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Implementing a thermal model to assess the capacity fade of lithium-ion automotive batteries using real-world driving data

Elena Paffumi[1], Giorgio Martini [1]

[1]*European Commission – Joint Research Centre (JRC), Ispra, Italy, elena.paffumi@ec.europa.eu*

Summary

This work combines recent capacity performance-based models for NCM-LMO Li-ion variant batteries with a battery thermal model from literature to develop a scenario based analysis for predicting in-vehicle performance degradation of automotive traction batteries. The mobility pattern dataset used in these analyses refer to the Modena province in Italy and includes approximately 16.9 million records representative of 14.98 million km and 2.64 million trips. The results show the effect that the ambient temperature, the recharging power, and the driven kilometers have on the in-vehicle battery ageing.

Keywords: battery ageing, BEV (battery electric vehicle), thermal model, GPS, lithium battery

Nomenclature

BEV	Battery Electric Vehicle
BoL	Beginning of Life
BMS	Battery Management System
EoL	End of Life
UN ECE	United Nation Economic Commission for Europe
EVE IWG	Electric Vehicle and Environment Informal Working Group
GPS	Global Positioning System
GTR	Global Technical Regulation
HVAC	Heating, Ventilation and Air Conditioning
Li-ion	Lithium-ion
LMO	Lithium Manganese Oxide
MPR	Minimum Performance Requirements
NCM	Nickel Cobalt Manganese Oxide
SOC	State of Charge
TEMA	Transport tEchnology and Mobility Assessment

1 Introduction

In-vehicle battery durability is a key element for evaluating the economic, social and ambient impact of electrified vehicles. A better understanding of the battery degradation mechanisms relevant for automotive applications is highly desirable, together with a quantification of the battery lifetime in real-world use conditions. This work combines real-world vehicle driving data with recent publicly available ageing models for lithium-ion batteries and with a thermal model from literature [1] to develop a scenario-based analysis of the in-vehicle performance degradation of batteries. The results of this work and the flexibility shown by the European Commission Transport tEchnology and Mobility Assessment (TEMA) platform battery aging analyses contributed to inform the discussion on the new vehicle global technical regulation (GTR) N. 22 on in-vehicle battery durability developed within the United Nation Economic Commission for Europe (UN ECE) Electric Vehicles and Environment Informal Working Group (EVE IWG) [2]. This marks the first international effort to regulate the battery degradation. The new provisions will require manufacturers to certify that the batteries in their electric vehicles (EVs) will lose less than 20% of their initial capacity over 5 years or 100,000 km and less than 30% over 8 years or 160,000 km. This will ensure that only durable batteries are installed in EVs, increasing consumer trust, and improving the environmental performance of EVs [3].

2 The TEMA platform and the ageing model

The JRC TEMA platform [4] is a modular big data platform designed to reproduce mobility behaviors of vehicles from GPS datasets [5], [6], [7]. The platform has been extended with the calendar and cycle capacity fade models [8], [9], [10], enabling the simulation of a large variety of EV deployment scenarios with different driving styles, recharge patterns, vehicle architectures and ambient conditions [11], [12]. The work focus on one of the twenty available databases, the one related to the Italian province of Modena [5], mostly or exclusively including passenger vehicles, and has originally involved 52,834 conventional fuel vehicles (i.e. 12.0% of the fleet in this province) [13]. The analysis is then restricted to 16,263 vehicles in Modena (30.7% of the original sample), in order to consider only the share of the fleet predominantly driven in urban areas (defined as more than 50% of the trips carried out within the province area). The analysed database consist of approximately 16.9 million records representative of 14.98 million km and 2.64 million trips.

The ageing models implemented in TEMA are all performance-based models that correlate the battery capacity and power fade to the relevant stressing factors, by adopting algebraic empirical correlations [14]. They are typically sub-categorized in calendar and cycle ageing models, distinguishing between the effect of calendar time and usage, i.e. charge-discharge cycles. 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 and robust results, highlighting the direct link between ageing and its influencing factors [15]. This work focuses on the capacity fade of NCM-LMO electrochemistry only, being this more representative of modern mass market available batteries for electric cars. This specific ageing model is derived from [16], [17] for the calendar part and from [8] for the cycle part. The total capacity fade is calculated as sum of the calendar and cycle ageing at net of the capacity fade reserve. This last is a region of the State of Charge (SoC) used to balance the loss of capacity of the cell during the first life.

3 Reference vehicles, battery architectures and recharge strategies

To assess the battery durability performance in this work, the authors considered one reference battery pack associated with a reference battery electric vehicle (BEV) as depicted in Table 1. The vehicle is generically labelled as BEV-1. It adopts a parallelepiped battery and it is considered to reach its end of life (EoL) when its usable energy becomes equal to 80%. In addition, the battery allows for an energy reserve value, equal to 15% of its nominal capacity.

Table 1. Characteristics of the reference vehicle and battery architecture.

	Vehicle Type	Battery Size [Wh]	Battery Shape and cells type	Reference Voltage [V]	Usable Energy at BoL [Wh]	Usable Energy at EoL [Wh]	Reserve [% of battery capacity]	Energy consumption [Wh/km]
BEV-1	Medium-sized vehicle	24,000	Parallelepiped pouch cells	360	18,000	14,400	15%	210

TEMA replicates the driving behavior from the dataset in combination with recharge behavioral models, which aim at representing the most likely recharging behaviors, depending on the individual choices of the driver and on the recharge infrastructure available. Among the sixteen strategies of TEMA, slow and fast charging behaviors are presented in this paper.

4 Battery thermal model, battery management system and ambient temperature

A battery thermal model with theoretical electro and thermal characterization, publicly available in literature [1], has been implemented in TEMA to estimate the increase of the battery temperature during the recharge of the battery. The nominal voltage of the battery pack is assumed to be 360V, while the initial capacity of the battery pack is assumed to be equal to 112.6 Ah. The thermal model prescribes the lumped capacitance thermal network of the battery in relation to the environmental temperature as [1], [18]:

$$C_{th} \cdot \frac{dT_{batt}}{dt} = \frac{1}{R_{th}} \cdot (T_{amb} - T_{batt}) + P_j \tag{1}$$

where T_{batt} is the temperature of the battery, T_{amb} is the ambient temperature, P_j are the joule losses of the battery, R_{th} is the thermal resistance of the battery and C_{th} is the thermal capacitance of the battery.

The joule losses generated by the battery are defined as:

$$P_j = I_{batt}^2 \cdot R_{batt} \tag{2}$$

with I_{batt} the battery current, and R_{batt} the electrical resistance of the battery calculated by adding the resistance of the series connected cells and calculating the resistance of the parallel connected cells. The resistance of the single cell of the battery depends on the temperature and state of charge (SoC) level and it is dynamically derived by interpolating the open circuit voltage test data at 25 degrees reported in [1].

The thermal resistance R_{th} of the battery is assumed to be equal to 0.073 K/W, while the thermal capacitance C_{th} equal to 229,680 J/K, as defined in [1].

In the basic simulated scenario, the battery temperature is assumed to be regulated by the Battery Management System (BMS) both during the driving and recharging phases (cycle capacity fade modelling), and equal to the ambient temperature during the parking phase (calendar capacity fade modelling). This work will present also the case in which the battery temperature is estimated by applying the thermal model described above, during the charging of the vehicle. An additional control is added in this scenario on the battery temperature to avoid its increase above 35°C.

The analyses apply the monthly maximum and minimum temperatures of the geographic area and year during which the data have been collected. Moreover a specific case with the monthly temperatures referring to Lisbon is also reported to depict the additional effect of warm ambient temperatures on the in-vehicle battery durability given the same mobility patterns and battery thermal model [12].

5 Results

5.1 Mobility patterns

The derived mobility behavior of passenger cars is 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) [13]. In the weekend the shape of the curves is different, showing mainly two peaks, approximately at 12.00 and at 19.00. 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%.

5.2 Capacity fade results in real-world use conditions

Table 2 presents the EoL estimates in years and the years needed to reach both 100,000 and 160,000 cumulative kilometers, for both recharge strategies. The results refer to the case with and without the thermal model active during the vehicle charging. The predicted number of years needed to reach 100,000 km and 160,000 km of cumulative kilometers for a specific usage bin is calculated using the average km per month of that user scenario. Each value is then colored red if it is below 5.0 years, yellow if it is between 5.0 years and 10.0 years, and green if it is above 10.0 years. The coloring 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 1500 km/month (i.e., first three bins) experience the 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. Bins 4 and 5 are considered higher kilometer driven, and the EoL predictions suggest that the kilometer threshold is more likely to be reached before the capacity fade EoL threshold for all the scenarios. These bins are covered only by vehicles that are charged fast allowing more kilometers to be driven per months. Red scenarios are only predicted for the kilometer accumulation threshold for the considered battery chemistry. By comparing the recharge strategy #2 (fast charge) with the recharge strategy #1 (slow charge), aging is predicted to occur slightly quicker with fast DC charging with a larger effect if the thermal model is applied.

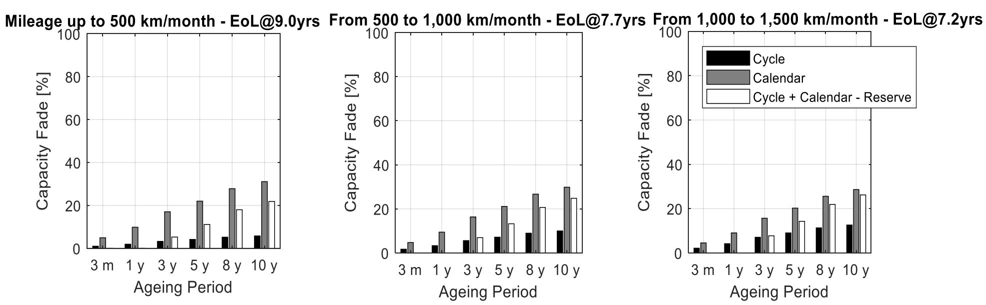
Applying the thermal model to estimate the battery temperature during the charging of the vehicle decreases the number of years to reach the EoL value of the capacity, Table 1, but still remaining complaint with slow charging with the regulatory minimum performance requirements (MPR) of 5 years or 100,000 driven kilometers for 20% capacity fade and 8 years and 160,000 driven kilometers for 30% capacity fade [2]. The worst cases against the MPR occur for the vehicles with higher driven kilometers per months and always charging fast for both the 5 years and 8 years MPR. Fig.1 shows the evolution over the years of the calendar aging, cycle aging, and calendar plus cycle aging minus the reserve for the case with the thermal model active during the vehicle charging for both the Recharge Strategy 1 and the Recharge Strategy 2.

Table 2. EoL in years, years needed to reach 100,000 km and 160,000 km

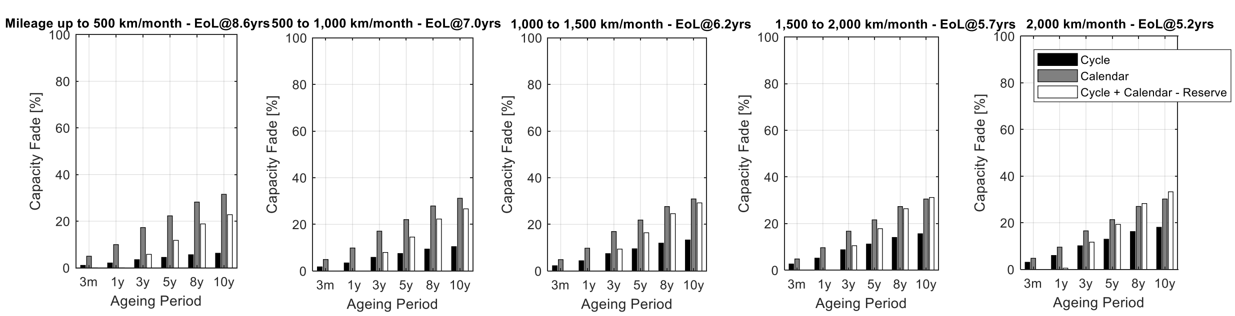
Capacity fade in [%] Years Driving to Set Thresholds Li-Ion NCM-LMO (2015) Modena province			0–500 km/Month: Years to EoL	0–500 km/Month: Years to 100,000 km	0–500 km/Month: Years to 160,000 km	500–1000 km/Month: Years to EoL	500–1000 km/Month: Years to 100,000 km	500–1000 km/Month: Years to 160,000 km	1000–1500 km/Month: Years to EoL	1000–1500 km/Month: Years to 100,000 km	1000–1500 km/Month: Years to 160,000 km	1500–2000 km/Month: Years to EoL	1500–2000 km/Month: Years to 100,000 km	1500–2000 km/Month: Years to 160,000 km	2000 + km/Month: Years to EoL	2000 + km/Month: Years to 100,000 km	2000 + km/Month: Years to 160,000 km
BEV-1	Recharge Strategy #1	Without thermal model	9.7	≥ 25	≥ 25	8.6	12.8	≥ 20	8.2	7.9	12.6		-			-	
		With thermal model	9.0			7.7			7.2				-			-	
	Recharge Strategy #2	Without thermal model	9.3	≥ 25	≥ 25	7.9	11.7	18.7	7.1	7.1	11.4	6.6	5.1	8.1	6.2	3.7	6.0
		With thermal model	8.6			7.0			6.2			5.7			5.2		

Legend

(red)	below 5.0 years;
(yellow)	above or equal to 5.0 and below 10.0 years;
(green)	above or equal to 10.0 years;



a)



b)

Figure 1 Calendar aging, cycle aging, and calendar plus cycle aging minus the reserve for the case with active thermal model during charging for a) Recharge Strategy 1, b) Recharge Strategy 2.

5.3 Effect of Warm Ambient Temperature

To estimate the effect of warm ambient temperatures on the battery capacity fade, the duty cycle of Modena is combined with the ambient temperature of Lisbon [19]. 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 [12], [20]. The basic scenario (Modena province duty cycle and ambient temperature) is compared to the warm ambient temperature scenario (Modena province duty cycle with the 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 the temperature of Lisbon) in Fig. 2 for Recharge Strategy 1.

Table 3 shows the EoL in years and years needed to reach 100,000 km and 160,000 km for the ambient temperature of Lisbon and Recharge strategy 1 and 2 to be compared to Table 1. In general, less years are needed to reach the EoL especially for the case of higher kilometers driven and fast charging where the values are slightly below the MPR in years of the UN GTR 22 [2].

Fig. 3 shows the evolution over the years of the calendar aging, cycle aging, and calendar plus cycle aging minus reserve for the case with the thermal model during the vehicle charging for both the Recharge Strategy 1 and the Recharge Strategy 2. Applying the thermal model to estimate the battery temperature during the charging of the vehicle decreases further the number of years to reach the EoL.

Fig. 4 shows the summary of the results for all the cases with and without the application of the thermal model during the charging for both the Recharge Strategy 1 and the Recharge Strategy 2. The worst case is the one with both warmer temperature and active thermal model, resulting in a higher ageing percentage, especially for higher kilometers driven per month and always fast charging, a scenario not jet fully deployed.

Table 3. EoL in years, years needed to reach 100,000 km and 160,000 km for Modena province area with the ambient temperature of Lisbon. BEV-1 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) + HVAC			**Fleet Share**	**0–500 km/Month**			**500–1000 km/Month**			**1000–1500 km/Month**			**1500–2000 km/Month**			**2000 + 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**
BEV-1	Recharge Strategy #1	Without thermal model	9.9%	7.0	≥ 25	≥ 25	6.3	13.2	≥ 20		-			-			-	
		With thermal model		6.4			5.5				-			-			-	
	Recharge Strategy #2	Without thermal model	19.9%	6.5	≥ 25	≥ 25	5.6	12.0	19.2	5.0	7.2	11.6	4.7	5.2	8.4	4.3	3.8	6.0
		With thermal model		6.1			5.0			4.4			4.1			3.7		

Legend

(red)	below 5.0 years;
(yellow)	above or equal to 5.0 and below 10.0 years;
(green)	above or equal to 10.0 years;

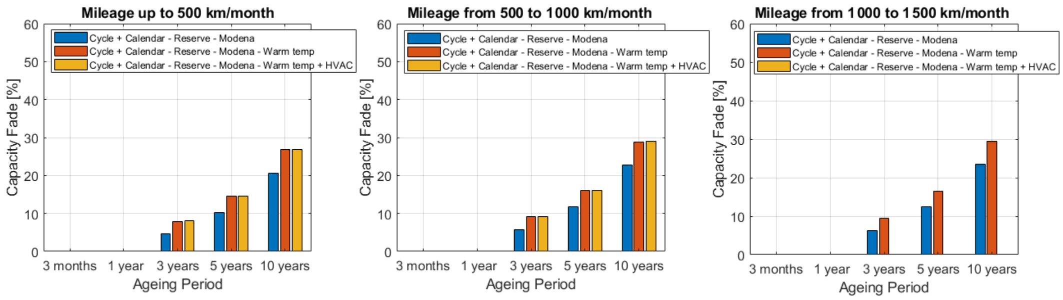
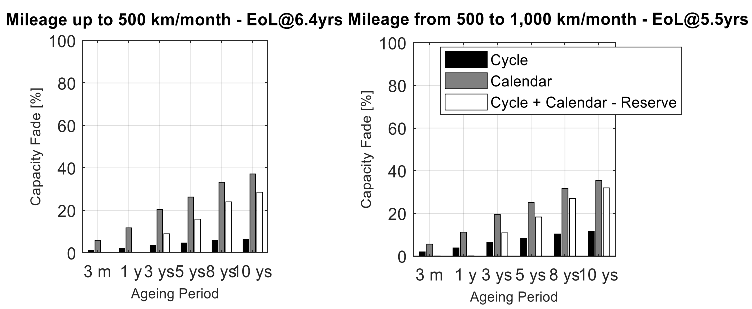


Figure 2 Comparison of the calendar plus cycle aging minus the reserve for the BEV-1 and Recharge Strategy 1- Li-Ion NCM-LMO (2015), for three scenarios: Modena province duty cycle and ambient temperature, Modena province duty cycle with the temperature of Lisbon, and the Modena province duty cycle with HVAC system in operation and the temperature of Lisbon.



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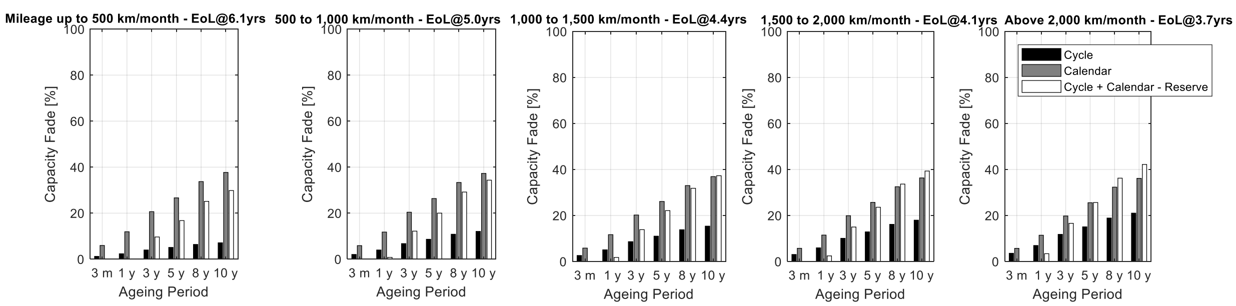
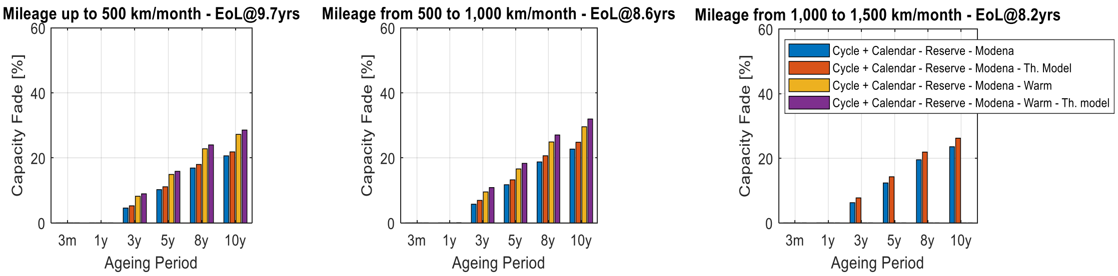
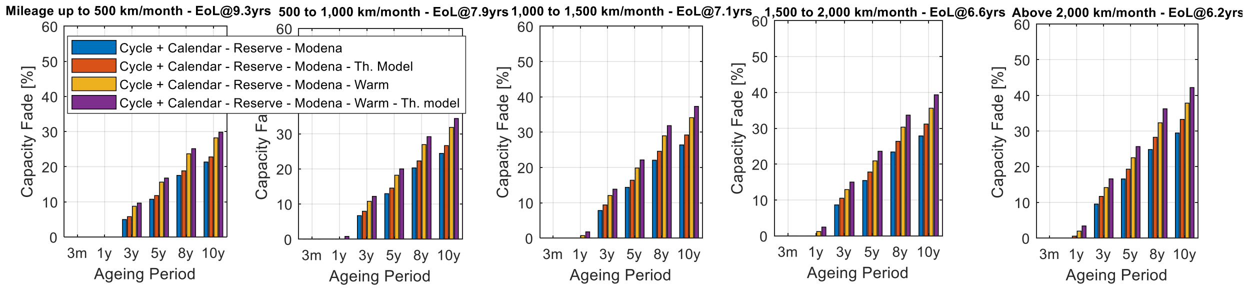


b)

Figure 3 Calendar aging, cycling aging, and calendar plus cycle aging minus the reserve for the case of Modena province duty cycle with HVAC system in operation, temperature of Lisbon and thermal model during charging for a) Recharge Strategy 1, b) Recharging Strategy 2.



a)



b)

Figure 4 Summary of the results: base case Modena province duty cycle and ambient temperature, Modena province duty cycle with HVAC system in operation and the temperature of Lisbon, with and without the thermal model applied during the charging for a) Recharge Strategy 1 and b) Recharge Strategy 2.

6 Conclusions

The results presented in this paper constitute part of the scientific efforts for the development of vehicle-level models that fairly compare the in-vehicle battery durability performance for different vehicles. The results aim at better representing the real-world scenarios, in view of informing future transport policy revisions related to the next generation of hybrid and electric vehicles. For the base case scenario with ambient temperature from Modena area the effect of an increase of the temperature of the battery during the recharge is of minor effect. The worst case scenario occur for vehicles with higher kilometers driven for months and always charged fast in warm ambient temperatures.

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Authors

Elena Paffumi is a scientific officer with the Joint Research Centre (JRC) located in Ispra, Italy. She is in charge of the European pre-normative research for hybrid and electric vehicles and policy support. She is member of the UN ECE working groups related to hybrid and electric vehicles and testing procedure definition. Her research focus includes e-mobility modelling, big data analysis, experimental testing of vehicles and transport policy support. She is author of several scientific articles.

Giorgio Martini holds a Nuclear Engineering degree obtained at the University of Rome, Italy. After ten years of experience in the field of fuel quality and vehicle emissions, he joined the Sustainable Transport Unit of the Joint Research Centre (JRC) of the European Commission. He is the coordinator of the research programmes and experimental activities for the development of the European policies in the field of fuel quality and vehicle emissions. He has been directly involved in the development process of the future European emission standards (Euro 5/6 and Euro VI) and in international programmes like the UN-ECE Particle Measurement Programme.