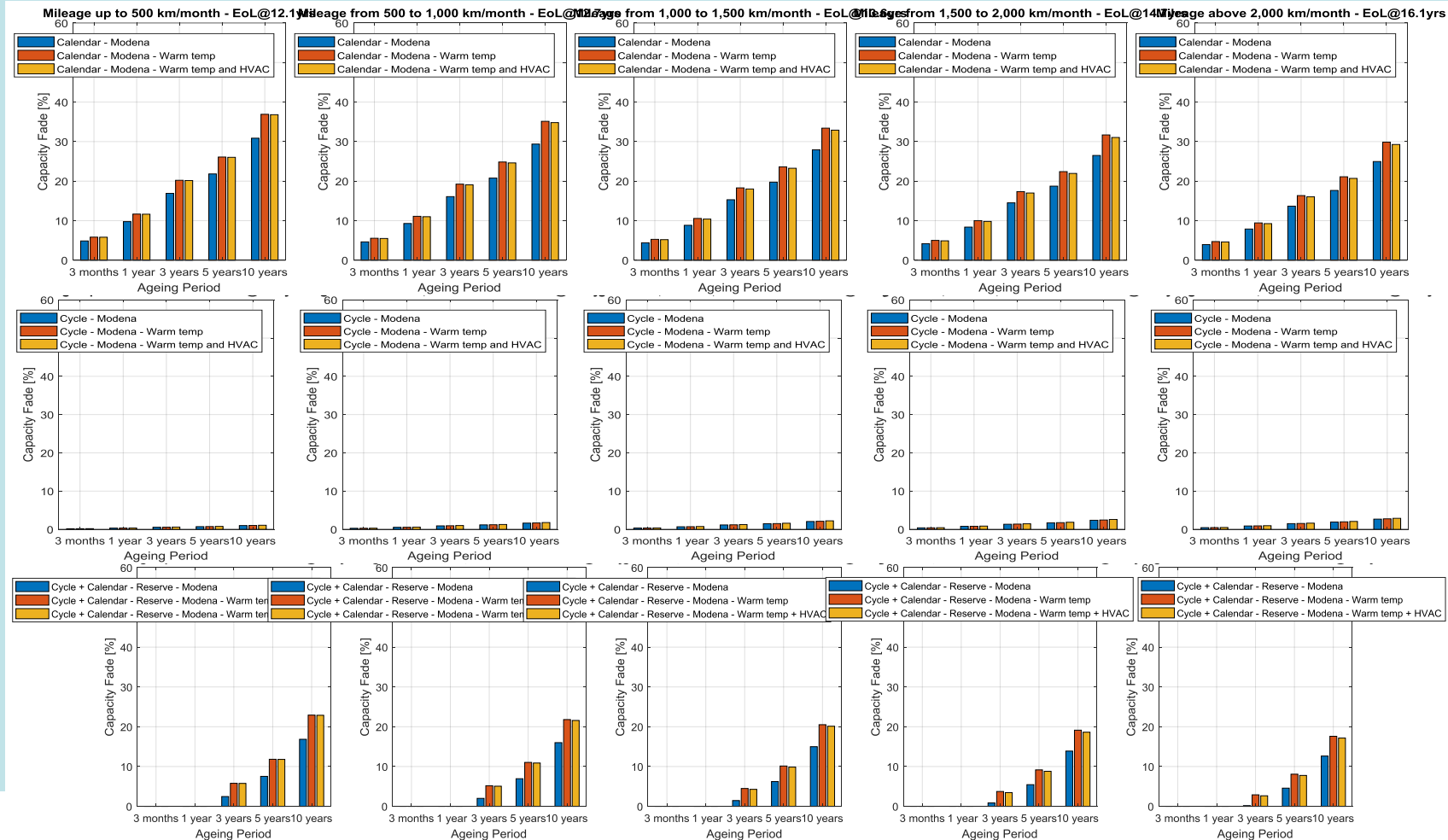
Further Scenarios (capacity fade – visualisation)

BEV 2 + Recharge Strategy 1 - Li-Ion NCM-LMO (2015)

Calendar Ageing

Cycle Ageing

Calendar + Cycle Ageing - Reserve



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Further Scenarios explored (EoL - tabulated)

EoL @ 80% capacity fade Li-Ion NCM-LMO (2015) Years Driving to Set Threshold Warm environment temperature (Lisbon 2017)				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	Modena Prov.	BEV-1	9.9% fleet share	NCM-LMO (2015)	7.0	≥ 20	≥ 20	6.3	13.2	≥ 20	-			-					
		BEV-2	46.4 % fleet share		8.5	≥ 20	≥ 20	9.2	11.3	18.0	9.9	7.0	11.3	10.8	5.2	8.3	11.9	4.1	6.5
Recharge Strategy #2	Modena Prov.	BEV-1	19.9 % fleet share		6.5	≥ 20	≥ 20	5.6	12.0	19.2	5.0	7.2	11.6	4.7	5.2	8.4	4.3	3.8	6.0
		BEV-2	75.0% fleet share		8.1	≥ 20	≥ 20	8.0	11.1	17.693	7.9	6.8	10.838	7.9	4.9	7.8	7.9	3.5	5.5

EoL @ 80% capacity fade Li-Ion NCM-LMO (2015) Years Driving to Set Threshold Environment temperature (Modena 2011)				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	Modena Prov.	BEV-1	12.1% fleet share	NCM-LMO (2015)	9.7	≥ 20	≥ 20	8.6	12.8	≥ 20	8.2	7.9	12.6	-			-		
		BEV-2	53.6% fleet share		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
Recharge Strategy #2	Modena Prov.	BEV-1	24.8% fleet share		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
		BEV-2	79.8% fleet share		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

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;
 - Driving pattern / mileage, i.e. *time, SOC, DOD, Ah, C-rate*;
- Level 2 (high influence) →
 - 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	<ul style="list-style-type: none"> • Age of the car since manufacture [yrs] • Run-in km • Vehicle technology (BEV, PHEV) • EoL threshold for capacity fade and power fade
Environmental parameters	<ul style="list-style-type: none"> • Ambient temperature max and min for each month of the year [°C]
Duty cycle parameters	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Average recharging time [h] • Recharging power [kW] • Charging mode/level • Average number of recharge per month
Battery parameters	<ul style="list-style-type: none"> • 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

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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