The European Commission's science and knowledge service

Joint Research Centre

European Commission

EU-Commission
JRC Contribution to EVE IWG

M. De Gennaro, E. Paffumi

24th Meeting of the GRPE Informal Working Group on Electric Vehicles and the Environment (EVE)

October 24th - 25th 2017, Vienna (AT)

European Commission

Presentation Summary (1/2)

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

Summary after Geneva (June 2017), i.e. what’s old:

- Literature review and ageing models;
- Methodology;
- Implementation and earliest results;
- Status of database processing;

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 (Oct. 2017), i.e. what's new:

- Implementation of ageing models completed;
- Durability and EoL scenario analysis completed;
- In-vehicle validation running;
- EU-wide scale driving data running;
- Ready to discuss next steps!

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

Cathode:

Lithium-Cobalt-Oxide ($LiCoO_2$);

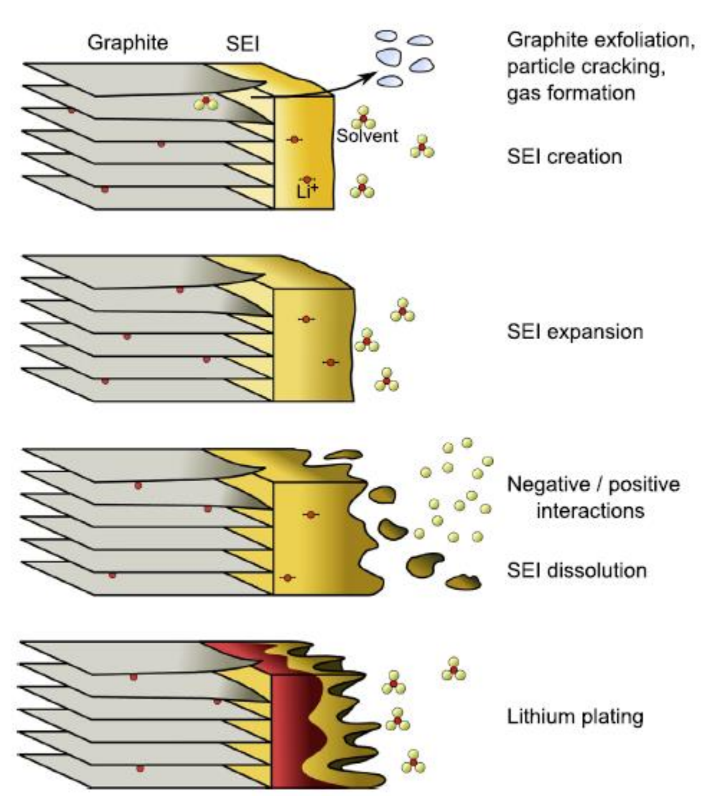
Lithium-Iron-Phosphate ($LiFePO_4$);

Nickel-Cobalt-Manganese (NCM);

Lithium-Mang.-Spinel-Oxide (LMO);

Anode:

graphite/carbon/titanate/silicon;



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)

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):

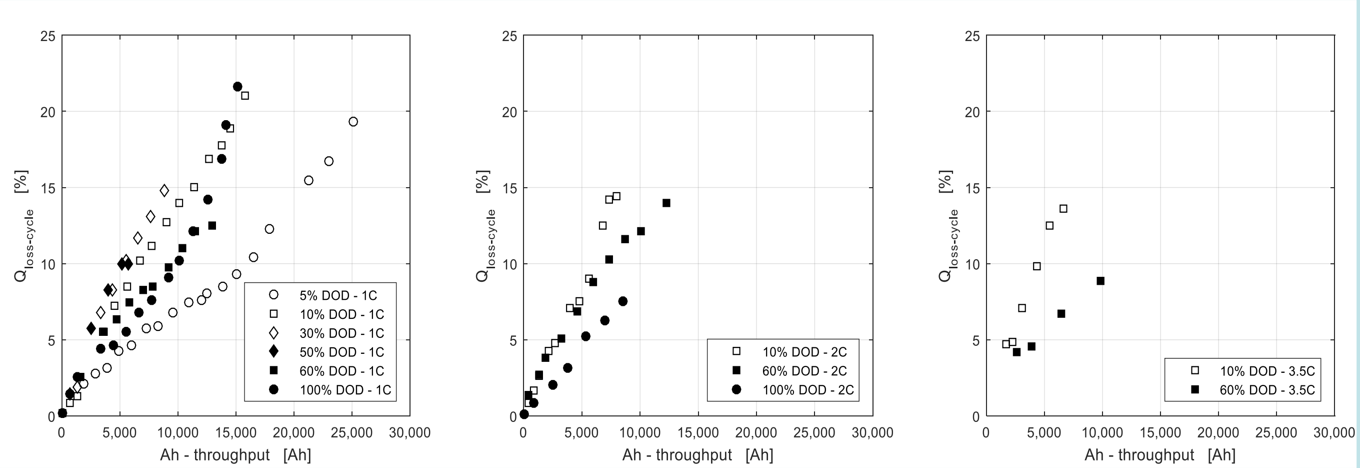
- **#1 ($LiFePO_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Wang et Al. (2011) model for cycle;**
- **#2 ($LiFePO_4$): Sarasketa-Zabala et Al. (2013/14) model for calendar plus Sarasketa-Zabala et Al. (2015) model for cycle;**
- **#3 (NCM + Spinel Mn): Wang et Al. (2014) for calendar plus Wang et Al. (2014) for cycle;**
- **#4 (NCM-LMO): Wang et Al. (2014) for calendar plus Cordoba-Arenas et Al. (2015) for cycle;**

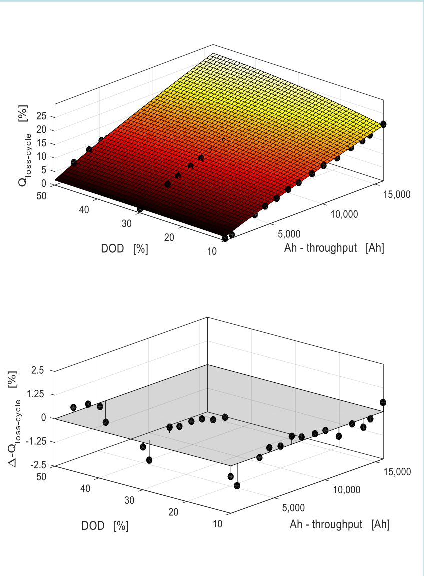
Performance based models (re-engineering)

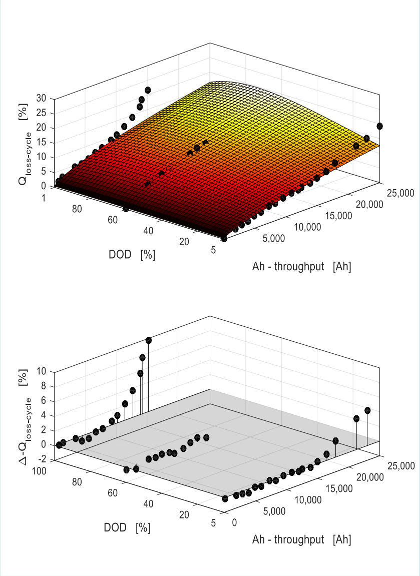
Example of the calculation of the coefficients of the Sarasketa-Zabala et Al. capacity fade model (2015)

$$Q_{loss-cycle} = (\gamma_1 \cdot DOD^2 + \gamma_2 \cdot DOD + \gamma_3) \cdot k \cdot Ah^{0.87} \quad if\ (10\% \leq DOD \leq 50\%)$$

$$Q_{loss-cycle} = \left(\alpha_3 \cdot e^{(\beta_3 \cdot DOD)} + \alpha_4 \cdot e^{(\beta_4 \cdot DOD)}\right) \cdot k \cdot Ah^{0.65} \quad if\ DOD < 10\%\ OR\ DOD > 50\%$$





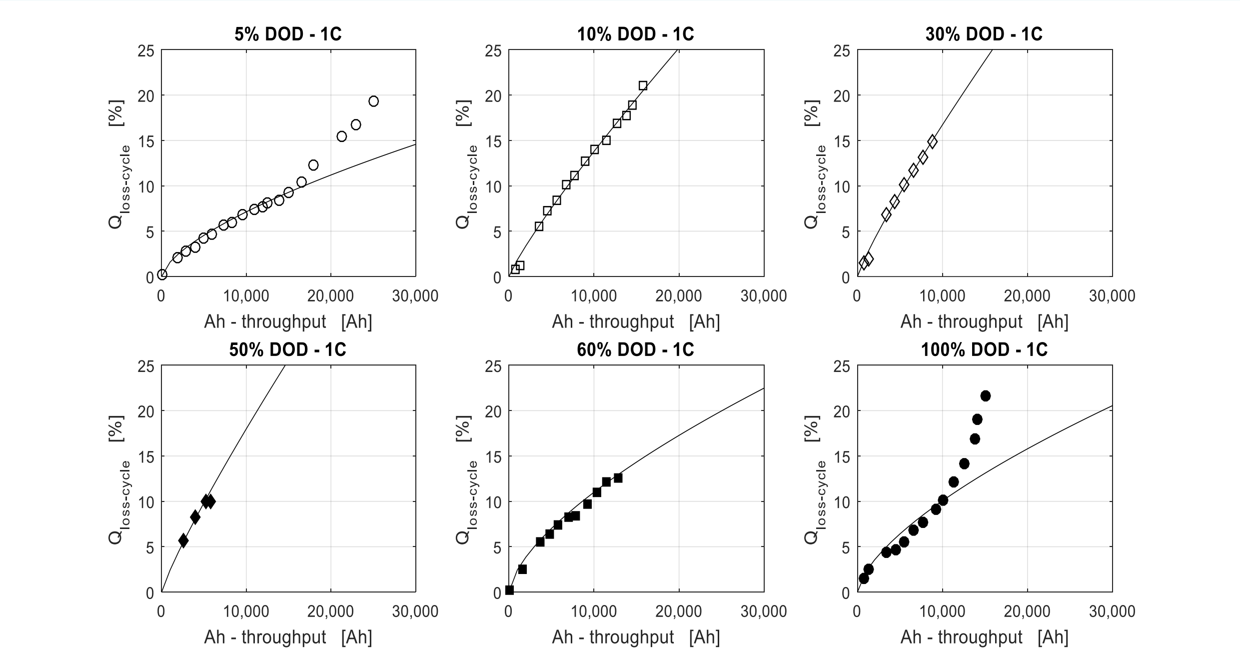


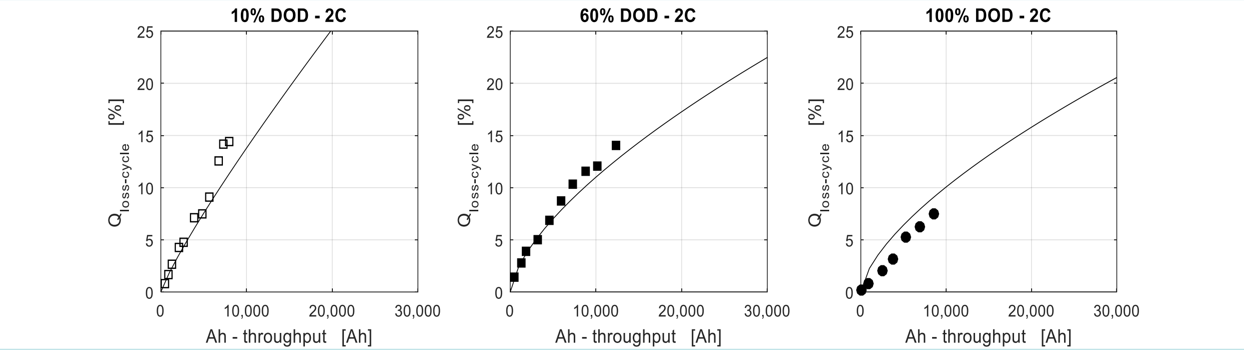
$$\begin{cases} \gamma_1 = -6.956e-05 \quad \gamma_2 = 7.650e-05 \quad \gamma_3 = 3.870e-5 \quad R-square = 0.9941 \\ \alpha_1 = 0.01184 \quad \beta_1 = 1.821 \quad \alpha_2 = -0.01167 \quad \beta_2 = 1.832 \quad R-square = 0.9582 \end{cases}$$

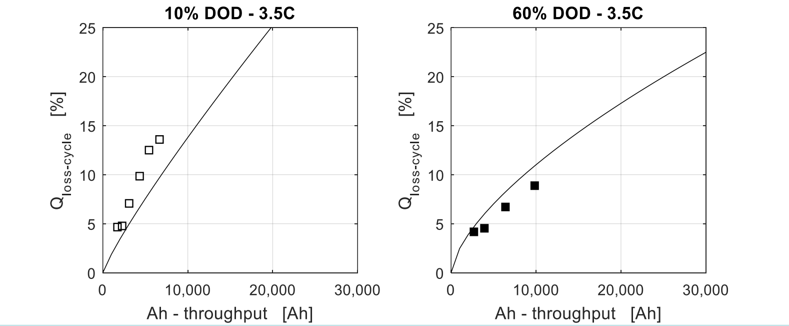
The non-linear least squares problem has been solved by using a damped least-square algorithm, i.e. the Levenberg–Marquardt (LM), in Least Absolute Residuals (LAR) formulation;

Performance based models (re-engineering)

Verification of the coefficients of the Sarasketa-Zabala et Al. capacity fade model (2015)

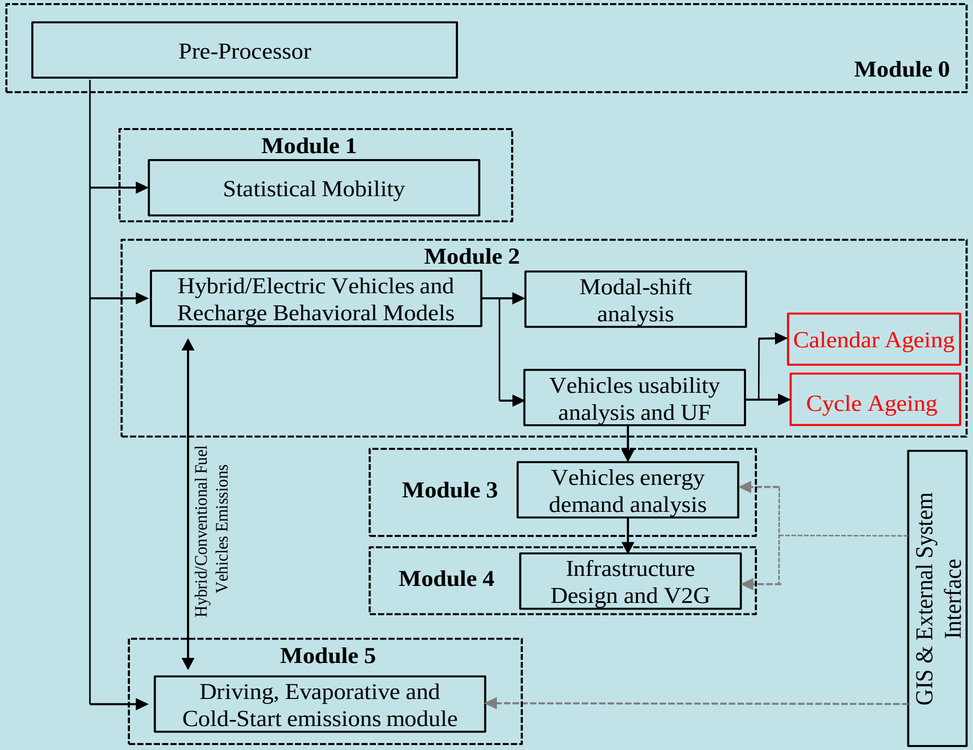






Implementation of the Performance based models into TEMA (assumptions, 1/2)

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 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.:**

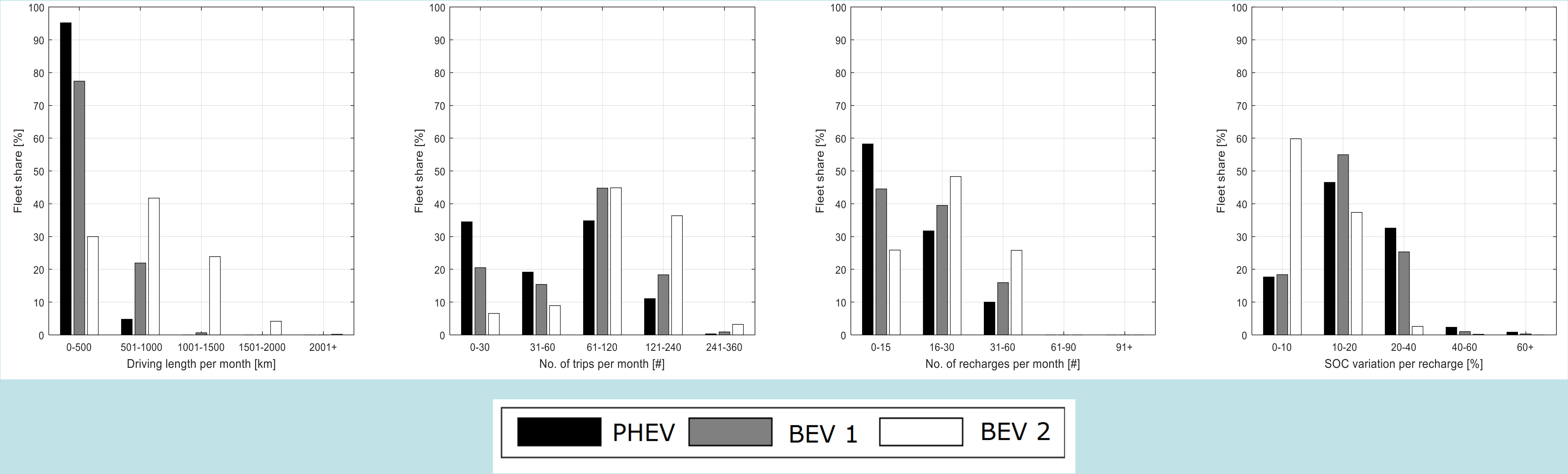
$$Q_{loss\text{-}total} = Q_{loss\text{-}calendar} + Q_{loss\text{-}cycle} - Reserve$$

- **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;**

European Commission

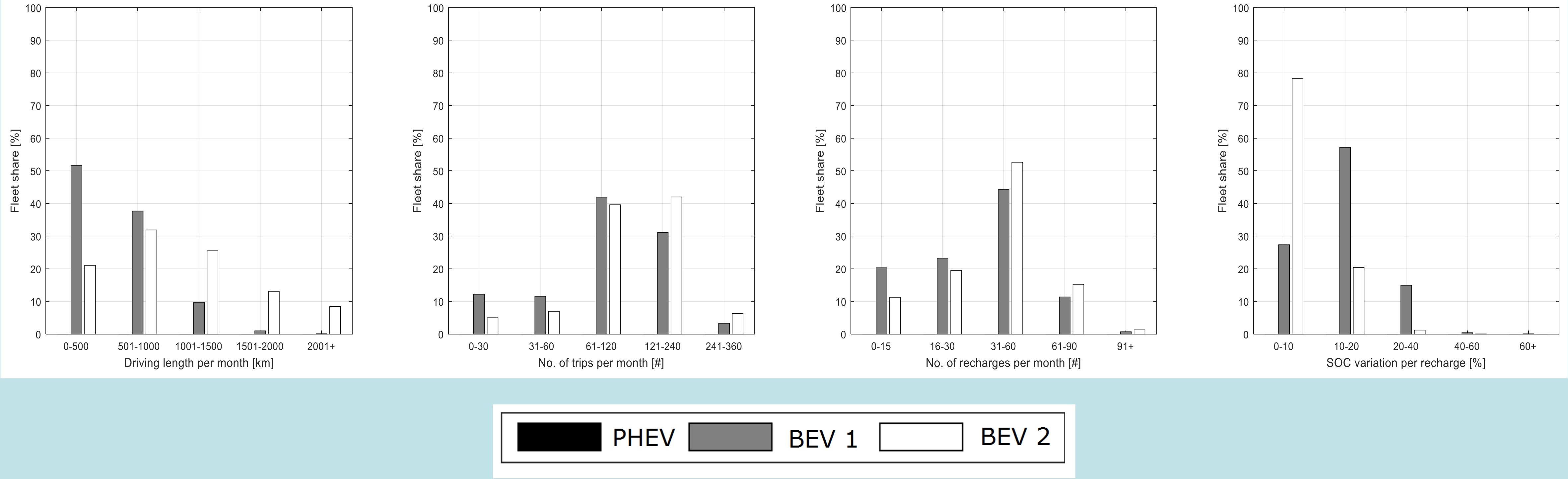
Results (mobility)

Recharge Strategy 1



Results (mobility)

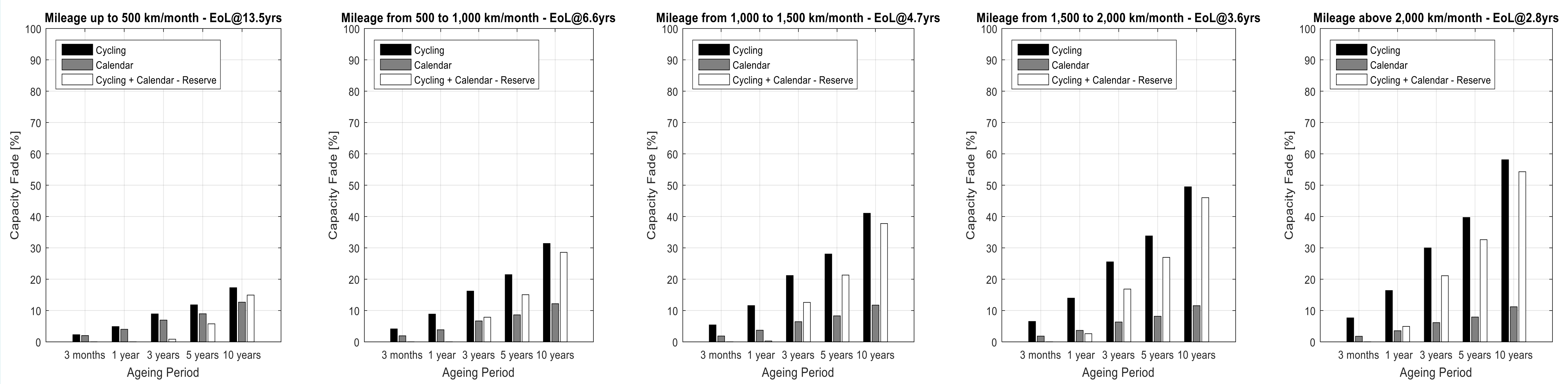
Recharge Strategy 2



European Commission

Results (capacity fade – visualisation)

BEV 1 + Recharge Strategy 2



European Commission

Results (Durability and EoL – tabulated)

Years of Life

					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 per EoL	Years per 100,000 km	Years per EoL	Years per 100,000 km	Years per EoL	Years per 100,000 km	Years per EoL	Years per 100,000 km	Years per EoL	Years per 100,000 km
Recharge Strategy #1	PHEV	Ageing Model	#1	$LiFePO_4$	≥ 20	≥ 20	12.1	14.2	-		-		-	
			#2	$LiFePO_4$	≥ 20		7.8		-		-		-	
			#3	NCM-Mn	14.2		9.1		-		-		-	
			#4	NCM-LMO	15.5		13.1		-		-		-	
	BEV 1		#1	$LiFePO_4$	14.1	≥ 20	6.9	12.8	4.9	7.9	-		-	
			#2	$LiFePO_4$	11.6		5.1		3.4		-		-	
			#3	NCM-Mn	8.5		5.8		4.6		-		-	
			#4	NCM-LMO	8.9		7.5		6.9		-		-	
	BEV 2		#1	$LiFePO_4$	≥ 20	≥ 20	≥ 20	11.2	≥ 20	6.9	≥ 20	5.1	≥ 20	4.0
			#2	$LiFePO_4$	≥ 20		≥ 20		≥ 20		≥ 20		≥ 20	
			#3	NCM-Mn	12.6		13.4		14.2		15.0		15.8	
			#4	NCM-LMO	11.9		12.4		13.1		13.9		14.9	
Rech. Strategy #2	BEV 1	Ageing Model	#1	$LiFePO_4$	13.5	≥ 20	6.6	11.7	4.7	7.1	3.6	5.1	2.8	3.7
			#2	$LiFePO_4$	9.2		3.8		2.4		1.8		1.3	
			#3	NCM-Mn	7.9		5.2		3.9		3.1		2.6	
			#4	NCM-LMO	8.6		6.9		6.1		5.5		5.0	
	BEV 2		#1	$LiFePO_4$	≥ 20	≥ 20	≥ 20	11.0	≥ 20	6.8	≥ 20	4.8	≥ 20	3.4
			#2	$LiFePO_4$	≥ 20		≥ 20		≥ 20		≥ 20		≥ 20	
			#3	NCM-Mn	12.1		11.9		11.8		11.6		11.3	
			#4	NCM-LMO	11.5		11.1		10.9		10.8		10.7	

Mileage @ EoL

					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
Recharge Strategy #1	PHEV	Ageing Model	#1	$LiFePO_4$	58,429.2	85,063.0	-	-	-
			#2	$LiFePO_4$	43,610.2	54,834.0	-	-	-
			#3	NCM-Mn	30,061.4	63,973.0	-	-	-
			#4	NCM-LMO	32,813.5	92,093.0	-	-	-
	BEV 1		#1	$LiFePO_4$	39,649.2	53,937.3	62,176.1	-	-
			#2	$LiFePO_4$	32,619.2	39,866.7	43,142.6	-	-
			#3	NCM-Mn	23,902.0	45,338.6	58,369.4	-	-
			#4	NCM-LMO	25,026.8	58,627.5	87,554.1	-	-
	BEV 2		#1	$LiFePO_4$	156,223.8	≥300,000	≥300,000	≥300,000	≥300,000
			#2	$LiFePO_4$	189,992.7	≥300,000	≥300,000	≥300,000	≥300,000
			#3	NCM-Mn	42,978.6	120,090.8	205,289.4	295,710	≥300,000
			#4	NCM-LMO	40,590.9	111,128.8	189,386.7	274,024.6	≥300,000
Rech. Strategy #2	BEV 1	Ageing Model	#1	$LiFePO_4$	41,823.0	56,482.8	66,213.6	71,114.4	74,818.8
			#2	$LiFePO_4$	28,501.6	32,520.4	33,811.2	35,557.2	34,737.3
			#3	NCM-Mn	24,474.2	44,501.6	54,943.2	61,237.4	69,474.6
			#4	NCM-LMO	26,642.8	59,050.2	85,936.8	108,647.0	133,605.0
	BEV 2		#1	$LiFePO_4$	147,465.0	≥300,000	≥300,000	≥300,000	≥300,000
			#2	$LiFePO_4$	180,009.0	≥300,000	≥300,000	≥300,000	≥300,000
			#3	NCM-Mn	41,019.0	107,861.6	174,368.6	239,238.4	≥300,000
			#4	NCM-LMO	38,985.0	100,610.4	161,069.3	222,739.2	≥300,000

Legend	
(red)	EoL below 5 years;
(yellow)	EoL between 5 and 10 years;
(green)	EoL above 10 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;***

Level 3 (mid-to-low influence) →

- **Temperature;**

Is there an in-vehicle battery durability potential issue (i.e. customer-expectation / comparison of technologies)? Apparently YES

Is the phenomenon fully comprehended? NO → More efforts needed

Is there the necessity of informing / protecting the customer? YES

Is there an environmental aspect to be considered (i.e. life-cycle balance)? YES

Is a regulatory activity desirable? Let's discuss…

Limitations and next steps

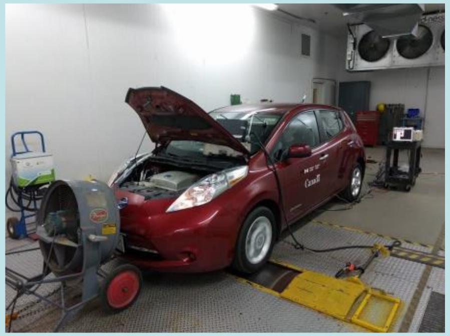
- Li-chemistry is evolving → follow the technical evolutions;
- Account for better/wider battery usage management strategies;
- Thermal aspects needs to be further refined (thermal dynamics of the battery);
- Active BMS and BMS designed for ageing? A possibility, need bi-directional DC-DC per module and or per-cell. Expensive for cars, but sometimes applied for stationary applications;
- Validation of the models at a vehicle level (on-going);
- Extend the use patterns baseline (on-going);

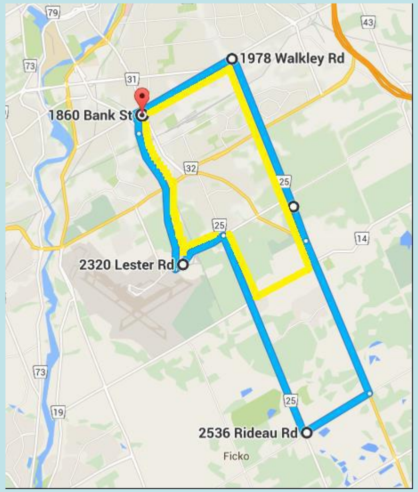
Can we use capacity fade results to better steer the test-matrix?

How to define the Deterioration Factor? Should we opt for a base-test + correction?

Reference-method and/or candidate method? Mixed?

Experimental data from Canada (on-going)





Additional analysis from Canada for double validation of the models

Table 1: BEV1 - DCFC (50kW charger)

Stage	Odometer Start [km]	Odometer End [km]	Distance [km]	Type	Energy Drive, In [kWh]	Energy Drive, Out [kWh]	Energy Charge, In [kWh]	Energy Charge, Out [kWh]	UBE degradation vs. Round 1
1	1,663	4,684	3021	In-Lab	27.1	467.0	491.6	0.1	0.0%
2	4,684	15,049	10365	On-Road	280.2	1619.4	1425.4	0.0	
3	15,049	16,177	1128	In-Lab	16.0	176.5	173.5	0.0	-3.4%
4	16,177	34,860	18683	On-Road	457.3	3444.2	3197.1	0.0	
5	34,860	36,199	1339	In-Lab	17.5	204.0	198.0	0.1	-6.5%
6	36,199	50,057	13858	On-Road	398.2	2102.7	1847.8	0.0	
7	50,057	51,241	1184	In-Lab	16.5	183.5	178.5	0.0	-10.0%
8	51,241	62,469	11228	On-Road	262.9	2101.9	1887.4	0.0	

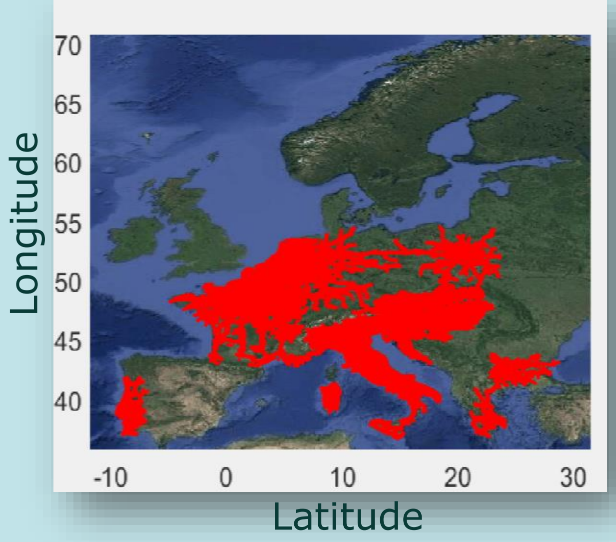
Table 2: BEV2 - ACL2 (7.2kW charger)

Stage	Odometer Start [km]	Odometer End [km]	Distance [km]	Type	Energy Drive, In [kWh]	Energy Drive, Out [kWh]	Energy Charge, In [kWh]	Energy Charge, Out [kWh]	UBE degradation vs. Round 1
1	2,214	3,978	1764	In-Lab	18.2	294.7	287.3	0.2	0.0%
2	3,978	14,949	10971	On-Road	275.6	1712.7	1427.2	2.1	
3	14,949	16,247	1298	In-Lab	16.8	219.5	207.8	0.3	-3.4%
4	16,247	34,963	18716	On-Road	412.9	3300.0	2975.8	7.9	
5	34,963	36,274	1311	In-Lab	17.5	209.2	187.9	0.4	-5.3%
6	36,274	49,044	12770	On-Road	348.4	1989.6	1639.1	2.9	
7	49,044	50,378	1334	In-Lab	16.6	211.0	195.2	0.2	-6.8%
8	50,378	62,454	12076	On-Road	283.8	2258.6	2039.4	8.5	

Source: Presentation from Transport Canada @ EVE-22 (Ann-Arbor, April 2017)

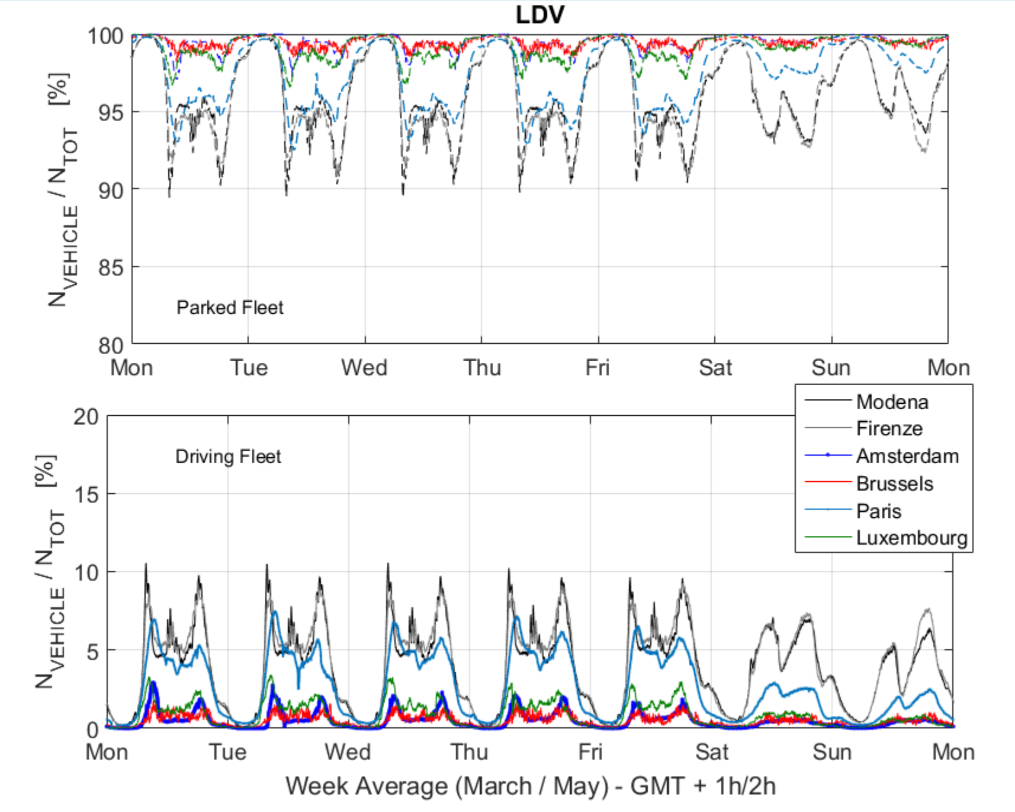
EU-wide extension of the activity data (on-going)

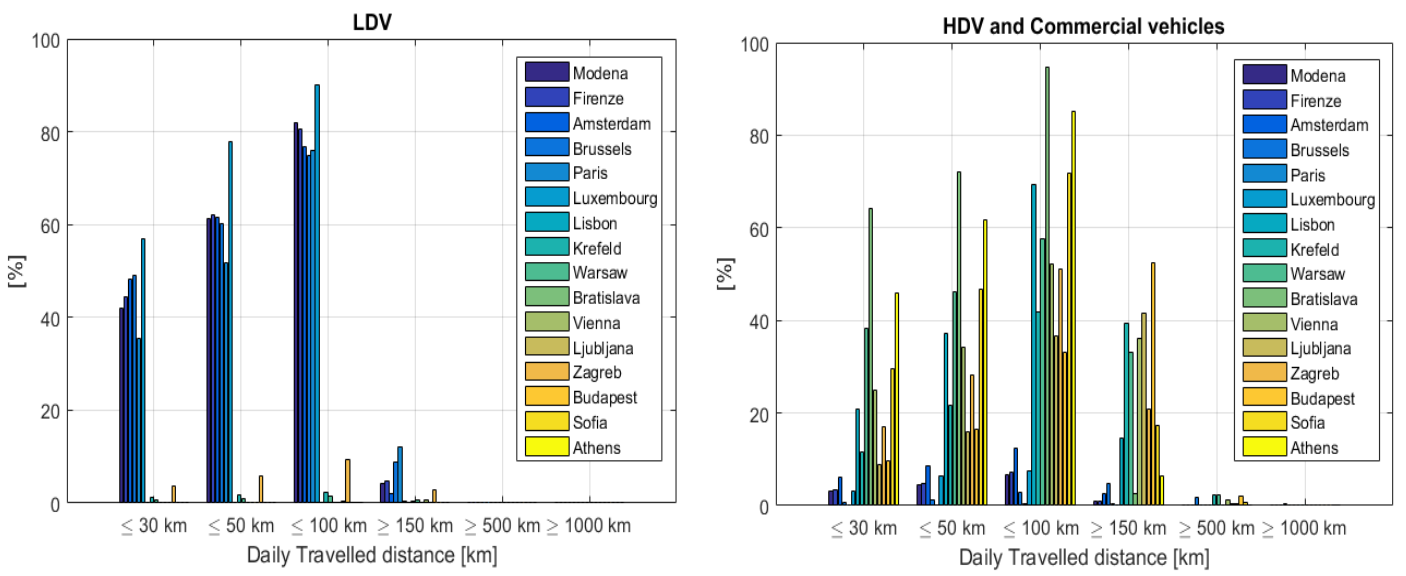
	No. of vehicles	Total trips lengths [km·10⁶]	No. of days	Trip length [km] - (mean)	Daily driven distance – [km]	LDV Share	HDV Share	TOTAL
Province of Modena	16,263	14.98	31	7.8	51.9	91.6%	8.4%	**632,186 vehicles 139.57 million km 2.57 billion records**
Province of Firenze	12,478	20.66	31	8.0	51.3	90.9%	9.1%	
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 Luxembourg	14,090	1.0	7	12.2	30.8	92.0%	8.0%	
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 Athens	15,366	1.49	7	11.0	53.9	-	100%	
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%	



EU-wide extension of the activity data (on-going)

Earliest results





European Commission

Thank you for the attention

Q&A

Contacts Info:
EC DG JRC DIR C ETC Sustainable Transport Unit

michele.degennaro@ec.europa.eu
elena.paffumi@ec.europa.eu

European Commission