



Research Paper



Real driving emissions of cars, buses and trucks determined by Plume Chasing in Czechia: Fleet screening and intercomparison with other methods

Christina Schmidt ^{a,b} , Denis Pöhler ^{a,b} , Markus Knoll ^c , Michal Vojtíšek ^{d,e} , Martin Pechout ^d , Thomas Frateur ^f , Jan Pieter Lollinga ^g, Norbert E. Ligterink ^{f,1} , Ulrich Platt ^a

^a Institute of Environmental Physics, Heidelberg University, INF 229, Heidelberg, 69120, Germany

^b Airyx GmbH, Hans-Bunte-Str. 4, Heidelberg, 69123, Germany

^c Institute of Electrical Measurement and Sensor Systems, Graz University of Technology, Inffeldgasse 33/I, Graz, 8010, Austria

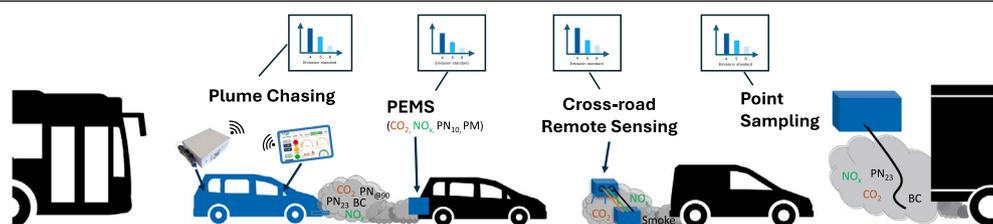
^d Department of Vehicles and Ground Transport, Czech University of Life Sciences, Kamycka 129, Praha-Suchbát, 165 21, Czech Republic

^e Department of Automotive, Combustion Engine and Railway Engineering, Czech Technical University of Prague, Technická 4, Prague, 166 07, Czech Republic

^f Department of Sustainable Transport and Logistics, TNO, The Hague, 2595 DA, The Netherlands

^g Department of Environmental Modelling, Sensing & Analysis, TNO, Utrecht, 3584 CB, The Netherlands

GRAPHICAL ABSTRACT



HIGHLIGHTS

- NO_x, NO₂, BC, PN emissions from several hundred LDVs, buses and trucks measured.
- 3–17% (BC, PN) and 16–28% (NO_x, NO₂) of dirtiest vehicles cause 50% of emissions.
- Downhill sections and high emitters in front/oncoming negatively influence results.
- Instruments to measure PN in Plume Chasing setups have to be selected carefully.
- Plume Chasing is more representative than a single remote sensing measurement.

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ABSTRACT

Real world NO_x, particle number (PN) and black carbon (BC) emission factors of light duty vehicles (LDVs), trucks, and city buses were investigated using Plume Chasing. The study was conducted in Czechia, focusing on the capital city of Prague. In total 402 distinct LDVs, 66 city buses and 948 trucks were measured. We found that 50% of the emissions come from 3–28% of the dirtiest vehicles, depending on pollutants, vehicle category and fuel. The most pronounced are BC emissions from diesel cars with just 3% of cars responsible for 50% of emissions. In this study, for the first time, different remote emission sensing techniques were compared with Plume Chasing in real urban driving. To achieve this, Plume Chasing measurements were performed at locations where Point Sampling and cross-road remote emission sensing (OPUS-RSE) were co-located. In addition, comparisons with Portable Emission Measurement Systems (PEMS) were performed for three different

* Corresponding author at: Institute of Environmental Physics, Heidelberg University, INF 229, Heidelberg, 69120, Germany.

E-mail address: cschmidt@iup.uni-heidelberg.de (C. Schmidt).

¹ currently at Dutch Human Environment and Transport Inspectorate.

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test LDVs and the three different remote emission sensing methods in real urban traffic. The comparison between the three different remote emission sensing techniques gives similar average emission factors for the three test vehicles and for the measured fleet. However, for individual measurements the emission factors can differ quite strongly. The individual Plume Chasing measurements deviate the least from PEMS results, likely because the measurement interval is longer when following the vehicle through different sections of road and engine states. For Plume Chasing, different recommendations are made based on the PEMS comparison, such as excluding downhill sections or sections with high emitting vehicles in front of the chased vehicle or in oncoming traffic.

1. Introduction

Nitrogen Oxides (NO_x) and Particulate Matter (PM) emissions from road vehicles remain a significant contributor to poor air quality in urban areas, posing serious health risks (World Health Organization, 2021). To address this problem, increasingly strict emission regulations are being enforced worldwide. In Europe, vehicle emissions are regulated by the Euro emission standards, which are periodically updated through European Union directives that provide for the gradual introduction of increasingly more stringent standards. However, even when applying emission abatement devices such as Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR) or Diesel Particulate Filters (DPFs), not all vehicles comply with these standards under real driving conditions during their lifetime. Non-compliance can result from e.g. an insufficient emission reduction system designed by the manufacturer, from cheating (e.g. defeat devices from the manufacturer), from a defect or ageing of the system, from tampering by the owner, or from vehicle operation conditions not covered by the regulation. Defective vehicles often emit several times higher levels of pollutants than vehicles with properly functioning emission reduction systems. Although these defective vehicles make up only a small fraction (<20%) of the fleet, they are responsible for the majority of the total fleet emissions (Ježek Brecelj et al., 2025; Olin et al., 2023). Identifying and addressing the emissions from these vehicles is crucial for improving air quality. Currently, emissions from the entire fleet are primarily tested during periodic technical inspections (PTIs). Although PTIs can be efficient if implemented correctly, they do not cover the emission of pollutants such as NO_x, and in most countries they also do not cover particle number (PN). Furthermore, they can potentially be circumvented, and PTI cannot provide any information on emissions during real-world driving. The current implementation of in-service conformity tests measures real driving emissions (RDE) using portable emission measurement systems (PEMS). While this approach provides accurate data, it is too time-consuming and expensive for large-scale application. Moreover, it cannot detect intentional tampering. A more efficient and cost-effective approach to measure the emissions of a large number of vehicles over their lifetime is Remote Emission Sensing (RES). RES techniques include different approaches for measuring vehicle emissions without direct installation on the target vehicle. These include open-path spectroscopy, which measures emissions across the road (Bishop et al., 1989) or from above the road, Point Sampling (PS), where stationary instruments sample and analyse the diluted exhaust from passing vehicles at the roadside (Hansen and Rosen, 1990), and Plume Chasing, where an instrumented vehicle follows a target vehicle sampling and analysing the emissions from behind the vehicle (Pirjola et al., 2004). In recent years, RES techniques have been further developed through projects such as the EU project CARES (City Air Remote Emission Sensing) (EU Horizon, 2020; Farren et al., 2023; Knoll et al., 2024a; Schmidt et al., 2025a), as well as through global research conducted over the past three decades (Leinonen et al., 2023; Tong et al., 2022; Ježek Brecelj et al., 2025; Lau et al., 2015; Dallmann et al., 2013; Wang et al., 2012; Ban-Weiss et al., 2009; Zavala et al., 2006). Recent developments and the usefulness of RES have also been recognized by policymakers. An overhaul of the EU's road safety and vehicle registration rules was proposed by the EU Commission in April 2025 (European Commission, 2025). This included an update on emission

testing, in which the use of RES and Plume Chasing was strongly recommended for screening emissions and identifying high emitters.

Compared to the other RES techniques, Plume Chasing cannot measure as many vehicles in the same time frame, but at the same time has the advantage of longer measurement periods from individual vehicles, making the resulting data of the investigated vehicle emissions more robust. Studies showed that the Plume Chasing technique can be used for reliable high-emitter identification by avoiding false positives (Schmidt et al., 2025a,b). Plume Chasing also operates reliably under most weather conditions, including during rain. Unlike stationary RES systems, it is more difficult for drivers to evade the measurements. Multiple validation studies of Plume Chasing against established methods such as PEMS and SEMS (Smart Emission Measurement System) measurements have previously shown excellent agreement for heavy-duty vehicles (HDVs) (Janssen and Hagberg, 2020; Farren et al., 2022; Schmidt et al., 2025a; Tong et al., 2022; Farren et al., 2023) as well as for light duty vehicles (LDVs) and two-wheelers (Simonen et al., 2019; Farren et al., 2023; Schmidt et al., 2025a).

In this study, we report on emission measurements of several hundred vehicles in Czechia using the Plume Chasing method. Plume Chasing results are compared with results from the RES techniques PS and cross-road RES (OPUS RSE). Plume Chasing measurements were conducted on the same streets in real traffic where the two stationary techniques were simultaneously deployed, allowing for direct comparison. In addition, we present validation data for particle and NO_x emissions, acquired from three test vehicles with different particle emission levels, based on tailpipe measurements using PEMS. The emission results of all three RES techniques are compared with the reference PEMS data. Unlike most previous studies, validation measurements were performed under real traffic conditions in the city of Prague, rather than on a test track or on roads with minimal traffic. Additionally, we present emission factors for 402 distinct LDVs, 66 buses, and 948 trucks, all of which were measured using the Plume Chasing method.

2. Methods

2.1. Plume Chasing

Two different Plume Chasing setups were used during the campaign. The first setup was a scientific measurement setup (bottom left in Figure S1, Appendix), which had different instruments for particle and gas measurements installed in a research measurement van from TNO (VW transporter, type T5 TDI 4 motion (high top)) (see Table S1). To analyse the gases NO_x, NO₂ and CO₂ of the plume signal, an ICAD-NO_x-150DE-M instrument (Airyx GmbH) was installed (Horbanski et al., 2019; Platt and Stutz, 2026). Black carbon (BC) concentrations in the plume were analysed by a recently developed black carbon tracker (BCT) using a photoacoustic based sensor (Knoll, 2024). PN concentrations in the plume signal were quantified using a TEN AEM Particle Counter (AEM). The AEM measured non-volatile PN larger than 23 nm (PN_{23 AEM}). In addition, a Scanning Mobility Particle Sizer (SMPS) measured the PN concentration with an electrical mobility diameter of around 90 nm (PN_{@90}). 90 nm was selected because the accumulation mode of diesel vehicles peaks at around 50–120 nm, and because 90 nm was found to be reliable in detecting tampering of DPF in an earlier study (Schmidt et al., 2025a). The selection of instruments was based on prior measurement campaigns, during which the setup was optimized (Schmidt

et al., 2025a). Since then, the AEM device has been further improved to provide more stable data. An ultrasonic anemometer measured the wind speed and direction on the roof of the measurement vehicle, while a radar determined the distance to the chased vehicle. A dashboard camera captured images of the chase to provide additional information for interpreting the data.

The second setup (Figure S1, bottom right) was an already market ready setup with only a single ICAD-NOx-200DE instrument (Airyx GmbH) for online NO_x and NO₂ emission factor calculation and high-emitter identification (Horbanski et al., 2019; Janssen and Hagberg, 2020) and at some measurement days with a particle number counter based on diffusion charging (Counter, AVL DiTEST GmbH) measuring solid PN (PN_{23Counter}, cut-off 23 nm) (Schriefel et al., 2020). Prior to the campaign, the instruments were calibrated and during the campaign, the instruments were regularly checked. For more details see Appendix Section 1.

The exhaust plume of the chased vehicles was sampled and analysed by the different instruments. The emission ratio R_E is calculated according to a standard procedure (Eq. (1), Hansen and Rosen (1990), Schmidt et al. (2025a)) from the average emitted concentration E_X of pollutant X and the average emitted CO₂ concentration E_{CO_2} .

$$R_E = \frac{E_X}{E_{CO_2}} = \frac{\sum_{t=0}^T ([X(t)] - [X_{BG}(t)])}{\sum_{t=0}^T ([CO_2(t)] - [CO_{2BG}(t)])} \quad (1)$$

To calculate the averages of the background (BG)-corrected time-series, the BG values of CO₂ (CO_{2BG}) and of the pollutant X (X_{BG}) are determined from the 5 s moving average of the time series of the measured signals. The BG values are determined as the smallest CO₂ value within a time interval of 120 s before each individual measurement point at time t and its associated pollutant value X. For further descriptions and analysis of the used Plume Chasing technique, see Schmidt et al. (2025a).

To ensure that only emissions from the plume of the chased vehicle are taken into account with sufficient signal strength, only those data points of the time series were considered valid where the CO₂ concentration was more than 20 ppm above the BG. Additionally, measurements were only considered valid if the speed of the Plume Chasing vehicle was greater than 10 kmh⁻¹ to ensure that the influences of plumes from other vehicles were minimized. Previous studies have highlighted the impact of other traffic on correct Plume Chasing measurements (Janssen and Hagberg, 2020; Schmidt et al., 2025a,b). Acknowledging this influence, the measurement was paused if there were high-emitting HDVs or light commercial vehicles in front of the chased vehicles or in the oncoming traffic. A minimum of 6 valid emission measurement data points (each one second) for each vehicle were required to consider measurements of this vehicle as valid for further analysis. On average a measurement had 70 (LDVs), 100 (HDVs) and 190 (buses) valid datapoints.

The emission factor of pollutant X per kilogram CO₂ is calculated via

$$EF_{kgCO_2}(X) = R_E \cdot \delta_x. \quad (2)$$

δ_x is dependent on the pollutant type X: $\delta_x = \frac{M(X)}{M(CO_2)}$ for $X \in (NO_x, NO_2)$ and $\delta_x = \frac{T \cdot R}{p \cdot M(CO_2)}$ for $X \in (PN, PM)$ with M the molar mass of pollutant X and CO₂, respectively, T and p the instrument specific ambient standard temperature and pressure (STP) and R the ideal gas constant. The fuel-based emission factors are calculated via

$$EF_{kg fuel}(X) = EF_{kgCO_2}(X) \cdot \omega_c \cdot \frac{M(CO_2)}{M(C)} \quad (3)$$

with $M(C)$ the molar mass of carbon and ω_c the carbon mass fraction in fuel (Tong et al., 2022). ω_c depends on the type of fuel. For petrol and diesel, a ω_c of 0.86 is used in this study, for CNG, 0.71 and for LPG, 0.82 (Prussi et al., 2020). To compare emission factors with the Euro standards, the fuel-based emission factors are converted to a distance-based emission factor (Eq. (4)) for LDVs and to an energy-specific

emission factor (Eq. (5)) for HDVs and buses. The distance-based emission factor is given by

$$EF_{km}(X) = EF_{kgCO_2}(X) \cdot CO_{2ta} \cdot \alpha \quad (4)$$

with the type approval CO₂ consumption CO_{2ta} and the correction factor α . CO_{2ta} is given in the vehicle technical information provided from the local authorities. If no CO_{2ta} was given, the average CO₂ of the vehicle's Euro emission standard was used. The value of α corrects for the average real world CO₂ gap (Bernard et al., 2018; Dornoff et al., 2020) and is typically between 1.1 and 1.4.

For HDVs, the energy-specific emission factors are calculated via

$$EF_{kWh}(X) = EF_{kg fuel}(X) \cdot FC_{CO_2 WHTC} \quad (5)$$

with the WHTC (World Harmonized Transient Cycle) fuel consumption $FC_{CO_2 WHTC}$ dependent on the engine displacement (Kazemi Bakhshmand et al., 2022). If the engine displacement is not given, a $FC_{CO_2 WHTC}$ of 0.211 kg fuel kWh⁻¹ was assumed (correspondent to a 40% motor efficiency). This is close to the optimal motor efficiency and may result in slightly underestimated emission values.

2.2. Point sampling

PS is a RES technique, where the exhaust plume of the passing vehicles is sampled and analysed by stationary instruments (Hansen and Rosen, 1990). Like for the Plume Chasing system, the recently developed BCT was used for BC and CO₂ measurement (Knoll, 2024), and an ICAD-100DE-M for NO₂, NO_x and CO₂ (Horbanski et al., 2019). Solid PN measurements of particles with a diameter larger than 23 nm (PN_{23Counter PT}) were conducted with a custom developed diffusion charger (Schriefel et al., 2020). A catalytic stripper upstream of the diffusion charger removed volatile fraction of particles. Light barriers installed at the side of the road captured the passing time, speed and acceleration of the passing vehicles (see Fig. 2). An automated number plate recognition (ANPR) system recorded the number plates of the passing vehicles. The system was measuring 24/7. The PS technique and the used evaluation algorithm are further described in Knoll et al. (2024a). Prior to the campaign, the instruments were calibrated. During the campaign, the instruments were regularly checked. For more details see Appendix Section 1.

2.3. OPUS Remote Sensing Europe (OPUS RSE)

Traditional cross-road RES (Bishop et al., 1989) measurements were conducted by OPUS Remote Sensing Europe (OPUS RSE, Opus (2025)) using the Opus AccuScan™ RSD 5700 instrument. The Opus Remote Sensing Device (ORS) measured the emission ratios of NO_x, CO, HC and particulate matter (PM), with the latter being derived from an opacity measurement in the UV range (Opus, 2025). For the measurement, beams of IR and UV light are sent across the road, and are reflected back to the detector by a reflector unit (see Figs. 2 and 3). The system includes additional sensors and a camera to detect vehicle speed, acceleration, and licence plates. A technician supervised the ORSD system, performing regular calibrations with reference gases every few hours to account for ambient changes. In a later version (RSD6000), calibration is automated (Opus, 2025). OPUS provided emission factors for all recorded vehicle passes, with multiple validity flags. Only emission factors with all valid flags were considered for analysis.

2.4. Measurement locations

The Plume Chasing measurements were conducted mainly in Prague, on Czech highways and one day in Brno. In Prague the focus was on the areas around the measurement locations of the PS and ORSD measurements (see Table 1) to be able to compare the emission values of all three different RES systems. To facilitate a comprehensive

Table 1
Characteristics of measurement locations V Korytech, Kamycka and Brno highway ramp.

	V Korytech	Kamycka	Highway ramp
Traffic density [# /h]	300–450	200–370	400–750
Avg temp [°C]	15	11	10
Avg VSP [kW/t]	13.6	7.7	3.6
Slope [%]	1.2	4	1.7
Avg speed [km/h]	32	32	19

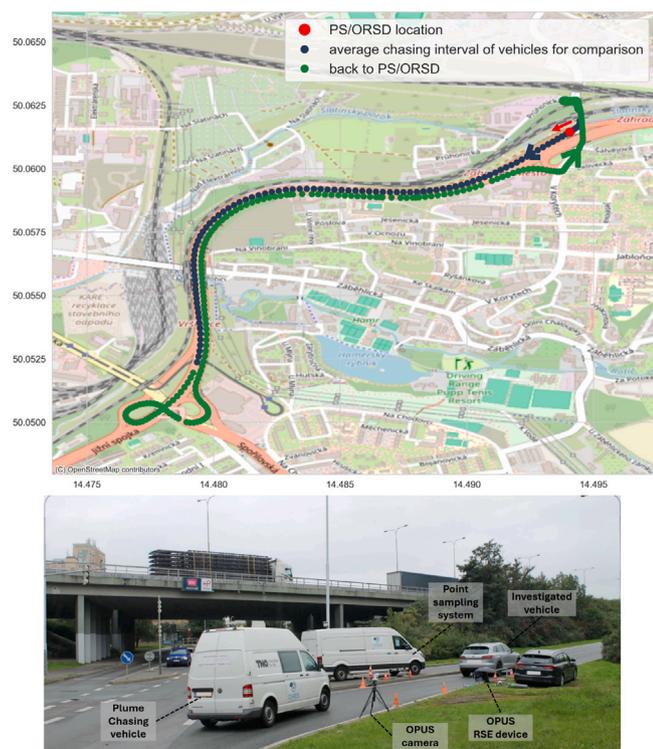


Fig. 1. Top: Example of the Plume Chasing route for the measurement site V Korytech, based on GPS data. The red point shows the location of the ORSD and PS instrumentation. Dark blue dots show the remainder of the chasing route, green dots the rest of the round back to the RES location. Bottom: PS and ORSD measurement location at V Korytech with passing vehicle and Plume Chasing vehicle.

comparison of HDV emission values between Plume Chasing and ORSD, additional measurements were performed on a highway ramp near Brno. In the following a detailed description of the measurement routes and the PS and ORSD measurement locations is given. The main criteria for choosing the PS and ORSD measurement locations were: single lane of traffic, separate from other lanes, with an incline and/or moderate acceleration resulting in positive VSP, sufficiently high traffic density for ORSD and sufficiently low traffic density for PS, permission from the relevant road authority, sufficient space for instrumentation and measurement vehicles, availability of electric power.

2.4.1. V Korytech

Plume Chasing measurements took place at the V Korytech highway ramp in Prague on 19 September 2022. PS and ORSD devices were installed side by side (see Fig. 1, bottom). The traffic density at this site was between 300 and 450 vehicles per hour, and the ambient temperature was approximately 15 °C. Passing vehicles had an average speed of 32 km/h, a vehicle-specific power (VSP) of 13.6 kW/t, and the road had a slope of 1.2% (Table 1).

The sample extraction by the PS system was performed from the left roadside. The Plume Chasing vehicle was passing the PS/ORSD location at the start of a chase, directly after the traffic lights at the entrance to

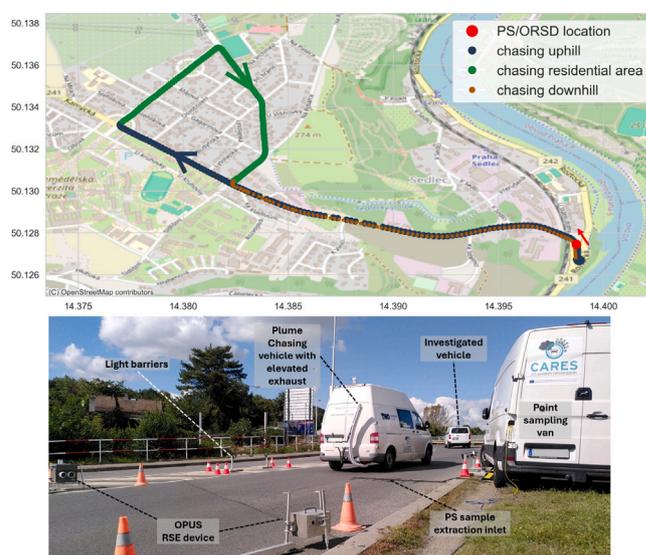


Fig. 2. Top: Example of the Plume Chasing route for PEMS measurements at Kamycka, based on GPS data. The red point shows the location of the PS and ORSD instrumentation. Dark blue dots show the uphill part of the route, green dots the residential flat area and orange dots the downhill part. Bottom: PS and ORSD measurement location at Kamycka with passing vehicle and Plume Chasing van.

the ramp. The chase continued for about 2–3 min (1.9 km) on the E65 city highway (see Fig. 1 top, blue markers) before driving back to the PS/ORSD location. On the way back, a further vehicle was typically chased. The entire round covered approximately 4.8 km. An influence of the relatively high exhaust emissions of the Plume Chasing TNO vehicle (diesel, Euro 5) on the stationary RES measurements cannot be definitively ruled out at this measurement location, even though passes where the TNO van was driving in close proximity to the vehicle being chased were excluded.

2.4.2. Kamycka

From 20 to 22 September 2022, the ORSD system was installed on Kamycka Street in Prague, in the direction of suburban area. The PS system was installed from 21 to 23 September 2022, with measurements taken next to the ORSD (see Fig. 2), both located at the beginning of a long uphill section. The traffic density at this site varied between 200 and 370 vehicles per hour during the period of co-location. The passing vehicles had a VSP of 7.7 kW/t. Further characteristics of the site can be found in Table 1.

At Kamycka, the sample extraction of PS was performed from the middle of the near side lane. Plume Chasing measurements took place around this location on several days, partly with focus on buses. Section 2.5 elaborates further on the PEMS measurements, which were also performed at this location. For this location, the tailpipe of the Plume Chasing TNO van was modified, i.e. its height was increased by about 1.5 m (see Fig. 2, bottom), to ensure that the van's exhaust emissions did not impact the stationary RES measurements.

2.4.3. Brno highway ramp

The third location for comparing truck measurements between ORSD and Plume Chasing was on the D2 to D1 highway ramp near Brno on 23 September 2022. The ORSD was directly installed at this highway ramp location, as illustrated in Fig. 3. The traffic density on the highway ramp was between 400 and 750 vehicles per hour. Passing vehicles had a VSP of 3.6 kW/t. Further characteristics of the site can be found in Table 1.

The focus at this particular site was on HDVs. The Plume Chasing vehicle followed a 6.1 km long defined route (see Fig. 3). The route

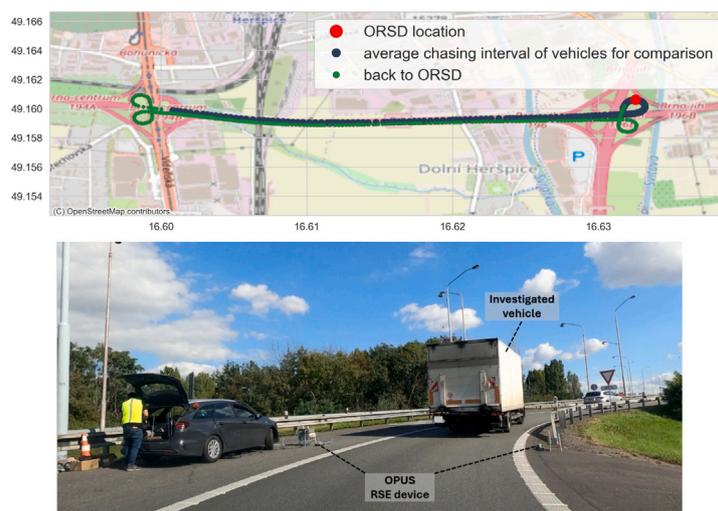


Fig. 3. Top: Example of the Plume Chasing route around the highway ramp, based on GPS data. The red point shows the location of the ORSD. Dark blue dots show the remainder of the chasing route of a truck shortly before and after the RES location, green dots show the rest of the round back to the ORSD location. Bottom: The ORSD measurement location near Brno at the highway ramp with a passing truck.

included passage by the ORSD measurement location on the highway ramp, indicated by the red marker. The chase of a HDV started in most of the cases directly before the highway ramp and ended about 2.6 km after (see blue markers). When interpreting the truck data from the Brno highway ramp, it must be taken into account that there was a traffic jam of about 2 km, which was probably caused or at least exacerbated by the ORSD measurement setup. While ORSD did not directly interfere with the traffic flow, it was an attractive nuisance, analogous to a traffic slowdown due to construction or accident in the opposite direction. In particular, the camera installed to capture the front licence plates of the trucks may have caused the drivers to slow down. Therefore, the engine of the vehicles might have become cold in the minutes before passing. In addition, the driving speed was not representative of the highway as the trucks passed the ORSD at a speed of around 19 km/h.

2.5. On-board reference measurements

Three different cars (see Table 2) with different Euro emission standards were selected as test vehicles. The test vehicles were selected to have different levels of NO_x and particle emissions, in order to enable a comparison of the three remote emission sensing techniques in this respect. These three cars were measured with all three RES techniques (Plume Chasing, PS and ORSD) multiple times on 22 September 2022. To compare the emissions of the test vehicles with reference measurements, a Portable Emission Measurement System (PEMS) consisting of a FTIR spectrometer (Vojtisek-Lom et al., 2020) and a NanoMet3 (NM3) was installed directly at the tailpipe of the three test vehicles. The NM3 is based on diffusion charging and measures solid PN larger than 10 nm (PN_{10}). The NM3 and FTIR were calibrated according to the manufacturers' specifications. Further details on the quality control procedures can be found in the Appendix Section 1. The average emissions from the on-board PEMS measurements are calculated using Eq. (1), with the BG values set to zero, since the on-board instruments measure directly in the exhaust.

To have comparable data between the different studied vehicles a testing round was defined. Each round was about 4.5 km long and started at a roundabout, containing first an uphill section passing the RES measurement location at Kamycka (Fig. 2), followed by a level to slightly downhill part through a residential area at the top of the hill. The route concluded with a downhill section returning to the roundabout (Fig. 2). The elevation profile of one round is shown in Figure S2. The number of rounds of each vehicle can be found in Table 2. It is important to note that for the Toyota ProAce test vehicle, certain rounds were executed without the PEMS system in place. These

Table 2

Test vehicles for on-board emission measurements. The number of rounds for each test vehicle with/without a PEMS installed are listed under 'Rounds'.

Model	Euro class	Fuel Type	Rounds	Plume Chasing vehicle
Skoda Octavia	Euro 4	diesel	11/- 6/-	TNO van Airyx van
VW Touran	Euro 5	petrol	15/-	TNO van
Toyota ProAce	Euro 6d	diesel	8/13	TNO van

measurements were taken during the transition of the PEMS system between vehicles, aiming to maximize the total number of passes at the ORSD within its operating time. For these rounds, emission values are only compared between different RES techniques, not with PEMS instruments.

The traffic conditions varied for each round, ranging from an empty street in front of the chased vehicle to a multitude of vehicles in front, including buses and HDVs. Driving conditions when passing the PS and ORSD location varied. GPS data provided information about speed and acceleration.

2.6. Comparison measurements of Plume Chasing with point sampling and OPUS remote sensing device

The Plume Chasing vehicle passed the locations of the other two RES techniques (see Section 2.4) while chasing a target vehicle. The derived emissions of the target vehicles allow a comparative analysis of the emission factors determined by Plume Chasing with those obtained by PS and ORSD. Both ORSD and PS provided emission measurements, including vehicle passing times and vehicle IDs, allowing individual passes to be matched. Passes that could not be confidently matched were excluded from the comparative analysis to ensure data accuracy.

3. Results and discussion

3.1. On-board reference measurements

Table 3 shows the average and median emissions of the three test vehicles at the Kamycka measurement location for the different emission measurement techniques. Fig. 4 shows the distribution of the emission results. When interpreting the data, it is important to note that the PM values from the NM3 instrument are not directly measured; rather, they are calculated based on the PN_{10} measurements of the NM3. As a result, PM comparisons using this data can only be considered as rough

Table 3

Overview of the median and average (std) emission factors (in ppm pollutant per % CO₂ and mg or # per kg fuel) of the three test vehicles Skoda Octavia, VW Touran and Toyota ProAce equipped with on-board instrumentation at the Kamycka measurement location. The emission factors are determined by PEMS, PS, ORSD and Plume Chasing (PC) measurements.

Pollutant X	Method	R_E and $E_{F_{kg\ fuel}}$					
		Skoda Octavia Euro 4		VW Touran Euro 5		Toyota ProAce Euro 6d	
		Median	Average(std)	Median	Average(std)	Median	Average(std)
NO _x [ppm/%]	PEMS	35	35(4)	4	4(1)	3	7(10)
	PS	18	42(48)	0	1(14)	8	15(18)
	ORSD	43	49(35)	2	4(10)	10	9(10)
	PC	29	28(8)	5	7(4)	8	9(5)
NO ₂ [ppm/%]	PEMS	13.7	13.4(2.9)	0.1	0.2(0.2)	0.3	0.3(0.1)
	PS	6.2	6.2(5.3)	0.1	-0.5(2.1)	1.3	1.9(1.9)
	ORSD	11.5	12.5(16.7)	1.3	2.3(7.5)	-2.4	-2.1(8.2)
	PC	8.6	8.5(3.6)	0.9	1.3(0.9)	1.0	1.2(0.7)
PM, BC [mg/kg fuel]	PEMS	419	412(82)	47	52(21)	0.05	0.07(0.06)
	PS	974	1014(639)	96	100(35)	10	46(98)
	ORSD	363	585(535)	89	91(109)	38	21(181)
	PC	501	572(192)	136	118(60)	17	32(55)
PN [#·10 ¹³ /kg fuel]	PEMS	113	111(9)	17	17(3)	0.006	0.006(0.003)
	PS	163	177(84)	44	52(41)	0.03	1.4(14.3)
	ORSD	-	-	-	-	-	-
	PC (PN _{23 AEM})	172	170(44)	35	32(18)	6.3	9.4(16.0)
	PC (PN _{23 Counter})	120	120 (32)	-	-	-	-

estimates. Furthermore, it should be considered that BC measured by the BCT (Plume Chasing and PS) and PM derived by the ORSD from opacity are different measures. Only a rough comparison is possible in this case. To calculate the Plume Chasing emission factors, the data is filtered as described in Section 2.1 (e.g. traffic filter) and, additionally, downhill sections with a road grade steeper than -2% are automatically excluded. As shown in Section 2 of the Appendix, if no traffic filter can be applied, automatically excluding downhill sections can already help to improve the results. The median absolute deviations from the reference values were found to be several times higher for downhill sections (up to 12 times higher for PN) than for uphill sections. Further investigations on the influences of downhill sections on Plume Chasing measurements can be found in Section 2 of the Appendix. Plume Chasing and PEMS measure the emissions from the test vehicles over several minutes (one complete round), while PS and ORSD measure them over much shorter time intervals (up to a few seconds). This means that differences in the results are to be expected, as vehicle emissions can vary considerably. However, this comparison is included here as it investigates how representative the measurement is relative to the average emissions recorded by PEMS over a defined test route.

An example time series of NO_x and PN data for one complete round passing the measurement location Kamycka (see Section 2.4.2), both from on-board measurements and Plume Chasing, is shown in Figure S2 in the Appendix. The calculated emissions per round from the different RES techniques plotted against PEMS are also shown in the Appendix in Figure S3. Colour coded dots indicate the different vehicle types.

The particulate emissions (PM and PN) of the test vehicles differ due to the different fuel types (gasoline and diesel) and Euro standards (Euro 4 to Euro 6d). On average, the PEMS PN₁₀ emission measurements give a result of 111(9) × 10¹³ #/kg fuel (total number of particles per kg fuel) for the Skoda Octavia, 17(3) × 10¹³ #/kg fuel for the VW Touran and 6(3) × 10¹⁰ #/kg fuel for the Toyota ProAce. All RES techniques are capable of detecting significant differences in PM, BC and PN emissions between the three test vehicles. Their results show higher average emissions compared to the PEMS measurements for all vehicles. This also applies to most of the individual measurements (see Figure S3, measuring points above the 1:1 line). Only the PM measurements from ORSD for the Skoda Octavia show a lower median value (363 mg/kg fuel) compared to the median PEMS PM results (419 mg/kg fuel). The average and median PS values for BC emissions of the Skoda Octavia are about twice as high as those of the other

methods, while they are in a similar range for the other two test vehicles. These high BC emission of PS are in contrast to the PEMS and Plume Chasing measurements, which are performed over one drive cycle. The ORSD may not observe this difference because they use a different measurement technique (opacity measurement). For the VW Touran, but especially for the Toyota ProAce (with DPF), the deviations for BC and PN measurements of PS are similar compared to those of Plume Chasing. The higher deviations for the high emitters could be due to the larger emissions dynamic range expected from vehicles without a particle filter for different driving situations, whereas for vehicles with a functional filter, the variations are much smaller. For Plume Chasing, the overestimation compared to PEMS measurements is more pronounced for the PN_{23 AEM} measurements than for PN_{23 Counter} measurements. The differences may be due to sampling differences (lower losses in the PN_{23 AEM} setup), differences in calibration, or differences in the two instruments used. This can be either due to underestimation of the Counter device, or might be attributed to the fact that the used AEM instrument in the Plume Chasing measurements overestimates the number of particles larger than its calibration diameter (Fraturet et al., 2024). Another possible reason is that there is a high proportion of volatile particles that are not fully removed, which could potentially cause an overestimation (Melas et al., 2021). The PN_{23 Counter} emission values of the Skoda Octavia deviate only about 10% from the PEMS emission values. There is no Counter data for the other two test vehicles, since the Airyx Plume Chasing vehicle with this instrument installed only measured the Skoda Octavia (see Table 2).

The PEMS measurements determined higher average NO_x (and NO₂) emissions of the Skoda Octavia (Euro 4, diesel) compared to the other two test vehicles, which both showed emissions in the same range (Euro 5 petrol and Euro 6d diesel). The average NO_x emissions were 35(4) ppm/% for the Skoda Octavia and 4(1) ppm/% and 7(10) ppm/% for the VW Touran and Toyota ProAce, respectively (see Fig. 4). The different RES techniques observed similar emission characteristics. The average NO_x emission values of the different RES techniques agree with each other and with the PEMS measurements within their uncertainty ranges. The PS NO_x and NO₂ emission of only a small fraction of passes could be determined as the PS measurements were not optimal at this location. One issue was that the sample flow rate was too low (about 1.51/min in comparison to 131/min for the particle instruments). This smeared the response and, in combination with the relatively high traffic (up to 640 vehicles per hour), limited the plume detection

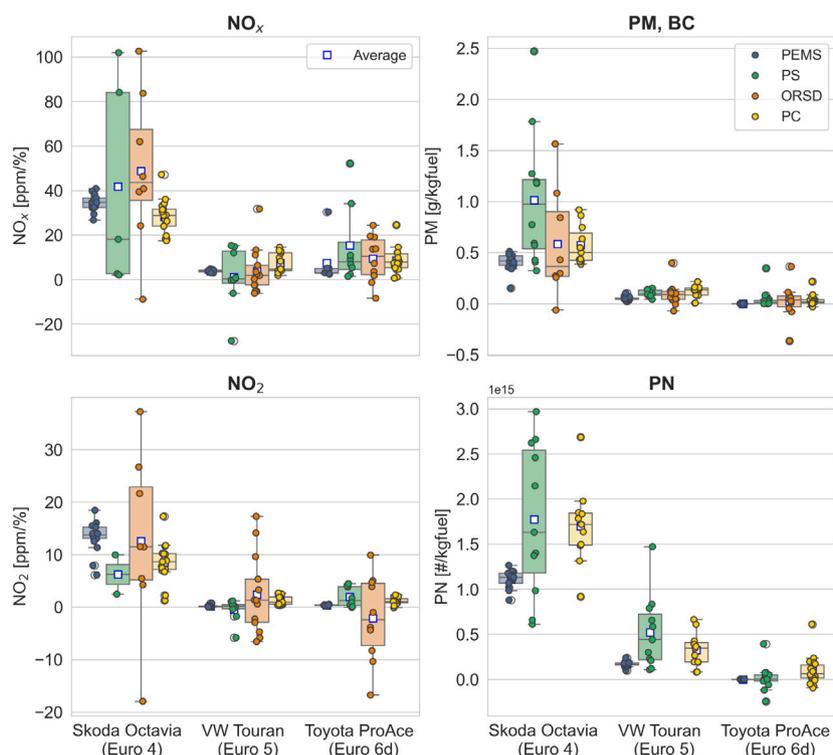


Fig. 4. The four panels give the average NO_x , NO_2 , PM or BC, and PN emissions per round (measurement location Kamycka, see Section 2.4.2) determined by PEMS (blue), PS (green), ORSD (orange), and Plume Chasing (yellow) for the three tested vehicles, Skoda (left), VW (middle) and Toyota (right). The Plume Chasing PN values shown are the $\text{PN}_{23\text{ AEM}}$ data. The $\text{PN}_{23\text{ Counter}}$ data is not shown here (can be found in Table 3). The whiskers represent the 1.5 interquartile range (IQR).

capability. The deviation of the average Plume Chasing NO_x emission values from the reference PEMS values is higher for all three test vehicles than in earlier studies, where the deviation from the reference emission value was found to be around 10 % for LDVs and even lower for HDVs (Schmidt et al., 2025a). Unlike the earlier study, the measurements were not performed on a test track with a stable background and no influence from other vehicles, but in an urban environment with real traffic conditions. It was found in the earlier study that the emission measurements can be significantly influenced by other vehicles: up to 35 % of emissions can come from a high-emitting vehicle driving directly in front. Even though the earlier studies' findings were considered in the measurements, with paused measurements whenever a high emitter was present or approaching, not all high emitters may have been correctly identified.

For the PEMS data, the emission values of one test vehicle remain similar from round to round (no big scatter in the data). It can be observed that the scatter of the observed emission values in most cases is significant smaller for the Plume Chasing data compared to the measurements obtained through PS and ORSD. Similar scatter can be observed between Plume Chasing and PS for low PM emitters. The higher accuracy of Plume Chasing is likely due to the longer averaging intervals, which derives a more representative emission value than a PS measurement of a few seconds or an ORSD measurement of hundreds of milliseconds. If only Plume Chasing data are used of an interval of 6 s (± 3 s around passing the PS/ORSD location), the scatter and deviation also increase (Figure S4). The increase in scatter is more pronounced for the vehicle with higher emissions (Skoda Octavia), as this vehicle exhibits greater variability in its emissions (Jerksjö et al., 2022).

3.2. Comparison measurements of Plume Chasing with point sampling and OPUS RSE

The Plume Chasing vehicles passed 33 times at the measurement site V Korytech, 137 times at Kamycka and 26 times at the highway

Table 4

Overview of the capture rate of PS and ORSD of the chased vehicles by Plume Chasing (PC) at the sites V Korytech, Kamycka and highway ramp.

Site	PC passes	valid/non-valid ORSD passes	valid/non-valid PS passes
V Korytech, Prague	33	24/2 (92%/8 %)	10/23 (30%/70 %)
Kamycka, Prague	137	60/24 (71%/29 %)	86/34 (72%/28 %)
Highway ramp, Brno	26	25/1 (96%/4 %)	–

ramp in Brno (Section 2.4). The capture rate of these passes at the different sites is listed for both RES techniques (PS and ORSD) in Table 4. The numbers for ORSD and PS passes do not always correspond to the Plume Chasing passes. This is either because the systems were installed in different locations at the time of passing, or because the passes took place outside of the ORSD operating hours.

The V Korytech site, due to vehicles driving in close proximity, exhibits a suboptimal measurement location for PS (Knoll et al., 2024a), resulting in a capture rate of only 30 % (ten valid PS measurements for 33 PC passes). For those passes, the distance between the Plume Chasing vehicle and the chased vehicle was sufficiently large, such that the emissions could still be distinguished and calculated. In order to increase the number of valid PS passes at the Kamycka measurement site on subsequent days, the exhaust pipe of the Plume Chasing vehicle was extended upwards to ensure that the emissions do not interfere with the PS instruments. The used PS algorithm filters out vehicles that are driving too close, as consecutive plumes become indistinguishable or are referred to the wrong vehicle (Knoll et al., 2024a). For the comparison measurements the Plume Chasing vehicle passes were filtered out of the PS dataset to avoid automatic exclusions of chased vehicles and maximize the number of valid PS passes. The capture rate for PS at the Kamycka measurement site could be increased to 72 %. The PS capture rate can be improved further by applying different algorithms, such as the plume regression approach (Farren et al., 2025),

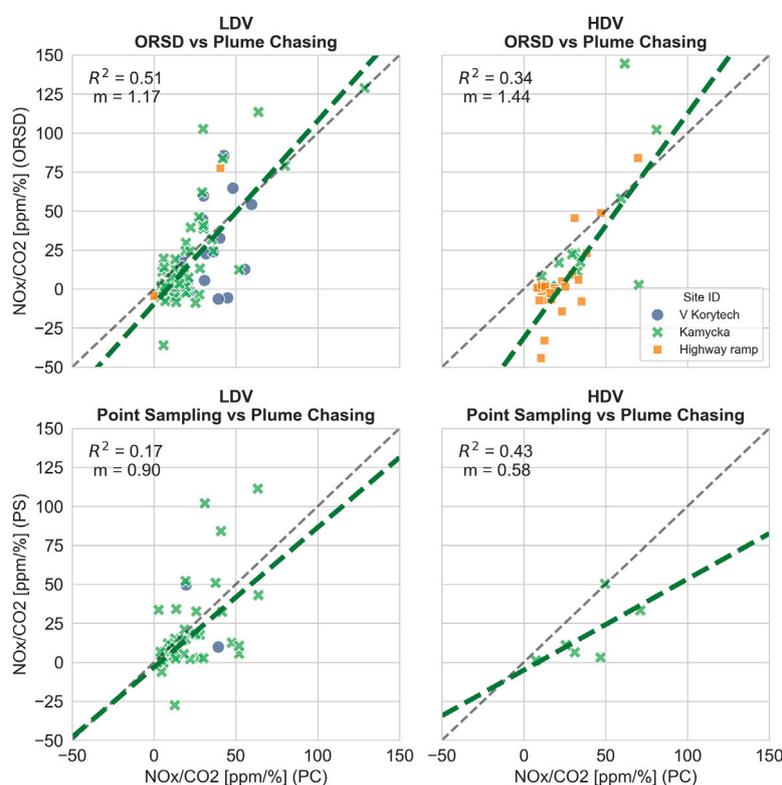


Fig. 5. Comparison between the NO_x emission ratios determined by Plume Chasing (PC), PS and ORSD for LDVs (left) and HDVs (right). The green dashed line shows the linear model fit with the regression slope m and the coefficient of determination R^2 . The 1:1 line is shown by the dashed black line.

which uses average plume profiles to process overlapping plumes. Peak detection (Knoll et al., 2024a) was used to process the PS data in this study, which is currently unable to resolve plumes that overlap excessively.

The ORSD benefits from the high traffic volume at the V Korytech site, enabling the system to capture a larger number of vehicles within the same time frame. At Kamycka, the ORSD faced challenges recognizing the licence plates, leading to a lower capture rate (71 %) in comparison to the V Korytech site or the highway ramp near Brno, both of which achieved a capture rate over 90 %. It is important to note that the ORSD measurements were confined to a specific time frame (between around 9 am and 3 pm) and that PS and ORSD did not measure at identical locations. They were a few meters apart.

Fig. 5 shows the results of the comparison between the NO_x emission ratios determined by Plume Chasing with PS and the ORSD for LDVs (left) and HDVs (right). The different colours and markers indicate the three measurement sites. When ORSD and Plume Chasing are compared, the results for NO_x show R^2 values of 0.51 and 0.34 for LDVs and HDVs, respectively. This is a fairly good agreement, considering that it is a comparison between a measurement of longer duration (Plume Chasing) and an instantaneous measurement of ORSD. The high number of negative ORSD results suggests high measurement uncertainty. Assuming no systematic negative bias and actual NO_x emissions to be zero, we estimate this uncertainty. This likely underestimates it, as true emissions are mostly above zero. Excluding outliers below -25 ppm/%, we obtain standard deviations of 5.2 ppm/% for LDVs and 7.5 ppm/% for HDVs.

For PS, the correlation with Plume Chasing is lower ($R^2 = 0.17$) for LDVs and higher ($R^2 = 0.43$) for HDVs. The relatively small number of PS NO_x and NO_2 measurements and increased deviations are largely due to the previously mentioned too low sample flow in combination with the high traffic flow.

Overall, the three different RES techniques produce significantly different results for the emissions of individual vehicles. Which is to be

expected because Plume Chasing measures several minutes, while PS and ORSD only measure up to a few seconds. Also, the PS and ORSD systems were not measuring from exactly the same position. High HDV NO_x emissions over 50 ppm/% (equivalent to approx. 3500 mg/kWh) were also recognized by ORSD and PS, except for one HDV at the measurement site Kamycka by ORSD. For this HDV, ORSD observed more than twice the emission factor of Plume Chasing. On the highway ramp, ORSD determined low emissions for almost all HDVs (orange squares), while Plume Chasing measured higher emissions on average for those vehicles. This is plausible, as the trucks passed the ORSD at a speed of around 15 km/h and only accelerated again after the highway ramp (see Section 2.4.3) and thus could have had lower emissions at the ORSD location. For LDVs, the spread is even greater. For some of the LDVs, Plume Chasing measured NO_x emissions above 20 ppm/% (equivalent to approx. 300 mg/km), and ORSD and PS determined emissions close to zero, or even negative. This is analogous to the behaviour that has been discussed in the context of the LDV PEMS measurements: a single emission measurement obtained by snapshot sampling may not be representative, as the vehicle may be either caught in a high- or low emission state. However, when several passes of the same vehicle are used at different measurement locations, the ORSD or PS results should become more robust (e.g. Qiu and Borken-Kleefeld, 2022).

Fig. 6 shows the results of the comparison between the BC emission factors determined by Plume Chasing and the BC and PM emission factors determined by PS and ORSD, respectively, for LDVs (left) and HDVs (right). The correlation between LDV emission results determined by Plume Chasing is stronger for PS ($R^2 = 0.63$) than for ORSD ($R^2 = 0.25$). The different measures PM (ORSD) and BC (Plume Chasing) are responsible for a certain portion of the observed differences between ORSD and Plume Chasing. For HDVs, only a few data points (all of which are low emitters) are available and no conclusion from the correlation coefficient can be made ($R^2 = 0.38$ for ORSD and $R^2 = 0.13$ for PS). When we estimate the uncertainty for low PM emission values

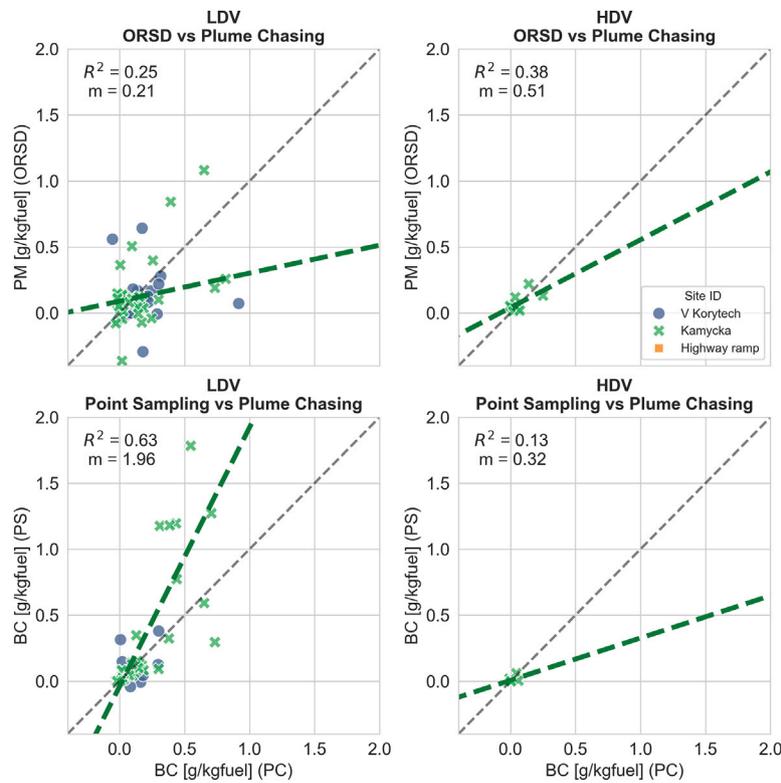


Fig. 6. Comparison between the PM and BC emission factors determined by Plume Chasing (PC), PS and ORSD for LDVs (left) and HDVs (right). The green dashed line shows the linear model fit with the regression slope m and the coefficient of determination R^2 . The 1:1 line is shown by the dashed black line.

from the negative values of ORSD, we obtain a standard deviation of 0.17 g/kg fuel for LDVs and 0.14 g/kg fuel for HDVs when we exclude outliers over -0.5 g/kg fuel.

For more HDV emission results including a comparison with $PN_{23\text{Counter}}$ emission factors measured by the Airyx Plume Chasing vehicle see Figure S7 in the Appendix. When using the same PN instrumentation for PS and Plume Chasing generally leads to a good correlation between the two techniques (Figure S8). For PN, the selection of instruments has a significant impact on the results, which, in the case of solid PN measurements, depend on the measuring principle, size cut-off, calibration and volatile particle removal efficiency. Comparisons between PS and ORSD BC, PM and NO_x emission factors can be found in detail in Knoll et al. (2024b).

3.3. Fleet screening

3.3.1. Overview of measured vehicle fleet

An overview of vehicles (category, fuel type, Euro emission standard) measured by the Plume Chasing method can be found in Table 5. In total, 402 distinct LDVs, 66 different buses (type M3) and 948 trucks (N2, N3) were used for the analysis. The LDVs and buses were primarily measured at various locations in Prague, while the trucks were measured mainly on the D1 highway. The LDVs are separated in passenger cars (M1 including M1G) and light commercial vehicles (LCVs) (N1 including N1G). The results of the emission statistics and high-emitter identification of the in total 922 trucks with known Euro emission standard can be found in detail in Schmidt et al. (2025b). Here, in addition the $PN_{23\text{AEM}}$ and $PN_{@90}$ data is shown and the data is separated in Euro V and Euro V EEV as well as Euro VI and Euro VI-D. This separation was only possible for Czech trucks with available vehicle information.

If a vehicle was chased several times, time-weighted averages were calculated to determine the average emissions for each vehicle based on

the emissions EF_{km} or EF_{kWh} (Eqs. (4), (5)) of a single chase. This was the case for 8 passenger cars, 4 LCVs and 25 buses. In total, 108 chases of buses were conducted during the campaign in Czechia with some buses being chased up to seven times at different times and locations.

To ensure the precision of our analysis, vehicles without proper vehicle information (including LDVs not originating from Czechia or those with incorrectly identified licence plates) were excluded from the analysis, which affected 26 out of 428 LDVs (6%). Trucks from abroad are further analysed as long as their Euro emission standard could be clearly identified (visible through stickers on the front of the truck or evident from the vehicle's model and make). For these trucks, it was not possible to distinguish between Euro V and Euro V EEV as well as Euro VI and Euro VI-D. In the analysis, therefore, some of the emission results from Euro V EEV and Euro VI-D trucks are included in the Euro V and Euro VI emission data respectively.

Approximately half of the measured LDVs belong to the Euro 6 category or higher, followed by 24% Euro 5 (Table 5). The main brands of these vehicles are Skoda, which make up about 20% of the LDVs, followed by VW with 16%. The vehicles mainly run on diesel (54% of passenger cars and 84% of LCVs). 42% of the passenger cars run on petrol. A few CNG and LPG vehicles were also measured (Table 5). For 2 passenger cars and 1 LCV, a Euro emission standard was not available in the vehicle information.

From the 66 distinct buses roughly 50% are of the Euro V and Euro V EEV category, followed by 36% Euro VI and 14% Euro VI-D. Only two buses have Euro IV category. The Euro emission standard of the buses is visible on the rear of the bus and also provided from the official vehicle data. These data match for 85% of the buses. In case of discrepancies, the official vehicle data is used. The manufacturer of all but four of the buses is SOR, and they are used as city buses in Prague.

The majority (81%) of the HDVs that were measured are Euro VI vehicles, followed by about 16% Euro V trucks. Similar shares of trucks were measured from Mercedes, DAF, Volvo, Scania and MAN.

Table 5

Overview of investigated vehicles of category M1 (passenger cars), N1 (LCVs), M3 (buses) and N2, N3 (trucks) by Plume Chasing. Vehicle categories are differentiated by fuel type.

Type	Fuel	All	Euro 2/Euro II	Euro 3/Euro III	Euro 4/Euro IV	Euro 5/Euro V	Euro V EEV	Euro 6/Euro VI	Euro 6d-TEMP	Euro 6d/Euro VI-D	no info
M1 (incl. M1G)	Diesel	168	3	18	31	41		48	13	13	1
	Petrol	133	6	10	31	25		18	27	15	1
	CNG	4	–	–	1	–		1	–	2	
	LPG	9	2	1	3	2		1	–	–	
N1 (incl. N1G)	Diesel	74	1	13	18	18		16	3	4	1
	Petrol	4	–	–	1	1		1	–	1	
	CNG	9	–	–	–	1		4	4	–	
	EL	1	–	–	–	–		1	–	–	
M3	Diesel	64			2	11	20	22		9	
	CNG	2			–	–	–	2		–	
N2, N3	Diesel	948	1	9	21	128	17	687		59	26

Table 6

Overview of the median emission factors (in mg or # per km or kWh) of investigated vehicles by Plume Chasing.

Type/Fuel	Pollutant X	EF_{km} (for M1, N1) and EF_{kWh} (for M3, N2, N3)								
		Euro 2/Euro II	Euro 3/Euro III	Euro 4/Euro IV	Euro 5/Euro V	Euro V EEV	Euro 6/Euro VI	Euro 6d-TEMP	Euro 6d/Euro VI-D	
M1/petrol	NO _x	576	274	287	210		171	167	156	
	NO ₂	32	38	39	32		32	25	19	
	BC	–	2	7	4		5	5	4	
	PN _{23 Counter} ($\cdot 10^{12}$)	39	3	6	6		3	5	1	
	PN _{23 AEM} ($\cdot 10^{12}$)	13	5	19	13		12	6	12	
	PN _{@90} ($\cdot 10^{10}$)	2	3	10	6		6	3	6	
M1/diesel	NO _x	852	658	619	524		287	310	260	
	NO ₂	57	99	102	52		35	29	42	
	BC	–	79	18	1		5	4	3	
	PN _{23 Counter} ($\cdot 10^{12}$)	51	112	31	1		5	7	7	
	PN _{23 AEM} ($\cdot 10^{12}$)	175	57	98	12		19	10	12	
	PN _{@90} ($\cdot 10^{10}$)	98	42	61	4		7	7	5	
N1/diesel	NO _x	1058	557	622	734		640	330	153	
	NO ₂	98	46	83	100		46	45	43	
	BC	10	77	23	4		0	10	6	
	PN _{23 Counter} ($\cdot 10^{12}$)	–	31	11	2		5	–5	–4	
	PN _{23 AEM} ($\cdot 10^{12}$)	32	131	44	16		3	24	30	
	PN _{@90} ($\cdot 10^{10}$)	–	104	37	11		4	13	12	
M3/diesel	NO _x			4841	3106		5489	1859	624	
	NO ₂			86	87		108	134	70	
	BC			43	33		27	5	1	
	PN _{23 Counter} ($\cdot 10^{12}$)			26	27		28	10	3	
	PN _{23 AEM} ($\cdot 10^{12}$)			97	145		100	13	6	
	PN _{@90} ($\cdot 10^{10}$)			60	60		42	5	2	
N2,N3/diesel	NO _x	7404	4093	4193	2943	2110	929		803	
	NO ₂	483	269	249	171	245	145		126	
	BC		23	32	14	16	3		4	
	PN _{23 Counter} ($\cdot 10^{12}$)	175	59	76	37	22	12		12	
	PN _{23 AEM} ($\cdot 10^{12}$)		15	125	66	90	63		57	
	PN _{@90} ($\cdot 10^{10}$)		49	40	25	10	9		8	

In the following analysis only vehicle categories with more than 10 vehicles are further considered (M1 diesel/petrol, N1 diesel, M3 diesel and N2, N3 diesel).

3.3.2. Emission statistics

For different Euro emission standards, distributions of the average NO_x, NO₂, BC, PN_{23 AEM}, PN_{23 Counter} and PN_{@90} emissions (EF_{km}) of LDVs are compared in Fig. 7 and in Table 6. The emission results per kg fuel can be found in Table S2.

The emissions of diesel vehicles are higher than those of petrol vehicles for the different Euro emission standards, but with higher Euro emission standards the difference becomes smaller. The emissions of NO_x and NO₂ decrease, not unexpectedly, with increasing Euro emission standard for passenger cars. LCVs show higher NO_x and NO₂ emissions for Euro 5 than for Euro 3 and 4 vehicles. The median NO_x emissions of LCVs decrease from 734 mg/km for Euro 5 to 153 mg/km for Euro 6d. This represents a reduction of approximately 80%. The PN_{23 Counter}, PN_{23 AEM}, PN_{@90} as well as BC emissions show a significant reduction of emissions from Euro 4 to Euro 5 diesel vehicles due to

the introduction of particle filters. However, no significant difference is observed between Euro 5 and Euro 6 vehicles. For petrol passenger cars, there is generally no significant difference in emissions between the different Euro emission standards for PN and BC emissions. This was also found in other studies (Knoll et al., 2024a; Lähde et al., 2022). One reason for this is that the PN type-approval limit for pre-Euro 6c petrol cars either does not exist (for pre-Euro 6 cars) or is higher (for Euro 6b cars with direct injection only, $6 \cdot 10^{12} \text{ km}^{-1}$) than the limit for diesel cars ($6 \cdot 10^{11} \text{ km}^{-1}$). This only becomes harmonized for all types with the Euro 7 standard. In general, the PN values from AEM (PN_{23 AEM}) show higher emissions than the Counter (PN_{23 Counter}) (see discussion in Section 3.1). The investigated vehicles are the same for BC, PN_{23 AEM} and PN_{@90} (measured by TNO Plume Chasing vehicle), but different for PN_{23 Counter} (measured by Airyx Plume Chasing vehicle). The trends for the three different particle measurement metrics are similar across the different Euro emission standards and fuel types. The AEM generally shows significantly higher emissions than the Counter, especially for N1 Euro 6d diesel vehicles. This may be due to the aforementioned overestimation of smaller solid or volatile particles, as particle filters generally

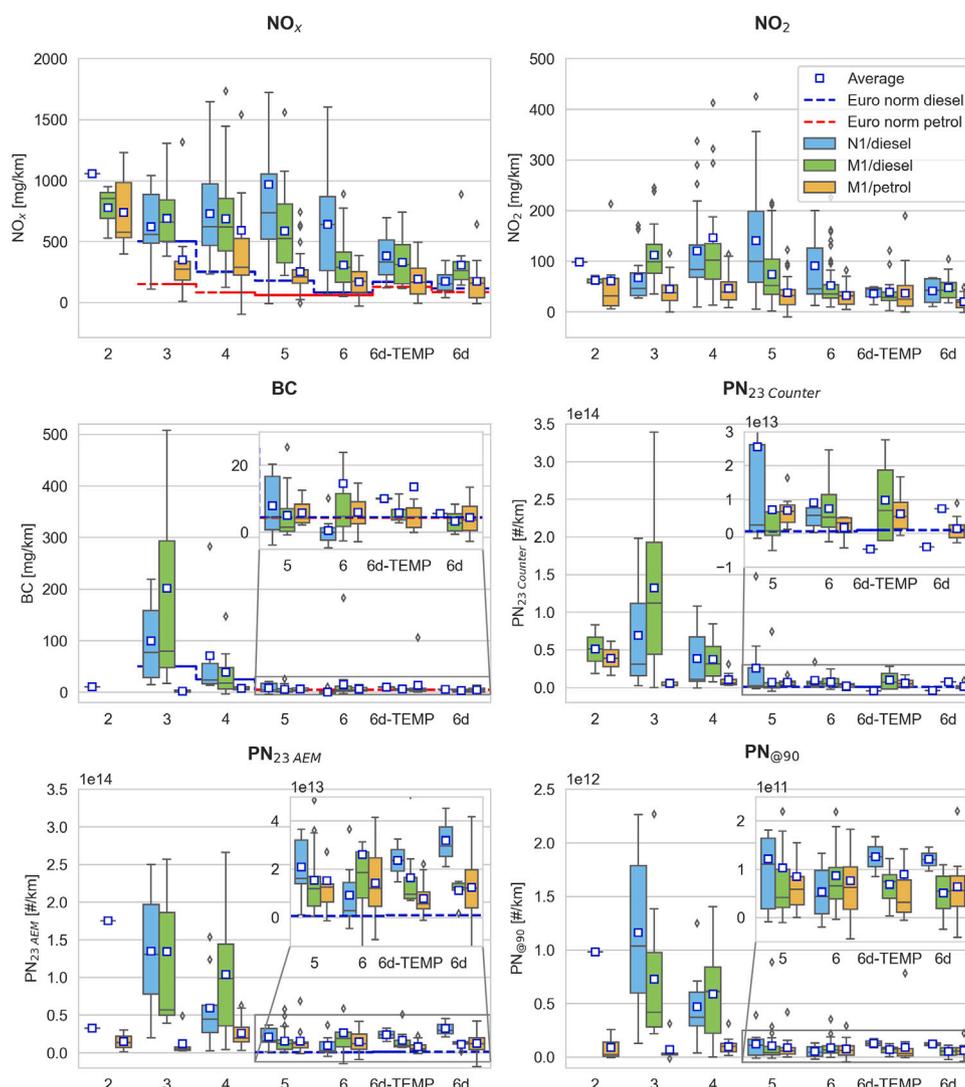


Fig. 7. Emission factors of the different measured pollutants per Euro emission standard. M1 vehicles are separated by petrol (orange) and diesel (green). N1 vehicles were mainly diesel (blue). The Euro norm limits shown are for laboratory tests up to Euro 6. For Euro 6d-Temp and 6d these are for real driving conditions, including the defined conformity factor (i.e. the difference between laboratory tests and real driving conditions). The upper whisker represents the 75th percentile +1.5 IQR and the lower whisker the 25th percentile -1.5 IQR. The diamonds represent the outliers.

favour homogeneous nucleation. Homogeneous nucleation is favoured when there are only a small number of particles present (e.g. due to removal by a filter), to which gas-phase species can adsorb (Kittelson and Imad, 1998).

Distributions of the average NO_x , NO_2 , BC, $\text{PN}_{23 \text{ AEM}}$, $\text{PN}_{23 \text{ Counter}}$ and $\text{PN}_{@90}$ emissions (EF_{kWh}) of the buses are compared in Fig. 8 and in Table 6 for different Euro emission standards.

NO_x emissions decrease with increasing Euro emission standard from about 5000 mg/kWh for Euro IV to 600 mg/kWh for Euro VI-D, with the exception of Euro V EEV, where NO_x emissions increase to the level of the measured Euro IV buses. This was also found in another study in Germany (Reber, 2018; Pöhler et al., 2020) where Euro V EEV buses were among the highest NO_x emitters. The median NO_2 emissions rise from 83 mg/kWh of Euro IV to 134 mg/kWh of Euro VI buses and only drop again for Euro VI-D buses to 70 mg/kWh. The proportion of NO_2 (i.e. the NO_2/NO_x ratio) in vehicle exhaust is relatively low (2 to 11% for M3 diesel) in comparison to the other vehicle types (6 to 16% for N2, N3 diesel and 6 to 28% for N1, M1 diesel and M1 petrol). With higher Euro emission standard, the proportion of NO_2 is increasing. The median PN and BC emissions are decreasing with increasing Euro emission standard. They show a decrease from Euro IV to Euro VI-D of a

factor of about 10. In contrast to NO_x emissions, the Euro V EEV buses show equal or smaller PN and BC emissions compared to the Euro V buses, as EEV focused mainly on reduced particle emissions (EU, 2000). From Euro V EEV to Euro VI buses, the PN and BC emissions show an additional decrease of 65 to 87%.

Distributions of the average NO_x , NO_2 , BC, $\text{PN}_{23 \text{ AEM}}$, $\text{PN}_{23 \text{ Counter}}$ and $\text{PN}_{@90}$ emissions (EF_{kWh}) of the trucks are compared in Fig. 9 and in Table 6 for different Euro emission standards. In contrast to the other vehicle types, which were mainly measured in the city, the trucks were mainly measured on the highway under high load.

In contrast to the buses, the NO_x emissions of the measured trucks decrease with increasing Euro emission standard also from Euro V to Euro V EEV. $\text{PN}_{23 \text{ Counter}}$ and $\text{PN}_{@90}$ also show decreasing emissions with increasing Euro emission standard. The same is true for NO_2 , BC and $\text{PN}_{23 \text{ AEM}}$ emissions, with the exception of Euro V EEV, where NO_2 emissions increase on the median by 43% to the level of the measured Euro IV trucks, BC by 14% and $\text{PN}_{23 \text{ AEM}}$ by 35%. It should be noted that the Euro V trucks also include some Euro V EEV and the Euro VI trucks include some Euro VI-D. This may reduce the difference in emissions between the respective Euro standards. Also, a significant portion of tampered and defective trucks are included in the statistics (Schmidt et al., 2025b).

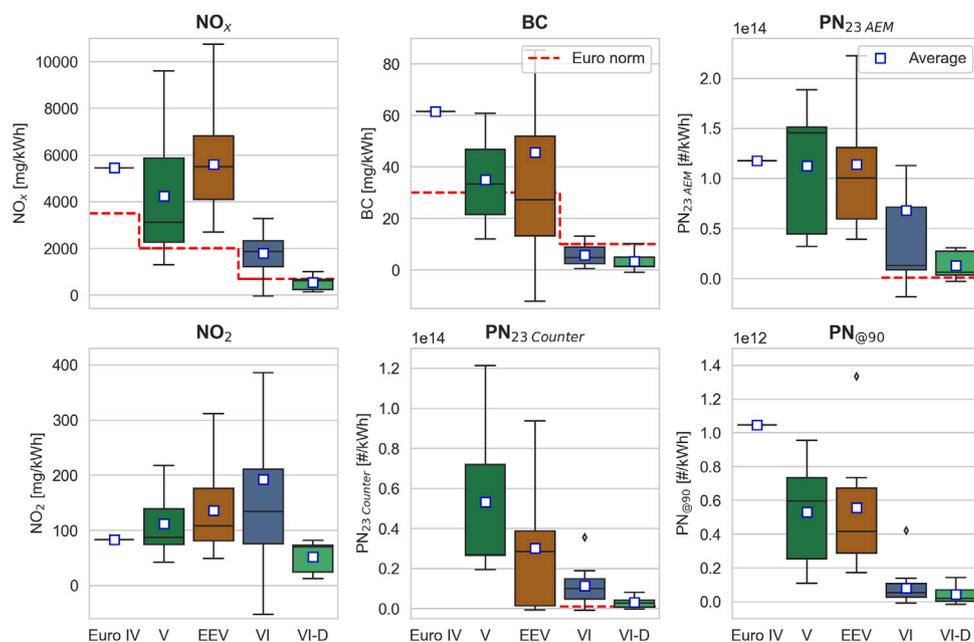


Fig. 8. Overview of the NO_x , NO_2 , BC, $\text{PN}_{23\text{Counter}}$, $\text{PN}_{23\text{AEM}}$ and $\text{PN}_{@90}$ emission factors of investigated diesel buses (M3) for different Euro emission standards by Plume Chasing. The upper whisker represents the 75th percentile +1.5 IQR and the lower whisker the 25th percentile -1.5 IQR. The diamonds represent the outliers.

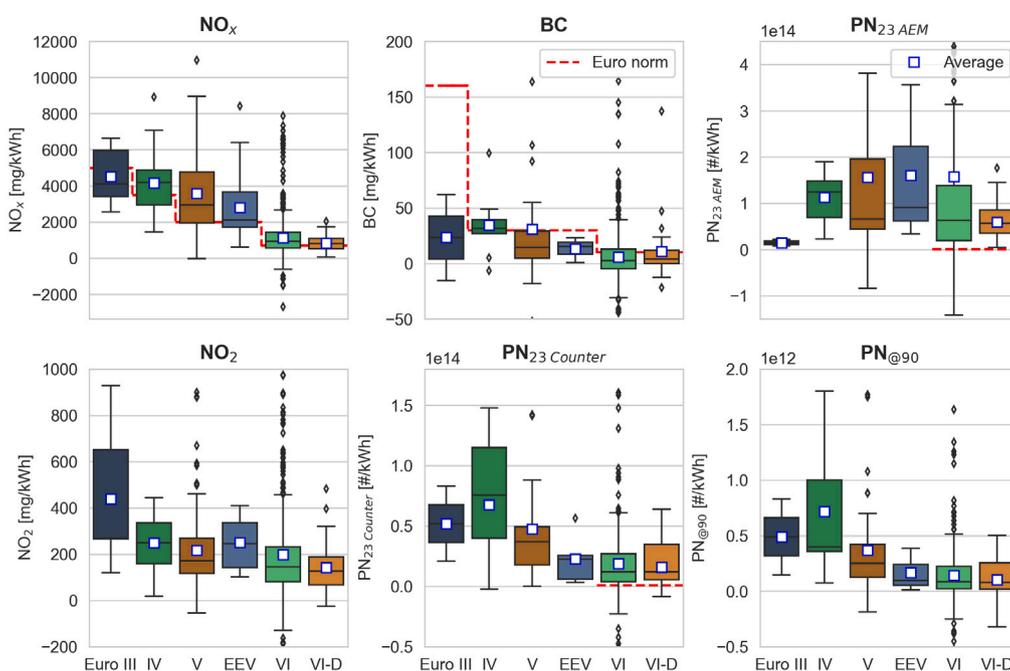


Fig. 9. Overview of the NO_x , NO_2 , BC, $\text{PN}_{23\text{Counter}}$, $\text{PN}_{23\text{AEM}}$ and $\text{PN}_{@90}$ emission factors of investigated trucks (N2, N3) for different Euro emission standards by Plume Chasing. The upper whisker represents the 75th percentile +1.5 IQR and the lower whisker the 25th percentile -1.5 IQR. The diamonds represent the outliers.

Within one Euro emission standard a relatively wide spread of the emission values was found (Figs. 7, 8 and 9). In most cases, the average emission value is higher than the median, showing that high emitters have a significant influence on overall average emissions. The magnitude of this influence is investigated further in Fig. 10. The cumulative distribution of emissions, defined as the fraction of total emissions in dependence of the fraction of the vehicles ordered by emissions from highest to lowest, is shown separately for each pollutant. For diesel passenger cars (top, left), diesel LCVs (bottom, left) and to a lesser extent

buses (bottom right), trucks (Appendix, Figure S9) and petrol passenger cars (top right), the proportion of vehicles responsible for 50% of the emissions is more pronounced for BC and PN than for NO_x and NO_2 . For BC, 3% (diesel passenger cars), 8% (trucks), 10% (diesel LCVs), 12% (buses) and 13% (petrol passenger cars) are responsible for 50% of the emissions. For the PN measures, the percentage responsible for 50% of the emissions is 1–8% higher than for BC in all cases. BC is generally a reliable indicator of high vehicle exhaust emissions, vehicle failure or poor condition. The soot accumulation mode, which is primarily

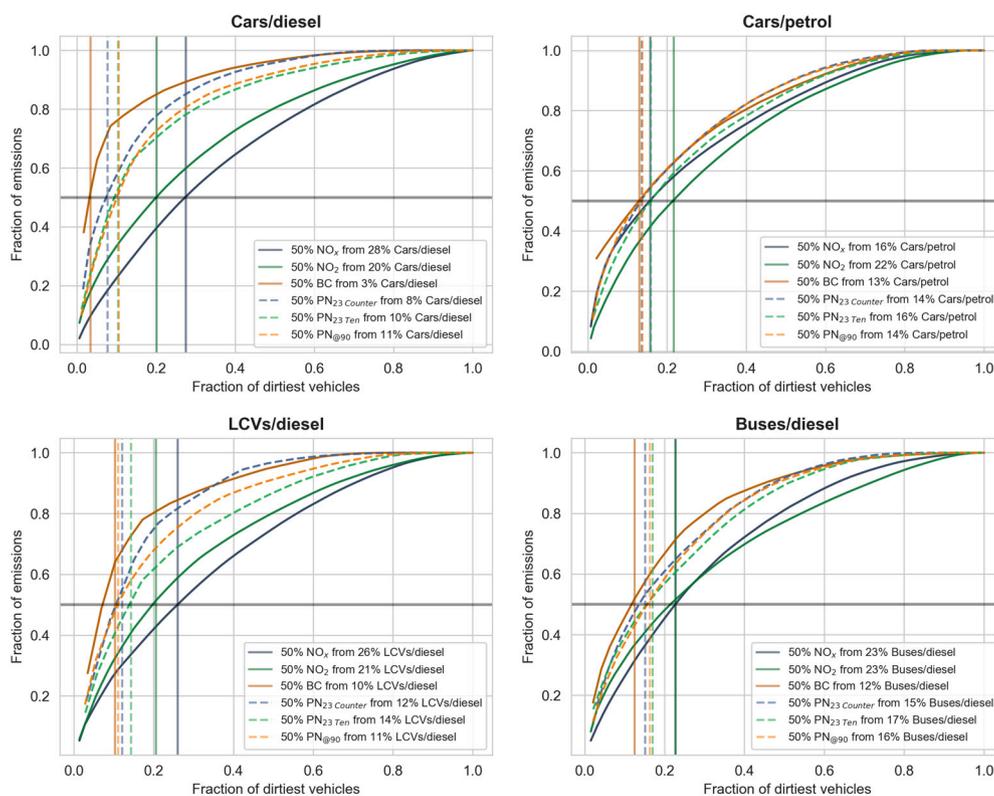


Fig. 10. Cumulative distributions — fraction of total emissions in dependence of the fraction of the vehicles ordered by emissions from highest to lowest. We set negative emission results to zero. Negative values appear due to the BG determination of the pollutants. If there is an elevated concentration of the pollutant (e.g. due to other emission sources in the environment) at the time when the CO₂ emissions have their minimum, negative emission values may occur.

responsible for BC emissions, is filtered with the highest efficiency. Therefore, in the case of vehicles without a filter, or with a damaged filter, this can be identified through BC measurement. For gasoline cars, BC emissions can be more pronounced at low temperatures and in the event of potential engine degradation (Platt et al., 2017). For NO_x, 28 % (diesel passenger cars), 18 % (trucks), 26 % (diesel LCVs), 23 % (buses) and 16 % (petrol passenger cars) are responsible for 50 % of the emissions in its vehicle group. For NO₂, these are 20 %, 20 %, 21 %, 23 % and 22 %, respectively.

3.3.3. Comparison with other remote emission sensing studies and techniques

Plume Chasing fleet measurements show good agreement with the results from PS and ORSD fleet measurements obtained during the 2022 Czech campaign (Figures S11 to S15). The consistency in the results is discussed in more detail in Section 4.1 in the Appendix. Tables 7 and 8 compare the average emissions from this study with previous Plume Chasing, PS and open-path RES studies. Only studies with available Euro emission standards are listed, to enable comparison of the findings separated by Euro emission standard. Overall, the RES techniques applied here deliver results consistent with the literature.

A significant decrease in average BC, PM and PN emissions is observed from Euro 4 to Euro 5 diesel vehicles, reflecting the introduction of DPFs. This pattern agrees with all cited studies. Average NO_x emissions of diesel cars are halved from Euro 5 to Euro 6 and further for Euro 6d vehicles due to the introduction of RDE requirements. This is consistent with previous studies such as from the TRUE initiative (Bernard et al., 2021). However, Plume Chasing measurements of this study found higher Euro 6d NO_x emissions (note limited sample size) than PS, ORSD and a Slovenian Plume Chasing study (Ježek Breclj et al., 2025). A similar trend is found for BC emissions of Euro 6 diesel cars measured by Plume Chasing.

For petrol cars, compared with diesel, all three RES techniques consistently found lower NO_x and particle (PN larger than 23 nm) emissions. The findings for PS and ORSD are consistent with those of previous studies (e.g. Knoll et al., 2024a; Bernard et al., 2021; Schmidt and Pöhler, 2023; Ježek Breclj et al., 2025). The same applies to Plume Chasing for BC and PN emissions, but for NO_x emissions higher values are found for Euro 4 to 6d petrol cars by Plume Chasing. Deviations can be attributed to the smaller Plume Chasing sample size and different driving conditions relative to PS and ORSD measurements.

For LCVs, similar NO_x emissions are found as in a study in Slovakia in 2023 (Schmidt and Pöhler, 2023). For Euro 6 LCVs, the emissions in Schmidt and Pöhler (2023) are found to be lower. This is plausible, as the Euro 6 category of this study includes Euro 6d-TEMP and 6d LCVs, which have lower emissions than Euro 6b,c LCVs. The Plume Chasing study in Slovakia found significantly lower BC and PN emissions, likely due to different characteristics of the vehicle fleet and measurement locations. PS finds (up to 4 times) higher average PN emissions for Euro 3 and 4 LCVs than Plume Chasing. These differences are to be expected, given the higher variability in emissions for high-emitting vehicles and the fact that PS measurements were conducted at spots where vehicles were accelerating (higher emissions expected).

For trucks, the average emissions of our study are in good agreement with the results of previous Plume Chasing (e.g. Schmidt et al., 2025a; Ježek Breclj et al., 2025), PS (e.g. Knoll et al., 2024a) and open-path RES (e.g. Bernard et al., 2023) studies. For a more detailed comparison and discussion, see Schmidt et al. (2025b).

For buses, the found Plume Chasing NO_x emissions are consistent with those from an earlier Plume Chasing study (Reber, 2018) when the separation of Euro VI and Euro VI-D buses is taken into account. PS studies (e.g. Knoll et al., 2024a) reported lower Euro V NO_x emissions for buses than those obtained here with the three RES techniques. BC and PN emissions agree with previous PS studies, except for Euro III and IV PN emissions, which are a factor 2 to 5 lower. Due to differences

Table 7

Comparison of the mean emission factors (in g or # per kg fuel). If the studies do not differentiate between Euro 6, 6d-TEMP and 6d, the emissions are assigned to Euro 6.

Type/Fuel	Study	Pollutant X	$EF_{kg\ fuel}$					
			Euro 3	Euro 4	Euro 5	Euro 6	Euro 6d-TEMP	Euro 6d
M1/petrol	This study Plume Chasing	NO _x [g/kg fuel]	6.2	11.5	5.2	3.6	4.6	4.3
	This study PS, ORSD		6.3, 8.4	6.5, 6.9	2.6, 2.7	2.3, 1.8	1.6, 0.9	1.3, 1.3
	Plume Chasing studies ^{1,3}		4.1–12.0	1.5–4.3	0.9–3.5	1.8–4.2		3.5
	PS studies ²		7.0	5.7	3.9	2.3		
	Open-path RES studies ^{4,5,6,7}		5.1–14.5	3.8–7.2	2.5–3.3	–0.5–3.2		
	This study Plume Chasing	BC, PM [g/kg fuel]	0.03 ^a	0.14 ^a	0.15 ^a	0.13 ^a	0.26 ^a	0.10 ^a
	This study PS, ORSD		0.15 ^a , 0.14 ^b	0.12 ^a , 0.12 ^b	0.18 ^a , 0.09 ^b	0.14 ^a , 0.06 ^b	0.06 ^a , 0.04 ^b	0.04 ^a , 0.05 ^b
	Plume Chasing studies ^{1,3}		0.06–0.35 ^a	0.06–0.2 ^a	0.07–0.1 ^a	0.03–0.06 ^a		0.11 ^a
	PS studies ²		0.19 ^a	0.15 ^a	0.17 ^a	0.10 ^a		
	Open-path RES studies ^{4,5,6,7}		0.03–0.67 ^b	0.02–0.2 ^b	0.03–0.09 ^b	0–0.1 ^b		
This study Plume Chasing	PN ₂₃ (-10 ¹³) [#/kg fuel]	10.1	18.9	12.4	3.7	16.4	3.8	
This study PS		35.8	16.2	28.7	24.4	13.9	7.4	
Plume Chasing studies ³			10.1	9.8	2.1			
PS studies ²		24.3	17.4	21.0	13.2			
M1/diesel	This study Plume Chasing	NO _x [g/kg fuel]	14.0	12.6	12.8	7.2	8.1	5.9
	This study PS, ORSD		17.3, 17.9	14.1, 13.1	12.4, 11.7	7.3, 6.2	3.4, 2.5	2.5, 1.8
	Plume Chasing studies ^{1,3}		11.3–19.9	11.9–15.9	8.1–14.2	5.0–12.3		1.4
	PS studies ^{2*}		14.3	13.5	12.6	5.5		
	Open-path RES studies ^{4,5,6,7}		13.7–18.7	11.6–15.4	11.7–14.4	5.8–8.5		
	This study Plume Chasing	BC, PM [g/kg fuel]	3.97 ^a	0.76 ^a	0.12 ^a	0.42 ^a	0.08 ^a	0.04 ^a
	This study PS, ORSD		2.23 ^a , 1.09 ^b	1.25 ^a , 0.61 ^b	0.25 ^a , 0.13 ^b	0.08 ^a , 0.04 ^b	0.10 ^a , 0.04 ^b	0.05 ^a , 0.04 ^b
	Plume Chasing studies ^{1,3}		0.67–2.25 ^a	0.54–0.95 ^a	0.15–0.37 ^a	0.07–0.16 ^a		0.05 ^a
	PS studies ²		1.79 ^a	0.92 ^a	0.26 ^a	0.08 ^a		
	Open-path RES studies ^{4,5,6,7}		0.17–1.84 ^b	0.13–1.08 ^b	0.02–0.27 ^b	0.01–0.07 ^b		
This study Plume Chasing	PN ₂₃ (-10 ¹³) [#/kg fuel]	25.6	70.6	12.3	18.2	19.9	12.0	
This study PS		286.6	183.0	31.1	10.1	14.1	4.7	
Plume Chasing studies ³		152.6	92.2	28.3	6.7			
PS studies ²		222.3	137.7	35.1	11.7			
N1/diesel	This study Plume Chasing	NO _x [g/kg fuel]	12.4	13.1	16.3	10.6	6.5	3.2
	This study PS, ORSD		10.1, 19.4	10.3, 15.1	15.3, 18.5	8.4, 9.3	3.1, 2.5	3.0, 2.4
	Plume Chasing studies ³		13.0	13.7	14.2	7.1		
	This study Plume Chasing	BC, PM [g/kg fuel]	2.00 ^a	1.37 ^a	0.14 ^a	0.01 ^a	0.17 ^a	0.11 ^a
	This study PS, ORSD		2.22 ^a , 1.48 ^b	2.00 ^a , 0.90 ^b	0.25 ^a , 0.14 ^b	0.08 ^a , 0.05 ^b	0.11 ^a , 0.02 ^b	0.09 ^a , 0.06 ^b
	Plume Chasing studies ³		0.60 ^a	0.51 ^a	0.05 ^a	0.06 ^a		
	This study Plume Chasing	PN ₂₃ (-10 ¹³) [#/kg fuel]	136.5	70.0	47.7	15.3	–8.1	–6.7
	This study PS		339.9	284.0	33.2	11.4	11.0	19.6
	Plume Chasing studies ³		161.0	103.0	–8.6	6.3		

¹ Ježek Breclj et al. (2025), ² Knoll et al. (2024a), ³ Schmidt and Pöhler (2023), ⁴ Cha and Sjödin (2022), ⁵ Jerksjö et al. (2022), ⁶ Bernard et al. (2021), ⁷ Hooftman et al. (2020)

^a BC, ^b PM.

in maintenance, bus emissions may vary significantly from city to city and country to country. For Euro VI-D buses, ORSD finds significantly higher NO_x and PM emissions due to one manufacturer measured only by ORSD, resulting in higher average Euro VI-D PM emissions than for Euro III buses.

In general, the range of measured particle emissions in studies is much wider (up to one order of magnitude) than that for NO_x. The reasons for this are manifold: there are various particle metrics, and the results depend heavily on the measuring setup and method. Additionally, the range of particle emissions is greater due to high emitters than it is for NO_x, for example. Sampling-based systems have different capabilities than spectroscopic open-path systems, as they are able to measure metrics such as BC and PN in addition to PM. The measured emissions are very dependent on the size of the particles, especially in the case of PN, as well as on whether volatile components are included. This is demonstrated by comparing with the work of Olin et al. (2023), who included semi-volatile particles with different size cutoffs. The results of PN measurements are expected to differ significantly depending on the size cut-off used (e.g. 2.5 nm or 23 nm) as well as on the expected particle size distribution of the emissions (e.g. difference between petrol and diesel). This shows that measurement results must be treated with care and carefully explored when compared.

Recently reported Plume Chasing truck measurements from China (Yang et al., 2025) show that Euro III and IV match the results from

China V (19.8–23.2 g/kg fuel NO_x emissions) and Euro V match the results from China VI vehicles (14.1–17.4 g/kg fuel NO_x emissions). Plume Chasing fleet measurements from 2024 in Uganda (Africa) (Crowe et al., 2025) show that the emissions of diesel and petrol cars, LCVs and minibuses showed emissions several times above the Euro 4 NO_x and PM regulatory limits. The NO_x emissions of trucks were found to be about 28.4 g/kg fuel which is close to our findings on the emissions of Euro III and IV trucks. BC emissions were found to be up to about 9.4 g/kg fuel for older trucks which is several times above the highest average BC and PM emissions we found in studies in Europe. This demonstrates the importance of legislation and enforcement on permitted vehicle emissions in improving air quality and, consequently, human health.

4. Conclusions

While many previous Plume Chasing validation studies focused on trucks, we have demonstrated the applicability of the Plume Chasing method for LDVs and buses in urban environments. The measurements were performed in Czechia over 11 days, focusing on the capital Prague for LDVs and buses and the D1 highway for trucks.

Validation measurements for Plume Chasing, PS and cross-road RES were performed using three light duty test vehicles (Euro 4, 5 and 6d). Portable on-board emission measurement systems (PEMS) were

Table 8

Comparison of the mean emission factors (in g or # per kg fuel). PN is PN_{2.3}. If not, it is indicated. If the studies do not differentiate between Euro V and Euro V EEV, or between Euro VI and Euro VI-D, the emissions are assigned to Euro V or Euro VI respectively.

Type/Fuel	Study	Pollutant X	$EF_{kg\ fuel}$						
			Euro III	Euro IV	Euro V	Euro V EEV	Euro VI	Euro VI-D	
buses/diesel	This study Plume Chasing	NO _x [g/kg fuel]	17.2, 28.0	22.7	19.7	25.9	7.9	2.5	
	This study PS, ORSD			–, 18.0	25.9, 20.0	9.3, 23.2	6.1, 8.2	0.9, 9.2	
	Plume Chasing studies ^{1,2}			20.8			4.4		
	PS studies ^{3,11}			16.0–20.6	13.7	5.5–15.0	3.7		
	Open-path RES studies ^{6,7}	16.5	14.0–17.5	19.0–21.5	18.0	6.8–12.8			
	This study Plume Chasing	BC, PM [g/kg fuel]	0.60 ^a , 0.93 ^b	0.20 ^a	0.16 ^a	0.21 ^a	0.04 ^a	0.02 ^a	
	This study PS, ORSD			–, 0.52 ^b	0.06 ^a , 0.08 ^b	0.07 ^a , 0.42 ^b	0.01 ^a , 0.02 ^b	0.01 ^a , 1.23 ^b	
	Plume Chasing studies			0.03 ^b –1.58 ^a	0.44 ^a	0.06 ^a –0.18 ^b	0.04 ^a		
	PS studies ^{3,11}			0.62 ^b	0.34–0.42 ^b	0.06–0.27 ^b	0.10 ^b	0.02–0.19 ^b	
	Open-path RES studies ^{6,7}								
This study Plume Chasing	PN (-10 ¹³) [#/kg fuel]	73.8 ^c	12.3 ^c	25.0 ^c	14.0 ^c	6.1 ^c	1.4 ^c		
This study PS, ORSD				12.1 ^c	9.5 ^c	0.4 ^c	–1.1 ^c		
Plume Chasing studies									
PS studies ^{3,11}			140.0 ^d –246.5 ^c	65.1 ^c	7.7 ^c –65.0 ^d	3.8 ^c			
trucks/diesel	This study Plume Chasing	NO _x [g/kg fuel]	21.3	19.6	17.0	13.5	5.4	4.0	
	This study PS, ORSD			14.1, 34.4	31.7, 30.0	18.1, 25.8	28.2, 25.8	5.9, 7.0	6.5, 4.6
	Plume Chasing studies ^{1,2,10,13}			24.0–44.8	10.1–34.9	9.3–27.5		2.7–10.7	
	PS studies ^{3,8}			22.7	19.8–25.6	15.4–22.2		3.1–6.4	
	Open-path RES studies ^{5,7,9}			19.8–29.4	13.3–23.7		2.7–7.9		
	This study Plume Chasing	BC, PM [g/kg fuel]	0.11 ^a	0.16 ^a	0.15 ^a	0.06 ^a	0.03 ^a	0.05 ^a	
	This study PS, ORSD			3.89 ^a , 0.96 ^b	0.73 ^a , 0.22 ^b	0.57 ^a , 0.27 ^b	0.26 ^a , 0.21 ^b	0.01 ^a , 0.22 ^b	–0.12 ^a , 0.13 ^b
	Plume Chasing studies ^{1,2,13}			0.63–0.72	0.18 ^a –1.56 ^a	0.03 ^a –1 ^a		0 ^a –0.12 ^a	
	PS studies ^{3,8}				0.17 ^b –0.38 ^a	0.15 ^b –0.29 ^a		0.01 ^b –0.04 ^a	
	Open-path RES studies ^{7,9}			0.21–1.24 ^b	0.04–0.21 ^b		–0.07–0.01 ^b		
This study Plume Chasing	PN (-10 ¹³) [#/kg fuel]	25.4 ^c	31.4 ^c	22.5 ^c	11.0 ^c	9.0 ^c	7.7 ^c		
This study PS, ORSD				100.5 ^c	126.4 ^c	4.7 ^c	10.8 ^c	–13.3 ^c	
Plume Chasing studies ^{2,4}				30.3–308.1	12.8–94.8		3.8–11.8		
PS studies ^{3,8}				46.0 ^c –87.2 ^d	52.1 ^c –97.1 ^d		8.5 ^c –84.8 ^d		

¹ Ježek Breclj et al. (2025), ² Schmidt et al. (2025b), ³ Knoll et al. (2024a), ⁴ Olin et al. (2023), ⁵ Bernard et al. (2023), ⁶ Lee et al. (2022) ⁷ Cha and Sjödin (2022), ⁸ Zhou et al. (2020), ⁹ Hoofman et al. (2020), ¹⁰ Vojtisek-Lom et al. (2020), ¹¹ Liu et al. (2019), ¹² Reber (2018), ¹³ Lau et al. (2015)

^a BC, ^b PM, ^c PN > 23 nm, ^d PN > 5.6 nm.

attached to the vehicles for reference purposes. To compare Plume Chasing, OSRD and PS measurements in real traffic conditions, multiple test drives were conducted on a defined route. When comparing the average emissions of multiple rounds all three RES techniques can clearly observe the emission difference for all pollutants. The results show good agreement with the reference data within the measurement uncertainties. As vehicles are usually only measured once to determine their emissions, it is important to also consider the single measurements. Here we found that Plume Chasing is generally more accurate than roadside measurements because it involves a longer measurement time compared to ORSD (hundreds of milliseconds) and PS (a few seconds). The standard deviation (scatter) of e.g. the NO_x measurements is two to six times higher for the other two RES technologies than for Plume Chasing. In the case of particle emissions, the difference is more pronounced for high emitters, but similar for Plume Chasing and PS for low emitters, where emission variability is lower. The more frequently a vehicle is measured by PS or ORSD, the closer the average result comes to the average reference (PEMS) emission result, similar to results obtained by Qiu and Borken-Kleefeld (2022). When comparing emission results of the investigated vehicle fleet between Plume Chasing, ORSD and PS, the results are similar to those of the test vehicles. The single PS and ORSD measurements deviate quite strongly from the single Plume Chasing measurements with a R^2 for LDVs of 0.51 and 0.17 (NO_x) and 0.25 and 0.63 (PM, BC) for ORSD and PS respectively. However, the regression slopes are closer to 1 for NO_x emissions (1.17 and 0.9 for ORSD and PS, respectively), whereas differences were observed for PM and BC emissions (0.21 and 1.96, respectively).

We have also demonstrated that interference from high-emission sources, such as buses or vans, can lead to the overestimation of vehicle emissions for Plume Chasing measurements of vehicles with lower Euro

emission standards. We proposed strategies to mitigate this issue, such as excluding downhill sections from the Plume Chasing processing, or sections with high-emitting vehicles in front of the chased vehicle or in the oncoming traffic. A comparison with modelled emission factors from COPERT or HBEFA for the investigated vehicles could further improve the understanding of the relevance of the measurement location, and also of model performance.

Significant differences were found between the instruments used to measure PN. It is very important to select the instruments carefully. When it comes to PN emissions, the following factors must be considered: the size cut-off (e.g. 10 or 23 nm), the counting efficiency curve, the efficiency of removing volatile particles, the measuring principle and the calibration. Significant differences of more than 100 % can be observed if these aspects are not taken into account.

In addition to the validation measurements, the Plume Chasing method was successfully used to measure several hundred LDVs, buses and trucks. Emission factors for NO_x, NO₂, BC and PN could be derived. As expected, the emissions of the measured diesel fleet decrease as Euro emission standards increase. We see a strong decrease in NO_x emissions of diesel passenger cars (M1) from Euro 6 onwards. This reduction is also visible for LCVs (N1) from Euro 6d-Temp onwards. BC and PN emissions of diesel and petrol LDVs reduce with Euro 5, and stay at about the level of Euro 5 with higher Euro emission standards. Some diesel vehicles have very high particle emissions, which is probably due to defective or removed DPFs. Compared to the official thresholds of the LDV Euro emission standards, most of the measured vehicles show higher real driving emissions. This is particularly true when it comes to NO_x and PN measurements. Here, the median is up to 8 times the Euro emission standard. For buses and trucks, the PN emissions are even up to 12 times the Euro emission standard. For NO_x and BC emissions, the situation is different for vehicles above Euro VI-D and Euro VI,

respectively, where most vehicles exhibit emissions within the expected range (below the Euro VI emission standard).

We found that 50% of the emissions come from only a few percent of the vehicles. This proportion is the smallest for BC emissions of diesel passenger cars (3%) and the highest for NO_x emissions of diesel passenger cars (28%).

CRedit authorship contribution statement

Christina Schmidt: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Denis Pöhler:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Markus Knoll:** Writing – review & editing, Resources, Methodology, Investigation. **Michal Vojtíšek:** Writing – review & editing, Resources, Methodology, Investigation. **Martin Pechout:** Writing – review & editing, Resources, Investigation. **Thomas Frateur:** Writing – review & editing, Investigation. **Jan Pieter Lollinga:** Investigation. **Norbert E. Ligterink:** Resources, Project administration. **Ulrich Platt:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL [DeepL.com] in order to improve readability and language of the work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2026.181391>.

Data availability

Data will be made available on request.

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