Sarica *et al.*
European Transport Research Review (2024) 16:34
https://doi.org/10.1186/s12544-024-00660-2

European Transport Research Review

ORIGINAL PAPER **Open Access**

Differentiated impact of low-exhaust-emission vehicles on NO_2 and particle concentrations in the Paris region

Thibaud Sarica[1*], Christophe Chaillou[2], Yelva Roustan[1], Clément Larrieu[2], Salah-Eddine Wali[2] and Karine Sartelet[1*]

Abstract

Higher concentrations of air pollutants, such as nitrogen dioxide (NO_2) and particulate matter (PM), are observed in streets compared to the urban background. These concentrations could be predominantly attributed to road traffic, which remains an important source despite relentless efforts. In this study, performed over the Paris area, the impacts of the evolution of the fleet composition on urban air quality down to the street scale is assessed with two scenarios assuming the introduction of very-low-emission vehicles. Exhaust emission factors for these vehicles are based on the improvement of engine and after-treatment technologies, leading to factors lower than those proposed for the European emission standard Euro 7. Using the year 2014 as the baseline, very-low-emission vehicles are introduced up to the year 2030 for the Paris region. NO_2 emissions are thus reduced by 68 % in streets, and concentrations by 53 %. However, PM concentration reduction is limited to 18 % in streets as non-exhaust emissions from tyre and brake wear and road abrasion are preponderant. PM emissions from non-exhaust sources represent 59 % of the total road-traffic emission of PM in 2014 and 89 % in 2030. Non-regulated pollutant concentrations are also reduced, by 42 % for black carbon and 30 % for organic matter. Considering only very-low-emission and electric vehicles in the fleet further reduce NO_2 emissions and concentrations by 99.5 % and 80 % respectively. PM concentrations are only reduced by 22 %. This study highlights the high reduction potential of NO_2 concentrations with very-low-emission and electric vehicles, because of reduction of exhaust emissions. However, difficulties remain to reduce PM concentrations in urban areas, with the large majority of PM traffic emissions coming from non-exhaust sources.

Keywords Emission reduction, Traffic, Prospective study, Numerical model, Nitrogen dioxide, Particles

1 Introduction

Despite efforts by the authorities to mitigate air pollution, populations are still exposed to high concentrations of pollutants, especially in urban areas. In 2020, among the 75 % of the European population living in urban areas, 89 % were exposed to concentrations of nitrogen dioxide (NO_2) above the 2021 World Health Organization (WHO) guidelines, reaching 96 % for particulate matter (PM) with diameters smaller or equal to 2.5 µm ($PM_{2.5}$) [11]. Exposure to high concentrations causes detrimental health effects, ranging from coughing and eye irritation to chronic diseases, e.g. chronic bronchitis and lung cancer [22]. PM is considered to be one of the most harmful pollutants [21]. The chemical composition of the particles also plays an important role in the impacts on human health. Particles of black carbon (BC) and organic matter (OM) are known to cause heart problems, lung

---

*Correspondence:
Thibaud Sarica
thibaud.sarica@enpc.fr
Karine Sartelet
karine.sartelet@enpc.fr
[1] CEREA, Ecole des Ponts, EDF R &D, IPSL, 6-8 Avenue Blaise Pascal, Cité Descartes, Marne-la-Vallée 77455, France
[2] Aramco Fuel Research Center, Aramco Overseas Company, 232 Avenue Napoleon Bonaparte, Rueil-Malmaison 92500, France

cancer and the aggravation of preexisting heart and lung disease [4, 7, 9, 10].

Numerous studies investigated the impacts of road traffic on urban air pollution, and ways to reduce its emissions [6, 16, 23, 27, 34–36]. Promoting alternative transport (cycling and public transport) could reduce concentrations of $PM_{2.5}$, by 25 % in Adelaide, South Australia [35]. Although not justified in terms of road safety, raising speed limits in urban areas from 30 km h^{-1} to 50 km h^{-1} could also reduce NO_2 and particulate matter with diameters smaller or equal to 10 µm (PM_{10}) concentrations by 3 % and 2 % respectively [34]. The use of recent vehicles appears to be an effective measure to reduce NO_2 and BC concentrations. For example, modernizing the fleet in Warsaw, Poland, to the most recent European emission standards would reduce the population's exposure to nitrogen oxides (NO_x) by almost 50 % [16]. Lugon et al. [23] modeled several scenarios of fleet renewal and evolution (business as usual and promotion of petrol and electric vehicles) from 2014 to 2024 over Paris, France, and observed reductions in concentrations of NO_2 and BC by up to 50 % and of PM_{10} and $PM_{2.5}$ by 20 %. Despite these large reductions of concentrations due to fleet renewal, more than 20 % of the Paris population would still be exposed to NO_2 and $PM_{2.5}$ concentrations exceeding the air quality guidelines. However, the exposure estimated in 2024 by [23] may be overestimated, because the decrease of emissions from sectors other than traffic between 2014 and 2024 was not taken into account.

The estimation of the population exposure to outdoor concentrations is strongly linked to the modeling scale. The high concentrations observed in streets are not represented by regional-scale modeling, which provides estimation of the background concentrations. However, in urban areas the people exposure to outdoor concentrations corresponds to street-scale concentrations, which are often more influenced by traffic than regional-scale concentrations [23].

This study aims to assess the maximum impact on air quality that can be expected from improvements in vehicle pollutant emission technology. This impact is assessed in terms of concentrations of NO_2, $PM_{2.5}$, BC, OM down to the street scale in the Paris area. To that end, very-low-emission vehicles are introduced in the traffic fleet, and the evolution of emissions from all activity sectors are taken into account. The exhaust emission factors of these very-low-emission vehicles are even lower than those proposed for the European emission standard Euro 7. The impact is estimated for the year 2030 on the Paris region and in the streets of a district in the eastern suburb of Paris. The concentrations are compared with those simulated for the year 2014, and to regulatory standards.

Section 2 introduces the emission factors related to the very-low-emission vehicles, as well as the two prospective scenarios and their impacts on fleet composition. The evolution of emissions related to the different activity sectors and to the two scenarios are presented in Sect. 3. Finally, the impacts of the scenarios on concentrations are discussed in Sect. 4.

2 Evolution of vehicle technology and fleet composition

The baseline simulation for year 2014, named 2014b, corresponds to the reference simulation, SCN0 of [30]. 2014 is established as the baseline in this study due to the availability of observational data both at regional and local scales, and also to the extensive evaluation of the models' performances [18, 19, 24, 25, 29, 30]. It uses the COPERT methodology, described in the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook [13] to calculate traffic emissions in streets. The emission factors and fleet evolution are presented below, following the nomenclature of the methodology for vehicles categories and European emission standards.

2.1 Emissions from very-low-emission vehicles

Table 1 presents the emission factors at exhaust for the very-low-emission vehicles used in this study. For passenger cars (PC) and light commercial vehicles (LCV), the emission factors for carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and ammonia (NH_3) are set to 50 % of the limit values proposed for the European emission standard Euro 7 (see Table 1). NO_x emission factors for PC are much lower than those proposed for the Euro 7 norm: 10 mg km^{-}1 against 60 mg km^{-}1. These very low emission factors could be obtained thanks to the improvement and addition of after-treatment devices, such as heaters, to reduce cold-start emissions in particular [8, 15]. Note that these emissions factors take into account both hot and cold emissions.

Table 1 Emission factors at exhaust for very-low-emission vehicles

	PC	LCV	HDV	Lcat
CO	250 mg km^{-1}[a]	250 mg km^{-1}[a]	50 % Euro VI	50 % Euro 5
NO_x	10 mg km^{-1}	20 mg km^{-1}	50 % Euro VI	50 % Euro 5
NMVOCs	34 mg km^{-1}[a]	34 mg km^{-1}[a]	50 % Euro VI	50 % Euro 5
NH_3	10 mg km^{-1}[a]	10 mg km^{-1}[a]	50 % Euro VI	50 % Euro 5
PM	100 % Euro 6	100 % Euro 6	100 % Euro VI	100 % Euro 5

[a] 50 % of the European emission standard Euro 7 proposal

For heavy-duty vehicles (HDV) and two-wheelers (Lcat), the emission factors of CO, NO_x, NMVOCs and NH_3 of the very-low-emission vehicles are set to 50 % of the most recent European emission standards (Euro VI for HDV and Euro 5 for Lcat). These values are also based on the improvement and addition of after-treatment devices. Concerning PM, emission factors for the very-low-emission vehicles are identical to the emission factors of the most recent emission standards for the corresponding vehicle category.

Emissions factors from non-exhaust sources (tyre and brake wear, and road abrasion) are computed using the values provided by the COPERT methodology. Despite their high uncertainties [17, 20, 25, 30], non-exhaust emissions are not expected to change much compared to current emission levels, unless mobility changes. Concerning the speciation of the emissions of NO_x, NMVOC and PM, in the absence of information specific to future vehicles, information provided by the COPERT methodology for the most recent emission standards is used.

2.1.1 Prospective scenarios and fleet evolution

Two scenarios of the fleet evolution are considered, one with a realistic evolution of the fleet (2030r with r for "realistic fleet") and one with a theoretical fleet made of only very-low-emission and electric vehicles (2030t with t for "theoretical fleet"). The second scenario is introduced to assess the maximum emission and concentration reductions.

The 2030r scenario is representative of a gradual evolution of the fleet, assuming a replacement of the oldest vehicles by newer vehicles, also considering electric vehicles. This fleet evolution is modeled using SIBYL baseline [14]. It is a projection tool for estimating vehicle fleet for 37 European countries based on historical data. In this study, the penetration rates of new vehicles are corrected for the years 2021 and 2022 using information from the European automobile manufacturers' association (ACEA) [1, 2]. In the 2030t scenario, the fleet is only composed of the most recent vehicles with very low emissions, and electric vehicles.

Table 2 presents the distribution of PC and LCV according to European emission standards and electric motorisation. For the other vehicle categories, the distributions are available in Table S2. The fleet for the 2014b baseline simulation is representative of the year 2014, thus Euro 6 a/b/c is the most recent emission standard for PC, but represents only 2 % of the category. More than 4 % are pre-Euro and Euro 1, and the majority falls into Euro 4 and Euro 5 standards, at 28 % and 42 % respectively. Electric vehicles represent less than 1 % of the PC. Concerning LCV, a similar trend is observed, with about 4 % of the vehicles being pre-Euro and Euro 1. The majority also falls into Euro 4 and Euro 5 standards, but with more Euro 4 than Euro 5, at 41 % and 33 % respectively.

Table 2 Distribution of PC and LCV in fleets according to European emission standards and electric motorisation, in %

		2014b	2030r	2030t
PC	Pre-Euro	1.3	-	-
	Euro 1	2.9	-	-
	Euro 2	7.2	0.6	-
	Euro 3	15.9	1.1	-
	Euro 4	28.1	8.3	-
	Euro 5	41.6	16.9	-
	Euro 6 a/b/c	2.1	18.3	-
	Euro 6 d-temp	-	6.2	-
	Euro 6 d	-	23.0	-
	VLEV[a]	-	12.3	86.8
	Electric	0.9	13.2	13.2
	Total	100	100	100
LCV	Pre-Euro	2.1	2.1×10^{-6}	-
	Euro 1	2.1	4.7×10^{-4}	-
	Euro 2	5.2	0.3	-
	Euro 3	17.1	5.4	-
	Euro 4	40.8	12.6	-
	Euro 5	32.5	16.3	-
	Euro 6 a/b/c	-	19.3	-
	Euro 6 d-temp	-	5.0	-
	Euro 6 d	-	17.0	-
	VLEV[a]	-	12.0	87.9
	Electric	0.3	12.1	12.1
	Total	100	100	100

[a] VLEV = Very-low-emission vehicles

The fleet evolution modeled in the 2030r scenario leads to the disappearance of pre-Euro and Euro 1 PC and negligible percentage of LCV vehicles. The other emission standards already present in the 2014b fleet are less represented, e.g. the percentage of Euro 5 vehicles drops from 42 % to 17 % for PC. Euro 6 d standard becomes preponderant for PC, at 23 %, while it is Euro 6 a/b/c standard at 19 % for LCV. The very-low-emission vehicles represent 12 % of the two categories and electric vehicles a higher portion for PC, at 13 %. In the 2030t fleet, it is considered that all non-electric vehicles are very-low-emission vehicles, while keeping the portion of electric vehicles similar to the 2030r scenario.

3 Evolution of emissions

At the regional scale, the domain is centered on the Île-de-France region, and a district in the eastern suburbs of Paris is defined at the street scale [30]. The meteorological conditions and biogenic emissions are taken from

[33]. They are assumed to be the same between 2014 and 2030. Anthropogenic emissions at the regional scale are computed using the EMEP gridded emission inventory for 2014 [12]. This section presents the evolution factors by activity sectors that are used to estimate the evolution of those emissions between 2014 and 2030, as well as the impacts on total emissions.

3.1 Non-traffic sectors

In order to model background concentrations consistent with year 2030, emission reductions of the non-traffic sectors are also taken into account. Table 3 presents the ratios applied to represent the emission evolution between 2030 and 2014. The majority of the evolution ratios are taken from [5] following the AME scenario ("Avec Mesures Existentes", i.e. with existing measures). This scenario, developed in 2021, projects anthropogenic emissions by activity sector to 2030, taking into account the regulations in place until December 31, 2019. Because, for some sectors, the evolution ratios for CO and NH_3 are not available in [5], those are taken as the average of the evolution ratios of NMVOC, PM and NO_x. For the emissions of NH_3 and PM from the solvent industry, ratios are extrapolated using information specific to Île-de-France region, provided by the Parisian air quality monitoring association [3]. As no information was available for the emissions from the sector "Other Stationary Combustion" (except sulfur dioxide, SO_2), it was decided to not modify these emissions.

Overall, emissions are reduced from 2014 to 2030, except for NH_3 emissions from the waste and public power sectors, which increase by 78 % and 69 % respectively. In the case of the waste sector, it is related to the quantity of waste entering the composting facilities and the degradation of livestock manure. For the public power sector, it is due to the incomplete combustion of the different energies sources, coupled with an increase in the combustion capacity. Offroad, shipping and aviation transport sectors present large reductions in emissions, especially for NO_x (70 %) and PM (62 %). Emission reductions for the agricultural sector are limited, with a maximum reduction of -15 % for CO. For the other sectors, mainly related to the industry, emissions of NO_x are PM are largely reduced, while emissions of NMVOC and NH_3 present a lower decrease.

3.2 Traffic sector

Traffic emissions and emission evolution ratios are first calculated at the street scale. Then, the influence of the prospective scenarios on reductions of traffic emissions at the regional scale is defined, using the same emission evolution ratios. Emissions of NO_x, VOCs and PM are speciated similarly to the street scale, i.e., taking into account the fraction of each vehicle type in the fleet.

At the street scale, emissions in the streets of the network are computed for both prospective scenarios using the software Pollemission [28], which estimates emissions for a detailed vehicle fleet using the COPERT methodology. The software was updated to take into account emission factors of very-low-emission vehicles. In the absence of a reliable method to estimate future traffic conditions (vehicle speed and flow), these are identical

Table 3 Emission evolution ratios for the non-traffic sectors between 2030 and 2014

Sector	CO	NO_x	NMVOCs	NH_3	PM	SO_2
Offroad	0.52[a]	0.30	0.58	0.81	0.38	0.65
Shipping	0.52[a]	0.30	0.58	0.81	0.38	0.65
Aviation	0.52[a]	0.30	0.58	0.81	0.38	0.65
Waste	0.83	0.94	0.83	1.78	0.92	0.75
Agri Livestock	0.85	0.94	0.98	0.95	0.93	1.00
Agri Other	0.85	0.94	0.98	0.95	0.93	1.00
Fugitive	0.68[a]	0.47	0.66	0.68[a]	0.91	0.43
Other Stationary Combustion	1.00[b]	1.00[b]	1.00[b]	1.00[b]	1.00[b]	0.11
Solvents	0.59[a]	0.73	0.92	0.18[c]	0.54[c]	0.84
Industry	0.59	0.60	0.70	0.66	0.38	0.52
Public Power	0.91	0.38	0.77	1.69	0.36	0.18
Other	0.62	0.39	0.47	0.84	0.46	0.41

[a] Average ratio of NMVOCs, PM and NO_x

[b] No information found

[c] Extrapolated from data of the Parisian air quality monitoring association [3]

Other ratios are taken from the AME scenario of [5]

Table 4 Emission evolution ratios for the traffic sector for the two prospective scenarios between 2030 and 2014

Scenario	CO	NO_x	NMVOCs	NH_3	PM	SO_2
2030r	0.48	0.35	0.40	0.77	0.66	0.65
2030t	0.33	0.03	0.33	0.04	0.61	0.65

Table 5 Reductions in total emissions for the two prospective scenarios compared to the baseline simulation for the Paris suburbs area. Average emissions are expressed in ng m^{-2} s^{-1}, and the relative differences is in %

	Average	Relative difference	
	2014r	2030r	2030t
NO	380.1	-57.4	-87.1
NO_2	184.9	-79.6	-96.2
NO_x	767.8	-62.7	-89.2
BC	9.2	-58.3	-63.1
$I/SVOCs_{gas}$	53.1	-74.6	-82.2

Table 6 Reductions in traffic emissions for the two prospective scenarios compared to the baseline simulation at the street scale. Average emissions are expressed in µg s^{-1}, and the relative differences are in %

	Average	Relative difference	
	2014r	2030r	2030t
NO	2727.7	-62.9	-96.5
NO_2	2067.3	-67.7	-99.5
NO_x	6249.8	-64.6	-97.5
BC	90.1	-71.6	-79.0
$I/SVOCs_{gas}$	192.3	-62.3	-71.1

to the baseline simulation, which correspond to typical urban fleet and flow for the Île-de-France region for 2014 [6]. The evolution of the fleet composition between 2014 and 2030 and the impact of introducing low-emission vehicles is detailed in Sect. 2.1.1. The emission evolution ratios observed at the street scale over the simulation period are averaged and presented in Table 4. Emissions present large reductions for both scenarios. They are particularly large for NO_x and NH_3, for which the 2030t scenario induces emission decrease as large as 97 % and 96 % respectively. For PM, the decrease is limited to less than 40 % as the majority of the emissions comes from non-exhaust sources, left identical in this study. The SO_2 emission is reduced by 35 % following the AME scenario of [5].

3.3 Impacts on total emissions

A subset of the regional domain, corresponding to the city of Paris and its outlying suburbs, where urbanization and transportation are most prominent [30], is extracted to study the prospective scenarios' impacts on emissions (hereafter referred to "Paris suburbs").

Table 5 presents the reductions in total emissions (emissions of all sectors) induced by the 2030r and 2030t scenarios at the regional scale. The gas-phase intermediate and semi volatile organic compound species (I/SVOCs) in the table are organic compounds with relatively low vapor pressure that will lead to the formation of lower-volatility compounds, partitioning more easily to particles. Both scenarios lead to significant emission reductions. In the 2030r scenario, emissions of nitric oxide (NO) and BC are reduced by around 58 %, and gas-phase I/SVOCs and NO_2 emissions by as much as 75 % and 80 % respectively. Emissions are even lower in the 2030t scenario. NO_x present the largest additional reduction, by almost 30 % for NO and 20 % for NO_2. The total emissions are reduced by 87 % and 96 % for NO and NO_2 respectively. Because PM emission factors are not reduced for very-low-emission vehicles (Table 1) and traffic is not the preponderant emitting sector, the additional reduction for BC is only 5 % and for I/SVOCs, the additional reduction is around 10 %.

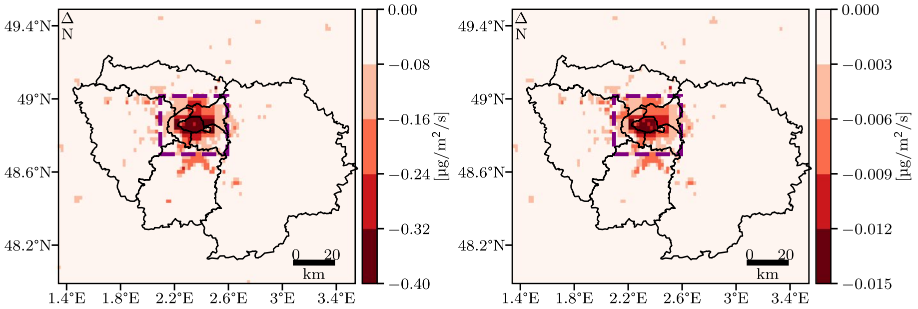
Table 6 presents the reductions in traffic emissions induced by the 2030r and 2030t scenarios at the street scale, where only traffic emissions are taken into account. As at the regional scale, both scenarios lead to significant emission reductions. Overall, the reductions tend to be larger at the street scale, especially in the 2030t scenario where only very-low emission and electric vehicles are considered. In the 2030r scenario, although the emission reduction is larger for NO_2 at the regional scale than at the street scale (-80 % against -68 %), the opposite it observed for NO (-57 % against -63 %), because of the different NO_2 fraction at regional scale induced by the non-traffic sectors. At the street scale, reductions observed in the 2030r scenario are only due to the replacement of the oldest vehicles by new ones, with lower emissions. The reductions from the 2030t scenario are larger than the ones from the 2030r scenario. This is expected as only the most recent vehicles, i.e. with the lowest emissions, are considered in the 2030t scenario. This leads to large reduction of

NO_x emissions: the additional reductions are larger than 30 %, with reductions of 97 %, 98 % to 99.5 % for NO, NO_x and NO_2 respectively compared to the 2014 baseline. For BC, the additional reductions induced by the 2030t scenario are limited, as non-exhaust emissions are not reduced.

The absolute differences in emissions of NO_2 and BC over the whole simulation domain for the 2030r scenario compared to the baseline are presented in Fig. 1. For the 2030t scenario, absolute differences present similar behaviors, with larger values (see Figure S1). The reductions are the largest where traffic is the most important: in Paris city and its outlying suburbs (purple rectangle on Fig. 1), with reductions up to 0.4 μg m−2 s^{-1} and 0.015 μg m−2 s^{-1} for NO_2 and BC emissions. In the 2030t scenario, emissions of NO_2 and BC are reduced by up to 0.45 μg m−2 s^{-1} and 0.015 μg m−2 s^{-1} respectively. Note that absolute differences are used here instead of relative differences because emissions in rural areas of the domain are extremely low, resulting in meaningless relative differences in these areas.

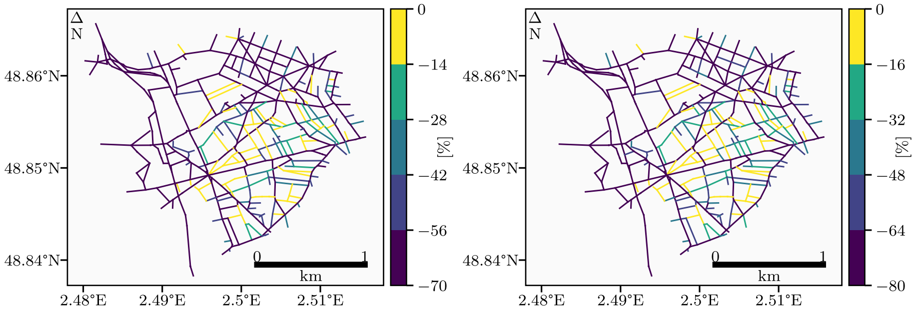
Figure 2 presents the relative differences in emissions of NO_2 and BC over the street network for the 2030r scenario. For the 2030t scenario, relative differences present similar behaviors, with larger values (see Figure S3). Emissions in the streets with high traffic are greatly reduced: by 70 % and 75 % for NO_2 and BC emissions respectively. In the 2030t scenario, emissions of NO_2 and BC are reduced up by to 90 % and 85 % respectively. On the contrary, streets with no traffic are not affected. The variability between trafficked streets is due to the variability of the vehicle types in the fleet.

Despite the different reductions applied to the emission sectors from 2014 to 2030 at the regional scale, the fraction of PM emissions attributed to road traffic remains relatively constant at 24 % between the 2014b baseline scenario and the 2030r scenario. For the 2030t scenario, it is reduced to 22 % of the total PM emissions. Table 7 highlights the increasing importance of the non-exhaust emissions compared to the exhaust ones. In the 2014b baseline scenario, non-exhaust sources are already preponderant, contributing to 59 % of the traffic PM



(a) (b)

Fig. 1 Absolute differences (in μg m−2 s^{-1}) in emissions of NO_2 (**a**) and BC (**b**) at the regional scale for the 2030r scenario compared to the baseline. The annual mean emissions of the baseline simulation are available in Figure S2. The purple rectangle represents the most urbanised area of the domain, Paris city and its suburbs



(a) (b)

Fig. 2 Relative differences (in %) in emissions of NO_2 (**a**) and BC (**b**) at the street scale for the 2030r scenario. The annual mean emissions of the baseline simulation are available in Figure S4

Table 7 Distributions (in %) of the traffic emissions for the baseline scenario and the two prospective scenarios at regional and local scales

Traffic emission sources		2014b	2030r	2030t
Exhaust		41	11	3
Non-exhaust	Brake wear	25	38	42
	Tyre wear	18	27	28
	Road abrasion	16	24	27

emissions. Brake-wear emissions are the most important, 25 %, followed by tyre-wear and road-abrasion emissions at 18 % and 16 % respectively. 89 % and 97 % of the traffic PM emissions are attributed to non-exhaust sources in the 2030r and 2030t scenarios respectively. Brake-wear source remain the main contributor, at 38 % and 42 % respectively for both prospective scenarios, followed by tyre-wear and road-abrasion sources.

4 Impacts on concentrations

This section presents the impacts of the scenarios on concentrations at both the regional and street scales. The evaluation of the multiscale modelling chain against observations for the 2014b baseline simulation is available in [30]. As for emissions, the impacts at the regional scale are studied on a subset of the domain corresponding to Paris city and its suburbs (purple rectangle on Fig. 1), and also to Paris city alone (green rectangle on Fig. 4) for the impacts on dense traffic areas. The concentrations presented at the regional scale are surface concentrations, i.e., they correspond to those simulated in the first vertical level of the domain (from 0 m to 30 m).

4.1 Modelling tools

Polair3D [26, 32] is used to simulate background concentrations at the regional scale with a horizontal resolution of 0.02°×0.02°. Concentrations in the streets of the network are simulated with the street-network MUNICH [18]. The simulation periods are from 8 January to 27 December 2014 for the regional scale, and 10 January to 27 December 2014 for the street scale. Both models are coupled to the chemistry and aerosol model SSH-aerosol [31] to represent gas-phase chemistry and aerosol dynamics.

Boundary and initial conditions are taken from [33]. Meteorological conditions are modeled using the WRF model (version 3.9.1.1), as detailed in [24]. Boundary, initial conditions and meteorology are kept the same in the reference and in the prospective scenarios.

Table 8 Impacts of the prospective scenarios on NO_2 and PM_{10} concentrations over the Paris suburbs and Paris city areas, and at the street scale. Average concentrations are expressed in $\mu g\ m^{-3}$ and relative differences in %

NO_2		2014b	2030r	2030t
Polair3D	Average	28.2	14.3	7.7
Paris suburbs	Relative difference	-	-49.8	-72.6
Polair3D	Average	45.8	24.6	13.7
Paris city	Relative difference	-	-46.5	-70.2
MUNICH	Average	49.9	23.4	9.6
	Relative difference	-	-52.5	-79.4
PM_{10}		2014b	2030r	2030t
Polair3D	Average	16.6	14.6	14.3
Paris suburbs	Relative difference	-	-11.4	-13.7
Polair3D	Average	19.8	16.3	15.7
Paris city	Relative difference	-	-17.8	-20.5
MUNICH	Average	20.1	16.3	15.7
	Relative difference	-	-17.9	-20.9
$PM_{2.5}$		2014b	2030r	2030t
Polair3D	Average	15.5	13.7	13.3
Paris suburbs	Relative difference	-	-11.6	-14.0
Polair3D	Average	18.1	14.8	14.2
Paris city	Relative difference	-	-18.4	-21.3
MUNICH	Average	18.7	15.1	14.4
	Relative difference	-	-18.6	-21.9

4.2 Regulated pollutants

This section presents the evolution of the concentrations of NO_2, PM_{10} and $PM_{2.5}$ in the Paris area, which are regulated by European air quality directives [11]. The European air quality standards for the annual average limits are 40 $\mu g\ m^{-3}$ for NO_2 and PM_{10}, and 25 $\mu g\ m^{-3}$ for $PM_{2.5}$. The air quality guidelines from the WHO are more stringent, with annual average limits of 10 $\mu g\ m^{-3}$ for NO_2, 15 $\mu g\ m^{-3}$ for PM_{10} and 5 $\mu g\ m^{-3}$ for $PM_{2.5}$.

Table 8 and Fig. 3 present the average concentrations and relative differences for the two prospective scenarios compared to the baseline simulation for NO_2, PM_{10} and $PM_{2.5}$. The average concentrations are lower in the Paris suburbs area than in the Paris city area and the street scale. This is particularly true for NO_2 (28 $\mu g\ m^{-3}$ against 46 $\mu g\ m^{-3}$ and 50 $\mu g\ m^{-3}$ respectively). This is because the Paris suburbs area includes districts less urbanized than the city.

In the two prospective scenarios, the concentrations at both the regional and street scales decrease, because of the decrease of emissions. For NO_2, in the Paris suburbs, the emission reductions of 80 % and 96 % for the 2030r and 2030t scenarios respectively lead to reductions in concentrations of 50 % and 73 %. In the Paris city, the concentration reductions are slightly lower,

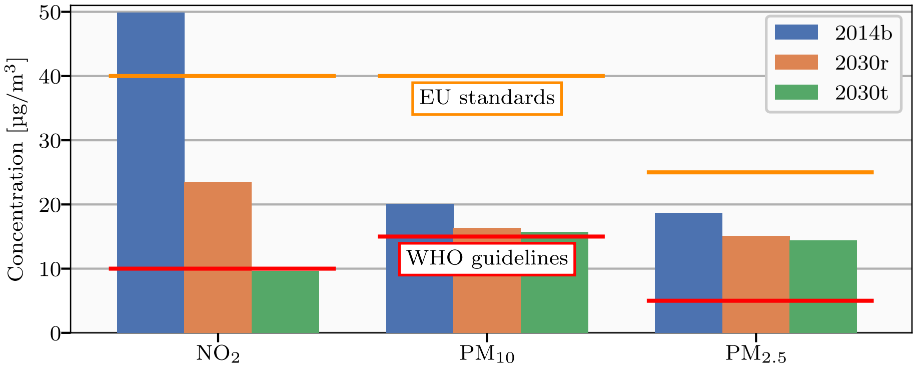
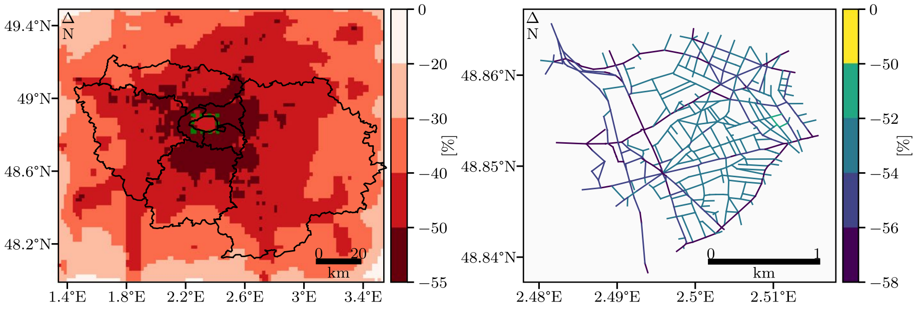
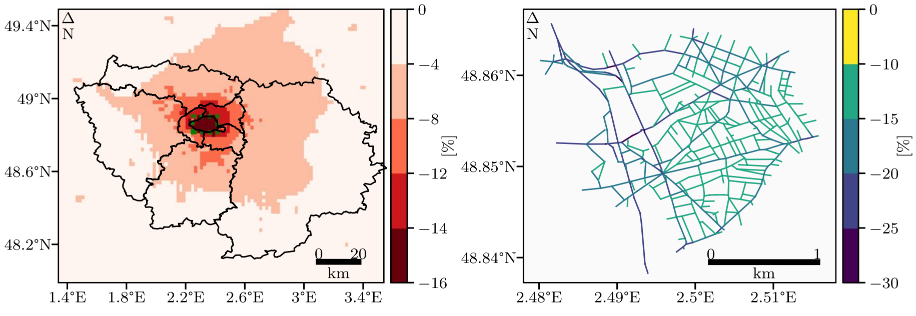


Fig. 3 Annual average concentrations of NO_2, PM_{10} and $PM_{2.5}$ for three scenarios at street scale. Orange and red lines represent European Union standards and WHO guidelines respectively



(a) Regional scale, NO_2 concentrations (b) Street scale, NO_2 concentrations



(c) Regional scale, PM_{10} concentrations (d) Street scale, PM_{10} concentrations

Fig. 4 Relative differences in concentrations of NO_2 (top panels) and PM_{10} (bottom panels) for the 2030r scenario at the regional scale (left panels) and street scale (right panels). The relative differences for the 2030t scenario are available in Figure S5 and the annual average concentrations for the baseline simulation are available in Figures S7 and S8. The green rectangle represents Paris city

at 47 % and 70 % respectively, but they correspond to higher absolute concentrations, e.g. 25 µg m^{-3} versus 14 µg m^{-3} for the 2030r scenario. At the street scale, the concentration reductions are more important at 53 % and 79 % for the 2030r and 2030t scenarios respectively, because of the predominance of the traffic and large traffic emission reductions for both scenarios (by 68 % and 99.5 %). Compared to the NO_2 level from the air-quality guidelines, for both scenarios, both the regional and street scale concentrations are lower than the limit value of 40 µg m^{-3} imposed by the European air quality directives. The WHO guideline of 10 µg m^{-3} for NO_2 is only met in the 2030t scenario on average over the Paris suburb area (average concentration of 7.7 µg m^{-3}) and the street network domain (average concentration of 9.6 µg m^{-3}). However, the street network studied is located in the Paris suburbs, but outside the city of Paris itself. Over Paris city, the average NO_2 concentration is slightly larger than the WHO guideline (13.7 µg m^{-3}).

As expected, since PM emissions are less reduced than NO_x, concentrations of PM_{10} and $PM_{2.5}$ are less reduced than NO_2 concentrations. In the Paris suburbs, PM_{10} concentrations are reduced by 11 % and 14 % for the 2030r and 2030t scenarios respectively, and by 18 % and 21 % for the Paris city area and the street scale. The decrease of $PM_{2.5}$ concentrations is slightly more important than PM_{10}, reaching 19 % and 22 % at the street scale. Concentrations of PM_{10} at the street scale for both scenarios are just above the WHO guideline of 15 $\mu g\ m^{-3}$, at 16 $\mu g\ m^{-3}$ for both scenarios. For $PM_{2.5}$, concentrations remain much larger than the WHO guideline of 5 $\mu g\ m^{-3}$, at 15.1 $\mu g\ m^{-3}$ and 14.4 $\mu g\ m^{-3}$ respectively. When considering the limit values imposed by the European air quality directives for PM_{10} (40 $\mu g\ m^{-3}$) and $PM_{2.5}$ (25 $\mu g\ m^{-3}$), concentrations of the 2014b baseline simulation are already in accordance, at 20 $\mu g\ m^{-3}$ and 19 $\mu g\ m^{-3}$ respectively. With exhaust emissions of PM already well regulated and controlled, the focus should be to better understand and reduce non-exhaust emissions from tyre and brake wear, and road abrasion to respect the more stringent WHO guidelines.

The impacts of the 2030r scenario on the concentrations of NO_2 and PM_{10} on the regional domain and the street network are presented in Fig. 4. The impacts of the 2030t scenario are similar to the 2030r scenario but with higher reductions (see Figure S5). At the regional scale, although NO_2 concentrations are reduced throughout the domain, the reductions are the highest in the most urbanized areas of the Paris area. This is due to the larger traffic emissions in the most urbanized areas, and to the assumption of keeping the same boundary conditions in the 2014 and 2030 simulations. For PM_{10}, concentration reductions are limited outside the city of Paris and its suburbs. The reductions are lower than for NO_2, with maximum reduction of 55 % and 16 % for NO_2 and PM_{10} respectively. At the street scale, concentrations reductions are larger than at the regional scale, particularly for streets with high traffic. These reductions reach 58 % and 30 % for NO_2 and PM_{10} respectively.

The 2030r scenario can be compared to the 2-BAU ("business-as-usual") scenario of [23]. The 2-BAU scenario simulates concentrations for 2024 with a fleet evolution from 2014 to 2024 promoting Euro 5 and Euro 6 petrol vehicles. The evolution of NO_2, PM_{10} and $PM_{2.5}$ is similar in 2-BAU and the 2030r scenario. The 6 years difference between 2024 and 2030 and the introduction of the very-low-emission vehicles in the fleet in the 2030r scenario induce slightly larger reductions of the concentrations of NO_2 compared to the 2-BAU scenario: 53 % against 38 %. For PM_{10}, the reduction is slightly more important in the 2-BAU scenario than in the 2030r scenario: 22 % against 18 %. For $PM_{2.5}$, reductions are very similar, at 19 %, in both scenarios. These differences on PM_{10} could be due to the different street networks considered in the two studies. In the 2-BAU scenario of [23], MUNICH represents the concentrations over the city of Paris, while, in this study, it represents a district in the eastern suburbs of Paris. The city of Paris is much more urbanized and the influence of traffic is thus greater.

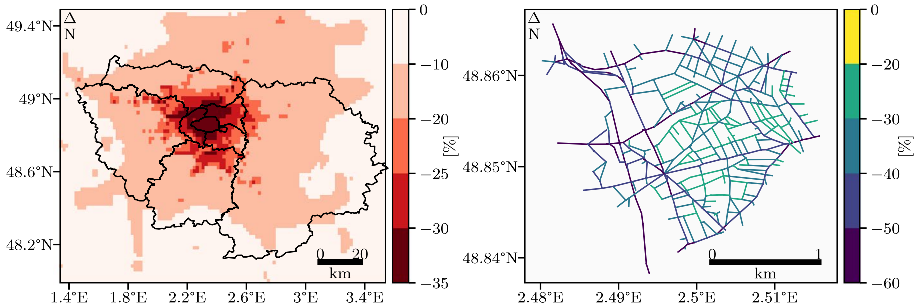
4.3 Non-regulated pollutants

BC and OM are compounds of particles that are known to have negative effects on the human health, and that are emitted by traffic. The impacts of the prospective scenarios on BC and OM concentrations are thus presented in Table 9. The reductions for these two pollutants are larger than the ones for PM_{10} and $PM_{2.5}$. The BC emission reduction of 58 % at the regional scale for the 2030r scenario induces reductions of BC concentrations by 30 % and 35 % for the Paris suburbs and Paris city. For the 2030t scenario, the emission reduction of 63 % induces slightly larger concentration reductions, by 32 % and 38 % respectively. At the street scale, reductions in BC concentrations reach 42 % and 45 % for the 2030r and 2030t scenarios respectively. Concerning the OM concentrations, the differences in reduction between the two scenarios are limited to 2 % maximum. For the Paris suburbs area, reductions are around 17.5 %, while they almost double for Paris city, around 31 %. At the street scale, concentration and reductions are very similar to Paris city, with 4 $\mu g\ m^{-3}$ and around 31 % of reduction.

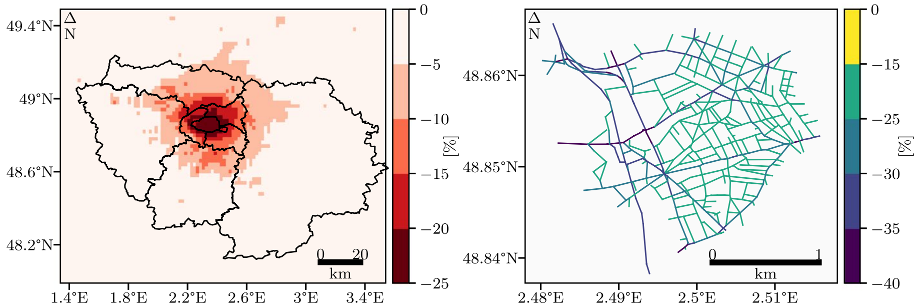
The impacts of the 2030r scenario on the concentrations of BC and OM on the regional domain and the street network are presented in Fig. 5. The impacts of

Table 9 Impacts of the prospective scenarios on BC and OM concentrations over the Paris suburbs and Paris city, and at the street scale. Average concentrations are expressed in $\mu g\ m^{-3}$ and relative differences are in %

BC		**2014b**	**2030r**	**2030t**
Polair3D	Average	0.7	0.5	0.5
Paris suburbs	Relative difference	-	-29.9	-32.1
Polair3D	Average	1.1	0.7	0.7
Paris city	Relative difference	-	-35.0	-37.7
MUNICH	Average	1.5	0.8	0.7
	Relative difference	-	-41.5	-45.2
OM		2014b	2030r	2030t
Polair3D	Average	4.6	3.8	3.8
Paris suburbs	Relative difference	-	-17.1	-17.7
Polair3D	Average	5.9	4.1	4.0
Paris city	Relative difference	-	-30.1	-31.5
MUNICH	Average	5.9	4.1	3.9
	Relative difference	-	-30.1	-32.1



(a) Regional scale, BC concentrations (b) Street scale, BC concentrations



(c) Regional scale, OM concentrations (d) Street scale, OM concentrations

Fig. 5 Relative differences in concentrations of BC (top panels) and OM (bottom panels) for the 2030r scenario at the regional scale (left panel) and street scale (right panel). The relative differences for the 2030t scenario are available in Figure S6 and the annual average concentrations for the baseline simulation are available in Figures S9 and S10

the 2030t scenario are similar to the 2030r scenario, but with higher reductions (see Figure S6). The distributions of BC and OM concentrations at the regional scale are similar to that of BC emissions (Fig. 2). The most significant reductions take place in the most urbanized areas of the Paris area while rural areas are less impacted. As for NO_2, this may be due to the low influence of traffic in rural areas and to the setup of the boundary conditions. The reductions reach 35 % and 25 % for BC and OM respectively. At the street scale, the concentration reductions are overall larger than at the regional scale, except for streets with low to no traffic. On the opposite, streets with high traffic present the highest reductions, up to 60 % for BC and 40 % for OM.

Compared to the 2-BAU scenario of [23], the reduction of the BC concentrations in the 2030r scenario is slightly lower, at 42 % against 48 %. As for PM, this difference can be linked to the different street networks and greater influence of traffic in the 2-BAU scenario, but also to the higher tyre-wear emission factors considered in [23]. For OM concentrations, the influence of the background concentrations, with emission reductions from all the activity sectors in this study, leads to a larger reduction in the 2030r scenario than in the 2-BAU scenario, at 30 % against 24 %.

5 Conclusions

Air quality for the emissions levels of the year 2030 has been simulated over the Paris area with two prospective scenarios, taking into account the introduction of very-low-emission vehicles in the fleet. Emission factors for these vehicles were defined based on the development of technologies, such as heaters, to reduce cold-start emissions in particular, and they are lower than those postulated for the forthcoming European emission standard Euro 7. The evolution of the fleet composition was modeled to replace the older vehicles by more recent, and less emitting, vehicles. Reductions of the emissions for all activity sectors were considered to simulate regional-scale concentrations consistent with the simulated year.

In the first scenario, representative of a gradual evolution of the fleet, NO_2 emissions are reduced by 80 % and 68 % at the regional and street scales respectively. However, the impacts on the concentrations are limited to 53 % at the street scale. Concentrations of PM_{10} and $PM_{2.5}$ are reduced by only 18 % at both scales, as traffic exhaust emissions are not the main source of PM. When looking into the concentrations of BC and OM, reductions are larger, up to 42 % and 30 % respectively on average at the street scale. Despite these reductions, concentration are still superior to the WHO guidelines, particularly for $PM_{2.5}$, while satisfying the less stringent European air quality directives.

The second scenario, composed only of very-low-emission and electric vehicles, presents larger reductions than the first scenario for all pollutants. NO_2 and BC emissions are reduced by up to 99.5 % and 79 %. The NO_2 concentrations at the street scale thus decrease by almost 80 %, allowing the WHO guidelines to be met over most of the Paris region and in the studied street network. NO_2 concentrations in Paris city are still slightly higher than the WHO guidelines (13.7 $\mu g\ m^{-3}$ for 10 $\mu g\ m^{-3}$). Concentrations of PM_{10} and $PM_{2.5}$ are less impacted than NO_2 (-22 % at the street scale) and do not meet the WHO guidelines, while being close to for the PM_{10}. The European air quality directives are met for NO_2 and PM. BC and OM concentrations are slightly more impacted than PM, with a reduction of 45 % and 32 % respectively.

This study shows that the development of new vehicles, with more efficient technologies to reduce exhaust emissions, is important for improving air quality in cities and streets. Considering only the evolution of the exhaust emissions in this study induced large reductions of the concentrations of NO_2 while having a limited impact on PM concentrations. The focus should now be to study the importance of the non-exhaust emissions (tyre and brake wear, and road abrasion) to reduce PM emissions from traffic.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12544-024-00660-2.

Additional file 1. The file "SupplementaryMaterials.docx" contains additional information about the fleet compositions and impacts of the prospective scenarios on pollutant emissions and concentrations.

Acknowledgements
Not applicable.

Authors' contributions

TS: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. CC: Conceptualization, Methodology, Resources, Funding acquisition, Writing – review & editing. YR: Conceptualization, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CL: Conceptualization, Methodology, Resources, Writing – review & editing. SEW: Methodology, Resources, Writing – review & editing. KS: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding
Not applicable.

Availability of data and materials

Data and materials will be made available on request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 9 November 2023 Accepted: 24 May 2024

References

1. ACEA (2022). Fuel types of new cars: battery electric 11.9 %, hybrid 22.6 % and petrol 37.8 % market share in q3 2022.
2. ACEA (2022). Fuel types of new passenger cars in the EU.
3. Airparif (2023). Les émissions.
4. Ali, M. U., Siyi, L., Yousaf, B., Abbas, Q., Hameed, R., Zheng, C., Kuang, X., & Wong, M. H. (2021). Emission sources and full spectrum of health impacts of black carbon associated polycyclic aromatic hydrocarbons (pahs) in urban environment: A review. *Critical Reviews in Environmental Science and Technology, 51*(9), 857–896.
5. Allemand, N., Andre, J., Bongrand, G., Cuniasse, B., Durand, A., Mazin, V., & Vieira da Rocha, T. (2021). Scénarios prospectifs d'émissions de polluants atmosphériques pour la france de 2020 á 2050 par intervalle de 5 ans selon un scénario ame et un scénario ams, sur la base du scénario énergie climat ame 2021. Technical report, Centre interprofessionnel technique d'études de la pollution atmosphérique (CITEPA).
6. André, M., Sartelet, K., Moukhtar, S., André, J. M., & Redaelli, M. (2020). Diesel, petrol or electric vehicles: what choices to improve urban air quality in the ile-de-france region? a simulation platform and case study. *Atmospheric Environment, 241*, 117752.
7. Chen, C., McCabe, D. C., Fleischman, L. E., & Cohan, D. S. (2022). Black carbon emissions and associated health impacts of gas flaring in the united states. *Atmosphere, 13*(3):385.
8. Clenci, A., Berquez, J., Stoica, R., Niculescu, R., Cioc, B., Zaharia, C., & Iorga-Simăn, V. (2022). Experimental investigation of the effect of an afterburner on the light-off performance of an exhaust after-treatment system. *Energy Reports, 8*, 406–418. Technologies and Materials for Renewable Energy, Environment and Sustainability.
9. Daellenbach, K. R. e. a. (2020). Sources of particulate-matter air pollution and its oxidative potential in europe. *Nature, 587*(7834), 414–419.
10. Dons, E., Int Panis, L., Van Poppel, M., Theunis, J., & Wets, G. (2012). Personal exposure to black carbon in transport microenvironments. *Atmospheric Environment, 55*, 392–398.
11. EEA (2023). Air quality in europe 2022. EEA Report no. 05/2022, European Environment Agency.
12. EMEP (2023). Grid emissions in 0.1° ×0.1° long-lat resolution.
13. EMEP/EEA (2019). EMEP/EEA air pollutant emission inventory guidebook 2019. EEA Report No 13/2019, European Environment Agency.
14. EMISIA (2023). Vehicle fleet, activity, emissions and energy consumption projections for the eu 27 member states.
15. Gao, J., Tian, G., Sorniotti, A., Karci, A. E., & Di Palo, R. (2019). Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. *Applied Thermal Engineering, 147*, 177–187.
16. Holnicki, P., Nahorski, Z., & Kałuszko, A. (2021). Impact of vehicle fleet modernization on the traffic-originated air pollution in an urban area - a case study. *Atmosphere, 12*(12):1581.
17. Jeong, C. H., Wang, J. M., Hilker, N., Debosz, J., Sofowote, U., Su, Y., Noble, M., Healy, R. M., Munoz, T., Dabek-Zlotorzynska, E., Celo, V., White, L., Audette, C., Herod, D., & Evans, G. J. (2019). Temporal and spatial variability of traffic-related pm2.5 sources: Comparison of exhaust and non-exhaust emissions. *Atmospheric Environment, 198*, 55–69.
18. Kim, Y., Lugon, L., Maison, A., Sarica, T., Roustan, Y., Valari, M., Zhang, Y., André, M., & Sartelet, K. (2022). Munich v2.0: a street-network model coupled with ssh-aerosol (v1.2) for multi-pollutant modelling. *Geoscientific Model Development, 15*(19), 7371–7396.
19. Kim, Y., Wu, Y., Seigneur, C., & Roustan, Y. (2018). Multi-scale modeling of urban air pollution: development and application of a Street-in-Grid model (v1.0) by coupling MUNICH (v1.0) and Polair3D (v1.8.1). *Geoscientific Model Development, 11*(2), 611–629.
20. Lawrence, S., Sokhi, R., Ravindra, K., Mao, H., Prain, H. D., & Bull, I. D. (2013). Source apportionment of traffic emissions of particulate matter using tunnel measurements. *Atmospheric Environment, 77*, 548–557.
21. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature, 525*(7569), 367–371.

22. Li, N., Friedrich, R., & Schieberle, C. (2022). Exposure of individuals in europe to air pollution and related health effects. *Frontiers in Public Health, 10*.
23. Lugon, L., Kim, Y., Vigneron, J., Chrétien, O., André, M., André, J. M., Moukhtar, S., Redaelli, M., & Sartelet, K. (2022). Effect of vehicle fleet composition and mobility on outdoor population exposure: A street resolution analysis in paris. *Atmospheric Pollution Research, 13*(5), 101365.
24. Lugon, L., Sartelet, K., Kim, Y., Vigneron, J., & Chrétien, O. (2020). Nonstationary modeling of no2, no and nox in paris using the street-in-grid model: coupling local and regional scales with a two-way dynamic approach. *Atmospheric Chemistry and Physics, 20*(13), 7717–7740.
25. Lugon, L., Vigneron, J., Debert, C., Chrétien, O., & Sartelet, K. (2021). Black carbon modeling in urban areas: investigating the influence of resuspension and non-exhaust emissions in streets using the street-in-grid model for inert particles (sing-inert). *Geoscientific Model Development, 14*(11), 7001–7019.
26. Mallet, V., Quélo, D., Sportisse, B., Ahmed de Biasi, M., Debry, E., Korsakissok, I., Wu, L., Roustan, Y., Sartelet, K., Tombette, M., & Foudhil, H. (2007). Technical Note: The air quality modeling system Polyphemus. *Atmospheric Chemistry and Physics, 7*(20), 5479–5487.
27. Roustan, Y., Pausader, M., & Seigneur, C. (2011). Estimating the effect of on-road vehicle emission controls on future air quality in Paris. *France. Atmospheric Environment, 45*(37), 6828–6836.
28. Sarica, T. (2021). Pollemission: computational tool for air pollutant emission factors from traffic (2.0). Zenodo. https://doi.org/10.5281/zenodo.5721253.
29. Sarica, T., Maison, A., Roustan, Y., Ketzel, M., Jensen, S. S., Kim, Y., Chaillou, C., & Sartelet, K. (2023). Modelling concentration heterogeneities in streets using the street-network model munich. *Geoscientific Model Development, 16*(17), 5281–5303.
30. Sarica, T., Sartelet, K., Roustan, Y., Kim, Y., Lugon, L., Marques, B., D'Anna, B., Chaillou, C., & Larrieu, C. (2023). Sensitivity of pollutant concentrations in urban streets to asphalt and traffic-related emissions. *Environmental Pollution, 332*, 121955.
31. Sartelet, K., Couvidat, F., Wang, Z., Flageul, C., & Kim, Y. (2020). Ssh-aerosol v1.1: A modular box model to simulate the evolution of primary and secondary aerosols. *Atmosphere, 11*(5):525.
32. Sartelet, K., Kim, Y., Couvidat, F., Merkel, M., Petäjä, T., Sciare, J., & Wiedensohler, A. (2022). Influence of emission size distribution and nucleation on number concentrations over greater paris. *Atmospheric Chemistry and Physics, 22*(13), 8579–8596.
33. Sartelet, K., Zhu, S., Moukhtar, S., André, M., André, J. M., Gros, V., Favez, O., Brasseur, A., & Redaelli, M. (2018). Emission of intermediate, semi and low volatile organic compounds from traffic and their impact on secondary organic aerosol concentrations over greater paris. *Atmospheric Environment, 180*, 126–137.
34. Tang, J., McNabola, A., Misstear, B., Pilla, F., & Alam, M. S. (2019). Assessing the impact of vehicle speed limits and fleet composition on air quality near a school. *International Journal of Environmental Research Public Health, 16*(1):149.
35. Xia, T., Nitschke, M., Zhang, Y., Shah, P., Crabb, S., & Hansen, A. (2015). Traffic-related air pollution and health co-benefits of alternative transport in adelaide, south australia. *Environment International, 74*, 281–290.
36. Zhang, X., Fung, J. C. H., Zhang, Y., Lau, A. K. H., Leung, K. K. M., & Huang, W. (2020). Assessing pm2.5 emissions in 2020: The impacts of integrated emission control policies in china. *Environmental Pollution, 263*, 114575.

Publisher's Note