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JRC Contribution to EVE IWG

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Joint Research Centre

Presentation Summary

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

- **Literature review;**
- **Ageing models;**
- **Implementation and earliest results;**
- **Status of database processing;**

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Battery technologies for xEV

Table I Typical Passenger Car Applications for Lithium-ion Batteries

Application	Typical voltage(s), V	Typical Power levels, kW	Typical energy, kWh	Commonest battery type today
SLI	14	3	0.7	Lead-acid
Idle stop	14	3	0.7	Lead-acid
Mild hybrid	48–200	10–30	0.3	NiMH
Full Hybrid	300–600	60	1–2.5	NiMH
PHEV	300–600	60	4–10	Li-ion
EV	300–600	60	15+	Li-ion

Table II Summary of the Main Lithium-ion Variants

	Cell level energy density, Wh kg^{-1}	Cell level energy density, Wh l^{-1}	Durability cycle life, 100% DoD	Price estimate, US$ Wh^{-1}	Power C-rate	Safety thermal runaway onset, °C	Potential, V	Temperature range in ambient conditions, °C
$LiCoO_2$	170–185	450–490	500	0.31–0.46	1 C	170	3.6	–20 to 60
$LiFePO_4$ (EV/PHEV)	90–125	130–300	2000	0.3–0.6	5 C cont. 10 C pulse	270	3.2	–20 to 60
$LiFePO_4$ (HEV)	80–108	200–240	2000	0.4–1.0	30 C cont. 50 C pulse	270	3.2	–20 to 60
NCM (HEV)	150	270–290	1500	0.5–0.9	20 C cont. 40 C pulse	215	3.7	–20 to 60
NCM (EV/PHEV)	155–190	330–365	1500	0.5–0.9	1 C cont. 5 C pulse	215	3.7	–20 to 60
Titanate *vs.* NCM/LMO	65–100	118–200	12,000	1–1.7	10 C cont. 20 C pulse	Not susceptible	2.5	–50 to 75
Manganese spinel (EV/PHEV)	90–110	280	>1000	0.45–0.55	3–5 C cont.	255	3.8	–20 to 50

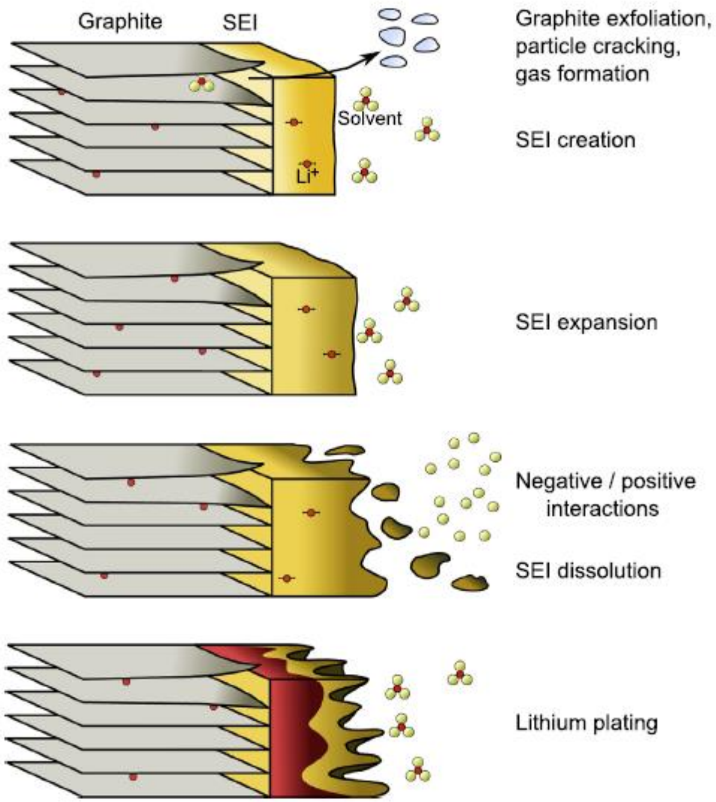
Cathode:

- **Lithium-Cobalt-Oxide (LiCoO2);**
- **Lithium-Iron-Phosphate (LiFePO4);**
- **Nickel-Cobalt-Manganese (NCM);**
- **Lithium-Manganese-Spinel-Oxide (LMO);**

Anode: graphite/carbon/titanate/silicon;

Source: *P. Miller, J. Matthey Tech. Review* (2015)

Electrochemical ageing effects at negative (in-focus look at Li-Ion techs)



SEI (Solid Electrolyte Interface): Creation/Expansion/Dissolution/Plating

↓

Ageing Consequences:

1) **Primary loss of cyclable Lithium (side reactions/decomposition);**
2) **Secondary loss of active material (dissolution/degradation/delamination);**
3) **Resistance increase due to passive films;**

↓

1) + 2) → capacity fade;
3) → reduction of available power;

Source: *Barre' et. Al.,* Journal of Power Sources 241(2013)

Electrochemical ageing models (in-focus look at Li-Ion techs)

Calendar Ageing: irreversible loss of capacity due to storage;
Cycle Ageing: consequence of the battery charge/discharge cycles;
→ Capacity Fade = *f(time, temperature, SOC, DOD, Ah, C-rate)*

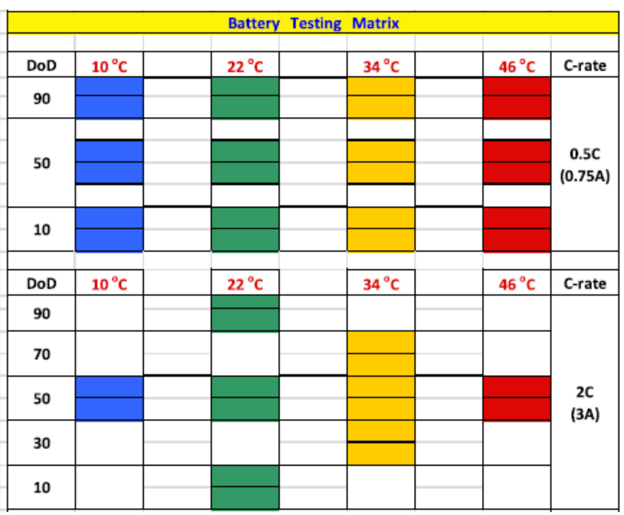
Electrochemical Ageing Models:

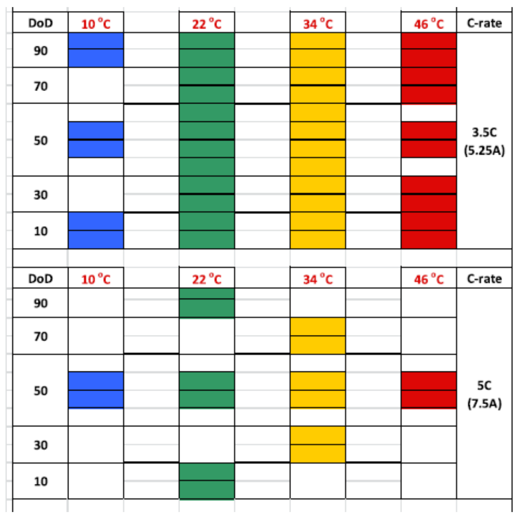
1) Electrochemical models (description of the in-battery phenomena – atomistic & molecular approaches);
2) Equivalent circuit based models;
3) Performance based models/analytical models with empirical data fitting;
4) Statistical methods;

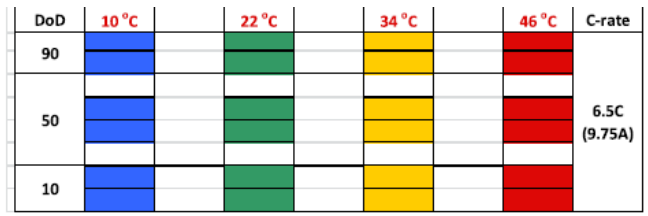
Source: *Barre' et. Al.*, Journal of Power Sources 241(2013)

Electrochemical semi-empirical ageing models

	Calendar	Cycling
LiFePO4	Sarasketa-Zabala et. Al. Journal of Power Sources, 272(2014)	Wang et Al., Journal of Power Sources, 196(2011)
		Sarasketa-Zabala et. Al. Journal of Power Sources, 275(2015)
NCM + Spinel Mn	Wang et Al. Journal of Power Sources, 269(2014)	







LiFePO4 Cycling (Wang et al. 2011)

$$Q_{LOSS-CYC} = Ae^{\left(\frac{-E_a}{RT}\right)}Ah^z$$

LiFePO4 Calendar & Cycling (Sarasketa-Zabala et al. 2014/15)

$$Q_{LOSS-CAL} = \alpha_1 e^{\left(\frac{\beta_1}{T}\right)} \cdot \alpha_2 e^{(\beta_2 \cdot SOC)} t^{0.5}$$

$$if \quad 50\% \geq DOD \geq 10\% \quad Q_{LOSS-CYC} = (\gamma_1 \cdot DOD^2 + \gamma_2 \cdot DOD + \gamma_3)Ah^{0.87}$$

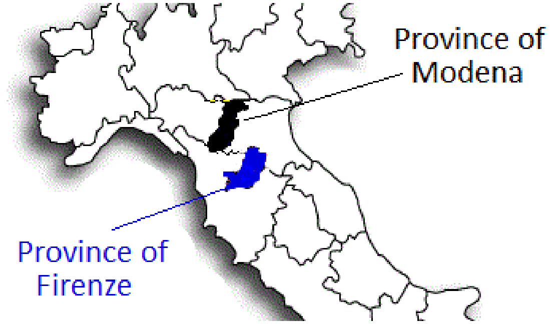
$$else \quad Q_{LOSS-CYC} = \left(\alpha_3 \cdot e^{(\beta_3 \cdot DOD)} + \alpha_4 \cdot e^{(\beta_4 \cdot DOD)}\right)Ah^{0.65}$$

NCM/LMO Calendar & Cycling (Wang et al. 2014)

$$Q_{LOSS-CAL} = fe^{\left(\frac{-E_a}{RT}\right)}t^{0.5}$$

$$Q_{LOSS-CYC} = (a \cdot T^2 + b \cdot T + c) \cdot e^{(d \cdot T + e)I_{rate}} \cdot Ah$$

TEMA - Transport tEchnology and Mobility Assessment



Transportation Data

	Monitored Vehicles	Database lines (after cleaning) [$\cdot 10^6$]	Trips No. [$\cdot 10^6$]	Trips' length [km$\cdot 10^6$]
Province of Modena	16,263	15.998	2.642	14.98
Province of Firenze	12,478	32.008	1.870	20.66

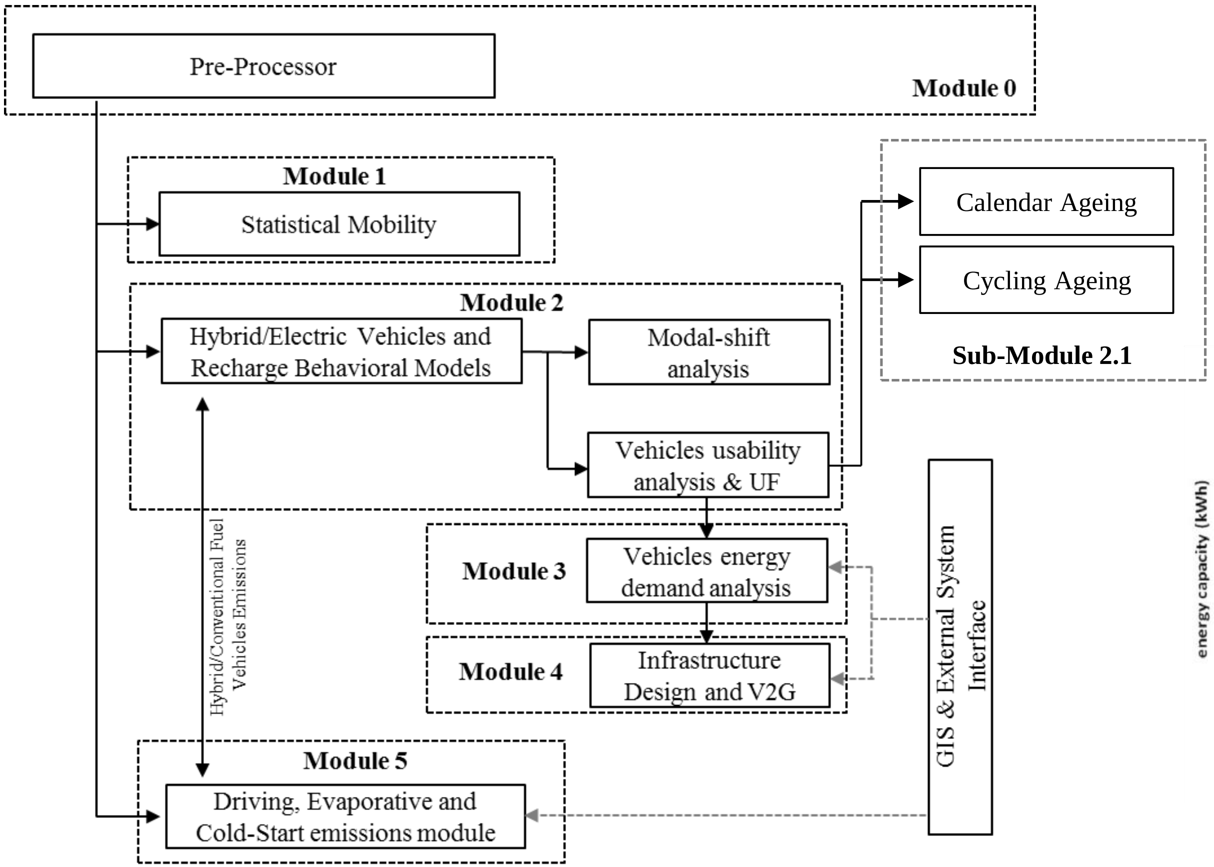
Vehicle Technologies (xEVs):

- EVs, from 450 to 2600 kg (curb weight) – from 13 to 85 kWh (battery size) – from 70 to 265 Wh/km (consumption);
- PHEV;
- Open Parameters;

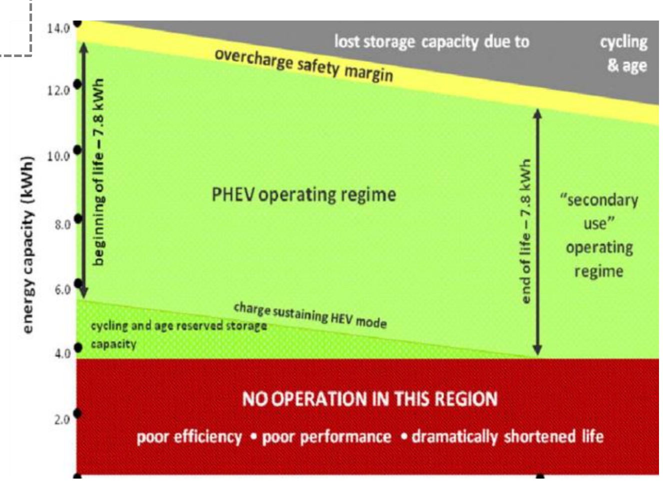
Behavioral Models (recharge with 16 behaviors):

- opportunistic-unconstrainted /constrained / price-based / smart-grid;
- AC (3.3 kW/10kW) and DC (50 kW);

Implementation of ageing models in TEMA



$$Q_{LOSS} = Q_{LOSS-CAL} + Q_{LOSS-CYC} - Reserve$$

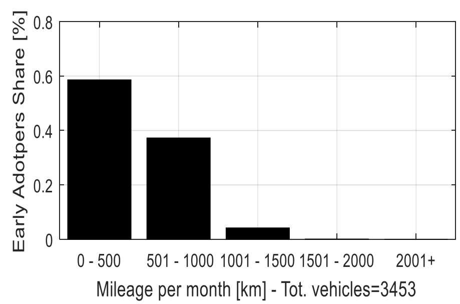


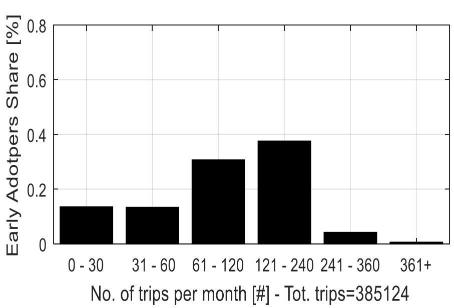
Source: *Marano et. Al.*, IEEE (2009)

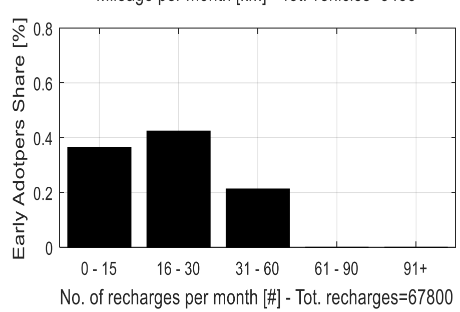
Earliest Results: Usability Statistics

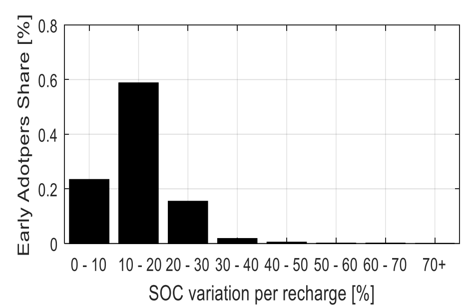
Vehicle Technologies (xEVs):
BEV @ 1,800 kg curb weight – 32 kWh Li-Ion (24 kWh usable) – 205 Wh/km;
Long Stop Random AC Recharge Strategy: Stop > 120 min AND Random > 0.6;
Recharge at 2kW (3.3 kW single-phase)

3,453 users out of
16,263 vehicles (21.3%)



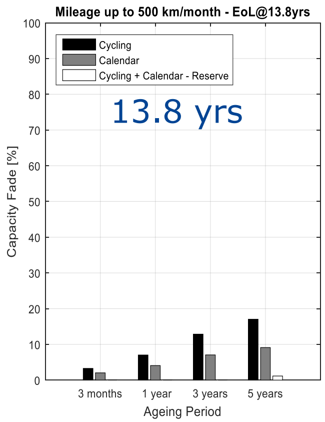


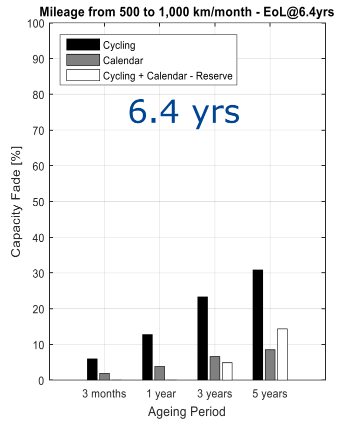


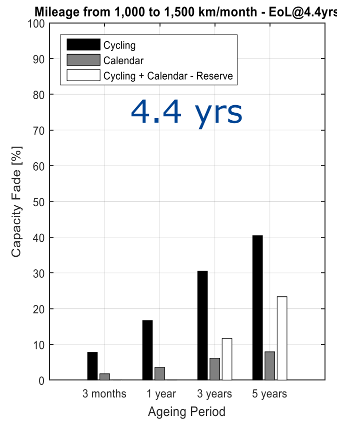


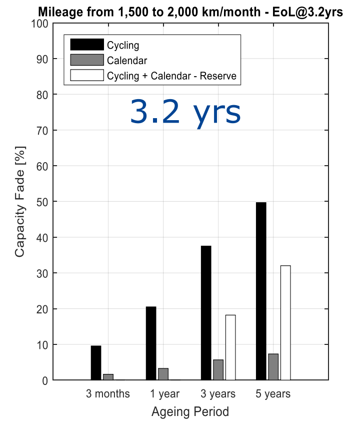
Earliest Results: ageing results (EoL @ 80%)

LiFePO4
Cycling: Wang
Calendar: Sarasketa

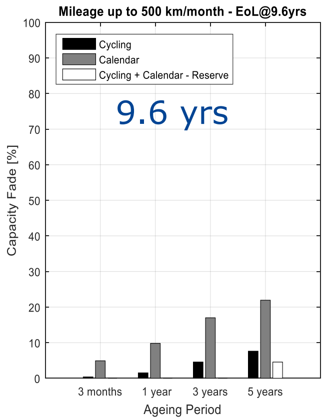


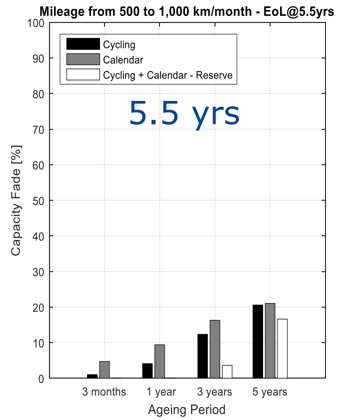


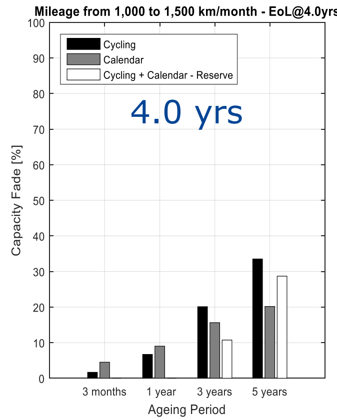


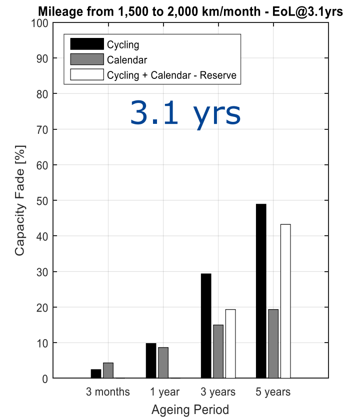


NCM + Spinel Mn
Cycling: Wang
Calendar: Wang









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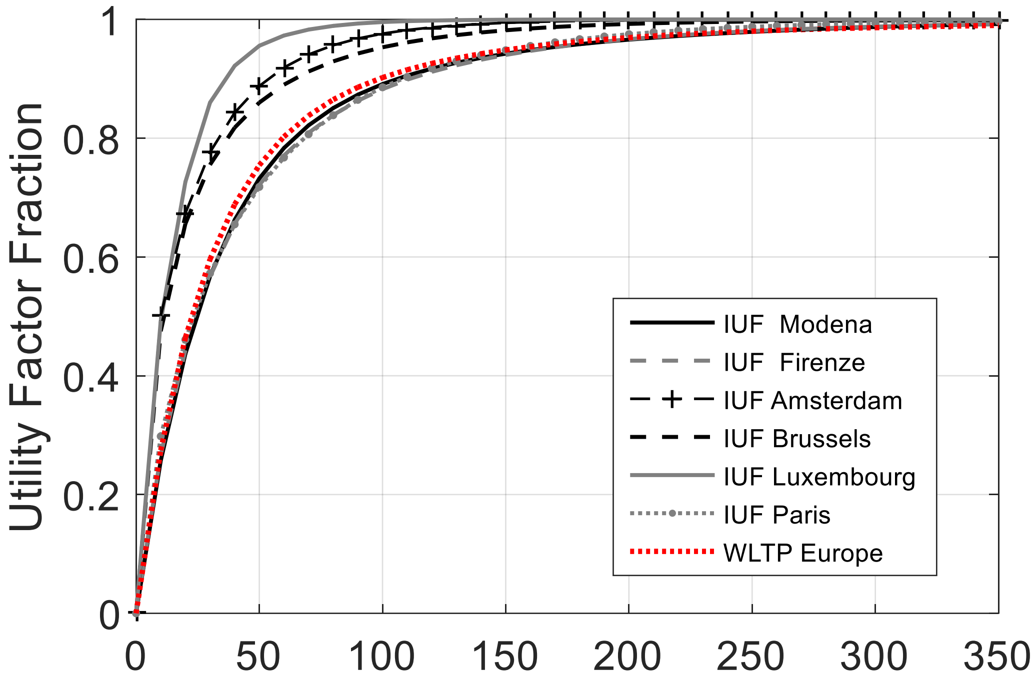
Status of database processing
(EU-wide – IT/NL/BE/FR/GR/PT/DE/LUX/PL/SK/AT/SLO/KR/HU/BG)

	No. of vehicles	Total trips lengths [km·10^6]	No. of days	Trip length [km] - (mean)	Daily driven distance – [km]	LDV Share	HDV Share	TOTAL
Province of Modena	16,263	14.98	31	7.8	51.9	100%	-	632,186 vehicles 139.57 million km 2.57 billion records
Province of Firenze	12,478	20.66	31	8.0	51.3	100%	-	
Province of Amsterdam	197,754	19.86	7	18.3	48.0	83.2%	16.8%	
Province of Brussels	96,802	11.21	14	10.2	74.0	91.2%	8.8%	
Province of Paris	171,220	38.39	7	17.1	72.2	99.1%	0.9%	
Province of Athens	15,366	1.49	7	11.0	53.9	-	100%	
Province of Lisbon	7,522	2.48	7	15.0	86.1	-	100%	
Province of Krefel	4,160	0.97	7	88.8	151.7	2.9%	97.1%	
Province of Luxembourg	14,090	1.0	7	12.2	30.8	92.0%	8.0%	
Province of Warsav	862	0.16	7	51.8	124.3	2.3%	97.7%	
Province of Bratislava	18,296	1.0	7	22.9	35.0	-	100%	
Province of Wien	9,943	2.14	7	37.9	469.9	0.9%	99.1%	
Province of Ljubljana	11,616	4.04	7	45.3	148.6	0.7%	99.3%	
Province of Zagreb	12,036	3.79	7	24.3	104.6	14.0%	86.0%	
Province of Budapest	32,410	14.10	7	44.1	179.0	0.1%	99.9%	
Province of Sofia	11,368	3.28	7	16.4	87.4	-	100%	

Status of database processing



Individual utility factor (support to the definition of the deterioration factor)

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Next Steps

- **Collect further data on ageing models;**
- **Experimental testing (?) – JRC needs support on this!;**
- **Perform several scenario analyses by varying:**
  - **(1) database;**
  - **(2) vehicle type;**
  - **(3) recharge strategy;**
  - **(4) battery type & ageing model;**

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