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

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Abstract. Real-world vehicle emissions measurement methods were developed to bridge the gap between laboratory tests and actual on-road emissions, including the variability in vehicles, drivers, and environmental conditions. The on-road chasing method is a cost-effective approach capable of capturing emissions from numerous vehicles. While it has been used extensively to measure truck emissions, it has not been applied systematically to diesel- and gasoline-powered cars. This study addresses that gap by comparing data from three on-road chasing campaigns conducted in 2011, 2017, and 2023 to evaluate the impact of emissions control technologies and regulatory policies on diesel- and gasoline-powered vehicles. Results show that diesel particulate filters (DPFs) reduce black carbon (BC) emission factors by 88 % compared to pre-DPF Euro 4 diesel-powered cars, while real driving emissions (RDE) regulations lower nitrogen oxide (NO_x) emissions by 86 % relative to pre-RDE Euro 6b diesel-powered cars. This is the first study to apply the chasing method over a decade to a representative sample of European vehicles and to report real-world BC emission factors for cars compliant with Euro 5b–6d. Lorentz curve analysis reveals a growing influence of high-emission vehicles ("super-emitters") on total fleet emissions, suggesting that targeting super-emitters could yield substantial reductions in traffic-related pollution. Despite methodological variability, the results are consistent across campaigns and align with major regulatory milestones, thus confirming the chasing method's utility as a robust tool for super-emitter identification and fleet-wide emissions monitoring. By providing real-world evidence of regulatory effectiveness, this work supports scientific understanding and confidence in emissions policy.

1 Introduction

Traffic contributes significantly to air pollution, compelling regulatory bodies to enact measures to reduce vehicle emissions. In the European Union (EU), regulations, such as 459/2012/EC (The European Commission, 2012) and 2016/646/EU (The European Commission, 2016) for passenger cars and light commercial vehicles, mandate compliance standards for all new vehicles. Over the years, the progressive tightening of European emissions standards has corresponded to mandatory implementation of exhaust after-treatment systems in vehicles. The Euro standards, which started with Euro 1 in 1992, first mandated the use of catalytic converters to meet initial carbon monoxide limits. Further reduction in nitrogen oxide (NO_x) emissions with Euro 3 (in 2000) necessitated the wider adoption of technologies like exhaust gas recirculation. More advanced systems like diesel particle filters (DPFs) and selective catalytic reduction (SCR) became increasingly essential with the introduction of the Euro 5 (in 2009) and Euro 6 (in 2014) standards, respectively (like the goods vehicle standards denoted by Roman numerals, i.e., Euro V and Euro VI). A more detailed description of progressive technological advances with respective Euro standards and associated costs can be found in Posada Sanchez et al. (2012).

In 2015, the "dieselgate" scandal shed light on critical issues within European legislation. The scandal underscored the discrepancy between emissions observed in laboratory tests, using the New European Driving Cycle (NEDC) (Economic Commission for Europe of the United Nations, 2011) – the cycle used for all new type-approved vehicles – and emissions encountered during everyday driving conditions. The cycle-beating controversy was particularly concerning, wherein vehicle manufacturers manipulated engine performance to regulate emissions solely for regulatory tests. Employing so-called defeat devices, these manufacturers optimized engine control systems to recognize testing conditions and automatically switch to a mode optimized for emissions compliance. The manufacturers defended the use of defeat devices as a measure to prevent clogging and aging. However, the Court of Justice of the European Union in case C-693/18 ruled that "only immediate risks of damage which create a specific hazard when the vehicle is driven ... justify the use of a defeat device" (Court of Justice of the European Union, 2020).

In the wake of the dieselgate scandal, the EU and its member states have recalled 8.5 million cars in the union. This initiative was aimed at repairing the affected vehicles. The rate of repair reported by the Volkswagen group reached 79.7 % by July 2018, and they offered technical service for the affected vehicles free of charge by the end of 2020. However, Volkswagen would not offer a full and clear guarantee against potential problems post-repair (Consumer rights and complaints – Coordinated actions – Dieselgate: https://commission.europa.eu/live-work-travel-eu/consumer-rights-and-complaints/enforcement-consumer-protection/coordinated-actions/dieselgate_en, last access: 20 September 2024).

The ensuing scrutiny prompted regulatory reforms, notably the introduction of the Euro 6c standard (2018), which incorporated a more realistic driving cycle – the Worldwide-harmonized Light-duty Test Cycle (WLTC) (The European Commission, 2017) – and mandated the use of a portable emissions measurement system (PEMS) in real driving emissions (RDE) tests alongside laboratory tests in conformity assessments.

Nevertheless, the response from the authorities seems insufficient. Many of the inadequate vehicles, now between 9 and 14 years old, are still in use. An analysis by the International Council on Clean Transport (ICCT) involved 1400 tests on Euro 5 and Euro 6 diesel cars done before RDE testing was implemented (Meyer et al., 2023). This study was carried out under controlled conditions by government bodies and revealed worrisome findings: "suspicious" NO_x emission levels were detected in 77 % to 100 % of the tests and vehicles tested, while "extreme" NO_x emissions occurred in 40 % to 75 % of the cases. These results suggest the likely and almost certain use of prohibited defeat devices in Euro 5 and pre-RDE Euro 6 diesel cars.

The study by Giechaskiel et al. (2022) confirmed that expert tampering is still possible for vehicles that comply with current Euro standards, leading to extreme increases in emissions. They showed that tampered passenger cars' NO_x and particle number emissions were 10 times higher than those during a regeneration event.

Adopting new exhaust after-treatment technologies brings additional production and maintenance expenses. In 2012, the cost of a complete exhaust after-treatment system compliant with Euro 6 standards for light-duty diesel vehicles was estimated to be between EUR 1300 and 1750 (Posada Sanchez et al., 2012). One basic maintenance requirement for systems using SCR is refilling the diesel emission fluid commonly known as AdBlue. The cost of refilling the fluid varies depending on the vehicle, its use, and its driving style. For a heavy-goods vehicle, this can add up to EUR 2700 annually. The system also includes several sensors, which can trigger dashboard warnings and initiate a countdown to engine shutdown if issues arise. To circumvent the maintenance costs, some have turned to using AdBlue emulators. These devices bypass the SCR system by sending false signals to the emission controls, suggesting that the system is functioning correctly and preventing the vehicle from entering the limp mode, where the vehicle's speed is reduced and less important parts like air conditioning are switched off (Ellermann et al., 2018). In a report to the Danish Road Traffic Authority (Janssen and Hagberg, 2018), the chasing method was tested against PEMS and was suggested as a possible screening tool to find heavy-duty vehicles not compliant in terms of emissions.

In this context, on-road vehicle emissions measurements serve as a critical tool not only for assessing compliance but also for driving policy discussions and fostering transparency within the automotive industry.

This paper seeks to explore the implications of on-road emissions measurements for diesel-powered cars, with a focus on the significant reductions achieved in BC and NO_x emissions. Although BC is not regulated as an exhaust pollutant, it represents 48 % of the emitted particle mass (Landis et al., 2007), is a strong climate forcer, and has well-documented health impacts (Bond et al., 2013; Janssen et al., 2012). Traffic emissions are the second-largest contributor to BC emissions (European Environment Agency et al., 2020). The inclusion of BC in the new EU Clean Air Directive 2024/2881 (The European Parliament, 2024) further highlights the need for robust real-world data. Our findings help fill this gap.

The on-road chasing method has thus far been used extensively in China to monitor the effectiveness of heavy-goods vehicles' emissions (Wang et al., 2023, 2015, 2011, 2012; Yang et al., 2025, 2024; Zeng et al., 2024). Ježek et al. (2015a) reported the first BC emission factors (EFs) for diesel cars in Europe. In this study, we updated the

BC EF for diesel-powered cars with previously unpublished Euro 5b–6d standards. Through a comprehensive analysis of three on-road vehicle-chasing campaigns, we aim to elucidate the effectiveness of regulatory measures, the role of independent monitoring, and the prospects for advancing toward cleaner and more sustainable transportation systems. Three on-road chasing measurement campaigns were conducted in the decade when exhaust after-treatment system devices such as DPFs and SCR were made mandatory for diesel-powered vehicles, capturing the dieselgate scandal and the effects of more stringent testing with PEMS and RDE for type approvals. The results of the three campaigns show a decreasing trend in vehicle BC and NO_x EFs. Categorizing vehicles by their respective vehicle emissions standards, we show the effectiveness of the standards and the consistency of the chasing method results. We also calculate the contribution of super-emitters and present them with Lorentz curves and Gini indices in order to compare the three campaigns.

2 Methods

Three on-road chasing campaigns were conducted in the 12 years in Slovenia (Europe). The first one was conducted in winter in December 2011, while the second and third campaigns were conducted in spring: March 2017 and May 2023. All three were carried out on regional roads and highways. The results of the 2011 campaign were published in Ježek et al. (2015a), while the results of the 2017 and 2023 campaigns were not published before.

The average daily weather conditions of each campaign are summarized in Table 1: temperature, relative humidity, and wind speed at the Ljubljana measurement station as reported by the Slovenian Environmental Agency. The entire list of measurement dates and weather conditions is shown in Table S1 in the Supplement.

We employed the same on-road chasing approach as tested in Ježek et al. (2015b) and adopted in the 2011 campaign by Ježek et al. (2015a), where more details on the method are described and a comparison to other remote sensing campaigns was made. In short, with the on-road chasing measurements, the increase in pollutants over their background concentrations is determined by chasing a single vehicle on the road and then deducting the background concentrations obtained before and/or after the vehicle measurement. Assuming equal dilution of all released pollutants and complete combustion of fuel, in which practically all of the carbon in the fuel is converted into CO_2 (Hansen and Rosen, 1990), the EF is then derived as the ratio of the pollutant (P) to CO_2, where CO_2 is then used to estimate the amount of fuel burned:

$$\mathrm{EF}_P = \frac{\int_{tj}^{ti} \left(P_{tj} - P_{ti}\right) \mathrm{d}t}{a \cdot \int_{tj}^{ti} \left(\mathrm{CO}_{2\,tj} - \mathrm{CO}_{2\,ti}\right) \mathrm{d}t} \cdot w_\mathrm{c}, \tag{1}$$

where the coefficient a in the denominator represents the mass ratio between C and CO_2 ($a = 12:44 = 0.2727$), thus converting the mass concentration of CO_2 in Eq. (1) into units of mass concentration of C (mg C per cubic meter). The carbon fractions in fuel w_c for both gasoline and diesel were set to 0.86 (Joint Research Centre: Institute for Environment and Sustainability et al., 2013). The subscripts t_i and t_j denote the times of the beginning and end of the integration step. NO_x was treated as NO_2 equivalent with a molar mass of 46 g mol (USEPA, 2010; Wang et al., 2012). Ježek et al. (2015b) found about −24/+26 % variation in the calculated EF due to the determination of the pollutant background concentration, and the dilution did not affect the calculated BC EF. Excluding other carbonaceous species from the denominator was estimated to produce a bias smaller than 10 % (Hansen and Rosen, 1990). More recent studies found < 1 % and 5 % positive biases when excluding other carbonaceous species (Dallmann et al., 2011, 2012).

Our mobile platform was a car in which we installed an Aethalometer (model AE33, Aerosol Magee Scientific) to measure an equivalent black carbon concentration (Petzold et al., 2013) (from here on denoted as BC), a NO_x monitor (CLD 86 in 2017 and CLDAL2 in 2023, EcoPhysics), and a CO_2 monitor (GMP 343, Vaisala). The list of the used instruments, their time resolutions, and their measurement uncertainties is provided in Table 2. The instruments were powered by three 100 Ah batteries. The inlet was positioned on the right-hand-side window of the mobile platform; isokinetic sampling was not attempted as it is not deemed necessary at the vehicle's speeds (Wang et al., 2011). The AE33 was equipped with a $PM_{2.5}$ cyclone as a size-selective inlet.

During each chase, we recorded the vehicle license plate number of each chased vehicle and thus obtained more detailed vehicle information such as vehicle age, fuel type used, and vehicle type according to Directive 2001/116/EC (The Commission of the European Communities, 2001) from the registry of the Slovenian Ministry of Infrastructure and Spatial Planning. We disregarded the measurement of vehicles for which we could not get the registry information.

On average, the duration of each chase was around 1.5 min in both the 2017 and 2023 campaigns, while in 2011 it was 2.5 min (Ježek et al., 2015a). We discarded any chase that was shorter than 0.5 min. The longest chases were 13.4 min in 2017 and 4.5 min in 2023. The traveling speed changed in each chasing episode. In 2011, most trucks' speeds were between 80 and 90 km h^{-1}, and for cars this was between 100 and 130 km h^{-1} (Ježek et al., 2015a). In 2017 and 2023, more measurements were made on regional roads or when traveling through small towns, so the speed was lower, mostly between 50 and 90 km h^{-1}.

Table 1. Summary of the average daily conditions as reported by the Slovenian Environmental Agency for the Ljubljana Bežigrad station (https://meteo.arso.gov.si/met/sl/app/webmet/, last access: 30 October 2024).

Campaign	Measurement period	Average daily T range (°C)	Daily avg. relative humidity range	Avg. wind speed ($m\,s^{-1}$)
2023	3 to 19 May	11.9 to 18.1	58 % to 85 %	0.7 to 2.3
2017	13 to 23 March	6.3 to 14.0	59 % to 89 %	0.6 to 3.1
2011*	6 to 21 December	−1.3 to 9.3	76 % to 94 %	0.6 to 1.7

* Published in Ježek et al. (2015a).

Table 2. The list of instruments used in the 2017 and 2023 campaigns, their time resolutions, their sampling flows, and their measurement uncertainties.

Instrumentation	Species measured	Time resolution	Instrument flow	Measurement sensitivity
NDIR sensor Carbocap GMP343 (Vaisala)	CO_2	2 s	6 $L\,min^{-1}$ (2017) 1 $L\,min^{-1}$ (2023)	3 ppm
Aethalometer AE33 (Aerosol Magee Scientific)	BC	1 s	5 $L\,min^{-1}$	700 $ng\,m^{-3}$
CLD 86 (Eco Physics) (2017) AL2CLD (Eco Physics) (2023)	NO_x NO_x	1 s 1 s	0.1 $L\,min^{-1}$ 1 $L\,min^{-1}$	1 % of the measurement value

3 Results

Our total fleet sizes were 406 and 256 vehicles in 2017 and 2023, respectively. We grouped vehicles into three major categories: gasoline cars, diesel cars, and goods vehicles, as in Ježek et al. (2015a). The sample sizes for each group and vehicle type as determined by European Directive 2001/116/EC (The Commission of the European Communities, 2001) are included in Table 3 along with the sample size of the 2011 campaign by Ježek et al. (2015a), where more details on which types of vehicles were included in each group can be found. The total sample size in the 2011 campaign reported by Ježek et al (2015a) was 139. However, in this analysis, we were only able to use the results of the vehicles with the registry information available, which gave 118 in total.

In the 2011 campaign, Ježek et al. (2015a) reported that their focus was on measuring diesel cars, for which the BC EF was not published yet. The 2017 and 2023 campaigns were intended to update the BC EF for diesel-powered cars with previously unpublished Euro 5b–6d standards and to monitor how the fleet emissions changed over the decade and how effective the emissions standards were in the BC and NO_x emissions. We therefore analyzed the changes in the total EU and Slovenian fleet compositions regarding the trends in fuel used, engine size, and vehicle age over time and compared them with our vehicle fleet to check that the captured fleet is a representative sample of the measured fleet. We found that the Slovenian fleet is a good representation of the European average fleet, as the size of both increases over time at the same rate, the share of diesel- and gasoline-powered cars is approximately the same, and the engine size and car age groups are similar. The samples were representative of diesel and gasoline cars but were not as representative of goods vehicles, where our sample size was smaller. The fleet analysis can be found in Sect. S1 in the Supplement. In Sect. 3.1 we present the general trends and improvements in the EF distributions, comparing the results of gasoline cars, diesel cars, and goods vehicles from the three campaigns in 2011, 2017, and 2023. We then break down the three main vehicle categories according to their vehicle emissions standards in Sect. 3.2 and explore the effectiveness of the implemented technology and legislation. In Sect. 3.3 we demonstrate how a small fraction of vehicles disproportionally contributes to the total fleet emissions and how the Lorentz curves became more skewed over the three measurement campaigns.

3.1 Trends and improvements in emission factor distributions – comparative analysis of gasoline cars, diesel cars, and goods vehicles (2011–2023)

The trends of BC and the NO_x EF over the three measurement campaigns for the three main vehicle groups – gasoline cars, diesel cars, and goods vehicles – are presented in Fig. 1. This figure shows the EF distributions for each vehicle group across the three campaigns using box–whisker plots, including the minimum and maximum values.

Gasoline-powered cars exhibit the lowest BC and NO_x EF distributions among the three vehicle categories (the median BC EF values are 0.28, 0.04, and 0.05 $g\,kg^{-1}$ for the 2011, 2017, and 2023 campaigns, respectively). In the 2011 campaign, gasoline-powered cars' BC and NO_x EFs were

Table 3. Sample sizes in the 2023 and 2017 campaigns compared to the 2011 campaign by Ježek et al. (2015a), with the vehicle categories and their corresponding 2001/116/EC categories.

Category	Vehicle type	2001/116/EC	2023	Category total 2023	2017	Category total 2017	2011 (Ježek et al., 2015a)
Gasoline cars	Gasoline cars	M1	101	103	118	121	24
	Gasoline/LPG	M1	1		3		
	Light-goods vehicles 1	N1	1		0		
Diesel cars	Diesel cars	M1	90	122	129	170	66
	Light-goods vehicles 1	N1	32		41		
Goods vehicles	Light-goods vehicles 2	N2	2	31	53	113	28
	Buses	M3	6		15		
	Minibus	M2	1		0		
	Heavy-goods vehicles	N3	22		45		
Total			256		404		118

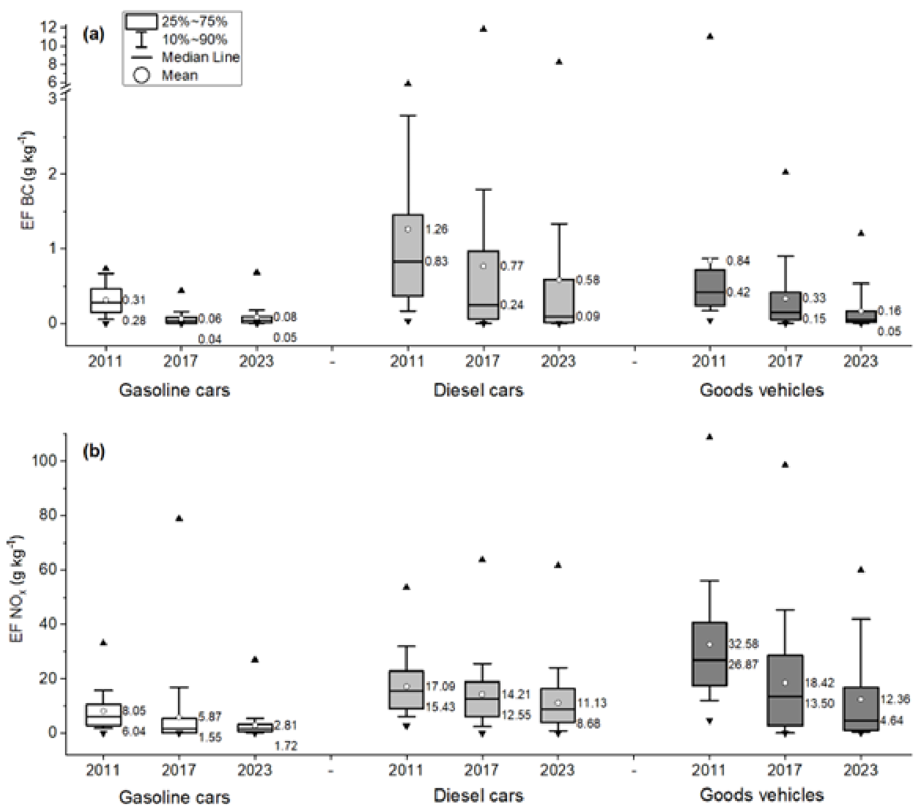


Figure 1. Box–whisker plot for the **(a)** BC EF and **(b)** NO_x EF of gasoline cars, diesel cars, and goods vehicles in the three on-road measurement campaigns conducted in 2011 (Ježek et al., 2015a), 2017, and 2023. The black triangles represent the group's minimum and maximum EFs measured in the respective campaigns. The numbers on the right of the boxplot are the median values. Note the scale break for the BC EF.

higher than those in the subsequent campaigns in 2017 and 2023. Gasoline-powered cars' maximum BC EFs from the three campaigns were all in the range of the median diesel-powered cars in 2011 ($0.83\,g\,kg^{-1}$) or the average for 2023 ($0.58\,g\,kg^{-1}$), while the maximum NO_x EFs ($33.01\,g\,kg^{-1}$ and $26.88\,g\,kg^{-1}$ in 2011 and 2023, respectively) were in the range of the 90th percentile of diesel-powered cars (or higher like in 2017, when the value was $78.83\,g\,kg^{-1}$).

Diesel-powered cars show a consistent reduction in the average, median, and interquartile range of the BC EF across the three campaigns: the median values decreased from $0.83\,g\,kg^{-1}$ in the 2011 campaign to 0.24 and $0.09\,g\,kg^{-1}$ in the 2017 and 2023 campaigns, respectively. This trend indicates significant progress in reducing particulate emissions from diesel-powered cars. However, the NO_x EF for diesel-powered cars only shows a slight reduction from the 2011 and 2017 campaigns (median values of 15.43 and $12.55\,g\,kg^{-1}$, respectively) and some improvement in 2023 (median value of $8.86\,g\,kg^{-1}$). This suggests that, while particulate emissions have been addressed effectively, NO_x emissions from diesel-powered cars remain a challenge, albeit with some improvements. The high maximum BC EF values skew the distribution of diesel-powered cars, so the median and the average values do not show the same level of improvement in the group, whereas the NO_x EF median and average are more aligned and show the same trend.

The BC EF distributions for goods vehicles generally feature slightly lower values than those of diesel cars within the same campaigns, and they exhibit a decreasing trend over time (the median values in the 2011, 2017, and 2023 campaigns were 0.42, 0.15, and $0.05\,g\,kg^{-1}$, respectively). This indicates progress in reducing particulate emissions from goods vehicles with DPFs. The goods vehicles' NO_x EF distribution values were higher than the diesel-powered cars' NO_x EF distribution in the 2011 campaign (median $26.9\,g\,kg^{-1}$), similar to the 2017 campaign (median $13.5\,g\,kg^{-1}$) and lower than diesel cars in the 2023 campaign (median $4.6\,g\,kg^{-1}$). Therefore, goods vehicles showed a more significant improvement in NO_x emissions over the three campaigns.

Overall, the EFs for BC and NO_x have generally decreased across all of the vehicle categories over the study period, reflecting advancements in vehicle technology and emissions control strategies. However, the varying reduction rates between the BC and NO_x EFs among the vehicle types highlight the ongoing challenges and areas for further improvement in emission reductions.

3.2 Analysis by vehicle emissions standards

To investigate the influence of the vehicle emissions standards, we broke down each main vehicle category into smaller subgroups according to the vehicle emissions standards for all three campaigns. To describe the locality, spread, and skewness of each group's EF distribution, we used the median and the first and third quartiles. Since the EF distributions are not normal Gaussian and are not symmetrical, the median is a more robust parameter for describing the central tendency of a distribution than the mean. The large variability in the vehicles' EF is represented by the first and third quartiles. The skewness of the data may be seen in Fig. 1, where in some cases the mean overlaps with the 75th percentile, i.e., the BC EFs for diesel cars and goods vehicles in 2023. Since we do not make any assumptions about the underlying statistics of the distribution, we use the median and the first and third quartiles to describe the locality, spread, and skewness of each group's EF distribution. Figure 2 illustrates the comparison for each subgroup across the three campaigns.

Figure 2 shows that the results for each subgroup are consistent over the three campaigns. This consistency highlights the reliability of our measurements and the trends observed in the total group EF distributions. The exceptions, as previously noted, are the gasoline cars in 2011 and the NO_x EF of goods vehicles. The discrepancies observed for gasoline cars in the 2011 campaign are likely due to the smaller sample size. Different weather conditions may have influenced the emissions, although this is unlikely since Grange et al. (2019) did not show temperature dependency on gasoline car NO_x emissions. In the case of goods vehicles, the diverse range of vehicle types and the smaller sample size contribute to the variability in NO_x emissions, making inconsistencies in these results less unexpected. The sample size of each subgroup is reported in Table S2 in the Supplement, the median and interquartile ranges for the BC and NO_x EF are in Tables S3a and S4a, respectively, and the averages for each subgroup are in Tables S3b and S4b, respectively.

Overall, the consistency in the results over the three campaigns underscores the effectiveness of the emissions standards and the improvements in vehicle technologies for reducing emissions. This detailed breakdown by vehicle emissions standards provides a clearer understanding of how specific groups have progressed over time.

Notable drops in the BC EFs were observed for diesel-powered cars and goods vehicles with the introduction of the Euro 5 and Euro V standards (88 % and 73 %, respectively). The reduction in both the median and interquartile range can be attributed to the mandatory implementation of DPFs to meet the desired particulate matter (PM) emission reductions set by these standards.

The Euro 5a diesel-powered cars' median BC EF dropped below the 25th percentile of Euro 4 in both the 2017 and 2023 campaigns. In the 2017 campaign, the Euro 5a median was $0.07\,g\,kg^{-1}$ and was much lower compared to the Euro 4 25th percentile of $0.18\,g\,kg^{-1}$. In the 2023 campaign, both values were $0.13\,g\,kg^{-1}$. With Euro 5b and later standards, the 75th percentile of the BC EF dropped below the 25th percentile of Euro 4 in both the 2017 and 2023 campaigns. These values are summarized in Table S3a.

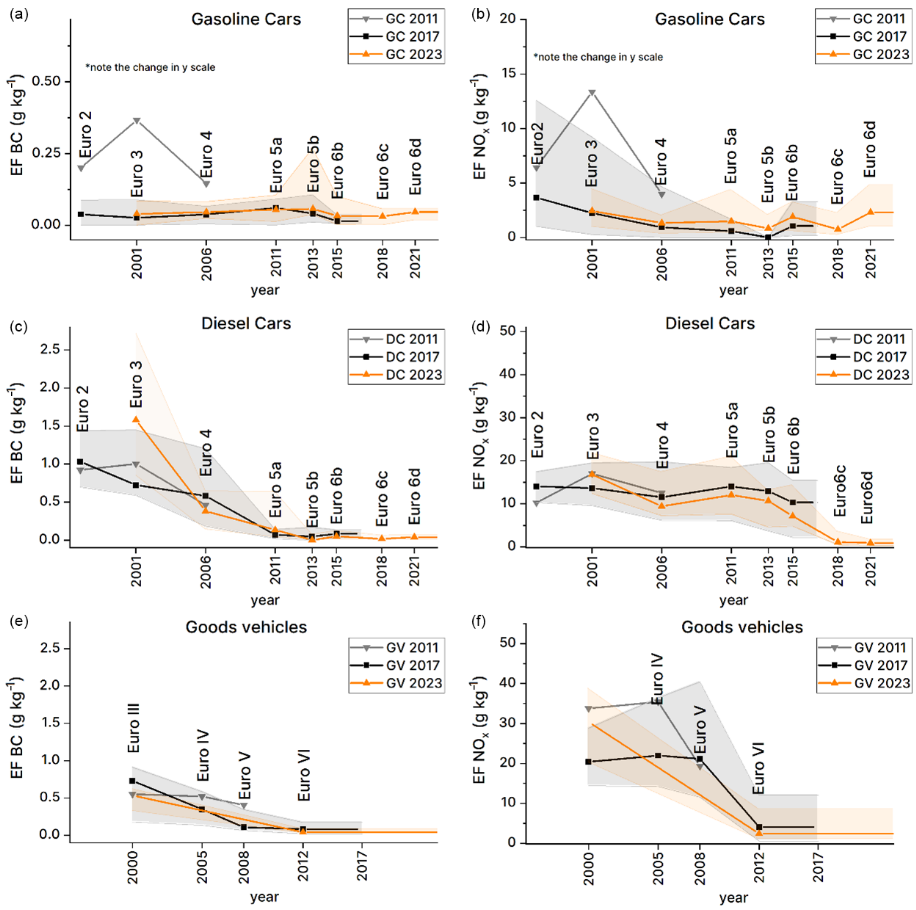


Figure 2. Black carbon **(a, c, e)** and NO_x **(b, d, f)** emission factors (EFs) for gasoline cars **(a, b)**, diesel cars **(c, d)**, and goods vehicles **(e, f)**. The points represented by the gray-inverted triangles, black squares, and orange triangles are the results for the 2011, 2017, and 2023 campaigns, respectively. They represent the median values for all vehicles that were registered after the point and belong to a specific emissions standard. The interpolated lines indicate the trend between the two standards, and the shaded area is an interpolated interquartile range of the period.

These reductions brought the diesel-powered car BC EF in line with the gasoline-powered car BC EF, reflecting the legislation that introduced PM emission limits for gasoline-powered cars with the Euro 5a standard and set the same PM emission limit for both gasoline- and diesel-powered cars ($0.005\,\mathrm{g\,km^{-1}}$ for Euro 5a and $0.0045\,\mathrm{g\,km^{-1}}$ for subsequent standards; see also Fig. S5).

Additionally, while the Euro VI standard managed to reduce the NO_x EF of goods vehicles in 2012 through the availability of new technologies such as SCR, a notable drop in the NO_x EF of diesel-powered cars was only observed after the enforcement of more stringent types of approval tests with RDE under the Euro 6c and Euro 6d standards in 2018. Our Euro 6 diesel-powered cars' results match those from the TRUE project (Bernard et al., 2021), which reports pre-RDE Euro 6 fuel-specific NO_x emissions of around $7.5\,\mathrm{g\,kg^{-1}}$ (we found a Euro 6b EF of $7.12\,\mathrm{g\,kg^{-1}}$) and $2.0\,\mathrm{g\,kg^{-1}}$ (in our work, Euro 6d was $0.9\,\mathrm{g\,kg^{-1}}$) by using the remote sensing method. Carslaw et al. (2019), who also used the remote sensing method, reported slightly higher diesel-powered cars' NO_x EF values, $9.1\,\mathrm{g\,kg^{-1}}$ for Euro 6 and $17.2\,\mathrm{g\,kg^{-1}}$ for Euro 5 in the United Kingdom. Compared to the averages of our fleet, we find that their results were similar or slightly higher. While measuring with different methods in a similar temperature range, we attribute the difference to the difference between the Slovenian and United Kingdom fleets, which would be consistent with Chen et al. (2020), who showed that the United Kingdom fleet generally had a higher NO_x EF than Spain, Switzerland, and Sweden.

Our measurements showed that gasoline-powered cars' emissions were much lower compared to diesel-powered cars until the introduction of RDE tests. Before Euro 6b, the median NO_x emissions for gasoline cars were 0 %–16 % of their diesel counterparts. For Euro 6b, gasoline-powered cars' emissions were 9 % (2017) and 27 % (2023) of diesel car emissions. After Euro 6b, diesel cars had similar or lower median NO_x emissions compared to gasoline cars.

While examining the impact of legislation on the measured fleet EF distribution, we observed that, although the median NO_x EF values did not show substantial improvement, there was a consistent reduction in the 25th percentile. Additionally, some improvement was noted in the median values of Euro 6b vehicles following the recall, as evidenced when comparing trends from the 2017 and 2023 campaigns. However, the positive shift in the EF distribution driven by lower-emission vehicles is offset by the persistence of highly polluting vehicles, particularly those at the 75th percentile, which exhibit no significant change. Despite the relative stability of median NO_x EF values among pre-RDE diesel-powered cars, a reduction in emissions can still be observed through the lowering of the 25th percentile. To evaluate whether the reductions in the diesel car NO_x EF fleet measured under real driving conditions reflected the legislation at all, we compared our NO_x EF distributions against legislative trends (Fig. 3), plotting the median, 25th percentile, and 75th percentile of each campaign's subgroups against NO_x standards from Euro 3 to Euro 6b. Euro 6c and d were excluded due to identical limits to Euro 6b but different testing methods (RDE). Linear regression and ANOVA ($\alpha = 5\,\%$) revealed that, for diesel cars, the 2023 campaign showed a significant downward trend in median and 25th percentile values, while the 2017 campaign showed a significant downward trend only in the 25th percentile values. For gasoline cars, only the 75th percentile values in the 2017 campaign showed a significant trend.

These results suggest an improvement in one-fourth of diesel cars' NO_x emissions, with vehicles achieving lower emissions in successive standards, as indicated by the decreased 25th percentiles in both campaigns. However, there was no significant change in the 75th percentile, implying that one-fourth of the vehicles remained unaffected by stricter legislation. In 2017, the median values for diesel cars did not change significantly with legislation, while in 2023 the median values for diesel cars correlated with the legislative changes. This discrepancy between the two campaigns may be the effect of the recall of 8.5 million cars in Europe by the Volkswagen group, which reached 79.7 % by July 2018.

While our goods vehicle sample size was relatively small in the 2023 campaign and most of the captured vehicles were compliant with Euro VI, we can see decreases in NO_x and BC emissions from both the 2017 and 2023 campaigns, as both drop to the level of car NO_x EFs. The results from the 2017 campaign for Euro V, Euro IV, and older (median of all $\sim 20\,\mathrm{g\,kg^{-1}}$, average $\sim 24\,\mathrm{g\,kg^{-1}}$) match the results from the Yang et al. (2025) China V vehicles (19.8–$23.2\,\mathrm{g\,kg^{-1}}$). Still, our Euro VI NO_x EF values (the medians of the 2023 and 2017 campaigns were 2.4 and $4.05\,\mathrm{g\,kg^{-1}}$, respectively, and the averages 7.76 and $10.73\,\mathrm{g\,kg^{-1}}$, respectively) are lower than those for China VI reported by Yang et al. (2025), which were 14.1 and $17.4\,\mathrm{g\,kg^{-1}}$ for medium- and heavy-duty trucks, respectively.

3.3 Super-emitter contribution

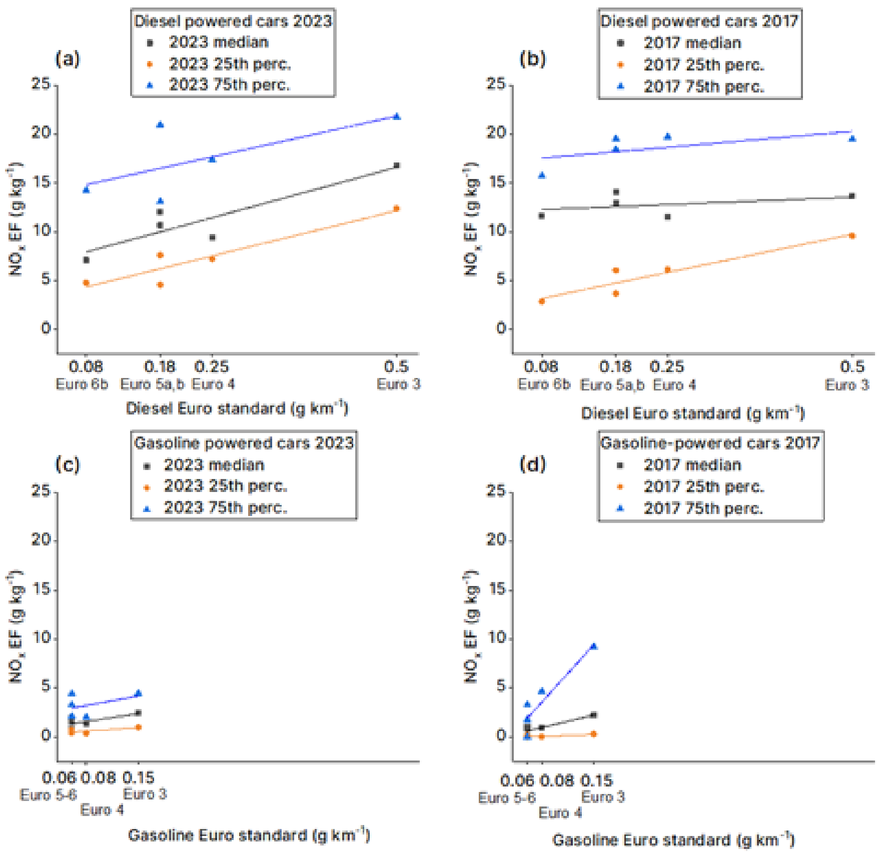
Lorentz curves are used to assess the impact of so-called super-emitters. The curves show the proportion of the total emissions (y axis) produced cumulatively by the bottom x % of the fleet, ranking vehicles from least to most polluting. A straight line between the origin (no emissions) and the maximum emissions on a 1 : 1 scale (and hence the line at 45°) would indicate equal pollution contributions by all vehicles. To compare these lines between the three campaigns, we calculated the Gini index, which represents the ratio of the area between the Lorentz curve and the perfect-equality line at 45° and the entire area under the perfect-equality line. We analyzed each campaign, vehicle group, and pollutant separately. Figure 4 reveals that the super-emitters' contribution is more skewed for BC emissions (panels a, b, and c) than for NO_x emissions (panels d, e, and f), as demonstrated by generally higher Gini indices closer to 1. The curves typically become more skewed over the three campaigns, as shown by the generally increasing Gini indices. A small fraction of vehicles contributes more pollution than most vehicles. A Gini index closer to 0 would indicate that all vehicles in the group contribute the same to the total fleet emissions.

The top 10 % of gasoline-powered car emitters with the highest BC EF contributed 21 %, 44 %, and 47 % of the total gasoline car fleet BC emissions in 2011, 2017, and 2023, respectively (Fig. 4a). The top 10 % of diesel cars with the highest BC EF contributed 36 %, 51 %, and 65 % of the total diesel car fleet BC emissions in the same years (Fig. 4b). For goods vehicles, the top 10 % contributed 53 %, 43 %, and 48 % of the total BC emissions in 2011, 2017, and 2023, respectively (Fig. 4c).

In terms of NO_x emissions, the top 10 % of gasoline-powered cars contributed 31 %, 59 %, and 44 % of the total gasoline car fleet NO_x emissions in 2011, 2017, and 2023, respectively (Fig. 4d). For diesel-powered cars, the top 10 % contributed 22 %, 28 %, and 29 % of the total NO_x emissions in the same years (Fig. 4e). The top 10 % of goods vehicles contributed 22 %, 30 %, and 41 % of the total goods vehicles' fleet NO_x emissions in 2011, 2017, and 2023, respectively (Fig. 4f). The contribution increases over the campaigns, which means that, by lowering EF in general, the super-emitters are even more important if we want to further improve the air quality in the cities.

Excluding vehicles that disproportionately contribute to total fleet emissions from city access would be a more effective measure for reducing traffic emissions than excluding vehicles based on specific emissions standards (Ježek et al., 2018). This approach would also notify and incentivize vehicle owners to maintain their vehicles better.

To prepare an effective strategy to reduce overall pollution in a city, the focus should be on targeting the highest-emitting vehicles, regardless of whether they are diesel- or gasoline-powered. The Gini index analysis showed that equal contribution to emissions does not necessarily mean the emissions



Diesel	2023 median	2023 25th perc.	2023 75th perc.	2017 median	2017 25th perc.	2017 75th perc.
R-Square (COD)	0.82	0.88	0.47	0.18	0.88	0.38
Intercept	6.30 ± 1.55	2.89 ± 1.12	13.49 ± 2.84	12.02 ± 1.04	1.95 ± 0.90	17.02 ± 1.32
Slope	20.60 ± 5.61	18.57 ± 4.04	16.67 ± 10.24	3.05 ± 3.74	6.49 ± 4.78	6.49 ± 4.78
Prob>F	0.035	0.019	0.202	0.475	0.017	0.267
Gasoline	2023 median	2023 25th perc.	2023 75th perc.	2017 median	2017 25th perc.	2017 75th perc.
R-Square (COD)	0.56	0.58	0.21	0.76	0.56	0.86
Intercept	0.66 ± 0.53	0.23 ± 0.21	2.10 ± 1.38	-0.47 ± 0.52	-0.10 ± 0.11	-3.05 ± 1.72
Slope	11.54 ± 5.94	4.69 ± 2.33	13.97 ± 15.51	18.02 ± 5.79	83.23 ± 19.27	83.23 ± 19.27
Prob>F	0.147	0.137	0.434	0.053	0.148	0.023

Figure 3. NO_x EF median (black squares), 25th percentile (orange circles), and 75th percentile (blue triangles) against the NO_x legislation standards. The top row shows the results for diesel-powered cars in the 2023 campaign **(a)** and 2017 campaign **(b)**. The bottom row shows the results for gasoline-powered cars in the 2023 campaign **(c)** and 2017 campaign **(d)**. The lines in coordinating colors are the linear regression lines with their parameters (R^2, intercept, slope, and Prob $> F$, where $\alpha = 5\,\%$) listed in the table below.

are good or desirable – as shown in Fig. 4, diesel cars with a more uniform NO_x emissions profile had problematic overall NO_x levels.

However, to find vehicles that may be using defeat devices, a more granular analysis of the different vehicle groups would be beneficial. The Lorentz curves could be used as a monitoring tool to identify outliers within specific vehicle categories, as they could indicate cars with malfunctioning emissions control systems or illegal tampering.

4 Discussion

Ježek et al. (2015a) found good consistency between the results of the different calculation approaches to chasing data and between the results of the various study types, including remote sensing, chasing, mobile measurements, and the European Environmental Agency's emission inventory. This further demonstrates the consistency and reliability of the measurement methods used in these studies. In recent years, new methodologies and dedicated instrumentation have been developed (Farren et al., 2023; Olin et al., 2023), with increased interest in determining the most robust independent

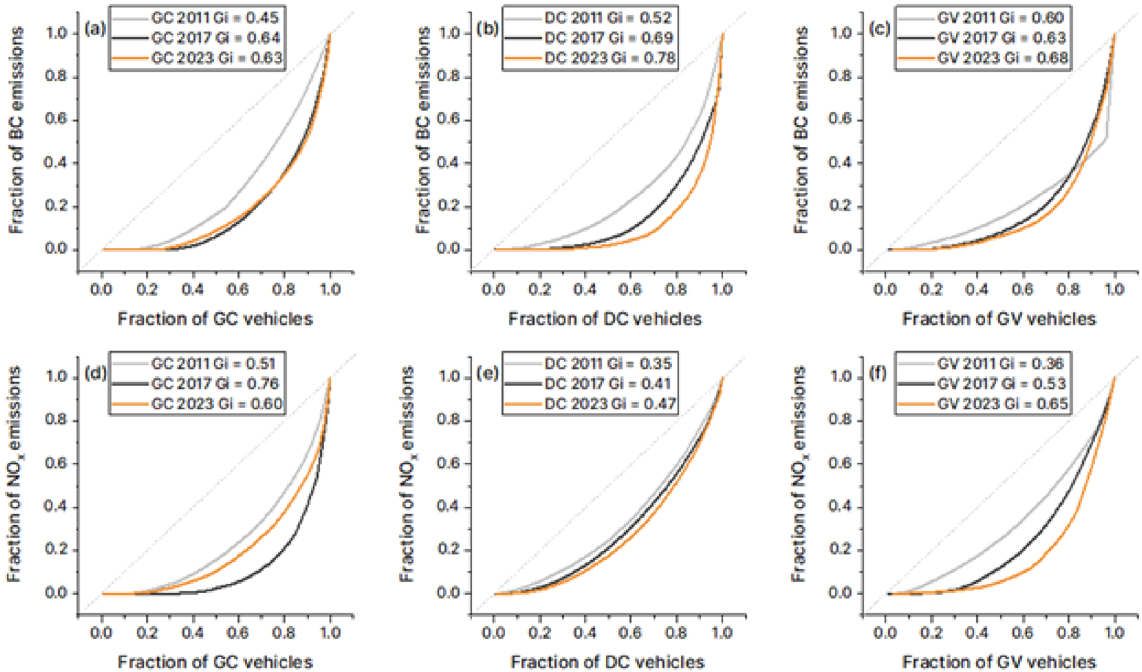


Figure 4. Super-emitter curves are presented as Lorentz curves, where we distribute vehicles within each group from least to most polluting and sum their emissions and Gini (Gi) indices. We did this separately for gasoline cars (GCs), diesel cars (DCs), and goods vehicles (GVs) and compared their results in the 2023 (orange), 2017 (black), and 2011 (gray) campaigns.

methodology for screening many vehicles for defeat devices (Ellermann et al., 2018; Janssen and Hagberg, 2018).

One significant challenge in measuring vehicle emissions under real-world conditions is the high variability in vehicle operation, which affects emissions. Considerable effort has been made to enhance the robustness and repeatability of on-road measurements using PEMS. The procedures for RDE testing with PEMS are summarized in the Joint Research Centre's Report (Valverde Morales and Bonnel, 2018). This report guides the preparation, execution, and data quality checks for emissions tests with PEMS for light-duty vehicles, following EU legislation. Additionally, Zardini and Bonnel (2020) present a detailed analysis of 79 tests conducted on 11 passenger cars, summarizing the latest EU RDE procedure (RDE-4, EU Regulation 2018/1832). They emphasize the responses provided by the RDE data analysis tool EMROAD version 6.03, developed and maintained by the Joint Research Centre.

The data collection includes RDE tests designed to cover a broad range of environmental conditions (e.g., temperature and altitude) and to challenge the trip dynamics requirements defined by legislation to represent typical vehicle use. The EMROAD tool evaluates trip validity based on factors such as trip duration, distance, distance shares in specific driving regimes (e.g., urban), vehicle speed and speed shares, trip dynamics, ambient conditions, elevation gain, trip severity relative to the WLTP driving cycle (based on CO_2), and emissions of pollutants, along with their correction for ambient boundary conditions and excess severity. For better understanding and comparison, it would also be useful to make such detailed assessments with the chasing method.

PEMS measurements typically last about 90 min per vehicle, whereas our chasing measurements averaged 90 s per vehicle in the 2017 and 2023 campaigns. Given the limited parameters controlled by the chasing method, further investigation is warranted. However, studies suggest that it can be a useful screening tool (Farren et al., 2023; Vojtisek-Lom et al., 2020).

5 Conclusions

Our analysis of three separate campaigns conducted in 2011, 2017, and 2023 demonstrates that the chasing method results are consistent over time and that the method can be used to determine the BC and NO_x EF under real driving conditions.

We have observed significant improvements in the BC EF of diesel-powered cars following the installation of DPFs. Furthermore, with the introduction of SCR and stricter regulations, manufacturers have drastically reduced the NO_x emissions of diesel-powered cars, bringing them down to levels comparable to those of gasoline-powered cars. Similar results were obtained for goods vehicles.

Our results show that the measures to reduce vehicle emissions with increasingly stricter vehicle emissions standards were reflected to some extent in the lower values of the real-world driving EF, regardless of the high variability in vehicle maintenance, environmental conditions, driving accelerations, and speeds. The effectiveness of DPFs was reflected in most of the fleet, since the 75th percentile of Euro 5b was reduced to below the 25th percentile of Euro 4, reducing the median by 88 %. The NO_x EF showed a gradual decrease in the cleanest 25 % of the vehicles, while the highest emitters' NO_x EF remained stable until RDE tests were introduced with Euro 6c, when the NO_x EF median was reduced by 86 % compared to the pre-RDE Euro 6b.

Despite significant technological advancements, such as the installation of DPFs and the introduction of SCR systems that have drastically reduced the NO_x emissions of diesel-powered cars and goods vehicles to levels comparable to gasoline vehicles, a small fraction of highly polluting vehicles is now the primary obstacle to substantially reducing traffic-related emissions. As demonstrated in Ježek et al. (2018), excluding high-emission vehicles is a more efficient strategy for reducing traffic emissions than excluding vehicles based on older emissions standards, since some super-emitters are newer vehicles. With the three major vehicle groups' BC and NO_x EFs now being nearly the same, targeting the highest-emitting vehicles, whether they are diesel- or gasoline-powered, should be the focus of any effective pollution reduction strategy.

We showed how Lorentz curves for BC emissions became more skewed, with 10 % of diesel cars with the highest BC EF contributing 36 %, 51 %, and 65 % of the total diesel car emissions in 2011, 2017, and 2023, respectively. The contributions of these high emitters remained more similar for NO_x emissions, with the top 10 % of the most polluting diesel-powered cars contributing 22 %, 28 %, and 29 % of the total NO_x emissions in the same years. Due to the success of RDE tests in lowering diesel vehicles' NO_x EF, we expect that Lorentz curves for NO_x emissions will also become more skewed in the future as most of the older cars are eliminated from the fleet.

A robust method for measuring vehicle emissions under real driving conditions, as suggested by our work, would be a valuable tool for monitoring vehicle emissions independently of the vehicle driver or owner's knowledge, thereby bypassing any potential interference from manufacturers and vehicle owners who may be using defeat devices or failing to properly maintain their vehicles.

Additionally, a comprehensive measurement base would facilitate the development of more accurate models for forecasting traffic emissions. It would also enhance the efficiency of measures implemented by cities to reduce traffic pollution and provide a means of monitoring and evaluating their effectiveness. This comprehensive data collection could guide policymakers in making informed decisions and implementing effective strategies to mitigate urban air pollution.

By combining the insights from the Gini index and Lorentz curve analyses, policymakers can identify the highest-emitting vehicles regardless of fuel type while also using real-world emissions monitoring to detect vehicles with malfunctioning or tampered emissions control systems. This holistic approach, focused on the actual emissions performance rather than just the vehicle technology, is essential for developing comprehensive policies to significantly improve air quality in cities.

Data availability. Due to the Personal Data Protection Act (Slovenia) and GDRP (EU), the distribution of the dataset is limited, though parts may be available upon request.

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Author contributions. IJB, AG, MR, and GM designed the experiments. IJB, LZ, and TR carried them out, and MI and BA provided technical assistance. IJB, LZ, TR, and MI performed the data analysis. GM and AG acquired the funds for the projects. MR, AG, IJB, and GM supervised the projects. IJB wrote the initial draft. All of the authors discussed the results and contributed to the final manuscript.

Competing interests. The authors Irena Ježek Brecelj, Asta Gregorič, Matic Ivančič, Balint Alfoldy, Griša Močnik, and Martin Rigler were employed by Aerosol d.o.o., the manufacturer of Aethalometers, at the time or part of the time while the study was conducted.

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References

Bernard, Y., Dallmann, T., Lee, K., Rintanen, I., and Tietge, U.: Evaluation of real-world vehicle emissions in Brussels, Real Urban Emissions Initiative, https://www.trueinitiative.org/publications/reports/evaluation-of-real-world-vehicle-emissions-in-brussels (last access: 12 August 2025), 2021.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res.-Atmos., 118, 5380–5552, https://doi.org/10.1002/jgrd.50171, 2013.

Carslaw, D. C., Farren, N. J., Vaughan, A. R., Drysdale, W. S., Young, S., and Lee, J. D.: The diminishing importance of nitrogen dioxide emissions from road vehicle exhaust, Atmos. Environ. X, 1, 100002, https://doi.org/10.1016/J.AEAOA.2018.100002, 2019.

Chen, Y., Sun, R., and Borken-Kleefeld, J.: On-Road NO_x and Smoke Emissions of Diesel Light Commercial Vehicles-Combining Remote Sensing Measurements from across Europe, Environ. Sci. Technol., 54, 11744–11752, https://doi.org/10.1021/acs.est.9b07856, 2020.

The Commission of the European Communities: Directive – 2001/116, http://data.europa.eu/eli/dir/2001/116/oj (last access: 13 August 2025), 2001.

Court of Justice of the European Union: Press release No. 170/20, https://curia.europa.eu/jcms/upload/docs/application/pdf/2020-12/cp200170en.pdf (last access: 13 August 2025), 2020.

Dallmann, T. R., Harley, R. A., and Kirchstetter, T. W.: Effects of diesel particle filter retrofits and accelerated fleet turnover on drayage truck emissions at the port of Oakland, Environ. Sci. Technol., 45, 10773–10779, 2011.

Dallmann, T. R., Demartini, S. J., Kirchstetter, T. W., Herndon, S. C., Onasch, T. B., Wood, E. C., and Harley, R. A.: On-road measurement of gas and particle phase pollutant emission factors for individual heavy-duty diesel trucks, Environ. Sci. Technol., 46, 8511–8518, 2012.

Economic Commission for Europe of the United Nations: Regulation No. 83 UN/ECE, http://data.europa.eu/eli/reg/2012/83/oj (last access: 13 August 2025), 2011.

Ellermann, T., Hertel, O., Winther, M., Risager Nielsen, J., and Rud Ingvardsen, C.: Measurements of cheating with SCR catalysts on heavy duty vehicles, Danish Environmental Protection Agency, ISBN: 978-87-93710-42-9, 2018.

The European Commission: Regulation – 459/2012, http://data.europa.eu/eli/reg/2012/459/oj (last access: 13 August 2025), 2012.

The European Commission: Regulation – 2016/646, http://data.europa.eu/eli/reg/2016/646/oj (last access: 13 August 2025), 2016.

The European Commission: Regulation – 2017/1151, http://data.europa.eu/eli/reg/2017/1151/oj (last access: 13 August 2025), 2017.

European Environment Agency, González Ortiz, A., Guerreiro, C. and Soares, J.: Air quality in Europe – 2020 report, Publications Office, https://data.europa.eu/doi/10.2800/786656 (last access: 13 August 2025), 2020.

The European Parliament: Directive EU 2024/2881, http://data.europa.eu/eli/dir/2024/2881/oj (last access: 13 August 2025), 2024.

Farren, N. J., Schmidt, C., Juchem, H., Pöhler, D., Wilde, S. E., Wagner, R. L., Wilson, S., Shaw, M. D., and Carslaw, D. C.: Emission ratio determination from road vehicles using a range of remote emission sensing techniques, Sci. Total Environ., 875, 162621, https://doi.org/10.1016/j.scitotenv.2023.162621, 2023.

Giechaskiel, B., Forloni, F., Carriero, M., Baldini, G., Castellano, P., Vermeulen, R., Kontses, D., Fragkiadoulakis, P., Samaras, Z., and Fontaras, G.: Effect of Tampering on On-Road and Off-Road Diesel Vehicle Emissions, Sustainability, 14, 6065, https://doi.org/10.3390/su14106065, 2022.

Grange, S. K., Farren, N. J., Vaughan, A. R., Rose, R. A., and Carslaw, D. C.: Strong Temperature Dependence for Light-Duty Diesel Vehicle NO_x Emissions, Environ. Sci. Technol., 53, 6587–6596, https://doi.org/10.1021/acs.est.9b01024, 2019.

Hansen, A. D. A. and Rosen, H.: Individual Measurements of the Emission Factor of Aerosol Black Carbon in Automobile plumes, J. Air Waste Manage. Assoc., 40, 1654–1657, 1990.

Janssen, J. and Hagberg, N.: Plume Chasing A way to detect high NO_x emitting vehicles, Haninge, https://www.danishroadtrafficauthority.dk/publications/plume-chasing (last access: 13 August 2025), 2018.

Janssen, N. A. H., Gerlof-Nijland, M. E., Lanki, T., Salonen, R. O., Cassee, F., Hoek, G., Fischer, P., Brunekreef, B., and Krzyzanowski, M.: Health effects of Black Carbon, WHO Regional Office for Europe, Bonn, ISBN: 978 92 890 0265 3, 2012.

Ježek, I., Katrašnik, T., Westerdahl, D., and Močnik, G.: Black carbon, particle number concentration and nitrogen oxide emission factors of random in-use vehicles measured with the on-road chasing method, Atmos. Chem. Phys., 15, 11011–11026, https://doi.org/10.5194/acp-15-11011-2015, 2015a.

Ježek, I., Drinovec, L., Ferrero, L., Carriero, M., and Močnik, G.: Determination of car on-road black carbon and particle number emission factors and comparison between mobile and stationary measurements, Atmos. Meas. Tech., 8, 43–55, https://doi.org/10.5194/amt-8-43-2015, 2015b.

Ježek, I., Blond, N., Skupinski, G., and Močnik, G.: The traffic emission-dispersion model for a Central-European city agrees with measured black carbon apportioned to traffic, Atmos. Environ., 184, 177–190, https://doi.org/10.1016/j.atmosenv.2018.04.028, 2018.

Joint Research Centre: Institute for Environment and Sustainability, Maas, H., Reid, A., Nelson, R., Godwin, S. et al.: Well-to-wheels analysis of future automotive fuels and powertrains in the European context – Tank-to-wheels (TTW) report, version 4, July 2013, edited by: Reid, A., Nelson, R., Godwin, S., Rose, K. D., Lonza, L., Edwards, R., and Krasenbrink, A., Publications Office, https://data.europa.eu/doi/10.2788/40409 (last access: 13 August 2025), 2013.

Landis, M., Lewis, C., and Stevens, R.: Ft. McHenry tunnel study: Source profiles and mercury emissions from diesel and gasoline powered vehicles, Atmos. Environ., 41, 8711–8724, https://doi.org/10.1016/j.atmosenv.2007.07.028, 2007.

Meyer, M., Bernard, Y., German, J., and Dallmann, T.: Reassessment Of Excess NO_x From European Diesel Cars Following The Court Of Justice Of The European Union Rulings, International Council For Clean Transport, Washington, https://theicct.org/publication/dieselgate-emissions-diesel-cars-europe-mar23/ (last access: 13 August 2025), 2023.

Olin, M., Oikarinen, H., Marjanen, P., Mikkonen, S., and Karjalainen, P.: High Particle Number Emissions Determined with Robust Regression Plume Analysis (RRPA) from Hundreds of Vehicle Chases, Environ. Sci. Technol., 57, 8911–8920, https://doi.org/10.1021/acs.est.2c08198, 2023.

Petzold, A., Ogren, J. A., Fiebig, M., Laj, P., Li, S.-M., Baltensperger, U., Holzer-Popp, T., Kinne, S., Pappalardo, G., Sugimoto, N., Wehrli, C., Wiedensohler, A., and Zhang, X.-Y.: Recommendations for reporting "black carbon" measurements, Atmos. Chem. Phys., 13, 8365–8379, https://doi.org/10.5194/acp-13-8365-2013, 2013.

Posada Sanchez, F., Bandivadekar, A., and German, J.: Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles, International Council for Clean Transport, Washington, https://theicct.org/publication/estimated-cost-of-emission-reduction-technologies-for-ldvs/ (last access: 13 August, 2025), 2012.

USEPA: Code federal regulations – Title 40: Protection of environment Part 86, 40 C.F.R. Part 86, https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-86?toc=1 (last access: 18 August 2025), 2010.

Valverde Morales, V. and Bonnel, P.: On-road testing with Portable Emissions Measurement Systems (PEMS), Guidance note for light-duty vehicles, Publications Office, https://doi.org/10.2760/08294, 2018.

Vojtisek-Lom, M., Arul Raj, A. F., Jindra, P., Macoun, D., and Pechout, M.: On-road detection of trucks with high NO_x emissions from a patrol vehicle with on-board FTIR analyzer, Sci. Total Environ., 738, 139753, https://doi.org/10.1016/j.scitotenv.2020.139753, 2020.

Wang, H., Zhang, S., Wu, X., Wen, Y., Li, Z., and Wu, Y.: Emission Measurements on a Large Sample of Heavy-Duty Diesel Trucks in China by Using Mobile Plume Chasing, Environ. Sci. Technol., 57, 15153–15161, https://doi.org/10.1021/acs.est.3c08593, 2023.

Wang, J. M., Jeong, C.-H., Zimmerman, N., Healy, R. M., Wang, D. K., Ke, F., and Evans, G. J.: Plume-based analysis of vehicle fleet air pollutant emissions and the contribution from high emitters, Atmos. Meas. Tech., 8, 3263–3275, https://doi.org/10.5194/amt-8-3263-2015, 2015.

Wang, X., Westerdahl, D., Wu, Y., Pan, X., and Zhang, K. M.: On-road emission factor distributions of individual diesel vehicles in and around Beijing, China, Atmos. Environ., 45, 503–513, https://doi.org/10.1016/j.atmosenv.2010.09.014, 2011.

Wang, X., Westerdahl, D., Hu, J., Wu, Y., Yin, H., Pan, X., and Zhang, K. M.: On-road diesel vehicle emission factors for nitrogen oxides and black carbon in two Chinese cities, Atmos Environ, 46, 45–55, https://doi.org/10.1016/j.atmosenv.2011.10.033, 2012.

Yang, J., Che, X., Tan, J., Qin, X., Duan, J., Liu, D., Duan, Y., Xiang, S., Shen, N., Zhai, X., Zhang, Y., Ning, Z., and Li, L.: Real-world emission characteristics and driving factors of diesel trucks: Insights from plume chasing experiments, Atmos. Environ. X, 25, 100311, https://doi.org/10.1016/J.AEAOA.2025.100311, 2025.

Yang, P., Wang, H., Wu, X., Xiao, S., Zheng, X., You, Y., Zhang, S., and Wu, Y.: Long-term plume-chasing measurements: Emission characteristics and spatial patterns of heavy-duty trucks in a megacity, Environ. Pollut., 361, 124819, https://doi.org/10.1016/J.ENVPOL.2024.124819, 2024.

Zardini, A. and Bonnel, P.: Real Driving Emissions Regulation: European methodology to fine tune the EU real driving emissions data evaluation method, Publications Office of the European Union, https://doi.org/10.2760/176284, 2020.

Zeng, L., Xiao, S., Dai, Y., Chen, T., Wang, H., Yang, P., Huang, G., Yan, M., You, Y., Zheng, X., Zhang, S., and Wu, Y.: Characterization of on-road nitrogen oxides and black carbon emissions from high emitters of heavy-duty diesel vehicles in China, J. Hazard. Mater., 477, 135225, https://doi.org/10.1016/J.JHAZMAT.2024.135225, 2024.