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Capacity fade of Lithium-ion automotive batteries using real-world driving behaviour

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Summary

This work combines recent capacity performance-based models for of NCM-LMO Li-ion variant batteries with real-world vehicle driving data from different geographical areas of Europe to develop a scenario based analysis for predicting in-vehicle performance degradation of automotive traction batteries. The analysis addresses different battery and vehicle architectures (PHEV and BEV), combined with different recharging strategies and mobility patterns and environmental temperatures. The mobility pattern datasets used in this analyses refer to six European cities and include up to 508,609 private vehicles, corresponding to 1.78 billion GPS records, 9.1 million trips and parking events and a total driven distance of 106.1 million kilometres.

The results show the effect that the environmental temperature, the recharging power and the driven kilometres have on the calendar and cycling ageing. The majority of the combinations of the considered vehicle architectures and recharge strategies do not lead to battery capacity drop below 80% of its nominal value in less than 5 calendar years for usage profile of up to 1,000 km/month.

Keywords: battery ageing, BEV (battery electric vehicle), PHEV (plug in hybrid electric vehicle), GPS, lithium battery

Nomenclature

BEV	Battery Electric Vehicle
BoL	Beginning of Life
BMS	Battery Management System
EoL	End of Life
EVE IWG	Electric Vehicle and Environment Informal Working Group
GPS	Global Positioning System
GRPE	Working Party on Pollution and Energy
HVAC	Heating, Ventilation and Air Conditioning

LiFePO4	Lithium-Iron-Phosphate
Li-ion	Lithium-ion
LMO	Lithium Manganese Oxide
NCM	Nickel Cobalt Manganese Oxide
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State of Charge
TEMA	Transport tEchnology and Mobility Assessment
WP.29	UN’s World Forum for Harmonization of Vehicle Regulations

1 Introduction

Battery durability is a key element for evaluating the economic, social and environmental impact of electrified vehicles [1], [2], [3]. Loss of environmental performance is important in particular because governmental regulatory compliance programs often credit electrified vehicles with a certain level of expected environmental benefit, which might fail to be realized over the life of the vehicle if sufficient battery degradation occurs. In addition to changes in driving range and energy consumption, for hybrid electric vehicles that are often equipped with both a conventional and electric powertrain, the criteria pollutants emissions from the conventional powertrain could be impacted by the degradation of the battery [4]. The problem of establishing battery durability for representative usage scenarios, chemistries, and configurations is extremely complex. Hence, a better understanding of the degradation mechanisms relevant for automotive applications is highly desirable, together with a quantification of the battery lifetime in real world use conditions.

This work presents the in-vehicle battery durability performance of different electrified vehicles and usage conditions. The work relies on performance-based models retrieved from literature implemented in the EU JRC Transport tEchnology and Mobility Assessment (TEMA) platform, [5], developed to explore the potential of big data in supporting transport policy assessments. EU-wide scale mobility driving patterns from conventional fuel vehicles [6] are the inputs for TEMA consisting of twenty databases of navigation data for a total of 691,751 monitored vehicles, 10.7 million trips and parking events, 146.7 million kilometres and 2.8 billion records [7], [8], [9].

Fig. 1 shows the European map of the cleansed database records, reporting 1.66 billion red dots. This map is intended to be purely indicative, aiming at visualising the geographical extension of the available databases [6].

2 Background information and methodology

2.1 TEMA platform

JRC TEMA [5] is a modular big data platform designed to reproduce mobility behaviours of vehicles from datasets of trips collected on conventional fuel vehicles by means of GPS [7], [8], [9]. It is used to quantify possible impacts of new vehicle technologies on real-world mobility and develop scenarios to assess the impact of policy actions in transport [10], [11], [12], [13], [14]. A comprehensive overview of TEMA with applications and results is provided in [5]. The platform has been extended with the calendar and cycle capacity fade models [3]. The advantage of adopting TEMA for estimating the capacity fade of lithium-ion batteries is that the platform allows for combining state-of-the-art cycle and calendar fade models with large-scale real-world driving data representative of thousands of vehicles and millions of kilometres [6]. This enables the simulation of a large variety of EV deployment scenarios with different driving styles, recharge patterns, vehicle architectures and environmental conditions. This work focuses on six provinces areas, Modena (IT), Florence

(IT), Amsterdam (NL), Brussels (BE), Paris (FR), and Luxembourg (LU), mostly or exclusively including passenger vehicles, as reported in Table 1.

Table 1: Data overview.

		No. of days [#]	No. of vehicles [#]	Records [$\cdot 10^6$]	Trips [$\cdot 10^6$]	Total trips lengths [$km\cdot 10^6$]	No. of trip per day (mean) [#]	Trip length [km] (mean)	Daily driven distance (mean) [km]	Private vehicles share	Commercial vehicles share	Analysed sample (% of the registered vehicles in the province area)
Private Vehicles	Province of Modena	31	16,263	16.00	1.9	14.98	6.6	7.8	51.9	91.6%	8.4%	3.68%
	Province of Florence	31	12,478	32.01	2.6	20.66	6.4	8.0	51.3	90.9%	9.1%	1.82%
	Province of Amsterdam	7	197,756	466.28	1.1	19.86	1.9	19.7	37.2	83.2%	16.8%	17.17%
	Province of Brussels	14	96,802	277.05	1.1	11.21	7.9	7.7	55.2	91.2%	8.8%	16.26%
	Province of Paris	7	171,220	963.27	2.3	38.39	4.2	17.0	71.7	99.1%	0.9%	2.43%
	Province of Luxembourg	7	14,090	24.33	0.08	1.0	2.5	11.9	30.1	92.0%	8.0%	17.63%
	TOTAL		508,609	$1.78\cdot 10^3$	9.08	106.1						

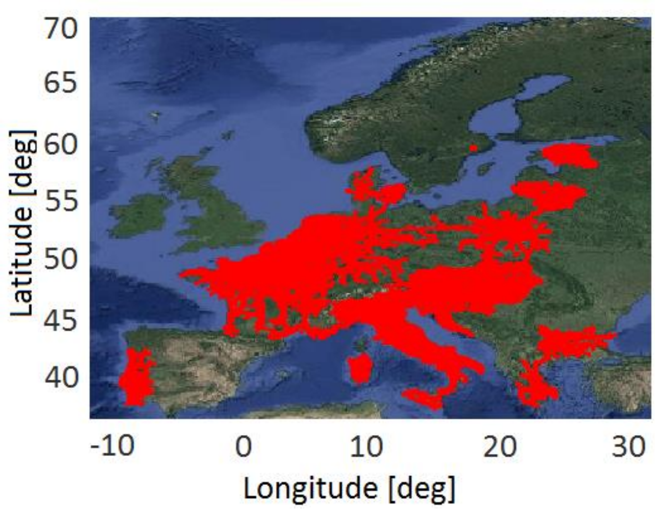


Fig. 1 Map of the EU-wide database billion data records.

2.2 Battery ageing models

Battery degradation is the result of electrochemical ageing, a process that degrades the electrical, chemical and mechanical properties of a cell. Several performance-based models from literature [15], [16], [17], [18], [19], [20], [21] have been implemented in TEMA. These models are typically calibrated using experimental datasets and despite the fact that their validity is confined to the boundaries of the experimental data used for calibrating the model, performance-based models can provide good results that highlight the direct link between ageing and its influencing factors [22]. Details information for all the ageing models implemented in TEMA are reported in [3]. A series of assumptions are applied to scale the capacity fade models from cell-level to vehicle-level in order to be combined with activity data and simplify a complex phenomenon as the in-vehicle battery durability. TEMA has been also generalized for using fitting coefficients of calendar and cycling ageing cell test data with given equations and parameters.

This work focuses on the capacity fade model, where the calendar ageing is given by [18], [19] and the cycling ageing by [20]:

$$Q_{loss-calendar} = A \cdot e^{\left(\frac{-E_a}{RT}\right)} \cdot \sqrt{t} \tag{1}$$

$$A = 14{,}786 \left[\frac{1}{\sqrt{day}}\right] \quad E_a = 24{,}500 \left[\frac{J}{mol}\right] \quad R = 8.314 \left[\frac{J}{mol \cdot K}\right] \tag{2}$$

$$Q_{loss-cycle} = (\alpha_c + \beta_c \cdot (Ratio)^{b_c} + \gamma_c \cdot (SoC_{min} - 0.25)^{c_c}) \cdot e^{\left(\frac{-E_a}{RT}\right)} \cdot Ah^z \tag{3}$$

$$\begin{cases} \alpha_c = 137 \quad \beta_c = 420 \quad \gamma_c = 9610 \quad b_c = 0.34 \quad c_c = 3 \\ E_a = 22{,}406 \left[\frac{J}{mol}\right] \quad R = 8.314 \left[\frac{J}{mol \cdot K}\right] \\ z = 0.48 \quad Ratio = 1 \end{cases} \tag{4}$$

where $Q_{loss\text{-}calendar}$ is the calendar loss, $Q_{loss\text{-}cycle}$ is the cycling loss, T is the cell temperature in K, t is the calendar time in days, Ah is the total ampere-hours exchanged by the battery and SOC_{min} is the minimum SOC value reached during the cycle.

The total capacity fade is calculated as net of the capacity fade reserve. This is a region of the SOC that is used to balance the loss of capacity of the cell during the first life. The total capacity fade of the vehicle is therefore calculated as per eq. (5), which considers calendar ageing and cycle ageing as additive components of total ageing, according to [21]:

$$Q_{loss-total} = Q_{loss-calendar} + Q_{loss-cycle} - Reserve\,. \tag{5}$$

TEMA model ageing results have been compared with real-world data from the field showing a good agreement in EoL years estimates [3], [22].

2.3 Reference vehicles, battery architectures and recharge strategies

To assess the battery durability performance, the authors considered in this work three reference battery packs associated with three reference vehicles available on the market. The vehicles are generically labelled as PHEV-1, BEV-1, BEV-2 [3]. PHEV-1 adopts a T-shaped battery pack of 192 pouch cells (2P-96S electric architecture) for a total of 16kWh nominal capacity, BEV-1 adopts instead a parallelepiped battery of 192 pouch cells (48S-2P-2S electric architecture) for a total of 24kWh nominal capacity, while BEV-2 has a flat battery pack, sometimes referred as "skateboard", of 6,912 cylindrical cells (16S-72P-6S electric architecture) for a total of 85kWh nominal capacity. Each battery is assumed to have a BoL usable energy equal to 75% of the nominal capacity, i.e. 12 kWh for the PHEV-1, 18 kWh for BEV-1 and 63.75 kWh for BEV-2. Each battery is considered to reach its end of life (EoL) when the usable energy becomes equal to 80%. In addition, each battery allows for an energy reserve value, equal to 25% of the nominal capacity for PHEV-1 and 15% of the nominal capacity for BEV-1 and BEV-2. Table 2 reports the assumed usable energy criteria for the reference vehicles together with their distance specific energy consumption from real drive-tests [23], [24], [25]. The presented results should not be taken as definitive predictions for their durability, neither must be intended to specifically address these vehicles, because of their different battery chemistries in respect of those considered in this work and the several assumptions made to address this complex phenomenon. TEMA replicates the driving behaviour from the selected datasets in combination with recharge behavioural models, which aim at representing the most likely recharging behaviours, depending on the individual choices of the driver and on the recharge infrastructure available.

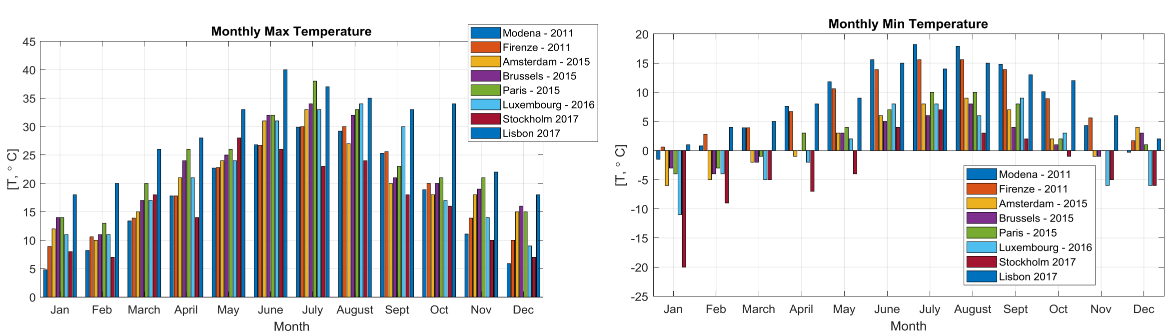
Table 2 Characteristic of the reference vehicles

	Vehicle Type	Battery Size [Wh]	Battery Shape	Usable Energy at BoL [Wh]	Usable Energy at EoL [Wh]	Reserve [% of battery capacity]	Energy consumption [Wh/km]
PHEV-1	Large-sized vehicle	16,000	T-shaped	12,000	9,600	25%	205
BEV-1	Medium sized vehicle	24,000	Parallelepiped	18,000	14,400	15%	210
BEV-2	Large-sized vehicle	85,000	Flat	63,750	51,000	15%	235

Among the sixteen strategies of TEMA [10], three are presented in this paper. Strategy 1 (Long-Stop Random AC) requires a vehicle stop longer than 120 minutes. It is assumed that charging uses conventional Italian recharge infrastructure (i.e. AC, single-phase at 3.3 kW, IEC 62196 Mode 1/2), and it is representative of a recharge that can take place at home or wherever the vehicle is subject to a long parking event (e.g. offices, shopping malls, airports or train station parking lots, etc.). The recharge power is scaled down to a constant value of 2 kW to account for the recharging profile (i.e. power modulation applied from the vehicle), and the recharge is subject to a random-generated threshold parameter between 0 and 1. Recharging is assumed to occur if this number is higher than 0.6 (i.e. 40% of the probabilities). This random threshold represents three possible situations: there is no recharge station where the vehicle is parked, the recharge station is not available, or the driver does not connect the vehicle to the recharge station (forgets or chooses not to recharge). Strategy 2 (Short-Stop Random DC) requires a vehicle stop longer than 20 minutes, (i.e. short-stop) and the recharge is done with high-power DC (55 kW, IEC 62196 Mode 4). It is representative of the recharge that could take place in parking lots equipped with fast-charging devices. In this case, the recharge power is scaled down to a constant value of 40 kW, to account for the recharging profile. Strategy 3 (Night AC) recharges a vehicle when it is parked in a specific time window between 22.00 and 07.00 and the parking event is longer than 4 hours. No random threshold is applied. The recharge is applied in AC (3.3 kW, IEC 62196 Mode 1/2) and the power is scaled down to a constant value of 2 kW as in Strategy 1. The charging efficiency has been set equal to 95% [10] for all strategies, according to measured values [24].

2.4 Ambient temperature

Fig. 2 depicts the monthly maximum and minimum temperatures in the several province areas for the year during which the data have been collected [26]. Moreover the monthly temperatures referring to Stockholm and Lisbon have been included in the plot being them used for studying the effect of a cold and warm environmental temperatures on the in-vehicle battery durability. Analysing Europe as a whole, in the first week of March 2015 the average minimum temperature was around 0°C [26] in Amsterdam, Brussels and Paris. Moreover, the average maximum temperature was 9°C in Amsterdam, 14°C in Brussels, 12°C in Paris. Paris has slightly higher temperatures in comparison to the other provinces.



a) b)

Fig. 2 Monthly a) maximum and b) minimum temperatures in the several geographical areas.

3 Results

3.1 Mobility patterns in different EU geographic regions

Fig. 3 depicts the share of the fleet parked (top) and in motion (bottom) in the week from Monday to Sunday [6]. The top and bottom pictures are complementary. The derived mobility behaviour of passenger cars is similar for all databases, periodically repeated in the days of the week, exhibiting three traffic peaks from Monday to Friday, i.e. in the morning (approximately at 7.30), at noon and in the evening (approximately at 18.30). In the weekend (Saturday and Sunday) the shape of the curves is different, showing mainly two peaks, approximately at 12.00 and at 19.00. Some vehicles are in motion during late Saturday night, although values above 99% of the vehicles are always parked between 1 and 5 o’clock in the morning. The share of the vehicles in motion at the same time never exceeds 11.7% of the complete fleet for Modena and 10.4% for Florence, with a mean value of 4.3% for Modena and 4.5% for Florence. It is observed that Amsterdam shows peak values below 7% while Brussels, Paris and Luxembourg well below 5% in line with [27], [28]. Analysis the main trip indicators, the averaged trip has a length between 5 and 20 km, the averaged trip duration varies between 10 and 20 minutes and the trips speed varies between 26 and 54 km/h. The averaged parking duration lasts between 2 and 12 hours. These values are average values on the full sample available in each dataset.

Following the approach depicted in [10], the work focuses only on the users that can drive all their trips electric on the analysed time period.For the majority of the vehicles, the number of trips ranges between 60 and 120 trips/month (i.e. 2-to-4 trips/day), with 15-to-30 recharging events per month in AC and 30-to-60 in DC [3] .

3.2 Capacity fade results in real-world use conditions

Fig. 4 shows the calendar, the cycling ageing and the calendar plus cycle ageing minus the reserve in function of the years for the several provinces considered in the analyses, given the mobility patterns of each geographical areas and temperature as described above. Fig. 4 refers to the case of BEV-1 and Recharge Strategy 1 as example. Each scenario is further broken down in five usage bins, representing different categories of users, e.g. from users that drive less than 500 km/month (6,000 km/year), to users that drive more than 2,000 km/month (24,000 km/year), and are key elements for classifying the EoL performance. The usage bins corresponding to more than 1500 km/month are not present for most of the provinces, showing that the combination of this specific vehicle characteristics and recharge strategy are not allowing to drive long distance in the month. This might be possible considering a recharge strategy with a higher frequency of recharge and higher recharging electricity power. The Battery Management System (BMS) that regulates the temperature of the battery is assumed active only during battery cycling, i.e., driving or charging the vehicle, and not during the calendar ageing, i.e. vehicle parked without being charged. Hence the environmental temperature of the areas affects more the calendar ageing. The cycling ageing is higher in the areas corresponding to higher average driven distance and charging power. Paris and Florence provinces correspond to a higher calendar and cycling ageing in respect to the other geographical areas, given the same recharging strategy, due to the average long driving distance and characteristic environmental temperatures. Table 3 presents the EoL estimates in years and the years needed to reach both 100,000 km and 160,000 km of cumulative kilometres, per each recharge strategy, vehicle type and geographical area. The predicted number of years needed to reach 100,000 km and 160,000 km of cumulative kilometres for a specific usage bin is calculated using average km per month of that user scenario. Each value is then coloured red if it is below 5.0 years, yellow if it between 5.0 years and 10.0 years and green if it is above 10.0 years. The colouring criterion is purely arbitrary, with the sole aim of providing the reader with a simpler visualization of the results [3]. The results show that the users that drive up to 1,500 km/month (i.e. first three bins) experience EoL beyond five years. It is interesting to note that through the first two bins, the capacity fade EoL criteria (<80% initial capacity) is normally reached before 100,000 km for BEV-1.

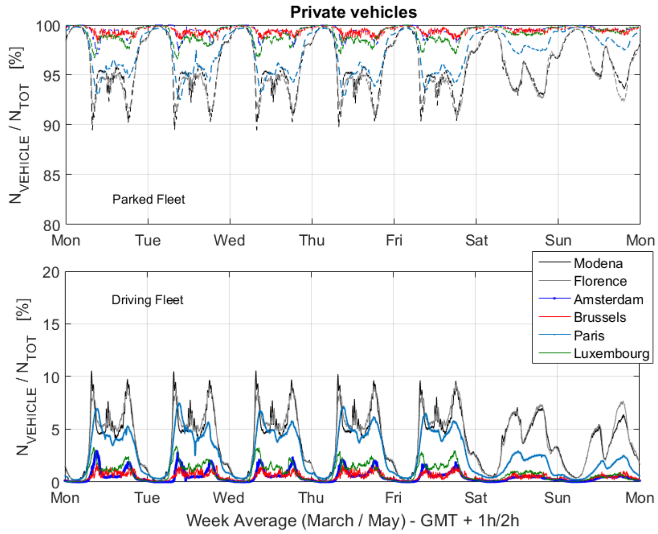


Fig. 3 Share of the private vehicles in motion and parked during a week.

Results for users in the third bin have EoL predictions that vary between the capacity fade and kilometres threshold, depending on battery architecture, charging strategy and vehicle technology. Bins 4 and 5 are considered higher kilometres drivers, and EoL predictions suggest that the kilometres threshold is more likely to be reached before the capacity fade EoL threshold for all the scenarios. Red scenarios are only predicted for kilometres accumulation threshold for the considered battery chemistry. BEV-2 never shows a predicted lifetime below 10 years, due to its battery architecture that minimizes the Ah-throughput for each individual cell and its large battery capacity. It is also important to note the mutual balancing of the calendar and cycle ageing mechanisms that can be observed for BEV-2, resulting in a vehicle that is aged independently from the kilometres accumulation. By comparing recharge strategy #2 (fast charge) with the other strategies (slow charge), ageing is predicted to occur slightly more quickly with fast DC charging, though this does not seem to be a dominant effect for BEV-2. PHEV-1 shows in general more than 15 years EOL criterion, in line with the concept of a battery for a hybrid vehicle lasting over the entire life of the vehicle.

3.3 Capacity fade results: effect on warm environmental temperature

To estimate the effect of warm environmental temperatures on the battery capacity fade the duty cycle of Modena is combined with the environmental temperature of Lisbon [29]. If a vehicle is driven in a warm environment, such as that of Lisbon in summer, it is assumed that the user operates the air conditioning system to cool the vehicle cabin down. This is reflected in higher energy consumption while driving the vehicle. In this simulation a constant increase of 15% in the driving energy consumption due to the air conditioning is assumed [24]. The basic scenario (Modena province duty cycle and environmental temperature) is compared to the warm environmental temperature scenario (Modena province duty cycle with temperature of Lisbon) and its combination with the usage of the Heating, Ventilation and Air Conditioning (HVAC) system (Modena province duty cycle with HVAC system in operation and temperature of Lisbon) in Fig. 5 for BEV-1 and Recharge Strategy 1. The effect of the warmer temperature is visible in the calendar ageing plots (red bars) in each figure in comparison to the base scenario (blue bars) (the BMS is not in operation). The HVAC system operation effects the cycling ageing (yellow bars) but in slightly the same way as the environmental temperature during driving and charging. Table 4 shows the EoL in years and years needed to reach 100,000 km and 160,000 km for the Modena province area with the environmental temperature of Lisbon and both BEV-1 and BEV-2 with Recharge strategy 1 and 2 to be compared to Table 3. In general, a lower number of years are needed to reach the EoL.

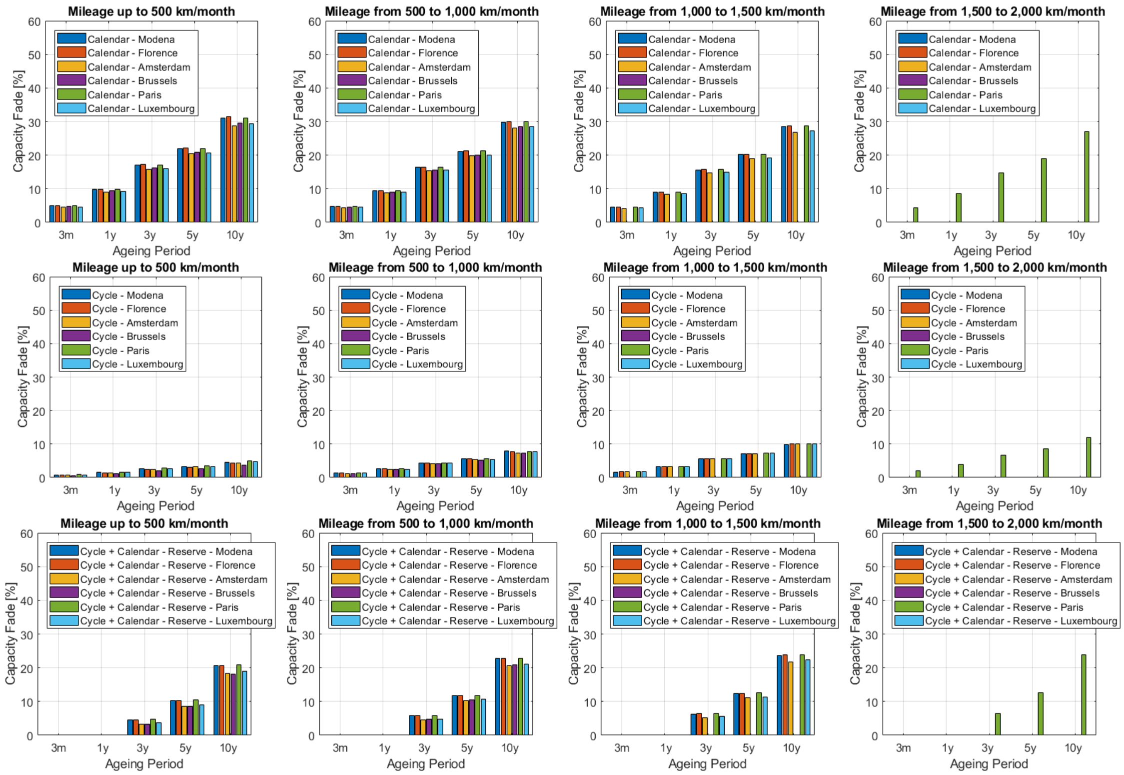


Fig. 4 Calendar ageing, cycling ageing and calendar plus cycle ageing minus reserve for the several provinces considered in the analyses. BEV-1 + Recharge Strategy 1- Li-Ion NCM-LMO (2015).

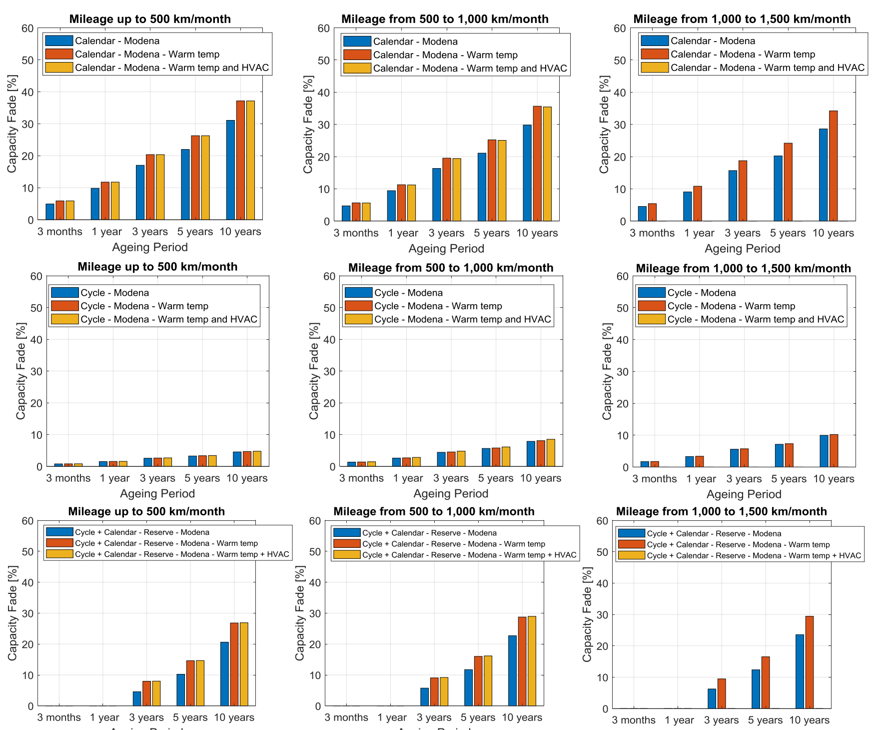


Fig. 5 Comparison of the calendar ageing, cycling ageing and calendar plus cycle ageing minus reserve for the BEV-1 with Recharge Strategy 1- Li-Ion NCM-LMO (2015), for three temperature scenarios.

Table 3. EoL in years, years needed to reach 100,000 km and 160,000 km for the different provinces areas, vehicle technologies and recharge strategies.

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.	16.5	≥ 20	≥ 20	14.6	14.2	≥ 20									
		Amsterdam Prov.	19.0	≥ 20	≥ 20	16.4	14.2	≥ 20									
		Brussels Prov.	18.9	≥ 20	≥ 20	16.1	15.0	≥ 20									
		Luxembourg Prov.	18.0	≥ 20	≥ 20	15.8	13.2	≥ 20									
		Paris Prov.	16.1	≥ 20	≥ 20	14.5	13.5	≥ 20									
	BEV-1	Modena Prov.	9.7	≥ 20	≥ 20	8.6	12.8	≥ 20	8.2	7.9	12.6						
		Amsterdam Prov.	11.1	≥ 20	≥ 20	9.7	13.9	≥ 20	9.0	7.5	12.0						
		Brussels Prov.	11.1	≥ 20	≥ 20	9.5	14.3	≥ 20									
		Luxembourg Prov.	10.6	≥ 20	≥ 20	9.4	13.2	≥ 20	8.8	7.4	11.9						
		Paris Prov.	9.5	≥ 20	≥ 20	8.6	12.9	≥ 20	8.1	7.5	12.0	8.1	5.2	9.5			
	BEV-2	Modena Prov.	12.1	≥ 20	≥ 20	12.7	11.2	17.9	13.6	6.9	11.0	14.7	5	8.1	16.1	3.9	6.3
		Amsterdam Prov.	13.9	≥ 20	≥ 20	13.7	11.6	18.6	13.7	7.2	11.5	14.3	5.2	8.3	15.7	4.0	6.4
		Brussels Prov.	13.4	≥ 20	≥ 20	13.4	13.2	≥ 20	14.1	7.5	12.0						
		Luxembourg Prov.	13.4	≥ 20	≥ 20	13.4	11.6	18.5	13.6	7.1	11.4	14.2	5.1	8.2	14.7	4.1	6.6
		Paris Prov.	12.0	≥ 20	≥ 20	12.0	11.2	17.9	12.1	7.0	11.3	12.8	5.1	8.1	14.1	3.8	6.1
Recharge Strategy #2	BEV-1	Modena Prov.	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.	11.0	≥ 20	≥ 20	9.2	13.3	≥ 20	8.1	7.4	11.8	7.5	5.2	8.3	7.0	4.0	6.5
		Brussels Prov.	11.0	≥ 20	≥ 20	8.9	13.2	≥ 20	7.9	7.1	11.4	7.4	5.1	8.2			
		Luxembourg Prov.	10.5	≥ 20	≥ 20	8.8	12.2	19.5	7.8	6.9	11.1	7.2	4.9	7.8	6.6	3.5	5.6
		Paris Prov.	9.3	≥ 20	≥ 20	8.0	12.0	19.2	7.2	7.0	11.2	6.7	4.9	7.9	6.3	3.7	5.9
	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	18.8	13.0	7.0	11.2	12.8	4.9	7.9	12.7	3.5	5.7
		Brussels Prov.	13.2	≥ 20	≥ 20	12.8	12.8	≥ 20	12.7	6.9	11.0	13.1	4.8	7.7	13.2	3.7	5.9
		Luxembourg Prov.	13.2	≥ 20	≥ 20	12.8	11.7	18.6	12.6	7.0	11.2	12.5	4.9	7.9	12.5	3.4	5.5
		Paris Prov.	11.8	≥ 20	≥ 20	11.5	11.3	18.0	11.4	6.8	10.9	11.3	4.8	7.7	11.4	3.0	4.8
Recharge Strategy #3	PHEV-1	Modena Prov.	16.1	≥ 20	≥ 20	14.4	12.3	19.8	13.7	7.7	12.3						
		Amsterdam Prov.	19.0	≥ 20	≥ 20												
		Brussels Prov.	18.8	≥ 20	≥ 20	16.1	14.9	≥ 20									
		Luxembourg Prov.	17.8	≥ 20	≥ 20												
		Paris Prov.	16.1	≥ 20	≥ 20	14.4	13.6	≥ 20									
	BEV-1	Modena Prov.	9.6	≥ 20	≥ 20	8.5	11.7	18.7	8.2	7.2	11.5	8	5.2	8.4			
		Amsterdam Prov.	11.1	≥ 20	≥ 20	9.6	14.3	≥ 20									
		Brussels Prov.	11.0	≥ 20	≥ 20	9.6	15.2	≥ 20									
		Luxembourg Prov.	10.4	≥ 20	≥ 20	9.3	13.7	≥ 20									
		Paris Prov.	9.4	≥ 20	≥ 20	8.6	13.9	≥ 20									
	BEV-2	Modena Prov.	12.1	≥ 20	≥ 20	12.7	11.1	17.7	13.7	6.8	10.9	14.8	4.9	7.9	16	4	6.4
		Amsterdam Prov.	13.9	≥ 20	≥ 20	13.6	11.7	18.7	13.4	7.4	11.8						
		Brussels Prov.	13.2	≥ 20	≥ 20	13.0	14.6	≥ 20									
		Luxembourg Prov.	13.4	≥ 20	≥ 20	13.1	11.5	18.4	13.0	6.7	10.7	12.7	5.0	8.1	12.4	3.5	5.6
		Paris Prov.	12.0	≥ 20	≥ 20	11.8	11.1	17.8	11.7	7.4	11.8	13.0	5.0	8.1			

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;

Table 4. EoL in years, years needed to reach 100,000 km and 160,000 km for Modena province area with the environmental temperature of Lisbon. BEV-1 and BEV-2 with Recharge strategy 1 and 2.

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

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;

4 Conclusions

The visible effects of electrochemical ageing of battery cells are a loss of energy capacity and a decrease of output power of the cell. An ageing model must aim at reproducing these two effects while considering driving cycles, environmental and battery temperature, charging rate and frequency and parking time. To this purpose the EU JRC has developed a dedicated in-vehicle battery durability assessment module within its TEMA platform, based on performance-based models and large-scale real-world driving data. JRC TEMA is a modular big data platform designed to reproduce mobility behaviours of vehicles from datasets of navigation system data of conventional fuel vehicles and quantify possible impacts of new vehicle technologies on real-world mobility while supporting transport policy assessment.

The mobility pattern datasets used in this analysis refer to six European cities and include up to 508,609 private vehicles, corresponding to 9.1 million trips and parking events and a total driven distance of 106.1 million kilometres. The analysis focuses on calendar and cycle capacity fade of NCM-LMO Li-ion variant, PHEV and BEV batteries architectures, derived combining different recharging strategies of different power and profiles with different driving duty cycles from the six cities mentioned above and related yearly environmental temperatures. The cycling ageing contribution is higher in the areas corresponding to higher average driven distance and charging power, while the environmental temperature affects more the calendar ageing. Additionally, ageing is predicted to occur slightly quicker with fast DC charging though this does not seem to be a dominant effect for BEV-2. TEMA model ageing results have been compared with real-world data from the field showing a good agreement in EoL years estimates.

Despite the assumptions and limitations of the ageing model, the results constitute a step forward in the topic of in-vehicle battery durability assessment combining calendar and cycle capacity fade models for electrified vehicle traction batteries with large-scale real-world driving data.

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