

Remote sensing of heavy-duty vehicle emissions in Europe

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Introduction

Air pollution is a significant environmental health hazard in the European Union. In 2019, long-term exposure to fine particulate matter (PM_{2.5}), nitrogen dioxide (NO₂) and ozone (O₃) contributed to 307,000 premature deaths in the 27 EU Member States (EU-27) (EEA, 2021a). Within the EU-27, road transport is responsible for 4% of total PM_{2.5} emissions and 9% of nitrogen oxide emissions (NO_x), which is comprised mostly of nitrogen monoxide (NO) and NO₂ (EEA, 2021b). NO_x is a pollutant of particular concern as it acts as a precursor to the formation of secondary PM_{2.5} and O₃. Heavy-duty vehicles (HDVs), which include commercial buses and trucks with a gross vehicle weight above 3.5 tonnes, have a disproportionate contribution to these emissions—accounting for 17% of total PM_{2.5} emissions and 65% of total NO_x emissions from all road transport, despite accounting for only 2.5% of the vehicle stock (EEA, 2021a; ACEA, 2021).

To address growing health concerns, HDV emission standards were first introduced in Europe in 1988. These standards later evolved into the current Euro standards which were first introduced in 1992 and increased in stringency with each iteration. There has been a clear decrease in the tailpipe emissions of NO_x, PM, and carbon monoxide (CO) since the introduction of these standards, despite rising levels of activity in the transport sector (Mulholland et al., 2021). However, concerns remain over the disparity observed between type-approval and real-world level emissions.

This disparity has been shown over a variety of testing campaigns conducted throughout Europe which identified the presence of high emitting vehicles.¹ Plume chasing studies conducted on 185 trucks in Germany (Pöhler & Adler, 2017), 284 trucks in Austria, Slovakia, and Germany (Annen & Helmerich, 2020), and 222 trucks in the Czech Republic (Vojtisek-Lom et al., 2020) found rates of high emitting vehicles ranging between 10% and 50%.² Remote sensing campaigns measuring 6,000 trucks in Scotland (Hager, 2017), 874 trucks in Denmark (Ellermann et al., 2018), and 1,277 trucks in Lithuania (Buhigas & Alonso de Lomas, 2021) found 8%, 25%, and 7.5% of vehicles

¹ There is no standard definition for a high emitting vehicle. Most commonly, studies identify high-emitter thresholds as statistical outliers across all recorded data measurements.

² Plume chasing is a method of recording the emissions from a vehicle by sampling the emissions through a mobile laboratory driven behind a target vehicle to collect its emissions.

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measured, respectively, to be high emitters.³ High emission measurements from trucks may result from unfavorable test conditions, such as low temperatures and high grades, or through the failure of emission control systems, potentially due to poor maintenance, malfunctions. Tampering with the emissions control system can also lead to high emission measurements; A roadside inspection conducted on 2,900 trucks in the United Kingdom found that one in twelve were fitted with tampering devices (Department for Transport, 2018).

Tampering with emission control systems is of growing concern within the EU-27. Many forms of tampering exist, including selective catalyst reduction (SCR) system removal, diesel particulate filter removal, exhaust gas recirculation blocking, exhaust temperature sensor inserts, urea emulator installation, or tuning of engine control units.⁴ Emission control systems may result in higher costs for operators through reduced efficiency or requiring inputs such as diesel exhaust fluid for SCRs, which can cost haulers up to €2,700 annually (Ellermann et al., 2018). As such, tampering offers a means for haulers to reduce their operational expenses at the cost of higher emissions.

To better understand the disparity between emissions measured during type approval and real-world emissions, and identify the presence of high-emitting trucks and buses in the EU-27, this study uses data collected from a variety of remote sensing campaigns to provide a comprehensive analysis of the level of real-world emissions from trucks and buses around Europe. Through this study, we aim to provide an insight into the average level of emissions of trucks and buses and identify thresholds for high-emitting vehicles.

Remote sensing uses roadside equipment to measure the emissions measurements from a large number of vehicles in a non-invasive manner. We identified the emissions of NO_x from 33,600 truck and bus measurements between 2017 and 2020 derived from six remote sensing campaigns conducted in Brussels (Bernard et al., 2021), London (Dallmann et al., 2018), Paris (Dallmann et al., 2019), Warsaw (Lee et al., 2022), Flanders (Hooftman et al., 2020), and Krakow (Bernard et al., 2020). The Brussels, London, Paris, and Warsaw data were obtained from The Real Urban Emissions (TRUE) Initiative which aims to provide information to cities regarding the emissions performance of their vehicle fleets. All remote sensing measurements related to trucks were collected from the Flanders campaign, while data measurements for buses were recorded across all six campaigns.

Remote sensing

Remote sensing offers a non-invasive method of capturing the real-world emissions of a vehicle by means of absorption spectroscopy using road-side equipment.⁵ It offers an advantage over other methods of emissions testing, such as plume chasing or portable emissions measurement systems, by allowing for the capture of a large volume of records while still providing accurate emission readings (Gruening et al., 2019).

During remote sensing, a snapshot of a vehicle's emissions is recorded along with the vehicle's license plate number, from which the manufacturer and year of registration can be derived. Based on the year of registration, it's possible to infer the vehicle emission standards under which the vehicle was subject to, allowing for a comparison between the mandated regulatory emissions standard and the real-world emissions. A schematic of remote sensing devices is shown in Figure 1, and a more detailed description of remote sensing is presented in a previous ICCT analysis (Borken-Kleefeld & Dallmann, 2018).

3 Remote sensing uses roadside emission measurement devices at a strategic location to capture a snapshot of emissions from a large quantity of vehicles.

4 An in-depth explanation of these tampering process can be found in Braun et al (2022).

5 Typically, emissions of carbon monoxide (CO), carbon dioxide (CO₂), nitric oxide (NO), and nitrogen dioxide (NO₂) are recorded during remote sensing campaigns, but it may be extended to include particulate matter (PM) and hydrocarbons. This analysis focuses only on NO_x emissions.

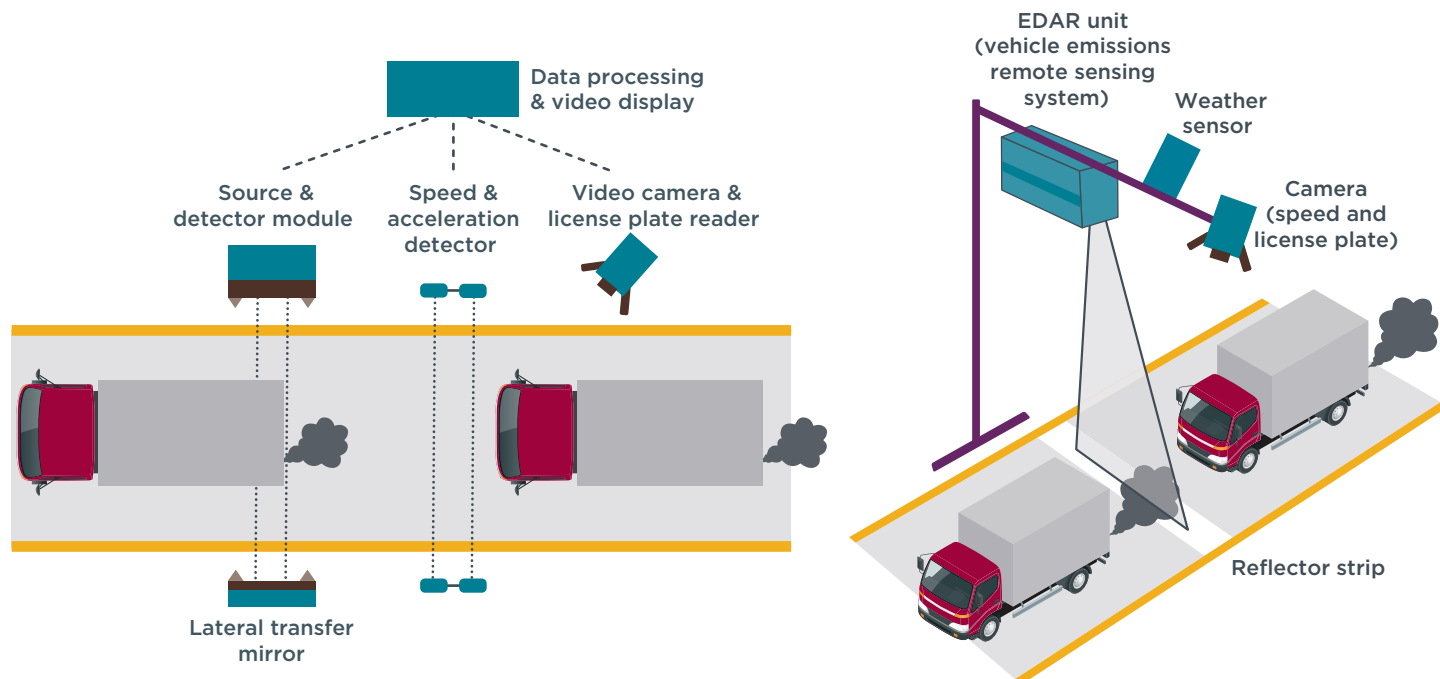


Figure 1. Remote sensing device schematic for *crossroad* remote sensing (left) and top-down remote sensing (right). Figure adapted from Borken-Kleefeld and Dallmann (2018).

Most remote sensing campaigns to date have been devoted to the monitoring of emissions from light-duty vehicles. This analysis quantifies remote sensing emission measurements from HDVs, which presents some challenges compared to other remote sensing campaigns. Remote sensing equipment is generally set up to capture the level of emissions at an elevation close to the ground, where the exhaust emissions for light-duty vehicles protrude. In the case that the exhaust pipe is above the vehicle cab, which may sometimes be the case for buses in particular, the emissions cannot be monitored without making the appropriate adjustments to the remote sensing device. In this analysis, an elevated emissions measurement device was used in the Brussels campaign to overcome this shortcoming. Another difficulty arises in the recording of the vehicle's license plate. Semi-trailers travelling in most countries in the EU are required to display a registration number unique to that of the motorized vehicle in addition to the license plate.⁶ As such, if the video system is only able to capture the rear of the vehicle, it may not be able to determine the motorized vehicle's characteristics.

Remote sensing campaigns for Brussels, London, Krakow, and Warsaw were conducted by Opus Remote Sensing Europe (Opus RSE) using a combination of the OPUS AccuScan™ RSD5000 and RSD5500 remote sensing devices, while the campaigns in Flanders and Paris were conducted by Hager Environmental & Atmospheric Technologies (HEAT) using the Emission Detection And Reporting (EDAR) system. A detailed description of these remote sensing devices is available from OPUS RSE (2021) and HEAT (2018), respectively.

Emissions testing campaigns

The data presented in this analysis were collected from six separate remote sensing campaigns in Brussels, Flanders, Krakow, London, Paris, and Warsaw. The data processed and analyzed from each campaign has previously been published; the analysis stemming from London, Paris, Brussels, and Warsaw have been released as TRUE Initiative reports (Dallmann et al., 2018; Dallmann et al., 2019; Bernard et al., 2021; Lee et al., 2022), the

⁶ Only countries who have signed up to the 1968 Vienna Convention on Road Traffic are obliged by this rule. In the EU-27, this excludes Ireland, Malta, Spain, and Cyprus.

analysis from Krakow as an ICCT consulting report (Bernard et al., 2020), and the analysis from Flanders as a report published by the Flemish government (Hooftman et al., 2020). This analysis aggregates the emission measurements recorded from HDVs in each of these individual campaigns.

The specific location of each testing site for each campaign is shown in Figure 2, and a full description is presented in Table 1.

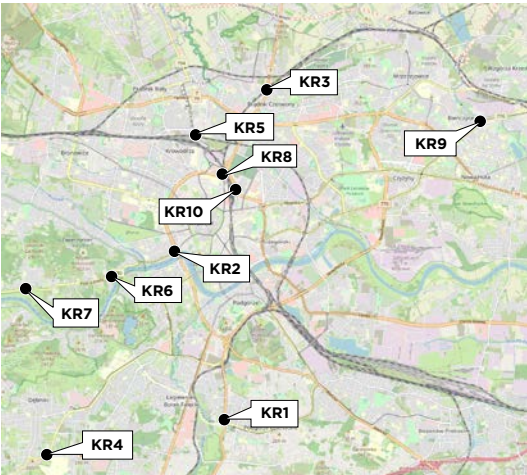
Brussels



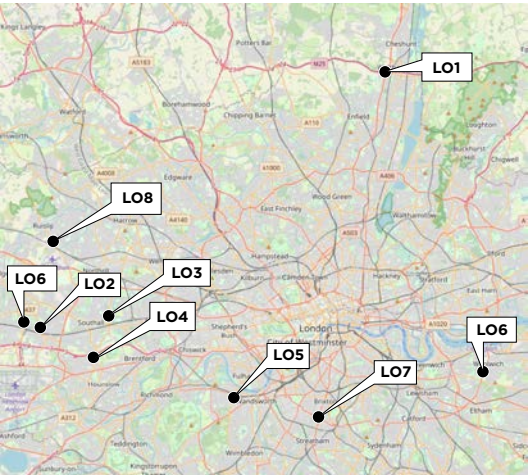
Flanders



Krakow



London



Paris



Warsaw



Figure 2. Location of remote sensing collection points. Maps sourced from OpenStreetMap.

Table 1. Description of remote sensing campaigns in this analysis

Campaign	Dates	Remote sensing technology	Number of measurements	RS point	Location	Road grade
Brussels	October–November 2020 (29 days)	Opus/ AccuScan RSD5000 & AccuScan RSD5500	2,800 buses	BR1	N266 at bus stop – urban road	0.50%
				BR2	N266 at bus stop – urban road	0.30%
				BR3	Tunnel N23 entrance – national road	0.70%
				BR4	Avenue Tervueren – urban road	0.50%
				BR5	Quai Léon Monnoyer – urban road	0.20%
				BR6	Rue de la Loi – urban road	0.50%
				BR7	Dépôt STIB Jacques Brel – urban road	6.80%
				BR8	PTI entrance – urban road	0.20%
Flanders	June–July 2019 (22 days)	HEAT/ EDAR	900 buses 20,000 trucks	FL1	Bruges – N31 – urban road	2.00%
				FL2	Ghent – R40 Charles de Kerckhovelaan – urban road	5.00%
				FL3	Aalst – E40 – motorway	1.90%
				FL4	Antwerp – N186 – urban road	2.10%
				FL5	Antwerp – E34 exit Kennedy tunnel – motorway	2.10%
Krakow	June–July 2019 (17 days)	Opus/ AccuScan RSD5000	1,200 buses	KR1	Jerzego Turowicza 13 Street – national road	0.10%
				KR2	Krasinskiego, 1 – urban road	1.30%
				KR3	29 Listopada Street – national road	2.10%
				KR4	Doktora Josefa Babinskiego, 30-393 – national road	1.30%
				KR5	Doktora Twardego – urban road	0.80%
				KR6	Ksiecia Josefa 65,30-206 – national road	0.20%
				KR7	Ksiecia Jozefa/Jodlowa – national road	0.80%
				KR8	Pawia Street – urban road	5.00%
				KR9	Kocmyrzowska Street – national road	0.10%
				KR10	Wita Stwosza bus station – urban road	3.00%
London	November 2017–February 2018 (41 days)	Opus/ AccuScan RSD5000	3,100 buses	LO1	A10/M25 Junction – motorway	-0.10%
				LO2	Dawley Rd., Hillingdon – roundabout	-1.00%
				LO3	Greenford Rd., Ealing – urban road	0.40%
				LO4	Heston Rd., Hounslow – urban road	0.00%
				LO5	Putney Hill, Wandsworth – urban road	1.70%
				LO6	Stockley Road, W. Drayton – motorway	0.00%
				LO7	Christchurch Rd. – urban road	2.60%
				LO8	West End Rd., Hillingdon – urban road	0.00%
				LO9	A205 South Circular – urban road	0.80%
Paris	June–July 2018 (22 days)	HEAT/ EDAR	4,400 buses	PA1	Rue de Tolbiac – urban road	0.00%
				PA2	Boulevard Diderot – urban road	0.00%
				PA3	Avenue de Choisy – urban road	0.00%
Warsaw	September–October 2020 (14 days)	OPUS/ AccuScan RSD5500	1,200 buses	WA1	Marywilskastreet – national road	0.30%
				WA2	Marywilskastreet – national road	0.10%
				WA3	Aleja Prymasa Tysiąclecia – motorway	0.60%
				WA4	Puławskastreet – national road	0.40%
				WA5	Wal Miedzeszynskastreet – national road	0.20%
				WA6	Wal Miedzeszynskastreet – national road	0.10%

Methodology

For this analysis, it was necessary to carry out a level of post-processing on the data recorded from the emission sensing campaigns. The first step included filtering for values where the vehicle's engine was not producing power, and therefore was not producing emissions. This filtering process was conducted through the calculation of the vehicle specific power, described further below. We also used existing fuel economy data from heavy-duty vehicles to convert the standardized data from terms of gram of pollutant per kilogram of fuel (g/kg) to the units specified in the Euro emissions standards, gram of pollutant per kilowatt hour (g/kWh). Upon this post-processing, we assigned the NO_x emissions of each vehicle class (trucks and buses) for each Euro standard to show how the average level of real-world emissions has changed with the increasing stringency of the standards. We also define thresholds for high-emitting vehicles.

Vehicle specific power

A vehicle's emissions are highly dependent on its operating and driving conditions. For instance, during a period of deceleration, a vehicle's engine does not generate power and the fuel injection process is deactivated, and thus, no further emissions are produced by the engine. Such a measurement should be excluded in a remote sensing analysis as to only capture instances where the vehicle has associated emissions. We quantify these periods of deceleration through the calculation of the vehicle specific power (VSP), which represents the instantaneous vehicle engine power during vehicle operation.

The VSP represents the engine power normalized by its mass required for the vehicle to overcome aerodynamic resistance, rolling resistance, auxiliary power demands, and transmission system losses to propel the vehicle forward. The engine load of the vehicle can be estimated for a given set of driving conditions (velocity and acceleration) and roadway specifications (grade), which are both derived from remote sensing measurements, together with vehicle dynamics information, such as rolling resistance, drag coefficient, and vehicle weight.

We calculated the VSP, described in the appendix, for each remote sensing measurement across all campaigns to quantify the operating condition of the vehicle at the time remote sensing emissions have been recorded. To exclude vehicles experiencing a period of engine braking, remote sensing measurements with negative VSP values are excluded from the analysis. These periods of deceleration occur more frequently in urban areas and particularly in the case of bus fleets where the drive cycle operates more frequently on a start-stop basis.

Conversion of emission factors

Throughout all remote sensing campaigns, emission factors are captured relative to the CO₂ concentrations and then calculated in terms grams of pollutant per kg of fuel burned (g/kg). However, the regulatory emission limits for HDVs within the EU are established on an energy-specific basis (g/kWh). To better compare the remote sensing emission measurements to the established regulatory limits across Euro standards, we convert the fuel-specific metric results to an energy-specific metric through Equation 1:

$$Emission\ Factor \left(\frac{g}{kWh} \right) = \frac{\frac{Pollutant\ (g)}{Fuel\ (kg)} \times FC \left(\frac{g}{kWh} \right)}{1000} \quad (1)$$

Where FC represents the brake specific fuel consumption of the vehicle in g/kWh. In this study, we apply HDV fuel consumption values based on the data reported by the European Environment Agency (EEA) for monitoring the CO₂ emissions from HDVs as required by regulation EU 2018/956 (European Environment Agency, 2021b). However, it should be noted that the reporting requirements of CO₂ emissions under this regulation

do not apply to all HDVs. The vehicle segments currently obliged to report this data only represent approximately 65% of annual HDV sales (Ragon & Rodriguez, 2021). Notably, buses and coaches are currently not covered by this regulation. Moreover, the mentioned FC values represent the fuel consumption of the vehicle under World Harmonized Transient Cycle (WHTC) test conditions and might not present the exact rate of fuel consumption during remote sensing measurement in all the cases.

Furthermore, this data retrieved from the EEA is only representative of new HDVs sold in the period 2019–2020, while the vehicles recorded from our remote sensing campaigns date back to over a decade. However, previous ICCT research has found there to be very slight improvements in HDV fuel consumption in the absence of regulatory CO₂ emission standards in Europe prior to the genesis of these standards (Dallmann & Jin, 2020). As such, we apply this fuel consumption data to all HDVs in the various remote sensing measurements.

To provide a level of nuance in the variation of fuel consumption of HDVs with engine size, we link the vehicle engine displacement, a metric available from the remote sensing measurements, to the associated fuel consumption value derived from the data reported by the EEA. Figure 3 shows the distribution of the vehicle fuel consumption from the World Harmonized Test Cycle in g/kWh with respect to engine displacement in litres reported by the manufacturers in the EEA database. The engine displacement of the measured vehicles from the remote sensing data were divided into different engine displacement bins, presented in Table 2.

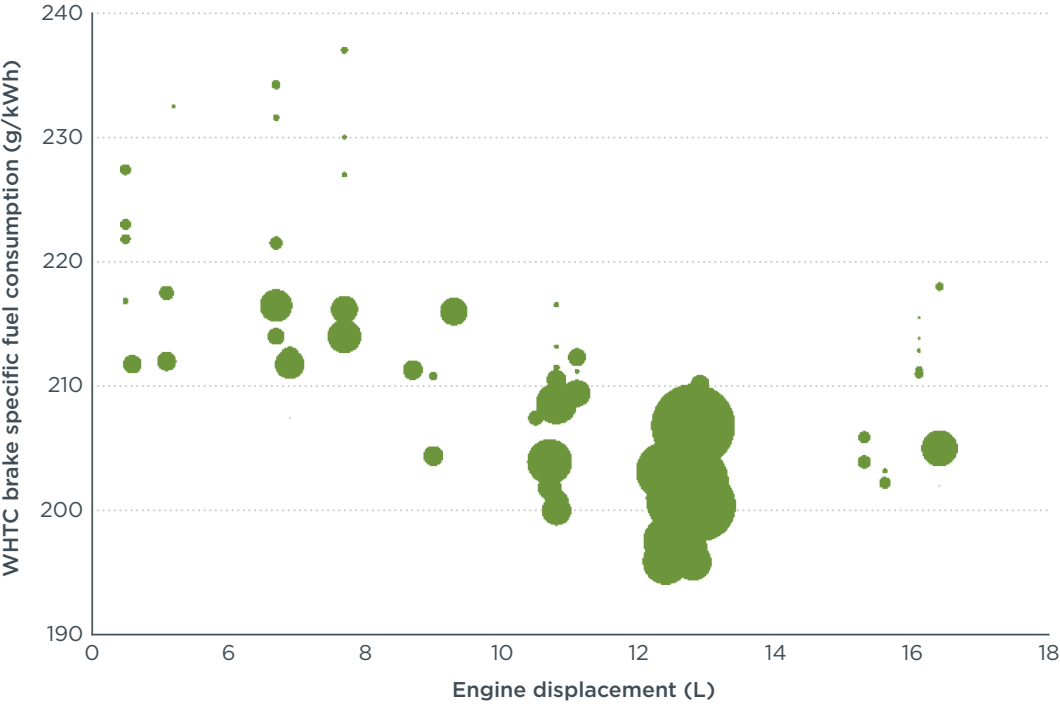


Figure 3. WHTC brake specific fuel consumption from European heavy-duty vehicles by engine displacement. The size of the bubbles represents the number of the vehicles reported by manufacturers. Data obtained from European Environment Agency (2021a).

Table 2. Fuel consumption data of the HDVs for various engine displacement bins (European Environment Agency, 2021a)

Engine displacement bins (L)	WHTC fuel consumption (g/kWh)
<6	215.5
6 – 8	215
8 – 10	212
10 – 12	205
12 – 14	202
>14	205

Upon calculation of the weighted average fuel consumption values based on the bins described in Table 1, we convert each remote sensing emission measurement from a fuel-specific metric (in terms of $g_{\text{pollutant}}/kg_{\text{fuel}}$) to an energy-specific metric (g/kWh) by applying the emission factor conversion shown in Equation 1. Subsequently, the resulting emission factors are compared to the regulatory emissions standard for each vehicle, based on the Euro standard which they were subject to at a time of registration.

Heavy-duty trucks

Characteristics of sampled fleet

All 20,000 truck measurements presented in this report were derived from the Flanders campaign. The five other campaigns which this study draws upon were conducted most prominently in urban locations, enabling the measurement of light-duty vehicles and buses but limiting the number of truck measurements. The Flanders campaign differed from these by placing more emphasis on capturing motorway vehicle emissions, allowing for a significant number of truck emission records to be captured. A report by the government of Flanders summarized the findings on the emissions of trucks from their analysis (Hooftman et al., 2020), however this study provides some additional novelty by employing the methods described above to convert the emission factors from g/kg of fuel to g/kWh, allowing for a comparison with the official regulatory limits of the Euro standards.

The majority of the truck fleet sampled, 89.3%, were of class N3 with a gross vehicle weight (GVW) greater than 12 t. The remaining 10.7% of the sampled fleet were class N2, with a gross vehicle weight of between 3.5 t and 12 t (see Figure 4). The scope of this analysis is exclusively for HDVs which constitutes vehicles with a GVW above 3.5 t, as such, we do not report on class N1 vehicles.



N2 truck – GVW 3.5 t – 12 t



N3 truck – GVW > 12 t

Figure 4. Typical N2 and N3 trucks in Europe

The Flanders campaign took place between June and July of 2019. The data collected only covers trucks certified to emission standards up to Euro VI but does not include the additional step Euro VI-D or Euro VI-E.⁷ Euro VI standards for trucks, first introduced in 2013, mandated a large reduction in NO_x emissions, accompanied by further cuts in the particle mass limit, the introduction of a particle number limit, and an ammonia concentration limit. Roughly 68.8% of the sampled fleet in this analysis is certified to Euro VI (see Figure 5). Vehicles certified to Euro V, Euro IV, and Euro III represent 23.7%, 4.3%, and 3.2% of the fleet, respectively, with a negligible number of pre-Euro III vehicles which are omitted from this analysis.

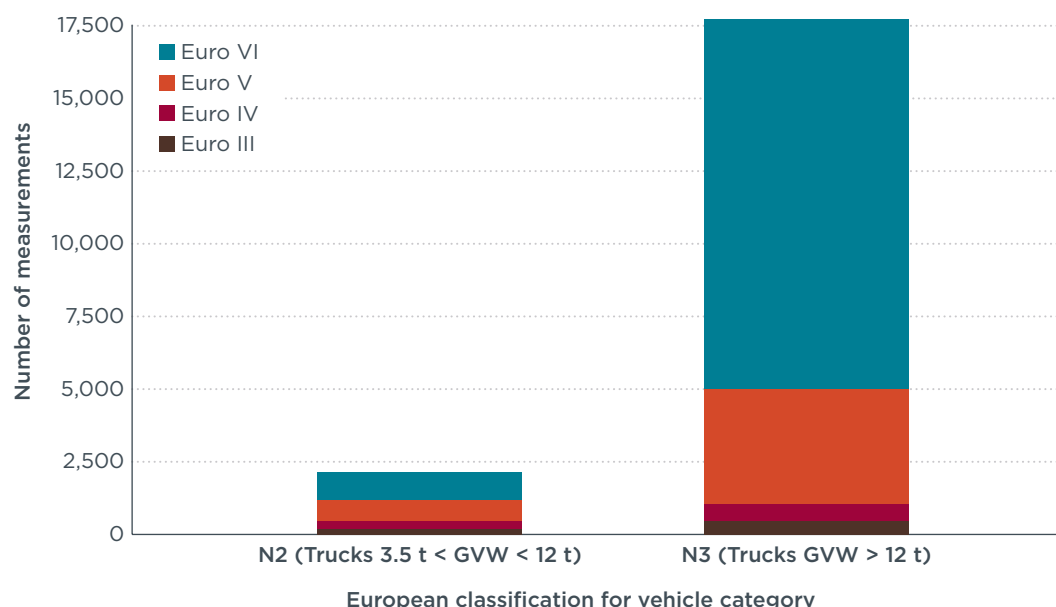


Figure 5. Sampled fleet characterized by category and Euro emissions standard

The fleet composition by manufacturer is comprised largely of seven major HDV manufacturers in the EU-27: DAF, Iveco, MAN, Daimler Trucks, Renault Trucks, Scania, and Volvo (see Figure 6). It should be noted that due to some technical issues it was not possible to capture the manufacturer information from some measurement data, which is indicated in the figure as not available for those vehicles. Combined, these seven manufacturers made up 96% of total truck sales in the EU-27 in 2021.⁸ The share of Euro standards across the various manufacturers remained broadly constant, and 99.5% of the trucks observed during this campaign were powered by diesel engines.

⁷ Euro VI is split further into different steps denoted by the suffixes A, B, C, etc., which apply a variety in the testing conditions such as the portable emission measurement system (PEMS) threshold, the minimum coolant temperature, and adding in the use of a conformity factor. However, no discernable change in emissions were observed until the new testing requirements introduced in Euro VI-D, which was brought into force after this remote sensing campaign. As such, we do not distinguish between the steps in Euro VI for trucks.

⁸ IHS Global SA; Copyright © IHS Global SA, 2022.

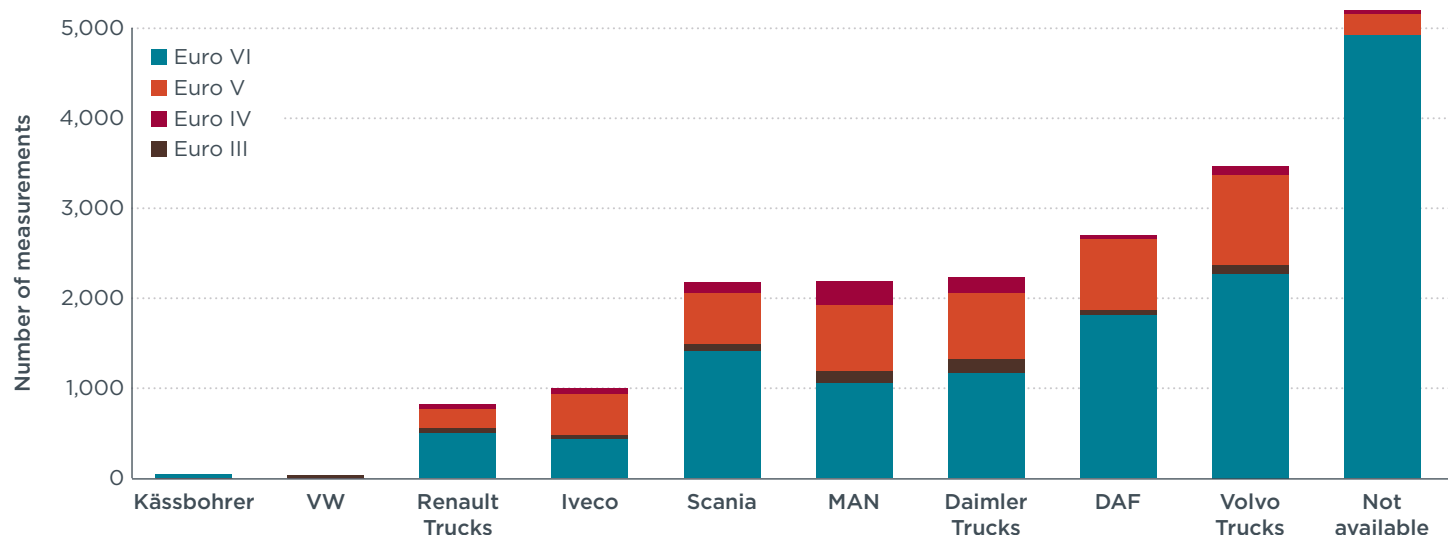


Figure 6. Sampled trucks characterized by manufacturer and Euro emissions standard

Figure 7 summarizes the testing conditions and the sampled truck characteristics from the Flanders campaign, broken down by Euro standards, after filtering for vehicles with a negative VSP by applying the methods described earlier. Measurements were conducted under an average ambient temperature of approximately 21°C which is broadly representative of the summer temperatures experienced in the region. The calculated VSP had an average value of 10.1 kW/ton for Euro VI trucks, with little variation observed across older emission standards.

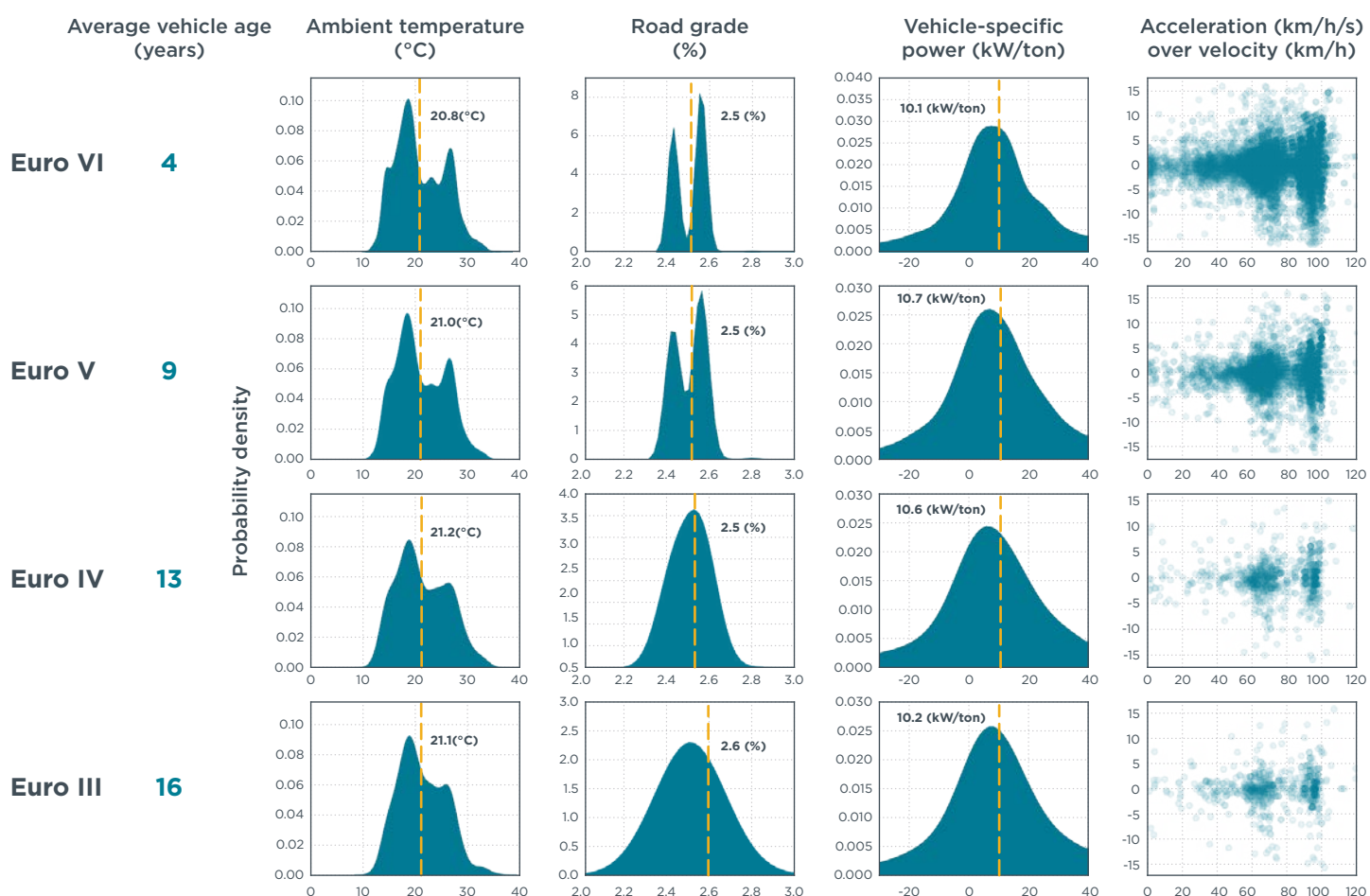


Figure 7. Summary of remote sensing testing conditions and truck characteristics from the Flanders measurement campaign.

Emissions results

The following section presents the level of NO_x emission resulting from our analysis for Flemish heavy-duty trucks collected during a remote sensing campaign conducted on motorways.

Heavy-duty truck NO_x emissions

Figure 8 presents the average NO_x emissions of heavy-duty trucks, disaggregated by Euro emission standard recorded in the Flanders campaign.⁹ The evolution of the Euro standards has resulted in a clear reduction of the average NO_x emissions from heavy-duty trucks. However, despite this reduction, the average real-world NO_x emissions consistently exceed regulatory limits, which are based on laboratory tests and cannot represent the real driving emissions of the vehicles. Moreover, as discussed previously, the NO_x emission unit conversion from g/kg of fuel to g/kWh is based on WHTC fuel consumption and may not represent the exact emission factor of the vehicle as the fuel consumption of the vehicle during remote sensing measurement would differ. Therefore, the regulatory limits used in this work serve as reference point to compare the remote sensing emission results and exceeding these limits could not necessarily imply the vehicles are not in compliance with the standards. The exceedance is particularly apparent for Euro IV and Euro V vehicles, where the regulatory limits were exceeded by 21% and 35%, respectively. The average real-world NO_x emission results of the currently applicable Euro VI standard are closer to regulatory limits, with a discrepancy between observed emissions and the official standard of just 15%.

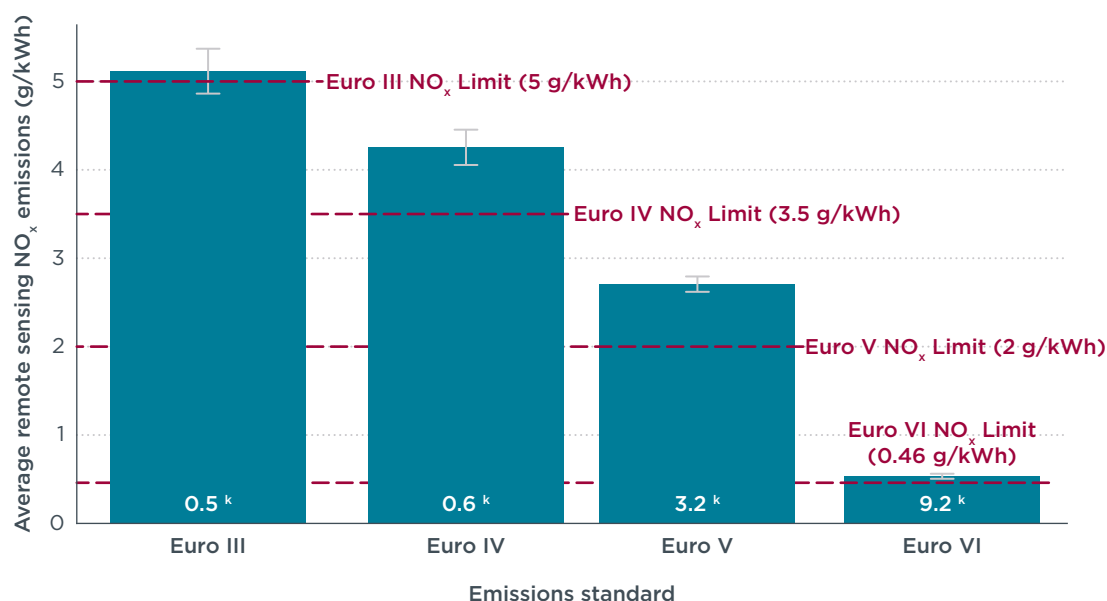


Figure 8. Average NO_x emissions of heavy-duty trucks by European emission standards for the Flanders remote sensing campaign data. The number of measurements is presented below each bar and the error bars represent the 95% confidence interval of the mean. The dashed red lines indicate the regulatory limit for each Euro standard. Only results of groups with positive VSPs are shown.

Vehicle cold starts, transient operations, and low load/speed operating conditions lead to higher NO_x emissions because in these conditions the aftertreatment system cannot perform at its optimized level. Such operating conditions occur frequently in urban areas. Most truck measurements recorded in the Flemish campaign were performed during motorway driving, during which there are fewer instances of stop-starts and low load/speed operations. These operating conditions could be reflected in the VSP values

⁹ Only 22 measurements were recorded from trucks certified to emission standards before Euro III. As such, we exclude them from this analysis.

of the vehicles. Figure 9, demonstrates the variation of the NO_x emissions with respect to vehicle VSP. As shown, a large number of the measured vehicles tend to operate in higher VSPs, and high-emitting vehicles are mostly observed in lower VSP (lower than 20 kW/ton). As such, the level of NO_x emissions presented here may be considered as a low representation, with urban drive cycles presenting a higher range in NO_x emissions.

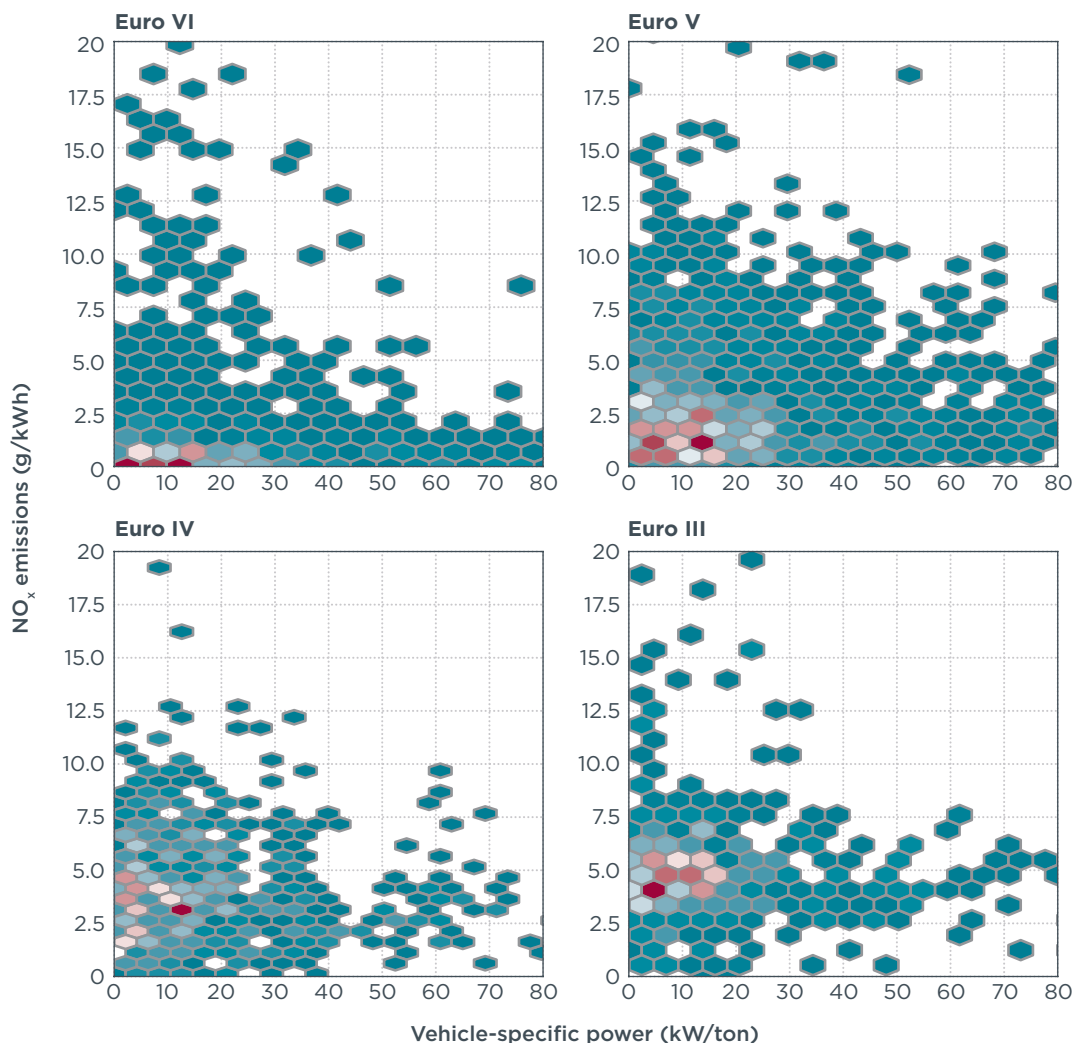


Figure 9. Distribution of the NO_x emissions with respect to vehicle specific power for different Euro standards. The colors of the areas represent the number of the trucks at each area, where the red and blue colored areas include the highest and the lowest numbers, respectively.

Figure 10 presents the distribution of NO_x emissions from truck measurements benchmarked against the corresponding regulatory emission standard.¹⁰ As shown, a number of high emitters, i.e., vehicles with emissions much higher than the average of recorded emissions, were found. There is no conformed value of emissions beyond which a vehicle is deemed as a high emitter. In previous analyses of remote sensing campaigns, thresholds have been suggested based on the statistical outliers across all vehicle measurements. A remote sensing campaign of 1,277 trucks and 314 buses in Vilnius, Lithuania suggested a threshold of 17 g NO_x /km for heavy-duty trucks and 7 g/km for buses by identifying the “tipping-point” on a curve displaying emissions by measurement sorted from highest to lowest (Buhigas & Alonso de Lomas, 2021). A similar analysis of 874 trucks in Denmark used a comparable method and identified a threshold of 25 g NO_2 /kg fuel for trucks certified to Euro V, and a threshold of 3 g NO_2 /kg fuel for Euro VI trucks

¹⁰ In the case of Euro VI, we do not account for the in-service conformity factor when considering the regulatory limit.

(Ellermann et al., 2018). The analysis of the measurements acquired during the emissions sensing campaign in Flanders, the same as used in this analysis, sets a threshold based on the statistical outliers of the measurements, i.e., vehicles with emission measurements above the third quartile plus 1.5 times the interquartile range, equating to 6.94 gNO_x/kg for Euro VI trucks, or approximately 1.5 gNO_x/kWh (Hooftman et al., 2020).

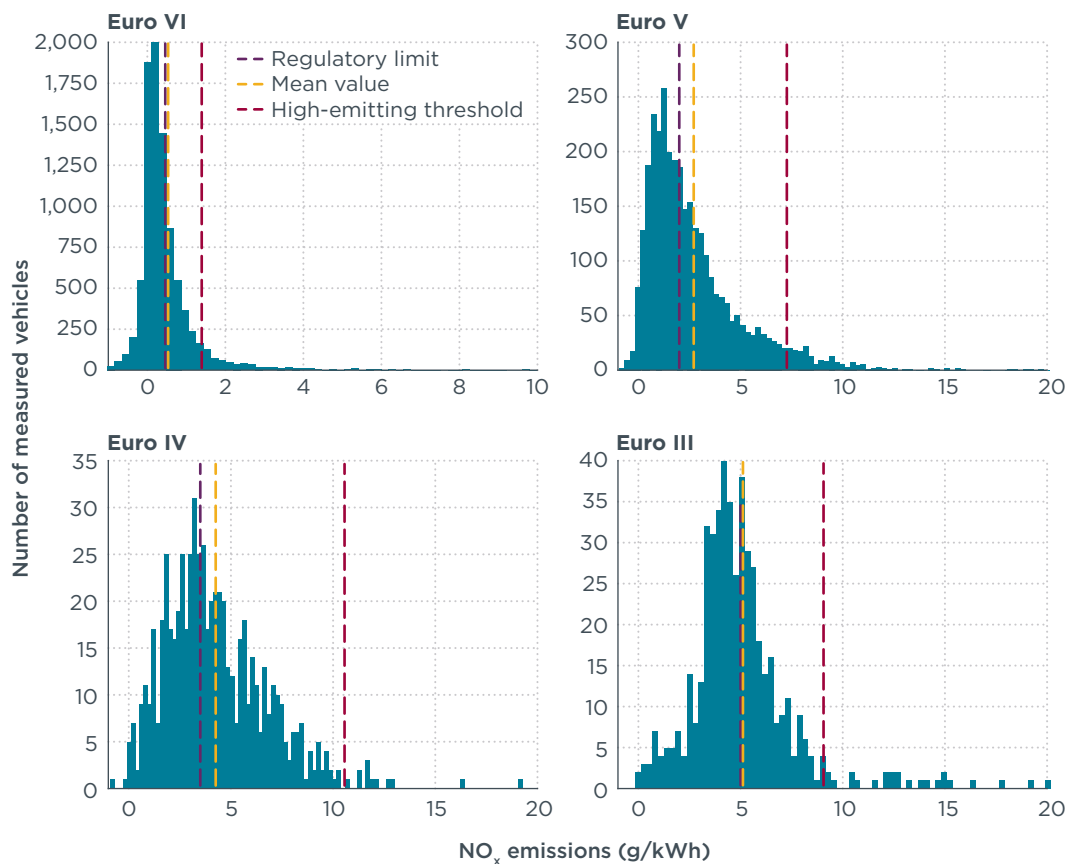


Figure 10. Measured NO_x emission distribution of heavy-duty trucks by European emission standards for Flanders remote sensing campaign data. The vertical blue line indicates the regulatory limit for each Euro standard, the vertical yellow line depicts the mean value of NO_x emissions, and the vertical red line demonstrates the emission level of the high-emitting vehicles.

In our analysis, we apply the same method as Hooftman et al., (2020) in setting our thresholds for high-emitting vehicles, equating to 10.5 g NO_x/kWh for trucks certified to Euro IV, 7.3 for Euro V trucks, and 1.4 for Euro VI trucks. Using these thresholds, 700 Euro VI trucks, or 7.5% of measured Euro VI trucks, are considered high emitters. In the case of Euro VI vehicles, these outliers emit from 4 to more than 20 times higher NO_x emissions than the regulatory limits.

These high emitters may be caused by failures in emission control systems such as malfunctions, tampering, and failing emission control strategies. Combining the remote sensing measurements from different campaigns can be a promising action to further develop emission thresholds for each Euro standard level and enforcement can occur during roadside inspections to detect potential issues with the emission control systems, such as tampering.

Figure 11 presents the NO_x emissions of the measured Euro VI trucks by manufacturer benchmarked against the regulatory limit of 0.46 g/kWh.¹¹ Scania has the lowest average NO_x emissions (red points in Figure 10). Iveco trucks emit, on average, higher NO_x emissions than other heavy-duty truck manufacturers.

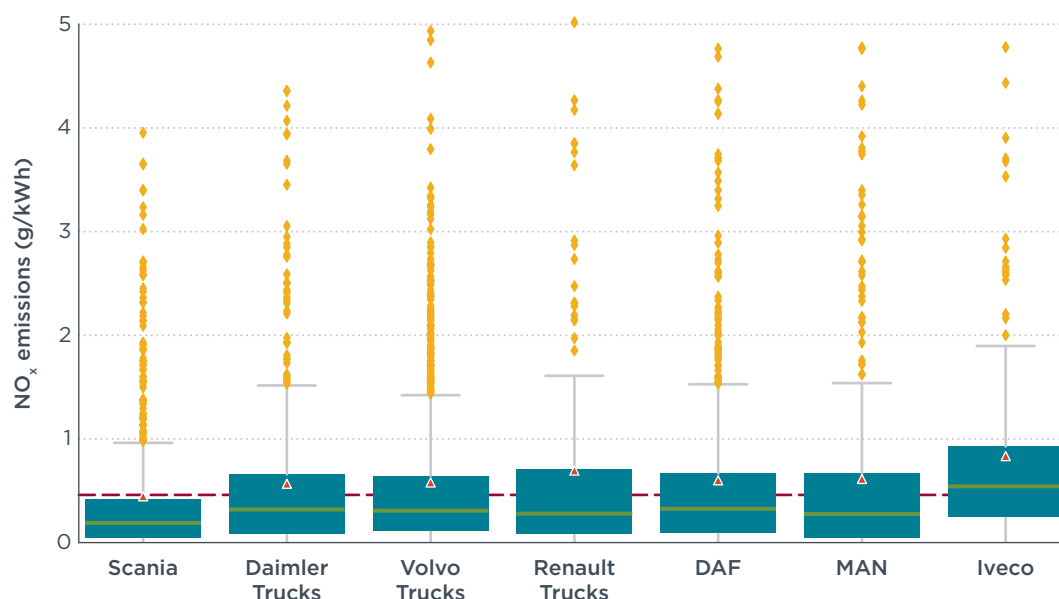


Figure 11. Measured NO_x emission distribution of Euro VI trucks by manufacturer. Yellow points represent the vehicles with emissions above the 3rd quartile plus 1.5 times the interquartile range of all measurements of each manufacturer and the error bars depict emission ranges which fall in between these two thresholds. The red colored triangles and dashed lines indicate the NO_x emissions mean values and the regulatory limit for Euro VI standard (0.46 g/kWh), respectively.

Buses

Characteristics of sampled HDV fleet

Unlike the data used for the truck analysis, which was derived from one remote sensing campaign in Flanders, the bus related data came from a combination of the six different remote sensing campaigns conducted between 2017 and 2020. A small number of Euro VI-D vehicles, the regulatory standard applied for vehicles certified between 2019 and 2021, were thus captured in the campaign. The most significant change to the testing requirements for Euro VI-D was the change of the on-road emission measurement power threshold from 20% of max power in Euro VI-C to 10% in Euro VI-D, which covers high-NO_x conditions at lower engine loads. No discernable change in testing requirements was evident in other Euro VI steps, and as such we combine these classes under the nomenclature of 'pre-Euro VI-D', i.e., covering Euro VI-A, -B, and -C compliant vehicles.

The vast majority of the bus fleet sampled, 96%, fell in the category of M3, which are mostly city buses with a GVW greater than 5 t. The remaining 4% of the sampled fleet were class M2, which are mostly minibuses with a gross vehicle weight of between 3.5 t and 5 t (see Figure 12). The scope of this analysis is exclusively for HDVs which constitutes vehicles with a GVW above 3.5 t. As such, we do not report on class M1 vehicles.

¹¹ Only manufacturers with at least 300 measurements are shown.



M2 bus - GVW 3.5 t - 5 t



M3 bus - GVW > 5 t

Figure 12. Typical M2 and M3 buses in Europe

Roughly 1.8% of the sampled buses in this analysis were certified to the Euro VI-D standard, while a much larger share, 67%, were certified to pre Euro VI-D standards (see Figure 13). Euro V, Euro IV, and Euro III compliant vehicles represent 23.7%, 4.3%, and 3.2% of the fleet, respectively, with a negligible number of pre-Euro III vehicles, which are omitted from this analysis.

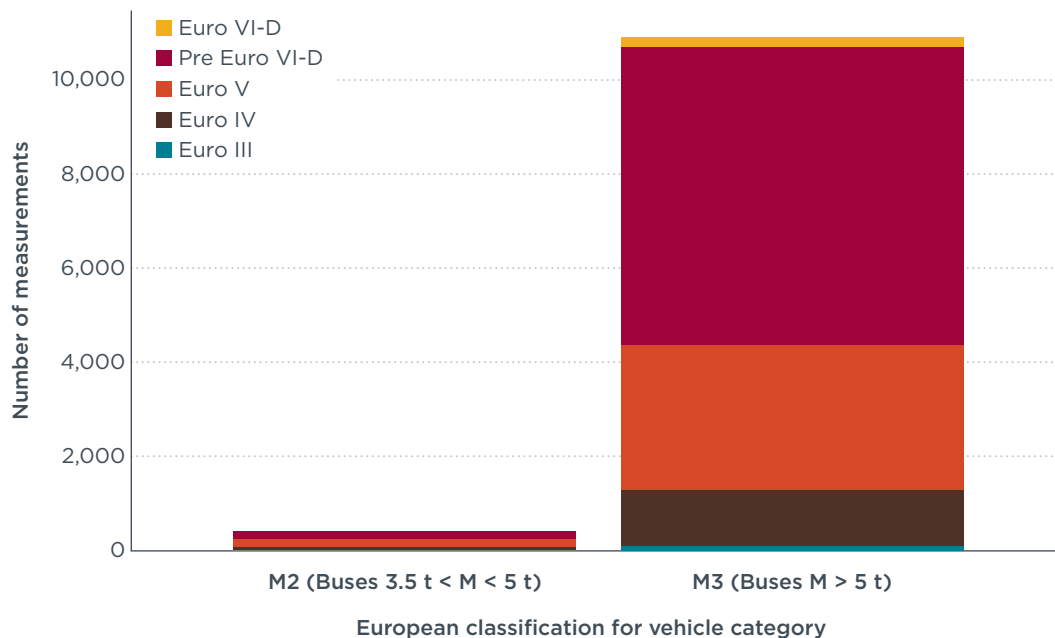


Figure 13. Sampled fleet characterized by category and Euro emissions standard

The bus market is considerably more segregated by manufacturer than the truck market. In 2019, the top seven truck manufacturers were responsible for 96% of the total sales in the EU-27 while the top seven bus manufacturers accounted for 69% of sales (see Figure 14).

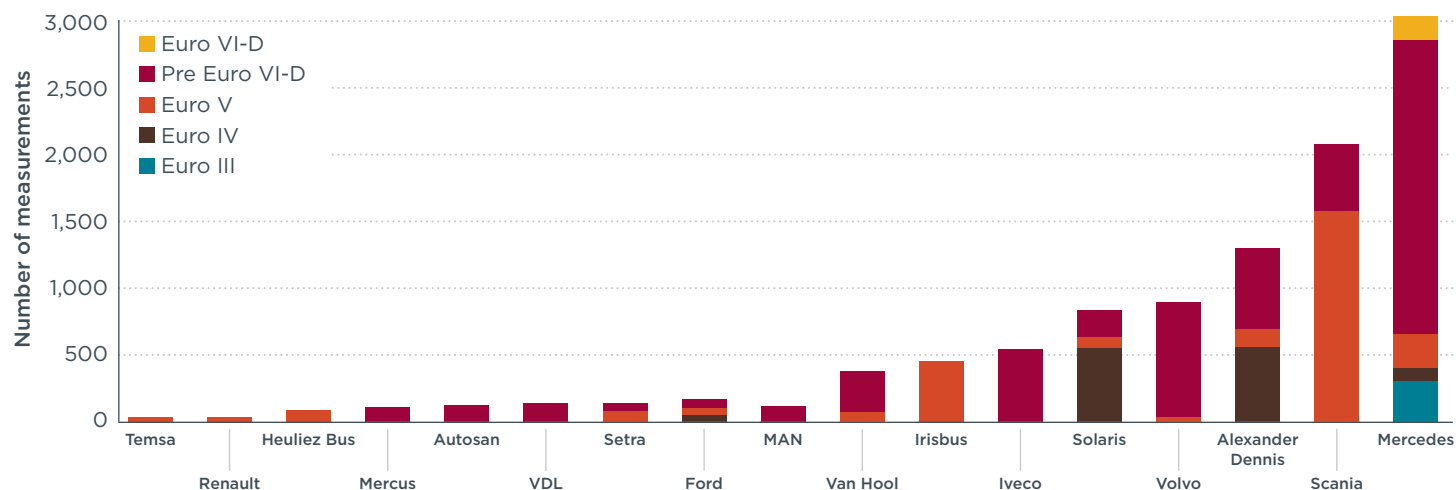


Figure 14. Sampled buses characterized by manufacturer and Euro emissions standard

Figure 15 summarizes the testing conditions and the sampled bus characteristics from the six campaigns broken down by Euro standards, after filtering for vehicles with a negative VSP through applying the method previously described.

Unlike the truck measurements which were all recorded over a one-month period, the measurements for buses were captured over a variety of years and seasons. On the upper bound, the testing data taken from Paris, which was conducted in June and July of 2018, had a mean ambient air temperature of 30°C, while the London testing campaign conducted between November 2017 and February 2018 had a mean value of 10°C. Similarly, the wide range of tests presented a variation in road grade from 0.6% to 6%. Buses certified under Euro VI-D were only recorded from Brussels and Warsaw campaigns, which took place later than 2020, while pre-Euro VI-D buses were collected from all campaigns.

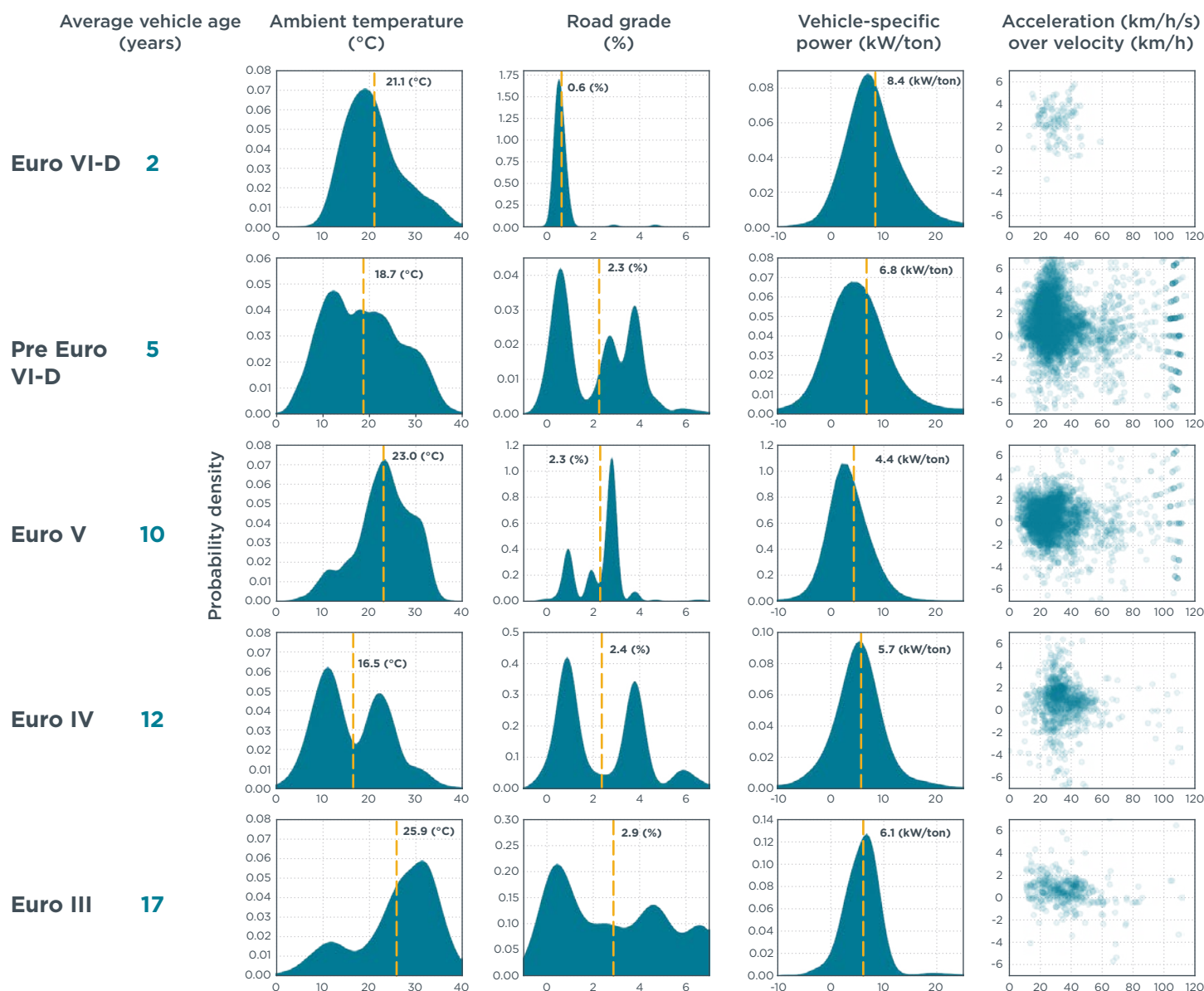


Figure 15. Summary of remote sensing testing conditions and bus characteristics from all measurement campaigns

Emission results

This section presents the NO_x emission results of from buses related to the six different remote sensing campaigns conducted in Brussels, Flanders, Krakow, London, Paris, and Warsaw.

Bus NO_x emissions

Figure 16 presents the average NO_x emissions of the European buses by emissions standard benchmarked against the official regulatory limits. The implementation of Euro VI-D standard stage coincides with a significant real-world NO_x emissions reduction. Pre-Euro VI-D buses emit approximately three times more NO_x emissions than Euro VI-D vehicles. However, it should be noted that the measurements of Euro VI-D vehicles are limited to just 200 vehicles compared to 4,100 pre-Euro VI-D buses and do not cover a wider variation in operating characteristics than the other campaigns. Additional remote sensing measurements of Euro VI-D vehicles are necessary to better understand their real-world emissions.

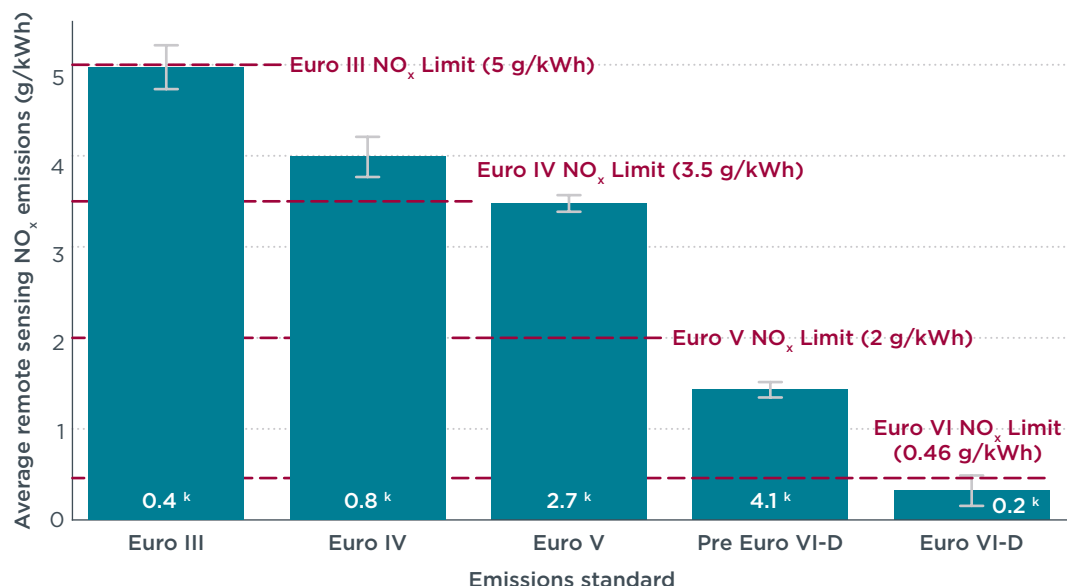


Figure 16. Average NO_x emissions of European buses by emissions standard for different remote sensing campaigns data around Europe. The number of measurements is presented below each bar and the error bars represent the 95% confidence interval of the mean. The dashed red lines indicate the regulatory limit for each Euro standard. Only results of groups with positive VSPs are shown.

NO_x emissions consistently decreased across the buses measured through the increasing stringency of the Euro emission standards. However, the average real-world NO_x emissions of all European buses measured are found to be higher than 1.5 g/kWh, with the exception of Euro VI-D buses. The average NO_x emissions of the pre-Euro VI-D buses are approximately 3 times higher than the Euro VI-D vehicles, whereas NO_x emissions from the pre-Euro VI-D trucks recorded from the Flanders campaign were 2.5 times lower than pre-Euro VI-D buses (see Figure 17). The difference in the observed emissions relative to the laboratory regulatory limits may be attributable to the different drive cycles: bus measurements were captured in urban areas where the engine works at lower loads and speeds, including start-stop drive cycle, and the aftertreatment system might perform poorly due to lower exhaust gas temperatures in which the SCR system does not operate in its optimum condition.

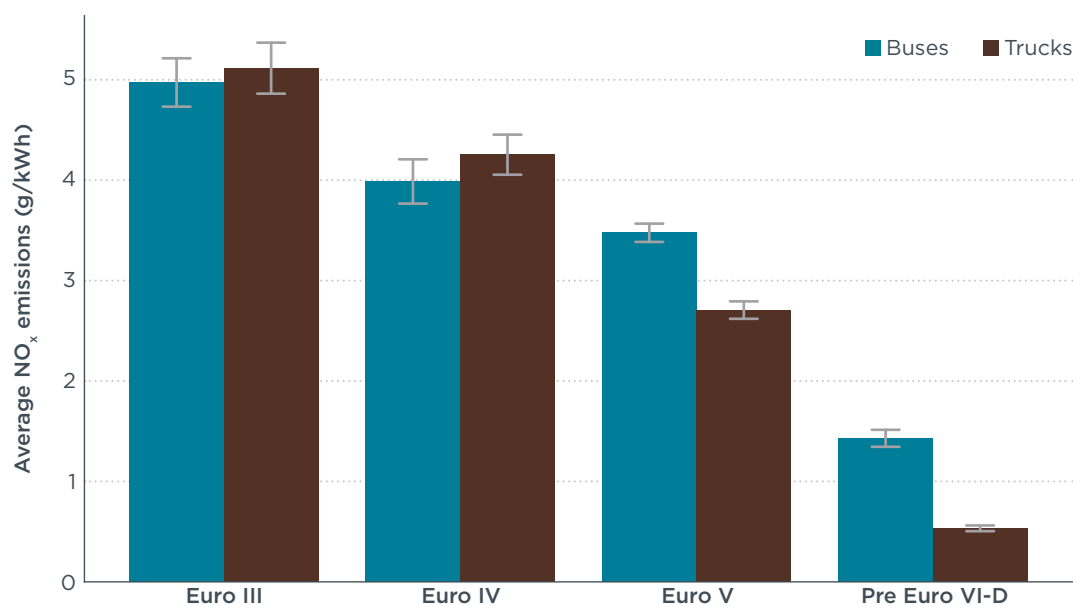


Figure 17. Average NO_x emission comparison of European buses and trucks by emissions standard for different remote sensing campaigns data around Europe. The error bars represent the 95% confidence interval of the mean.

Figure 18 illustrates the distribution of the bus NO_x emissions based on the vehicle specific power in which the emissions were measured. The majority of the measured buses were performing in low VSPs ($\text{VSP} < 20 \text{ kW/ton}$), where the measured NO_x emissions are in higher levels. This provides more evidence that implies vehicles under real driving conditions emit higher emissions than under the standard test conditions. In the current Euro VI in-service conformity (ISC) on-road testing requirement, measurement data below a certain engine coolant temperature and engine load threshold are removed and not considered. Consequently, it could be concluded that the current ISC Euro standard test procedure excludes the high emitting operating conditions which are occurring during real driving cycles. In contrast, the truck campaign was performed on a motorway where aftertreatment system may have a more optimized performance. This discrepancy in engine load and vehicle speed between the bus and truck measurements can be seen in the vehicle characteristics presented in Figure 7 and Figure 15.

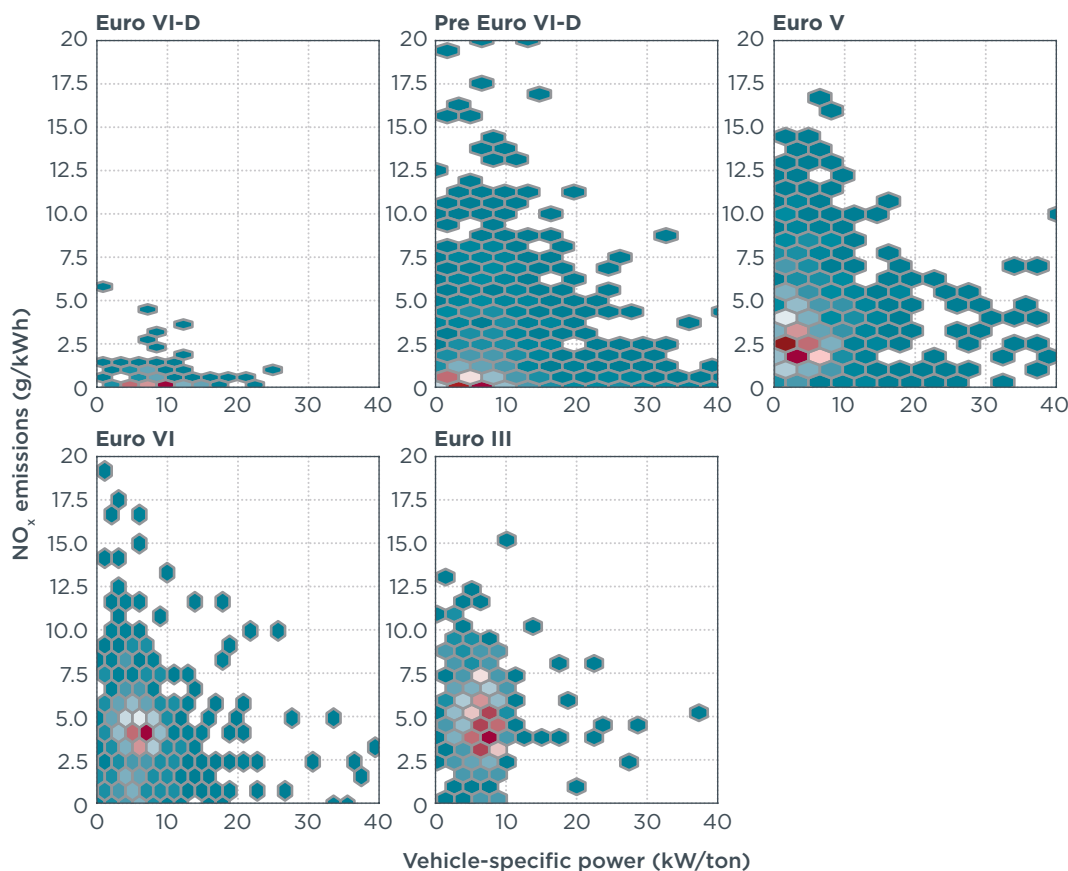


Figure 18. Distribution of the NO_x emissions with respect to vehicle specific power for different Euro standards. The colors of the areas represent the number of the buses at each area, where the red and blue colored areas include the highest and the lowest numbers, respectively.

Figure 19 illustrates the distribution of the NO_x emissions from the measured buses split by Euro standard. Here we identify high-emitting buses as statistical outliers, i.e., vehicles with emissions above the third quartile plus 1.5 times the interquartile range. This equates to 10 g/kWh for Euro IV buses, 9 g/kWh for Euro V buses, 4.8 g/kWh for pre-Euro VI-D buses, and 1.5 g/kWh for Euro VI-D buses. Applying these thresholds finds that 378, or roughly 10%, of the measured pre-Euro VI-D buses are deemed to be high-emitters. There are an insignificant number of Euro VI-D high-emitter outliers compared to pre-Euro VI-D buses. Pre-Euro VI-D buses include a portion of high-emitter outliers which emit from 10 to 20 times the Euro VI regulatory limit.

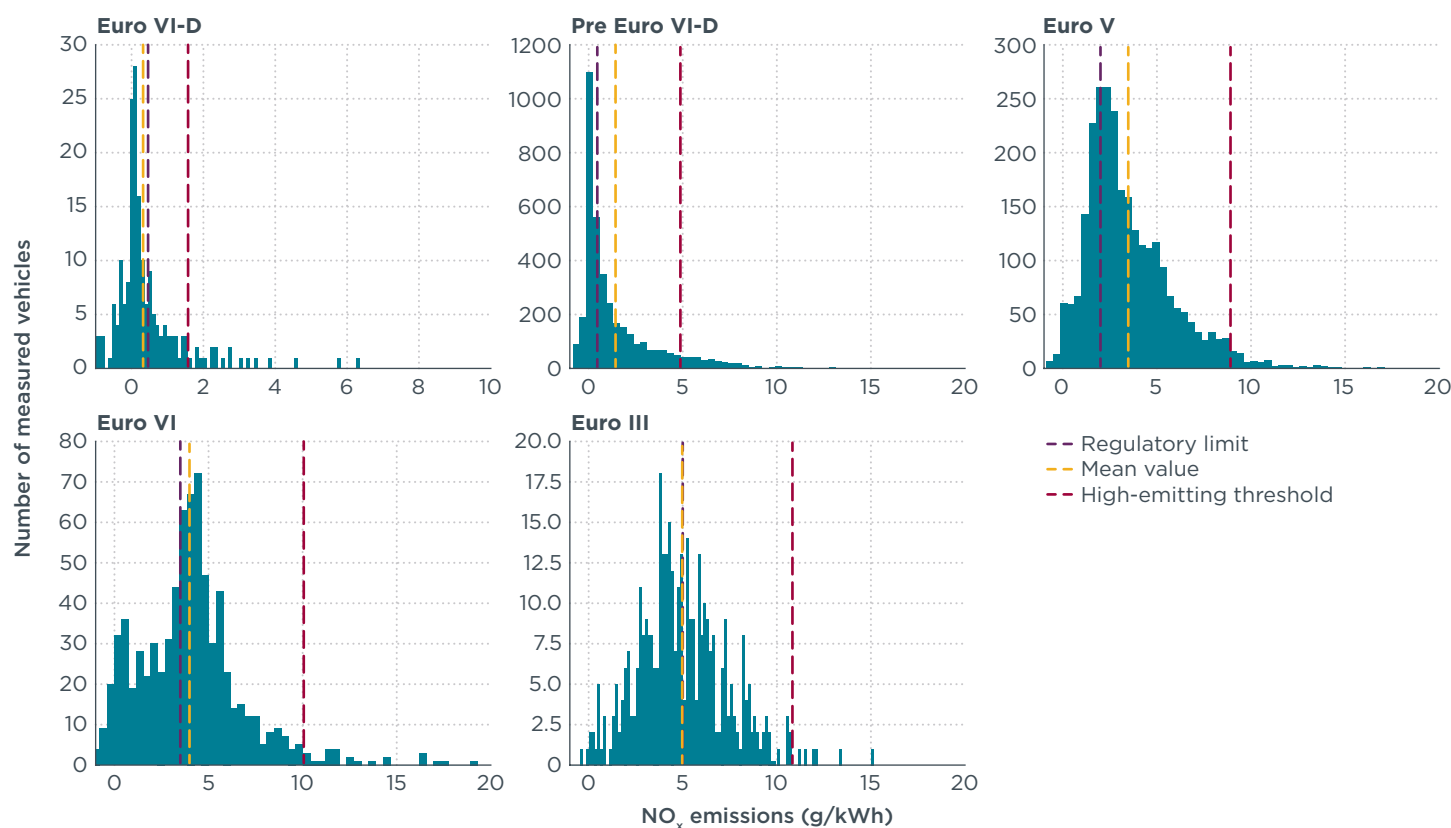


Figure 19. Measured NO_x emission distribution of European buses by emissions standard for different remote sensing campaigns data around Europe. The vertical blue line indicates the regulatory limit for each Euro standard, the vertical yellow line depicts the mean value of NO_x emissions, and the vertical red line demonstrates the emissions level of the high-emitter vehicles.

Figure 20 presents the NO_x emissions of the European buses in this analysis by manufacturers for Euro VI vehicles, including pre-Euro VI-D and Euro VI-D vehicles, benchmarked against the Euro VI regulatory emissions limit.¹² The average real-world NO_x emissions for most manufacturers are higher than the laboratory regulatory limit for Euro VI heavy-duty vehicles by a factor of 1.5–4 which indicates the significant gap between the current regulatory emission limits and the emission levels produced by heavy-duty vehicles under real driving conditions. Notably, buses manufactured by Mercedes, which comprise the majority of buses recorded in this analysis, had the highest average NO_x emissions compared to the other bus manufacturers.

¹² Only manufacturers with at least 30 measurements are shown.

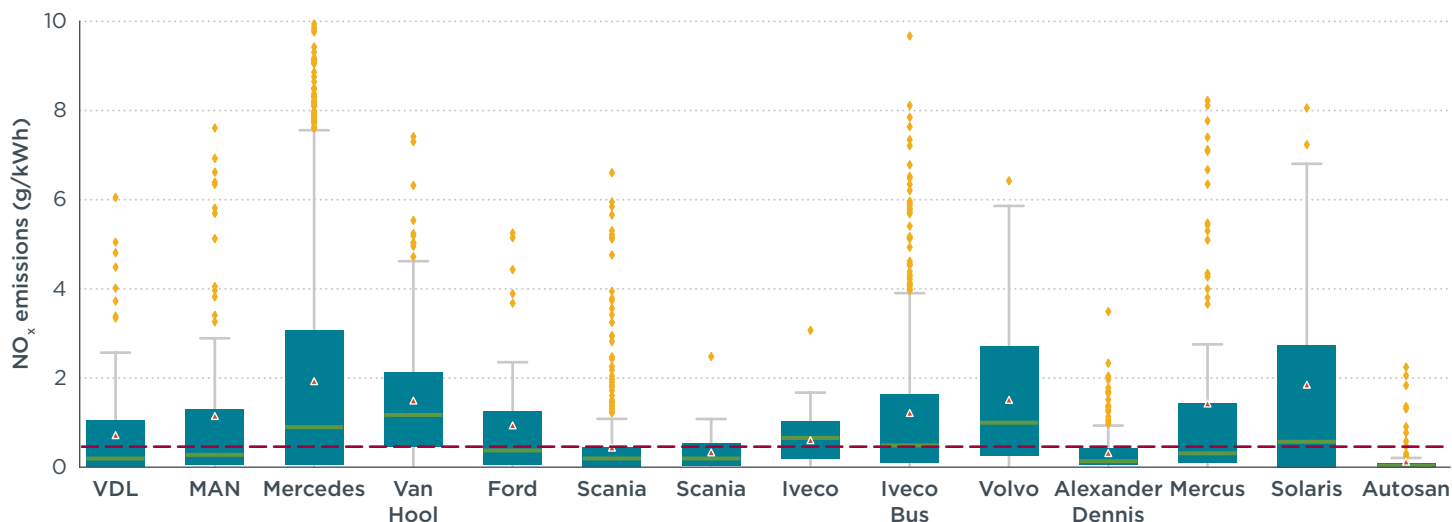


Figure 20. Measured NO_x emission distribution of pre-Euro VI-D buses by manufacturer. Yellow points represent the vehicles with emissions above the 3rd quartile plus 1.5 times the interquartile range of all measurements of each manufacturer and the error bars depict emission ranges which fall in between these two thresholds. The red colored triangles and dashed lines indicate the NO_x emissions mean values and the regulatory limit for Euro VI standard (0.46 g/kWh) respectively.

Due to the higher number of recorded vehicles and the higher average level of the NO_x emissions from the buses manufactured by Mercedes, we investigated these emission results in more detail. We divided these buses into three different classes, including city buses, coach buses, and travel vans, based on the models available from remote sensing measurements. Figure 21 demonstrates the average NO_x emissions of different Euro VI bus categories manufactured by Mercedes. City buses were associated with the highest amount of emissions, which could also confirm the potential adverse effects of city driving conditions on the NO_x emissions of the heavy-duty vehicles as discussed in previous sections. The results show that the NO_x emissions from city buses are approximately four times higher than the emissions from coach buses and twice as high as the emissions from the travel vans. As the coach buses and travel vans are typically used for long distance transportation, the vehicles seldom experience the high NO_x conditions such as low load cycles or cold starts.

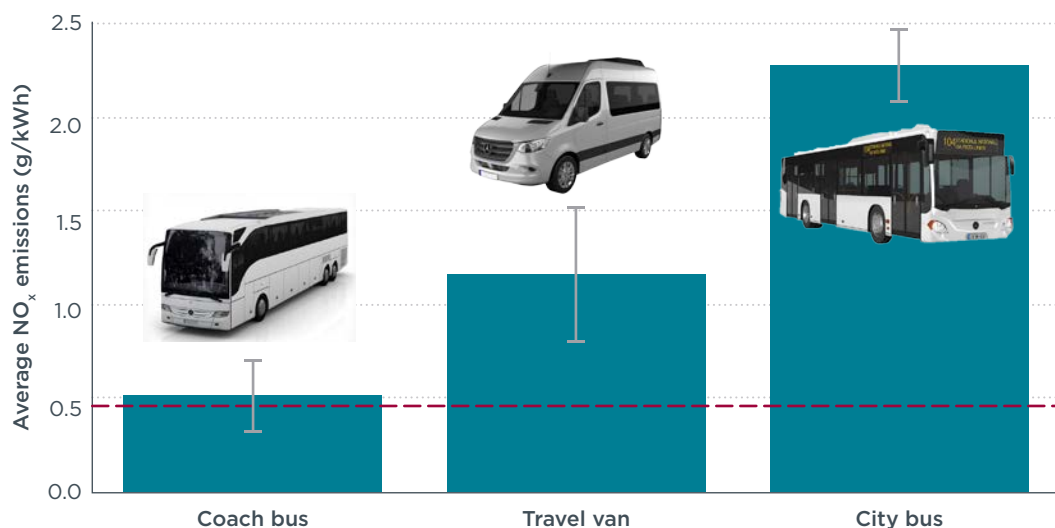


Figure 21. Average NO_x emissions of different Euro VI bus categories manufactured by Mercedes based on vehicle models. The dashed red line indicates the Euro VI standard emissions level as reference point. The error bars represent the 95% confidence interval of the mean.

Conclusion

This study presents a multi-regional remote sensing analysis of 33,600 European trucks and buses to quantify the real-world level of pollutant emissions across different vehicle emission classes. It draws on data recorded from six remote sensing campaigns in Europe conducted between 2017 and 2020, covering a range of ambient temperatures and vehicle driving conditions. The focus of this study was to determine the level of real-world NO_x emissions of trucks and buses and how this has evolved over the various Euro emission standards applicable to each vehicle.

The results of this study confirms the previous lessons learned from passenger car remote sensing campaigns, revealing that the real-world NO_x emissions of the heavy-duty vehicles are generally in exceedance of the regulatory limits, particularly in urban areas. This contributes to persistent air-quality problems in European cities and leads to harmful public health impacts. Despite this, a clear reduction in the average NO_x emissions of trucks and buses was observed over the increasing level of stringency of the Euro emission standards. For buses, the introduction of the Euro VI-D stage for new vehicles reduced the NO_x emissions of buses three-fold in comparison with other Euro VI buses predating this standard. In addition to the stricter test conditions imposed by emission standards for Euro VI-D vehicles, the emission control technologies of these vehicles operate effectively, although it is important to continue to monitor their performance throughout the vehicle lifetime.

Our findings are summarized in Figure 22. Here we show the number of low-emitting vehicles with NO_x emissions below the regulatory limit, high-emitting vehicles defined as statistical outliers (i.e., with a level of NO_x in the 3rd quartile of all measurements plus 1.5 times the interquartile range), and medium-emitting vehicles which fall in between these two thresholds, all based on the remote sensing measurement data. Vehicles with NO_x emissions falling above the regulatory limit are not necessarily non-compliant with the respective Euro standard, as these measurements were recorded over a variety of operating conditions not representative of test conditions.

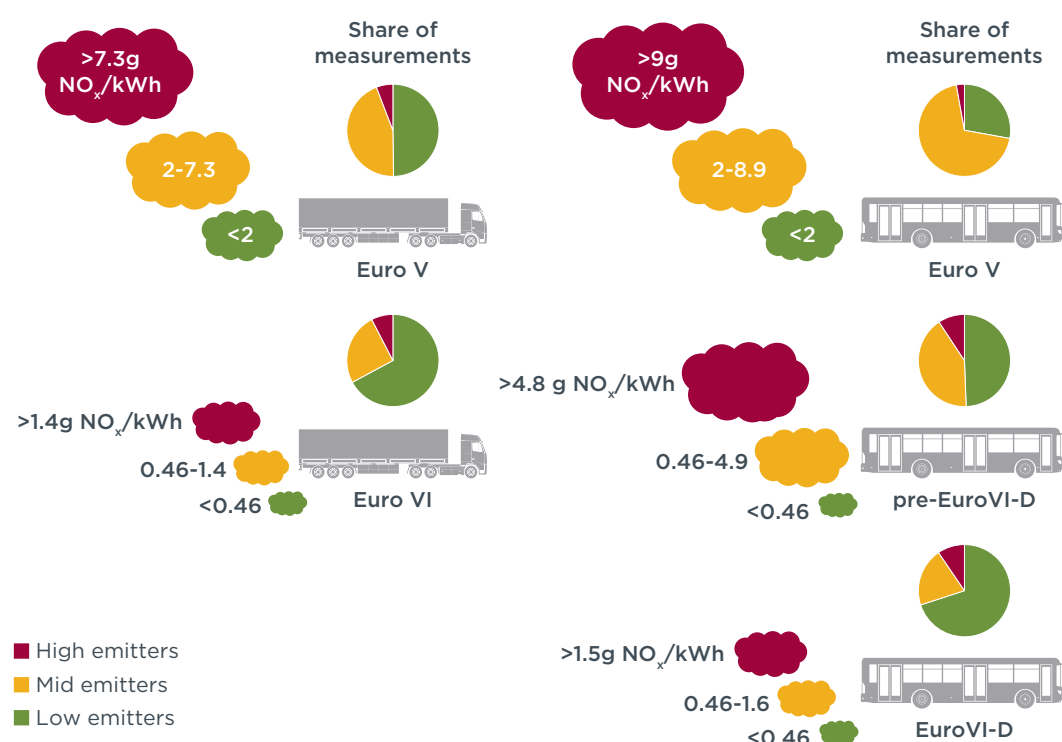


Figure 22. Summary of NO_x emissions from trucks and buses across all remote sensing campaigns. Low emitters are defined by vehicles with emissions recorded at a level below the limits imposed by the respective Euro standards. High emitters are defined as the 3rd quartile plus 1.5 times the interquartile range of measurements, and mid-emitters fall between the two.

Notably, the share of high-emitting vehicles is, in general, higher for more stringent Euro standards. Nearly 2% of Euro IV compliant trucks, 5.8% of Euro V trucks, and 7.6% of Euro VI trucks were found to be high emitters. For buses, 3.4% of Euro IV buses, 2.8% of Euro V buses, 9.3% of pre-Euro VI-D buses (i.e., Euro VI buses not including Euro VI-D), and 9.5% of Euro VI-D buses were found to be high-emitters.

The level of NO_x emissions from buses are higher than those from trucks across all Euro standards. This may be because bus measurements were recorded in urban areas where buses are more subject to a start-stop drive cycle and cold starts, whereas the Flemish campaign, from which we derive all of the truck measurements, was conducted on a motorway where the engine would be operating in steady-state conditions. Hence, driving conditions of the vehicles have significant effect on NO_x emissions and vehicles operating in urban areas produce a higher level of emissions.

Introducing remote sensing techniques may be a useful tool for monitoring the level of high-emitting vehicles. High levels of emissions from vehicles may be due to such causes as faulty emission control systems, tampering, or conditions not captured during certification testing, such as idling, low load cycles, or cold starts. Deploying remote sensing devices may assist in the identification of a high-emitting vehicle, albeit alone this will not determine the cause. Combining this with a roadside inspection would allow local authorities to further investigate the cause of high emissions from individual vehicles.

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Appendix

Calculation of vehicle specific power (VSP)

The required engine power during a driving cycle can be computed from the main power demands of the vehicle to overcome the power losses and accelerate the vehicle as follows:

$$P_{Eng} = P_{Accel} + P_{Roll} + P_{Aero} + P_{Grade} + P_{Trans} + P_{Aux} \quad (1)$$

Where:

P_{Eng} is the engine power demand

P_{Accel} is the power needed to accelerate the vehicle

P_{Roll} is the power losses caused by the vehicle rolling resistance

P_{Aero} is the aerodynamic power losses caused by air resistance

P_{Grade} is the power losses needed to climb the road grade

P_{Trans} is the power losses caused by transmission system

P_{Aux} is the vehicle auxiliary power demand including cooling fan, steering pump, pneumatic system, air conditioning, etc.

The following assumptions have been made in our calculation of VSPs for HDVs:

- » The power transmission losses from the engine to driven wheels is set to 8% (Borken-Kleefeld et al., 2018).
- » The auxiliary power demand for the trucks and buses is defined to be 4,000 W derived from the Certification Regulation (Commission Regulation (EU) 2017/2400, 2017).
- » Average air drag area ($C_d \times A$, in m^2) which is defined as the product of the drag coefficient (C_d) and the cross-sectional area of the vehicle (A) has been assumed to be 5.65 m^2 for the trucks and 5 m^2 for buses. Rolling resistance coefficients for the trucks and buses have been assumed to be 0.0055 and 0.008 respectively (Ragon & Rodriguez, 2021).
- » The mass of the vehicle for the trucks is assumed to be the 50% of its gross vehicle weight (GVW) and for the buses is approximated to be the bus unladen mass plus the mass of 30 passengers each 70 kg.

Based on the above-mentioned assumptions, the demanded engine power and VSP for a given velocity and acceleration is calculated as follows (Borken-Kleefeld et al., 2018):

$$\frac{P_{Eng} [kW]}{m[kg]} = \frac{\left[\frac{P_{Accel}}{m \times a \times 1.04} + \frac{P_{Roll}}{m \times g \times RR \times \cos(grad)} + \frac{P_{Aero}}{CdA \times 0.6 \times v^2} + \frac{P_{Grade}}{m \times g \times \sin(grad)} \right]}{m \times 1000} \times 1.08 \times v + \frac{P_{Aux}}{4000} \quad (2)$$

$$VSP \left[\frac{kW}{ton} \right] = [a \times 1.04 + g \times RR \cdot \cos(grad) + g \cdot \sin(grad)] \times 1.08 \times v + \frac{[CdA \times 0.6 \times 1.08 \times v^3] + 4000}{M \times 1000} \quad (3)$$

Where:

m = vehicle mass [kg]

a = vehicle acceleration [m/s^2]

g = gravitational acceleration, 9.81 [m/s^2]

RR = vehicle rolling resistance coefficient [-]

grad = roadway slope [$^\circ$]

$C_d A$ = Vehicle air drag area [m^2]

v = vehicle velocity [m/s]

M = vehicle mass [ton]