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On-road vehicle emissions measurements show a significant reduction in black carbon and nitrogen oxide emissions in Euro 6c and 6d diesel-powered cars

Irena Ježek Brecelj et al.

Correspondence to: Irena Ježek Brecelj (ibrecelj@aerosolmageesci.com)

SUPPLEMENT

Section S1: Representativeness of the sample fleet compared to Eurostat data for Slovenia and the EU

The vehicle fleet size in the EU and Slovenia has increased over the years (Figure S1). From 2014 to 2022, the size of the passenger car fleet increased by 13%. There has also been an increase in the number of lorries and tractors (in general, lorries correspond with N1 and N2 goods vehicles, while tractors are N3 goods vehicles), only here the Slovenian fleet grew more rapidly from 2014 to 2022 (by 72%) than EU fleet (by 39%).

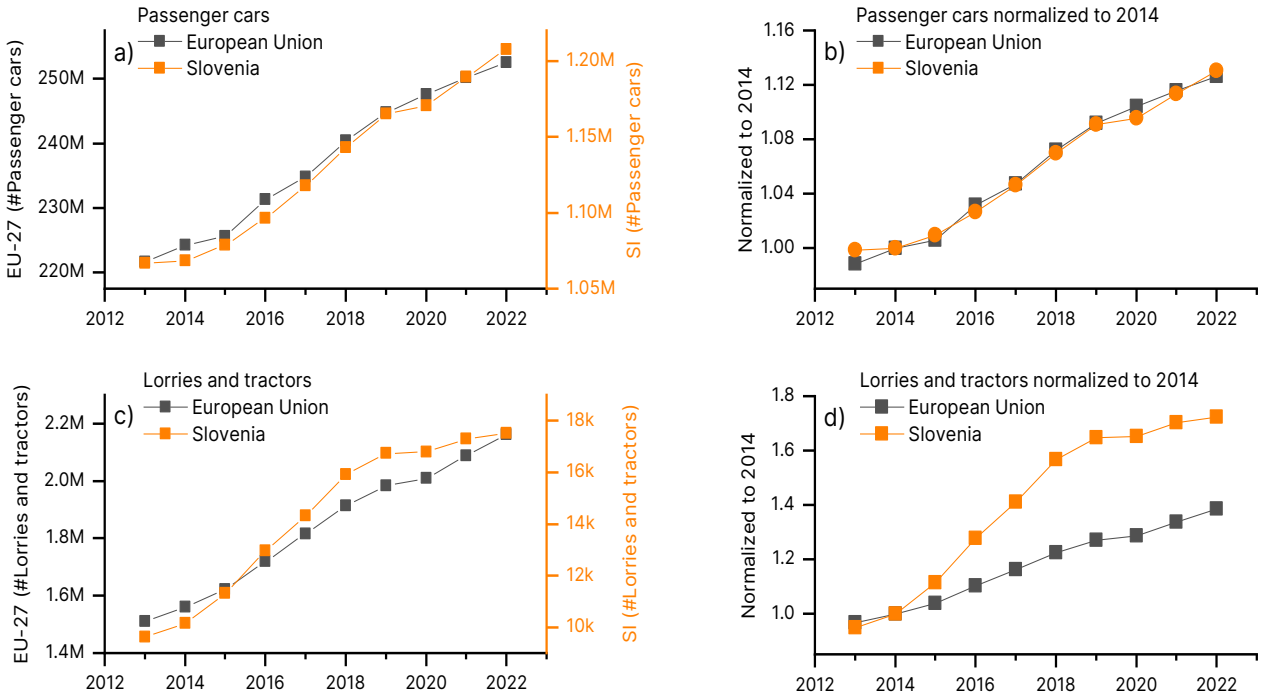

Figure S1 Passenger car fleet growth in the European Union and Slovenia (a), the rate of passenger cars' growth normalized to the year 2014. Lorries and tractors fleet growth in the European Union and Slovenia (c), the rate of lorries and tractors growth normalized to the year 2014.

While there was a lot of variability in different European countries' vehicle age composition (see Figure S2, where vehicle age composition is presented for all of Europe on 31st December 2022), Slovenia represents the average EU car fleet quite well. The average personal car age in Slovenia increased from 8.4 years in 2011 to 10.9 years in 2022 (Sistat https://pxweb.stat.si/SiStatData/pxweb/sl/Data/-/2221115S.px/table/tableViewLayout1/). In 2010, EU passenger cars were on

15 average 8.3-year-old, (ACEA_POCKET_GUIDE_2012_UPDATED). In 2022 the average passenger cars and vans were 12, trucks 14.2, and buses 12.7 years old. https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/

The average age of all vehicle types continues to increase. Since 2018, the average age of all vehicle types has risen by around one year.

The fractions of diesel cars in our measured fleets were 54% in 2023, and 58% in 2017, which is slightly more than in Slovenian and European fleets reported by Eurostat in those years (50% SI 2022, 38% EU2022, 47% SI 2017, 40% EU2017). From Figure S2 we can see that the engine size composition of the EU fleet has been stable over the years. Namely, there are about a quarter of gasoline-powered cars with engines smaller than 1400 cc (small engines), a quarter of medium-sized diesel-powered cars (engine size between 1400 and 2000 cc), there are small fractions (3 – 8%) of large engine size gasoline and diesel-powered cars (2000 cc and more) and a similar small fraction of small engine diesel powered cars. There are also 12 - 14% of cars powered by alternative propulsion systems (gas, electric, etc.). Compared to the Slovenian fleet composition, the largest difference is that there are little to no "other" power source cars in the Slovenian fleet, while the percentage of small-engine gasoline-powered cars and medium-engine diesel-powered cars increases. There is a trend in the Slovenian vehicle fleet towards more diesel-powered cars with medium-sized engines, which increased from 2011 to 2022 from 29% to 43% and fewer small and medium-sized gasoline cars. Also, other power sources started to take a small share - 1% in 2017 and 4% in 2022. The proportions of our captured fleets in 2017 and 2023 reflect the engine displacement composition of the Slovenian car fleet.

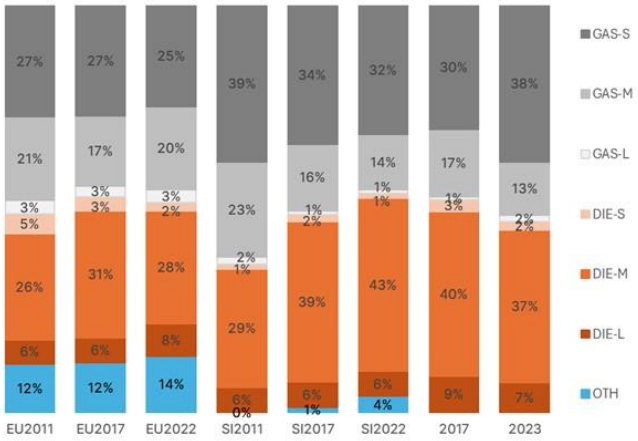

Figure S2 Composition of passenger cars according to engine size and fuel used for European Union (EU) and Slovenian (SI) personal cars for years 2011, 2017, and 2023 from Eurostat, compared with the measured fleets from our campaigns in 2017 and 2023. The legend abbreviations are GAS, DIE, and OTH for gasoline, diesel, and other, respectively; and S, M, and L for small engines sizes less than 1400 cc, medium engine sizes from 1400 – 2000 cc, and large engines - more or equal to 2000 cc, respectively.

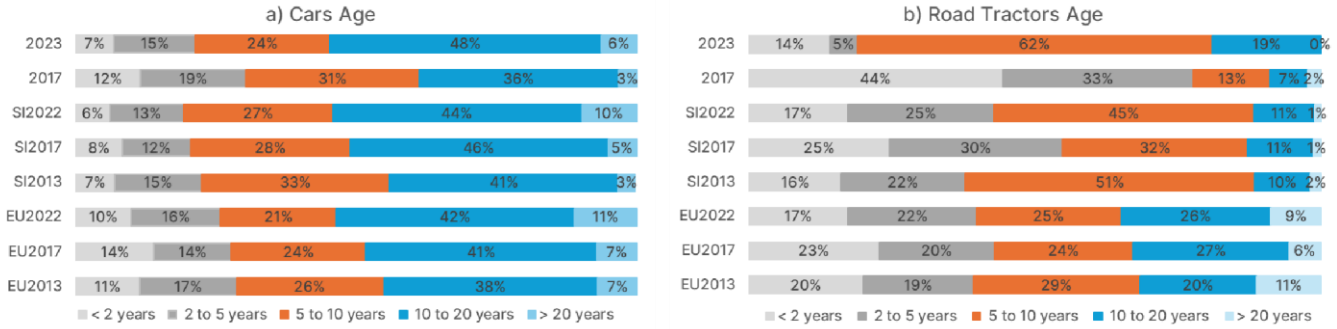

Figure S3 Age share of (a) Cars and (b) Road Tractors in our fleet from campaigns in 2017 and 2023, and in Slovenia (SI) 40 and the European Union (EU) for years 2013, 2017, and 2022.

The cars' age shares of total EU and Slovenia are very similar as presented in Figure S3 a. Over the years, the respective categories differ by up to 7%. Our 2023 car fleet had a similar age distribution as the 2022 Slovenian fleet, while our 2017 fleet had more cars in categories that were less than 5 years old, and fewer those that were in categories older than 5 years, up to 22% more than the respective year in the EU. And up to 16% less road tractors aged 10 – 20 years. Even though the data for goods vehicles in Eurostat is not as complete as that for cars (several countries did not report their numbers), we can see that the growth in car fleets was similar for Slovenia and Europe, while the growth of lorries and tractors was higher in Slovenian fleet Figure S1. We can also see in Figure S3 b that the Slovenian fleet had more Road tractors in categories less than 10 years old than the total EU. Our 2017 and 2023 samples have mostly road tractors less than 10 years old, but their shares are different than the Slovenian or the EU, and thus not the best representation of the goods vehicle fleet composition. Nevertheless, this sufficed, since we distinguished between younger than 10 and older than 10-year-old goods vehicles.

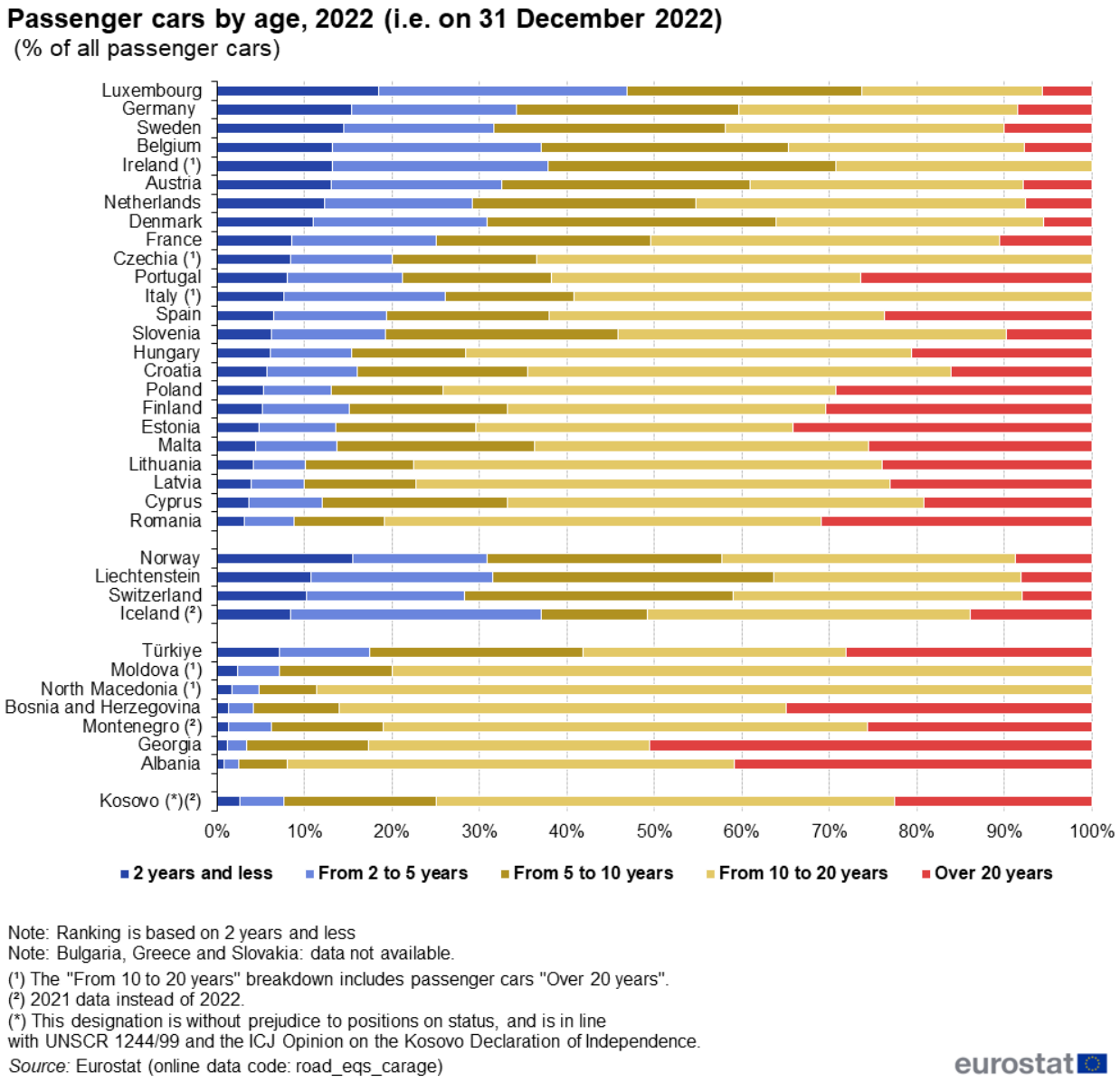

Figure S4 Passenger cars by age for different EU countries. Source Eurostat

We analyzed the representatives of our sampled fleets by comparing them to Slovenian and average European vehicle stock as reported by the Eurostat dataset titled "Passenger cars, by type of motor energy and size of the engine," last updated on March 27, 2020, 23:00, covering the years 2016 and 2022, which is also available online at https://ec.europa.eu/eurostat/data/database.

Section S2: Table with more detailed measurement days weather conditions data.

Table S1 Measurement days and weather conditions as reported by the Slovenian Environmental Agency for Ljubljana Bežigrad station. Last accessed 30.10.2024.

	Avg. daily T [°C]	max. T [°C]	min. T [°C]	Avg. wind speed [m/s]	clouds [%]	Avg. RH [%]
3.05.2023	13.6	17	10.7	1.1	83	74
4.05.2023	15	21.1	7.4	1.1	17	65
5.05.2023	18.1	26.2	8	1.3	17	58
12.05.2023	11.9	14.1	10.5	0.7	100	85
15.05.2023	15.7	20.4	9.9	2.3	70	71
18.05.2023	13.7	17.8	9.2	1.7	77	70
19.05.2023	13.7	17.3	11.8	1.7	100	76
13.03.2017	6.3	13.3	-0.2	1.2	3	59
14.03.2017	8.9	17.2	0	1.1	63	60
15.03.2017	9.5	16.9	2.3	0.7	67	61
16.03.2017	10.5	18.3	2.2	1	30	63
17.03.2017	11.8	19.9	2.7	3.1	13	60
20.03.2017	13.5	20.2	7	2.6	40	76
21.03.2017	14	19.2	7.4	2	67	67
22.03.2017	11.9	14.8	8.9	0.6	97	89
23.03.2017	13.6	19.6	8.8	1.7	57	68
6.12.2011	3.2	7.6	1	1.4	43	80
7.12.2011	1.4	2.6	-2.4	0.6	97	94
9.12.2011	7.9	11.3	-1.2	1.7	87	76
10.12.2011	9.3	12	7.5	1.7	67	79
11.12.2011	5.1	7.9	1.5	0.7	100	89
21.12.2011	-1.3	0	-3.5	0.9	77	88

Section S3: Tables with sample fleet size and emission factor values.

Table S2 Vehicle fleet sample sizes in 2023, 2017, and 2011 campaigns.

	Gasoline Cars			Diesel Cars			Goods vehicles			
	2023	2017	2011	2023	2017	2011		2023	2017	2011
older		7			2					
Euro2	2	22	11	1	12	7	older		10	
Euro3	14	29	6	13	21	32	Euro III	1	11	3
Euro4	25	33	7	21	63	27	Euro IV	2	19	10
Euro5a	15	14		15	27		Euro V	3	16	14
Euro5b	6	8		9	22		Euro VI	24	57	
Euro6b	15	8		18	23					
Euro6c	11			7						
Euro6d	13			5						

Table S3a Black Carbon Emission Factors. Median values and inter-quartile ranges in brackets for Euro standards sub-groups in the three campaigns (g kg^{-1}).

	Gasoline Car			Diesel Cars				Goods vehicles		
	2023	2017	2011	2023	2017	2011		2023	2017	2011
Euro2		0.04 (0 - 0.09)	0.2 (0.14 - 0.49)		1.03 (0 - 1.44)	0.92 (0.19 - 1.76)	older			
Euro3	0.04 (0-0.08)	0.03 (0 - 0.09)	0.37 (0.24 - 0.4)	1.58 (0.84-2.72)	0.72 (0.7 - 1.45)	1 (0.47 - 1.05)	Euro III		0.73 (0.18 - 0.91)	0.55 (0.44 - 0.78)
Euro4	0.05 (0.02-0.08)	0.04 (0 - 0.07)	0.15 (0.02 - 0.26)	0.38 (0.13-0.64)	0.58 (0.59 - 1.2)	0.46 (0.28 - 0.63)	Euro IV		0.35 (0.13 - 0.58)	0.52 (0.32 - 0.81)
Euro5a	0.05 (0.01-0.1)	0.06 (0.01 - 0.09)		0.13 (0.03-0.63)	0.07 (0.18 - 0.14)		Euro V	0.53 (0.310.61)	0.11 (0.06 - 0.34)	0.4 (0.2 - 0.55)
Euro5b	0.06 (0.04-0.27)	0.04 (0.01 - 0.11)		0 (0-0.07)	0.05 (0.02 - 0.17)		Euro VI	0.04 (0.010.07)	0.08 (0.02 - 0.17)	
Euro6b	0.03 (0-0.1)	0.01 (0.01 - 0.04)		0.05 (0-0.12)	0.09 (0 - 0.15)					
Euro6c	0.03 (0-0.06)			0.01 (0-0.06)	0 (0.03 - 0)					
Euro6d	0.05 (0.02-0.06)			0.04 (0-0.06)	0 (0 - 0)					

Table S3b Black Carbon Emission Factors averages (g kg^{-1}).

	Gasoline Car			Diesel Cars				Goods vehicles		
	2023	2017	2011	2023	2017	2011		2023	2017	2011
Euro2		0.06	0.31		1.24	1.72	older			
Euro3	0.06	0.07	0.35	2.25	0.99	1.66	Euro III		0.72	0.63
Euro4	0.09	0.06	0.20	0.60	0.95	0.68	Euro IV		0.42	1.56
Euro5a	0.08	0.08		0.44	0.53		Euro V	0.44	0.33	0.37
Euro5b	0.15	0.06		0.06	0.18		Euro VI	0.07	0.12	
Euro6b	0.06	0.03		0.09	0.16					
Euro6c	0.04			0.03						
Euro6d	0.11			0.05						

Table S4a Nitrogen Oxides Emission Factors. Median values and inter-quartile ranges in brackets for Euro standards sub-groups in the three campaigns (g kg^{-1}).

	Gasoline cars			Diesel Cars				Goods vehicles		
	2023	2017	2011	2023	2017	2011		2023	2017	2011
Euro2		3.66 (1.02 - 12.57)	6.42 (2.87 - 8.66)		14.04 (10.3 - 17.42)	10.25 (5.73 - 17.23)	older			
Euro3	2.44 (0.99-4.46)	2.24 (0.27 - 9.2)	13.37 (4.86 - 15.64)	16.79 (12.36-21.71)	13.62 (9.58 - 19.47)	16.99 (10.89 - 23.78)	Euro III		20.39 (14.42 - 28.8)	33.78 (26.47 - 57.57)
Euro4	1.34 (0.36-2.04)	0.93 (0 - 4.66)	3.99 (2.58 - 5.6)	9.39 (7.24-17.36)	11.53 (6.15 - 19.72)	12.5 (6.44 - 22.41)	Euro IV		21.97 (14.22 - 36.38)	35.42 (23.88 - 45.33)
Euro5a	1.49 (0.46-4.39)	0.8 (0.01 - 1.73)		12.03 (7.6-20.92)	14.02 (6.08 - 18.41)		Euro V	30.38 (20.1-38.57)	21.13 (11.54 - 40.43)	19.31 (12.61 - 29.74)
Euro5b	0.84 (0.67-2.09)	0 (0 - 0)		10.67 (4.57-13.09)	12.93 (3.66 - 19.52)		Euro VI	2.4 (0.86-8.38)	4.05 (0.56 - 11.98)	
Euro6b	1.9 (0.6-3.26)	1.06 (0.17 - 3.28)		7.12 (4.77-14.23)	11.63 (2.86 - 15.73)					
Euro6c	0.75 (0.25-2.28)			1.09 (0.46-3.5)						
Euro6d	2.3 (1.01-4.85)			0.91 (0.28-1.63)						

Table S4b Nitrogen Oxides Emission Factors averages (g kg^{-1}).

	Gasoline cars			Diesel Cars				Goods vehicles		
	2023	2017	2011	2023	2017	2011		2023	2017	2011
Euro2		14.12	8.13		15.82	12.15	older			
Euro3	4.09	6.35	11.98	19.89	18.55	18.62	Euro III		23.95	44.77
Euro4	1.47	2.99	4.63	12.54	13.88	15.93	Euro IV		24.69	34.92
Euro5a	3.76	1.39		15.24	12.69		Euro V	27.46	24.85	25.97
Euro5b	1.74	0.10		11.29	14.62		Euro VI	7.76	10.73	
Euro6b	2.03	3.06		10.16	12.29					
Euro6c	1.39			2.75						
Euro6d	3.45			1.39						

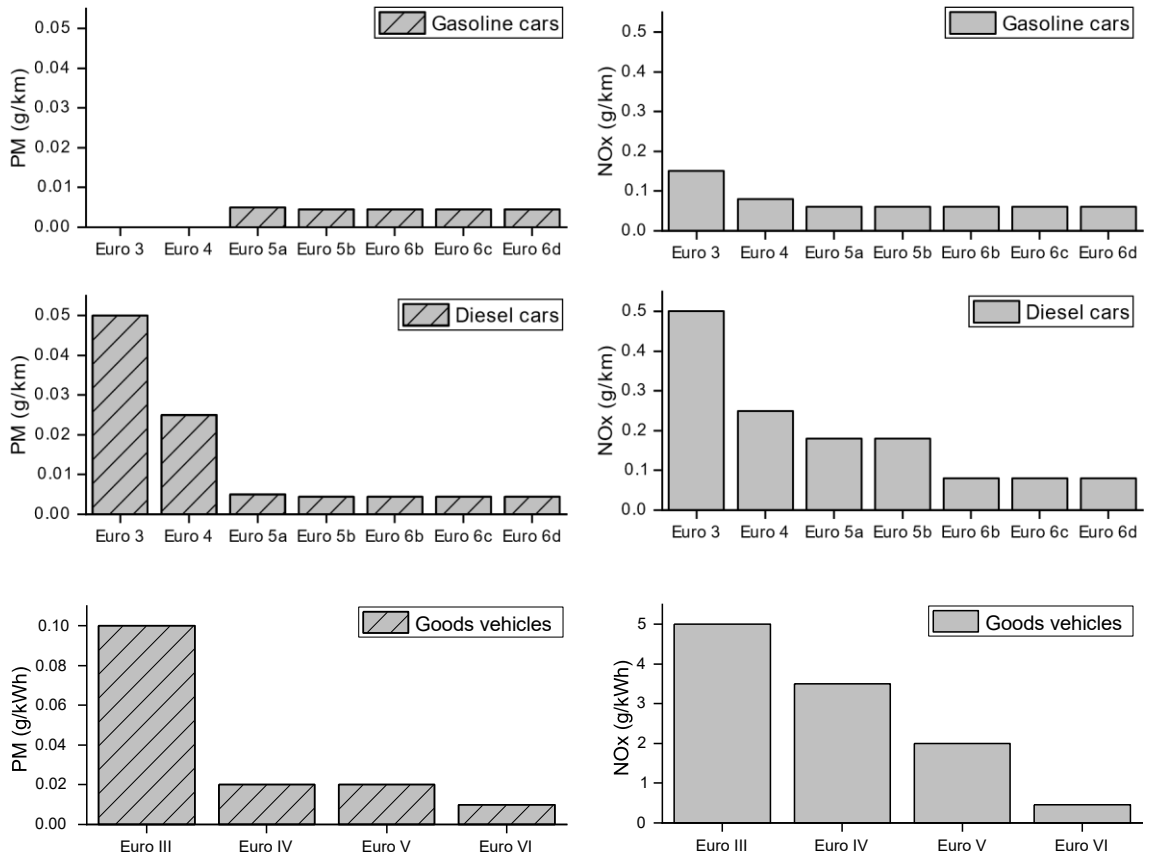

Figure S5 PM (left column) and NO_x (right column) European emission standards for gasoline-powered cars (top row), diesel-powered cars (middle), and goods vehicles (bottom row).