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TNO Public ⟩ **TNO-2026-16359**
24 April 2026

Mobility & Built Environment
www.tno.nl
+31 88 866 00 00
info@tno.nl

TNO-2026-16359 – 24 April 2026

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Author(s)	Thomas Frateur, Jann Aschersleben, Sander Spijker, Vincent Verhagen, Zakaria Boukallouht, Deveney Ackon
Copy number	2026-STL-REP-100361231
Number of pages	62 (excl. front and back cover)
Number of appendices	3
Sponsor	Dutch Ministry of Infrastructure and Water management
Project name	RWP & Plume Chasing 2026
Project number	060.65668

Summary

Measuring and monitoring a larger set of vehicles in the Dutch fleet is essential to improve insights into real-world emissions, the share of high-emitting vehicles, and to support effective air-quality policy in the Netherlands. Pollutant emissions can be measured using various techniques, of which the remote-sensing plume-chase method provides a suitable balance between measurement cost, measurement duration and accuracy when measuring emissions from a large number of vehicles under real-world driving conditions. This report presents the results of the 2025 plume-chase measurement campaign, conducted by TNO on Dutch motorways, with an expanded focus on Dutch and international heavy-duty vehicles (HDVs), light-duty delivery vans and the inclusion of initial particulate number (PN) measurements.

During the 2025 campaign, a total of 971 valid vehicle measurements were obtained, complemented by an additional 182 HDV measurements collected in early 2026. Validation measurements confirm that plume chasing provides robust estimates of real-world NO_x-emissions particularly for medium- and high-emitting vehicles. However, the validation campaigns also revealed that the current setup tends to overestimate NO_x-emissions at very low emission levels. Despite this limitation, plume chasing is demonstrated to be highly suitable as a large-scale screening tool for identifying high-emitting vehicles within the fleet.

The NO_x-emission results show a clear reduction in average emissions with successive Euro classes across all vehicle categories. Nevertheless, substantial vehicle-to-vehicle variability remains with individual vehicles exhibiting very high NO_x-emissions in all categories. Across the fleet, a relatively small fraction of vehicles is responsible for a disproportionately large share of total NO_x-emissions. Using a high-emitter definition based on a threshold of twice the average NO_x-emissions within each vehicle category, 10% of HDV diesel vehicles are categorised as high-emitters, which account for 35% of total NO_x-emissions of that category. For diesel delivery vans, this share is around 12% of vehicles contributing roughly 43% of total NO_x-emissions in the category. For petrol passenger cars, 13% of vehicles account for 33% of total NO_x-emissions in the category. Alternative high-emitter definitions are investigated and discussed in the main text. These findings underline the importance of targeted identification and possible follow-up of high-emitting vehicles.

International road tractors are found to show higher average NO_x-emissions and a significantly larger share of high-emitters compared to Dutch road tractors. While Dutch road tractors show a high-emitter share of only 9.0%, international road tractors were found to have a high-emitter share of 17.6%. This difference is statistically significant and is primarily driven by road tractors registered in Eastern European countries, which show a high-emitter share of 20%. In contrast, the high-emitter share of other international road tractors, which are not registered in an Eastern European country, is lower at 12.5% and not statistically different from that of the Dutch fleet. These results indicate that the high-emitter share among international vehicles is primarily driven by the Eastern European road tractors.

Mileage-dependent analyses indicate that NO_x-emissions generally tend to increase with higher vehicle mileage, although the magnitude of this effect differs between vehicle categories and Euro classes.

Initial PN measurements show that most Euro VI diesel HDVs and Euro 6 diesel delivery vans show very low to no particle emissions, meaning their emissions are below the detection limit of the high-emitter detection focussed measurement setup. A small fraction of vehicles shows elevated PN-emissions and based on a first conservative threshold definition, approximately 4-5% of diesel HDVs and diesel delivery vans are classified as suspicious. These vehicles may be considered suspicious for potential diesel particulate filter issues. As PN measurements have not yet been fully validated for plume chasing, these results are considered preliminary and will be further investigated in future campaigns.

Samenvatting

Het meten en monitoren van een groot aantal voertuigen in het Nederlandse wagenpark is essentieel om een beter inzicht te krijgen in de emissies van de vloot onder praktijkomstandigheden, het aandeel voertuigen met hoge emissies, en om ondersteuning te bieden aan het verbeteren van effectief luchtkwaliteitsbeleid in Nederland. Verschillende meettechnieken zijn beschikbaar voor het meten van vervuilende emissies. Van deze technieken biedt de plume-chase-methode een geschikte balans tussen meetkosten, meetduur en nauwkeurigheid bij het meten van emissies van een groot aantal voertuigen onder praktijkomstandigheden. Dit rapport presenteert de resultaten van de plume-chase meetcampagne van 2025 welke uitgevoerd werd door TNO op Nederlandse snelwegen. Deze campagne focuste op Nederlandse en internationale zware bedrijfsvoertuigen (HDV's), lichte bestelwagens en de toevoeging van fijnstof of deeltjesemissies (PN) metingen.

Tijdens de campagne van 2025 werden in totaal 971 geldige voertuigmetingen verkregen, aangevuld met nog eens 182 HDV-metingen die aan het begin van 2026 werden toegevoegd aan de dataset. In 2025 werden ook extra validatiemetingen uitgevoerd welke bevestigen dat plume chasing robuuste schattingen kan opleveren van NO_x-emissies onder praktijkomstandigheden, met name voor voertuigen met middelhoge en hoge emissies. De validatiecampagnes toonden echter ook aan dat de huidige opstelling geneigd is om NO_x-emissies bij zeer lage emissieniveaus te overschatten. Ondanks deze beperking is plume chasing zeer geschikt als grootschalig screeninginstrument voor het identificeren van voertuigen met hoge emissies binnen het wagenpark.

De NO_x-emissieresultaten laten een duidelijke afname zien van de gemiddelde emissies bij opeenvolgende Euroklassen voor alle voertuigcategorieën. Desondanks blijft er een aanzienlijke variatie tussen individuele voertuigen bestaan, waarbij in alle categorieën voertuigen met zeer hoge NO_x-emissies worden waargenomen. Binnen het wagenpark is een relatief klein deel van de voertuigen verantwoordelijk voor een onevenredig groot aandeel van de totale NO_x-emissies. Bij een definitie van een high-emitter op basis van een drempelwaarde van tweemaal de gemiddelde NO_x-emissies binnen elke voertuigcategorie, wordt 10% van de diesel-HDVs als high-emitter geclassificeerd. Deze voertuigen stoten samen zo'n 35% van de totale NO_x-emissies in die categorie uit. Voor dieselbestelwagens betreft dit aantal ongeveer 12% van de voertuigen, die circa 43% van de totale NO_x-emissies in de categorie bijdragen. Voor benzinepersonenauto's is 13% van de voertuigen verantwoordelijk voor 33% van de totale NO_x-emissies in de categorie. Alternatieve definities van high-emitters worden in de hoofdtekst onderzocht en besproken. Deze bevindingen onderstrepen het belang van gerichte identificatie en mogelijk opvolging van voertuigen met hoge emissies.

Internationale HDV trekker-opleggers vertonen gemiddeld hogere NO_x-emissies en een significant groter aandeel high-emitters dan Nederlandse trekker-opleggers. Waar Nederlandse trekker-opleggers een aandeel high-emitters van slechts 9,0% laten zien, werd voor internationale trekkers een aandeel hoog emitters van 17,6% gevonden. Dit verschil is statistisch significant en wordt voornamelijk veroorzaakt door trekkers geregistreerd in Oost-Europese landen, die een aandeel hoog emitters van 20% laten zien.

Daarentegen is het aandeel hoog emitters van overige internationale trekkers (niet geregistreerd in een Oost-Europees land) lager (12,5%) en statistisch niet verschillend van dat van het Nederlandse wagenpark. Deze resultaten geven aan dat het hogere aandeel high-emitters onder internationale voertuigen voornamelijk wordt bepaald door de bijdrage van Oost-Europese trekker-opleggers. Kilometerstand afhankelijke analyses geven aan dat NO_x-emissies over het algemeen toenemen bij een hogere voertuigkilometerstand, hoewel de omvang van dit effect verschilt tussen voertuigcategorieën en Euroklassen.

De eerste plume-chase PN-metingen laten zien dat de meeste Euro VI-diesel-HDVs en Euro 6-dieselbestelwagens zeer lage tot geen deeltjesemissies vertonen. Dit betekent dat hun emissies onder de detectielimiet van de meetopstelling komen te liggen (gezien deze gericht is op het opsporen van high-emitters). Een klein deel van de voertuigen vertoont verhoogde PN-emissies en op basis van een eerste conservatieve drempeldefinitie wordt ongeveer 4–5% van de diesel-HDVs en dieselbestelwagens geclassificeerd als verdacht. Deze voertuigen kunnen als verdacht worden beschouwd met betrekking tot mogelijke problemen met het dieselroetfilter (DPF). Omdat PN-metingen met plume chasing nog niet volledig zijn gevalideerd, worden deze resultaten als voorlopig beschouwd en zullen ze in toekomstige campagnes verder worden onderzocht.

Contents

Abbreviations

Abbreviation	Meaning
CO_2	Carbon dioxide
HDV	Heavy-Duty Vehicle
km	Kilometre
kWh	Kilowatt-hour
LDV	Light-Duty Vehicle
mg	Milligram
NO_x	Nitrogen oxides
PN	Particulate number
RDE	Real Driving Emissions (legislation)

1 Introduction

Over the years, road vehicle emission regulations have become increasingly stringent, leading to a gradual reduction in pollutant emissions from on-road vehicles as a result of improved exhaust gas aftertreatment systems, and the growing share of electric vehicles in the fleet. Emissions from the remaining internal combustion engine (ICE) vehicle fleet will, however, remain relevant even after the planned partial phase-out of new ICE vehicles in 2035 due to ageing effects within the existing fleet. At present, a large share of automotive emissions is already caused by a relatively small fraction of high-emitting vehicles, often as a result of poor maintenance or tampering, rather than limitations of the exhaust gas aftertreatment technology itself. This has been demonstrated in previous studies (Kadijk G. , et al., 2020; Kadijk G. , Elstgeest, Ligterink, & Mark, 2018), which showed that 6 % of petrol vehicles on Dutch roads were responsible for 36 % of the total NO_x-emissions from the petrol vehicle fleet. As well as in the predecessor to this report (Frateur, Kunz, & Aschersleben, 2025), where high emitter rates of respectively 8%, 7% and 6% for light-duty petrol, light-duty diesel and heavy-duty Euro 6 vehicles were found. Nevertheless, the available sample size remains limited, and measuring and monitoring a larger number of vehicles is essential to obtain more robust and statistically significant insight into the real-world emissions on Dutch roads and to support effective policymaking.

Fleet emission statistics have traditionally been derived from extensive emission testing of individual vehicles using on-road measurements with portable emission measurement systems (PEMS). This approach provides detailed insight into the emission behaviour of a specific vehicle, but typically requires multiple days of work, including vehicle instrumentation and testing. In contrast, the plume-chasing remote-sensing method offers a less detailed but considerably faster approach for measuring on-road NO_x-emissions from multiple vehicles without the need for extensive installation on individual vehicles. A typical plume-chasing measurement of a single vehicle takes approximately 2 to 5 minutes, allowing 10 to 15 vehicles to be measured per hour under practical conditions.

In (Vroom, et al., 2024), and in the predecessor to this report (Frateur, Kunz, & Aschersleben, 2025), the capability of the plume-chasing method to identify various low- and high-emitting vehicles on the road was described. In addition, the insights from a total of 520 measured vehicles on Dutch motorways were reported. In 2025, the plume-chase measurements described in (Frateur, Kunz, & Aschersleben, 2025) were expanded further with additional measurement to increase the statistical relevance of the analysis results.

In the 2025 campaign, the scope of the measurements was amended to include:
- A focus on measurements of heavy-duty vehicles and light-duty diesel delivery vans – in line with the priorities of the April 2025 update to the road side inspection agenda of the Road Worthiness Package (RWP) proposal of the European Commission (EC).
- Measurements on international heavy-duty vehicles
- Measurements on particulate number emissions for the purpose of identifying potentially malfunctioning Diesel Particulate Filters (DPF) in diesel vehicles.

L-cat vehicles and vehicles with a Euro class preceding Euro 4 are explicitly excluded from this study.

The results of this 2025 measurement campaign are detailed in this report.

Chapter 2 of this report describes the methodology applied in this study, including the plume-chasing measurement approach, data analysis and validation methods. The validation results are presented and discussed in Chapter 3. Chapter 4 provides the plume-chasing measurement results and discussion for heavy-duty and light-duty vehicles. Finally, the main conclusions of the study are summarised in Chapter 5.

This research has been performed as part of the programmatic collaboration between the Dutch Ministry of Infrastructure and Water Management (IenW) and TNO.

2 Methodology

As was previously explained in (Frateur, Kunz, & Aschersleben, 2025), pollutant emission measurements can be carried out using various techniques. Broadly, two main categories can be distinguished: direct tailpipe measurements and remote (indirect) sensing measurements. Direct tailpipe measurements provide highly accurate results for individual vehicles, but are prohibitively expensive when applied to a large subset of the Dutch vehicle fleet. Remote-sensing measurements are less accurate for individual vehicles, but do not require extensive instrumentation of the vehicles being measured. As a result, the cost and measurement time per vehicle are significantly lower for remote-sensing techniques compared to direct tailpipe measurements. Moreover, cooperation from owners of tampered vehicles is often limited in instrumented measurement campaigns, whereas remote-sensing allows for a more representative sampling of the vehicle fleet. Consequently, remote-sensing techniques are particularly well suited for determining fleet-wide emissions and the share of high-emitting vehicles based on a statistically relevant number of measurements.

Within the category of remote-sensing techniques, a further distinction can be made between stationary measurements, such as those provided by OPUS (Sano, et al., 2002) and HEAT (Ropkins, et al., 2017), and dynamic measurements, commonly referred to as plume-chasing measurements. This dynamic approach allow for longer measurement durations for individual vehicles and are less sensitive to the specific measurement location when determining vehicle emissions (Chen, Zhang, & Borken-Kleefeld, 2019). In contrast to stationary measurements, dynamic plume-chasing techniques can therefore provide relevant information on an individual vehicle based on a single measurement (Schmidt, et al., 2023).

In this report, Nitrogen Oxides (NO_x)-and Particulate Number (PN)-emissions measurements using the plume-chasing technique on vehicles in the Dutch fleet are discussed. The remainder of this chapter details the employed measurement setup, the relevant details of the measurement programme and the data post-processing methodology used to obtain the emission results further detailed in Chapter 3 and 4.

2.1 Measurement method

Plume chasing is a remote-sensing technique in which a measurement vehicle, equipped with various measurement instruments, is employed to measure vehicle emissions on the road without the need for instrumentation of the measured vehicle.

Each vehicle measurement is conducted by chasing a vehicle of interest for a minimum of two minutes. Based on the initial measurement results, additional measurement time is needed to obtain valid measurement results. A guideline for the measurement duration for different emission levels is based on the observed emissions as:

1. Normal emissions $\left(\frac{E_{measured}}{E_{ER}} < 3\right)$: 2 minutes
2. Increased emissions $\left(3 \leq \frac{E_{measured}}{E_{ER}} \leq 5\right)$: 5 minutes
3. High emissions $\left(\frac{E_{measured}}{E_{ER}} > 5\right)$: 5 minutes

Where $E_{measured}$ is the average measured NO_x-emission in g/km, and E_{ER} is the NO_x-emission factor (g/km) in the Dutch Emission Inventory (ER) of the vehicle-specific VERSIT[1] class.

When large temporal variations in the CO_2-normalised[2] emissions are observed, the measurement duration is increased to improve the statistical robustness of the vehicle specific emission calculations.

Results are valid when:

- at least 40 seconds of measurement data is available with CO_2-levels at least 20 ppm above the background concentration,
- vehicle information can be retrieved from the licence plate scan, or sufficient manual vehicle information was noted down by the plume-chase vehicle operator.
- and the vehicle falls within one of the target groups in this study.

Note that while the plume-chase measurement contains data over a longer period of time compared to stationary remote-sensing applications, the measurement result of the chased vehicles should still be considered as a spot measurement. Temporary high (or low) emissions can be the result of various causes which are unknown to the plume chase operator at the time of measuring.

During the measurement, the plume-chase vehicle remains at a normal driving distance behind the vehicle of interest. Vehicle information is automatically added to each measurement using information from the ANPR camera and a lookup database with information on the VERSIT class, Taxonomy[3] code and CO_2-emission factor of each vehicle in the Dutch fleet. Information on international heavy-duty vehicles (HDVs) is added manually by the plume-chase vehicle operator.

2.1.1 TNO plume-chase vehicle

The TNO plume-chase vehicle shown in Figure 2.1 incorporates the plume-chase technique for the measurement of NO_x- and PN-emissions as detailed in Section 2.1. To that extent, ambient NO_x, PN and Carbon Dioxide (CO_2)-measurement instruments are used to analyse the emission plume of a vehicle of interest. Relevant vehicle information is coupled to the measurements using a licence plate camera and vehicle database[4], or manual data input by the plume-chase operator in the data acquisition software when database information is unavailable.

[1] VERSIT+: Road traffic emission model developed by TNO to predict emission factors of vehicle fleets (Smit, Smokers, & Rabé, 2007). Emission factors of each VERSIT class are determined based on emission measurements and estimated ageing effects of the vehicles in this class.
[2] CO_2 normalised emissions: pollutant emissions expressed in gram pollutant per kilogram carbon dioxide.
[3] Taxonomy code: A controlled vocabulary and vehicle classification system for all passenger cars on the road (de Ruiter, et al., 2021)
[4] Only for vehicles registered in the Netherlands.

Figure 2.1: TNO plume-chase vehicle: Sample inlets and radar on the front bumper, and the licence plate camera behind the window (left). NO_x, PN and CO_2-measurement instruments and battery pack in the rear cabin (right).

The emission measurement instruments used in the TNO plume-chase vehicle are listed in Table A.1 of 0. The remainder of the plume-chase hardware is listed in Table A.2 of 0. A detailed description of the new PN measurement system is discussed in Section 2.1.1.1.

2.1.1.1 Particle Number measurement system

To enable the detection of diesel vehicles with potential Diesel Particulate Filter (DPF) issues, the measurement setup of the TNO plume-chase vehicle as presented in (Frateur, Kunz, & Aschersleben, 2025) was updated to include a PN measurement system. Similar to the NO_x measurement system onboard the plume-chase vehicle, the PN measurement system makes use of a CO_2-analyser as the reference instrument for plume identification. In addition, the PN-measurement system employs a particle number counter to give an indication of the number of solid particles in the measured exhaust plume sample. For this purpose, an adapted TEN Aerosol Electro Meter (AEM) instrument is used.

The AEM is a device developed for PN measurements on diesel vehicles in the Dutch Periodic Technical Inspection (PTI). In a previous study, this device was found to significantly overestimate particulate emissions on sources with larger particles (Frateur, et al., 2024). To account for this, the device in this application is equipped with an impactor in the sampling system to remove particles with an aerodynamic diameter above 206 nm, as was confirmed in a laboratory validation test. As such, diesel particulate emissions, for which between 58% and 92% of particles have an average aerodynamic diameter between 50 and 100 nm (Fujitani, et al., 2020), are allowed to pass in the sampling system while larger particles form different sources are removed from the sample. The PN measurement system is shown in Figure 2.2 for reference.

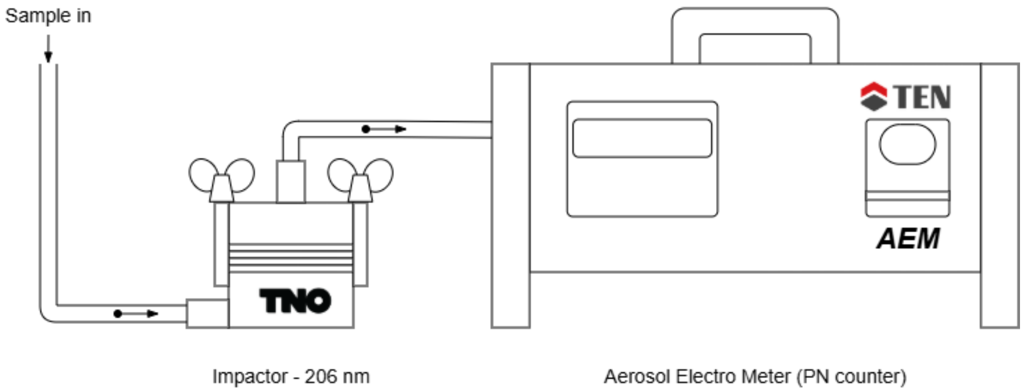

Figure 2.2: Schematic representation of the PN measurement system in the plume-chase vehicle.

While the particle counter in the PN-measurement system has been adapted to avoid interference from other sources, results from this system should only be used as an indication of possible issues with the DPF of diesel vehicles. Further validation of the setup is required to verify its suitability for the determination of accurate emission factors based on fleet measurements.

2.2 Data analysis method

Emission measurement instruments measure volume-based emission concentrations. To be able to determine the emissions of a measured vehicle, data post-processing and analysis is needed. Determination of distance-normalised emissions is well known and documented in literature such as (Bischop & Stedman, 1996), (Pöhler, et al., 2019) and (Tong, et al., 2022). For heavy-duty vehicles, emissions are expressed as work-normalised emissions (mg/kWh) to allow the comparison with regulatory limit values and to account for differences in engine load and vehicle operation (see for example (Mendoza-Villafuerte, 2017; Pöhler, et al., 2019)). In this work, the internally developed *Emission Control and Tracking Optimisation (ECTO)* software is used for data post-processing and analysis.

2.2.1 NO_x-emissions calculation method

2.2.1.1 Distance-normalised emissions

In remote-sensing, vehicle pollutant emissions are normalised with the measured CO_2-concentration in the emission plume. CO_2-emissions are directly correlated to the fuel burn and are therefore an ideal reference gas for pollutant emissions. When the average CO_2-emissions per driven kilometre are known for the measured vehicle, the distance-normalised NO_x-emissions can be calculated from the instantaneous measured concentrations as:

$$NO_x\left[\frac{g}{km}\right] = \frac{C_{NO_x}[ppb]\cdot m_{NO_x}[g/mol]}{C_{CO_2}[ppm]\cdot m_{CO_2}[g/mol]}\cdot E_{CO_2}\left[\frac{kg}{km}\right]$$

Here C_{NO_x} and C_{CO_2} are the measured concentrations of NO_x and CO_2 minus the ambient background concentration. The ambient background concentration is not explicitly measured, but is determined from the lowest measurements in the last 20 kilometres (rolling window) during which no vehicle was measured. m_{NO_x} and m_{CO_2} are the molar masses of NO_x and CO_2, equal to respectively 46.01 g/mol and 44.01 g/mol.

The CO_2-emission factor of the vehicle E_{CO_2} is retrieved based on the license plate from the M1 model (Ruiter, Gijlswijk, & Ligterink, 2021) for Light-Duty Vehicles (LDVs) and the bottom-up methodology (Geilenkirchen, et al., 2024) from the Dutch Emission Inventory for HDVs registered in the Netherlands. Note that the uncertainties on the CO_2-emission factor are not further considered throughout this report, as the analyses focus on the uncertainty estimations based on the plume chase validation measurements further discussed in section 3.

Distance-normalised emissions offer a unit that can be directly compared to documented emission factors. However, comparison should be handled carefully as the Dutch VERSIT+ emission factors are indicative of annual averages per road-type, which includes driving behaviour, and has therefore a different scope than what is captures during plume-chase measurements. Furthermore, as the distance-normalised NO_x-emissions of a vehicle are highly dependent on the distance-normalised CO_2-emissions of this vehicle, the unique vehicle results can be sensitive to the actual loading conditions of the vehicle during the measurement, as well as the individual driving behaviour of the vehicle. Especially for heavy-duty vehicles, where the payload has a significant influence on the total mass of the vehicle, this means individual vehicle measurement results should be assessed carefully. For these types of vehicles, the work-normalised emissions offer a better unit to assess individual vehicle results.

On the fleet level, the sensitivity to individual vehicle loading conditions is expected to average out. The conditions during plume-chase measurements however do not cover for the full range of expected driving behaviour per road-type of a measured vehicle.
For example, plume chase measurements are mainly performed under steady motorway driving, while emission factors are designed to capture the full expected driving behaviour per road-type. Moreover, plume chasing provides an emission estimate based on a relatively short measurement period of a few minutes, which can be influenced by factors such as traffic conditions, vehicle load and driving style. As a result, averaged plume-chase measurements cannot be expected to fully reproduce the average emission behaviour assumed in inventory-based emission factors. Nevertheless, distance-normalised emissions are the most relevant when making an inventory of emissions.

2.2.1.2 Work-normalised emissions

NO_x-emissions of diesel HDVs can also be calculated as work-normalised emissions. Work-normalised NO_x-emissions are calculated from the instantaneous measured concentrations as:

$$NO_x\left[\frac{g}{kWh}\right] = \frac{C_{NO_x}[ppb] \cdot m_{NO_x}[g/mol]}{C_{CO_2}[ppm] \cdot m_{CO_2}[g/mol]} \cdot \frac{K\ [(kg\ CO2)/(kg\ fuel)]}{\epsilon\ [-] \cdot u\ [kWh/(kg\ fuel)]}$$

Where $K = 3.15\ (kg\ CO2)/(kg\ fuel)$ represents the diesel carbon-to-CO_2 ratio (expressed as the mass of CO_2 emitted per kilogram of fuel burned), $\varepsilon = 40\%$ is the estimated engine efficiency that reflects the fraction of the fuel's chemical energy that is effectively converted into useful mechanical work, and $u = 12.6\ kWh/(kg\ fuel)$ is energy density of the diesel fuel, describing the amount of energy released per kilogram of fuel during combustion.

The NO_x-emission value of the measured vehicle is determined as the average of all instantaneous values where the measured CO_2-concentration was found to be at least 20 ppm above the CO_2-background concentration.

The threshold of 20 ppm is often used in literature (Schmidt, et al., 2023) to ensure only measurement values are taken into account from samples taken in the emission plume of the chased vehicle.

Work-normalised emissions for diesel HDVs can be directly compared to the applicable regulatory limit values. As the engine efficiency during motorway conditions is relatively stable over a wide range of vehicle loading conditions, this unit is also well suited to make assessments on the emissions of a unique vehicle.

2.2.1.3 High-emitter shares

Based on the calculated distance- or work- based NO_x-emissions, the fraction of high-emitting vehicles, so-called high-emitters, can be determined. In this study, vehicles with NO_x-emissions exceeding a predefined NO_x-threshold are classified as high-emitters. Here, the NO_x-thresholds can be defined in multiple ways. One of the options used in this study is to define the threshold as a fraction of the average measured emissions of the vehicle- and Euro-(sub)class. A fraction of two times the average measured emissions of the group refers to the proposed selection threshold in the European Commission proposal for the road worthiness package. However, other fractions are possible as well. High emitter shares based on this definition give an estimate on the amount of outliers in a given vehicle group, and are therefore well suited for statistical purposes. They should however be interpreted carefully for vehicle groups with very low average emissions, as for those groups this approach will potentially select vehicles that are still showing emissions in line with expected values.

When using this definition for selection of high-emitters for further inspection in an enforcement setting, care should be taken for vehicle groups with very low average emissions. An additional minimum threshold value could be defined to avoid selection of vehicles in well performing groups (Vroom & Vermeulen, 2025).

Another approach is to base the high-emitter threshold on a fixed emission value. We follow an approach used in the literature (Pöhler, Schmidt, Horbanski, Schmitt, & Lampel, 2023), which defines HDV high-emitter thresholds of 1200 mg/kWh (Euro VI) and 2500 mg/kWh (Euro V) for ‘suspicious’ vehicles, and 2200 mg/kWh (Euro VI) and 3500 mg/kWh (Euro V) for ‘high-emitters’. In contrast to the high-emitter threshold defined in the previous paragraph, this definition is fleet independent and is well suited for comparison to other studies. This approach allows for a direct comparison to absolute emission levels, which is particularly suited for identifying vehicles with potentially abnormal emission behaviour relative to fixed performance expectations rather than relative fleet performance.

Both definitions are used in this report to give insight in both the performance of specific vehicle categories and Euro (sub)classes, and of vehicles in the entire fleet. The effect of changing the exact ratios when applying the first definition are also shown by relating high-emitter shares with their share in emissions on the road.

2.2.1.4 NO_x-emissions of international road tractors

In contrast to Dutch vehicles, no vehicle information database is available for international vehicles. Therefore, the vehicle specific CO_2-emission factor E_{CO_2}, as well as details on the Euro class and vehicle mileage cannot directly be accessed. For the distance-normalised emission calculations of these vehicles, it is therefore assumed that the CO_2-emission factor of international road tractors corresponds to the average CO_2-emission factor of the Dutch road tractors.

The average CO_2-emission factor of the Dutch road tractors is determined based on the Dutch road tractor fleet measured with plume chasing and is calculated for each Euro class individually.

Due to some gaps in the available data, not all analysis can be performed on international road tractors data. The high-emitter rates in this vehicle category can however be compared to the one found for Dutch road tractors. To assess whether the fraction of high-emitters differs significantly between these groups, a two-proportion z-test is applied. The statistical significance is evaluated at a confidence level of 95 %.

2.2.2 PN-emissions calculation method

In contrast to the gaseous NO_x emission results, PN measurement results are not processed to either distance or work-normalised emissions in this report. The current measurement setup for PN-emissions in the plume-chase vehicle can give a preliminary indication of vehicles with potential malfunctioning or tampered DPF systems based on the measured particle number concentrations. Further dedicated PN on-road validation measurements are however needed to ensure proper conversion to absolute PN emission rates from the measured PN concentrations.

The PN values presented in this report are the average PN concentration per measured vehicle in thousand particles per cubic centimetre ($k\#/cm^3$), calculated from all instantaneous measurements on a vehicle for which the measured CO_2 concentration exceeded the background CO_2 level by at least 20 ppm.

The average measured concentrations are a good indicator for potential issues with the DPF of modern diesel vehicles. Vehicles with a well working DPF show very low to no particle emissions, meaning their emissions are below the detection limit of the high-emitter detection focussed measurement setup. Without determining the absolute emissions of a vehicle, a continuous PN signal well above the detection limit of the measurement device of 5 $k\#/cm^3$ can therefore be interpreted as a strong indication for issues with the DPF system.
As no direct link with the emission rate can be determined yet, these vehicles are indicated as suspicious vehicles, rather than as high emitting vehicles.

2.3 Validation method

Validation of the plume-chase technique for its use on diesel vehicles, both LD and HD, has been performed in for example European projects such as CARES (Borken-Kleefeld, et al., 2023) with a similar measurement setup. Especially for heavy-duty vehicles, the technique was found to be ideally suited to identify and measure high and low emitting vehicles (Borken-Kleefeld, et al., 2023) giving confidence in these measurements.

In addition to the validation studies performed on light-duty petrol vehicles in the predecessor to this report (Frateur, Kunz, & Aschersleben, 2025), 3 additional validation campaigns were performed on 1 petrol- and 3 diesel light-duty vehicles. The reference vehicles from the 2025 campaigns include: a Toyota Prius (petrol) equipped with PEMS[5], a Ford Transit (diesel) equipped with SEMS[6], a Volkswagen Transporter (diesel) equipped with SEMS, and a Mercedes Sprinter (diesel) equipped with a SEMS.

[5] Portable Emissions Measurement System
[6] Smart Emission Measurement System

These reference vehicles were set up to act as low or high-emitters, depending on the measurement. Validation routes included motorways, rural roads and low-traffic environments, and cover a range of driving behaviours such as constant speed driving, dynamic driving, and convoy driving with two reference vehicles. Emission measurements are performed simultaneously by the plume-chase vehicle and the in-tailpipe instruments from the reference vehicles. The NO_x-to-CO_2 ratios in the plume-chase and reference datasets are both calculated using the approach outlined in the Section 2.2, allowing for a direct comparison between the plume-chase and reference measurements. For the reference data, a fixed CO_2-background concentration of 400 ppm is assumed to approximate typical ambient air levels, while no background correction is applied for the NO_x signal, as the measurements are taken directly from the tailpipe.

Validation measurements are used to determine the uncertainty and bias on the calculated emission results of plume-chase data. Note, however, that the determined uncertainties and biases are solely used to indicate the error range of the plume-chase measurements in some parts of Section 4 where it is explicitly mentioned. Unless stated otherwise, the reported metrics in Section 4, such as the calculated high-emitter shares, are based on the non-bias-corrected measurement results. Bias-corrected values are not used for the main analyses to avoid the introduction of additional assumptions about the underlying behaviours, as the exact cause of the currently observed biases at low emission levels still needs to be further investigated. Thus, the non-bias-corrected results therefore represent the direct outcome of the plume-chase measurements and should be interpreted as measurements with potential systematic uncertainties.

3 Validation results and discussion

3.1 Results

To assess the accuracy of the NO_x emission estimates from the plume-chase measurements, the ratio of NO_x-to-CO_2 concentrations, denoted as c_{NO_x}/c_{CO_2}, is determined from both the plume-chase data as well as the reference data from PEMS or SEMS instrumented vehicles.

Overall, the plume-chase measurements are in good agreement with the data of the reference vehicle. While for higher NO_x-to-CO_2 ratios the plume-chase results align very well with the results of the reference vehicle, the plume-chase method tends to overestimate emissions at very low emissions, as shown in Figure 3.1. Figure 3.1 (left) presents a scatter plot of the NO_x-to-CO_2 ratio from the plume-chase vehicle versus the NO_x-to-CO_2 ratio from the various measured reference vehicles. Data points are color-coded according to test and road type. The marker styles indicate the fuel type of the reference vehicle. The convoy measurements[7] are separated from normal measurements on different road types as they are conducted in low-traffic environments to minimize external influences. The dashed lines indicate the 10%, 25% and 50% differences between the plume-chase and reference measurements. The figure shows that for NO_x-to-CO_2 ratios below approximately 0.5×10^{-3}, i.e. vehicles with very low emissions, plume chasing results in higher NO_x-to-CO_2 ratios than expected based on the reference measurements. Above this threshold, the plume-chase and reference measurements are generally in very good agreement.

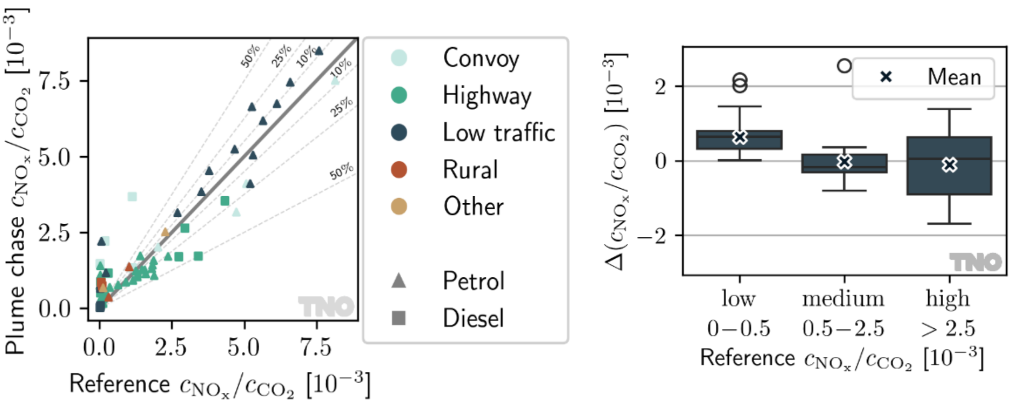

Figure 3.1: Comparison of NO_x-to-CO_2 ratios obtained from validation data. Left: NO_x-to-CO_2 ratios from the plume-chase data versus NO_x-to-CO_2 ratios from the reference data. Right: boxplot of the difference between plume-chase and reference ratios, grouped by reference ratio bins.

[7] Convoy measurements: measurements where different reference vehicles are driving in sequence to simulate the influence of vehicles in close proximity to the target vehicle.

Figure 3.1 (right) shows a boxplot of the difference between the NO_x-to-CO_2 ratios from the plume-chase and reference data, defined as

$$\Delta(c_{NO_x}/c_{CO_2}) = (c_{NO_x}/c_{CO_2})_{PC} - (c_{NO_x}/c_{CO_2})_{ref}$$

The data is grouped into three bins based on the reference ratio, where these bins have been chosen to reflect low, medium and high NO_x-to-CO_2 ratios. Each boxplot displays the median, interquartile range (IQR), whiskers extending to 1.5×IQR, and any outliers, where the IQR and the whiskers represent the spread of the data. The mean difference per bin, indicated with a cross, should be interpreted as a systemic bias on the calculated results in this bin. For lower ratios, i.e. vehicles with very low emissions, a consistent positive bias is observed. For higher emission rations, the bias approximates zero.

3.2 Discussion

The validation results show that the plume chasing method provides good NO_x-to-CO_2 ratios when compared to reference vehicle data, particularly for higher-emitting vehicles. While good agreement is observed overall, a consistent positive bias appears at lower ratios (below $\sim 0.5 \times 10^{-3}$), indicating a tendency to overestimate emissions in low-emission scenarios. As this effect is predominantly observed at low NO_x-to-CO_2 ratios, this may indicate that the current analysis underestimates the NO_x background, potentially influenced by emissions from nearby vehicles. When the target vehicle emits low levels of NO_x, the relative impact of background concentrations becomes more significant, leading to a greater influence on the final emission estimate. Nonetheless, the current validation demonstrates a clear capability to identify high-emitting vehicles within a fleet, highlighting the potential of plume chasing as a real-world screening tool.

The findings from the validation measurements are used as uncertainty and bias estimates in the final NO_x-emission values for distance and work-normalised emission results. Specifically, the mean of $\Delta(c_{NO_x}/c_{CO_2})$ per bin is referred to as the bias, while the 16th and 84th percentiles are used to define the uncertainty range, corresponding to a one-sigma error estimate. Note that while these uncertainty ranges give a good impression of the accuracy of the measured data, other uncertainties may influence the final reported emissions using this method. One example is the uncertainty resulting from using a modelled CO_2-emissions value based on vehicle properties to calculate emissions in g/km. These uncertainties are explicitly excluded from the error analysis described above.

4 Plume-chase results and discussion

During the 2025 plume-chase campaign, a total of 971 valid vehicle samples were obtained from measurements on motorways in the Netherlands. The 2025 dataset includes a total of 313 light-duty vehicles – consisting of 128 petrol passenger cars, 23 diesel passenger cars and 162 diesel delivery vans –, and 658 heavy-duty diesel vehicles consisting of 573 Dutch registered vehicles and 149 international registered vehicles. In addition, 182 heavy-duty vehicle records from measurements in January and February of 2026 are included in the dataset for this report. An overview of all valid vehicle measurements considered in this report is given per vehicle category in Figure 4.1. Note that in 2026 the plume-chase measurement campaign is ongoing, and additional data is expected to increase the statistical basis for conclusions on fleet-wide vehicle emissions. Results of the 2026 measurement campaign will be reported later.

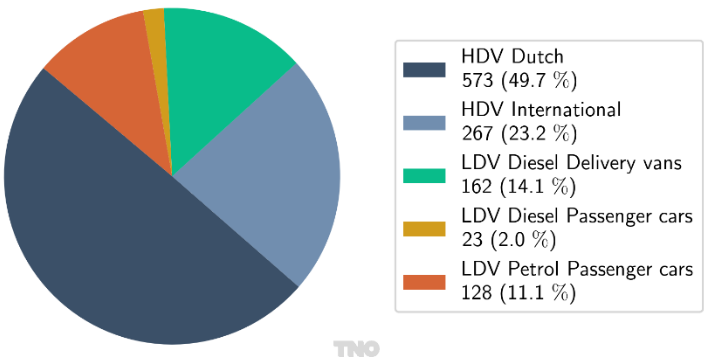

Figure 4.1: Overview of number of vehicles per vehicle category measured by plume chasing.

Similar to the measurements reported in (Frateur, Kunz, & Aschersleben, 2025), plume-chase measurements in this report were carried out on Dutch motorways as motorway measurements enable fast switching between target vehicles and offer relatively stable testing conditions such as engine load, wind direction, background levels, etc. While vehicles of all classes are measured in this campaign, the main focus has been put on measurements of heavy-duty diesel vehicles – both national and international registrations – and light-duty diesel delivery vans with Dutch license plates. On average, 8.8 vehicles per hour with valid measurements were recorded using this method during this campaign.

For reference, Figure 4.2 shows the share of kilometres driven on the motorways by the Dutch vehicle fleet. While the plume-chase measurements shown in Figure 4.1 were mainly focused on HDVs, Figure 4.2 shows that the large majority of kilometres is driven by LDV petrol vehicles, followed by LDV diesel and HDV diesel vehicles. Among all vehicle categories and fuel types, the most kilometres are driven by Euro 6 vehicles. The kilometres driven share of vehicles in the dataset should be considered when the influence on emission levels in the fleet are determined.

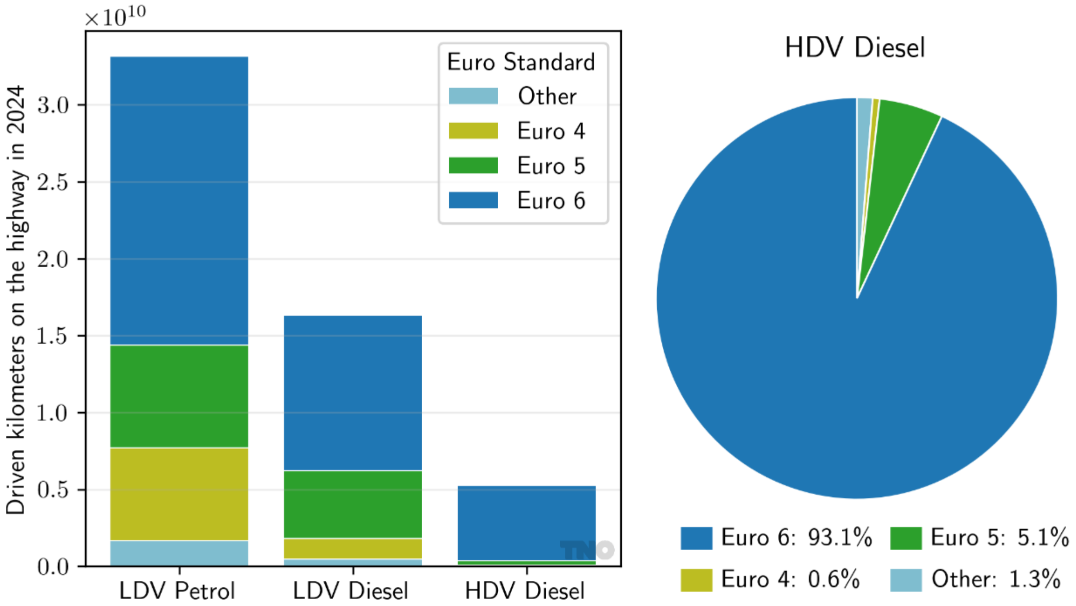

Figure 4.2: Distance driven share by vehicle type and Euro class for the Dutch 2024 vehicle fleet.

4.1 Heavy-duty vehicles

4.1.1 Vehicles registered in the Netherlands

This section details the plume-chase results on heavy-duty vehicles registered in the Netherlands. International heavy-duty vehicles registered outside the Netherlands are discussed separately in Section 4.1.2. The dataset on this vehicle category consists of 573 vehicles in total, as is shown in Figure 4.3. Euro VI vehicles make up the largest share with 96.4%; 51.5% are Euro VI step E, 19.4% are Euro VI step D, and 25.5% are Euro VI step A B C vehicles. The remaining 3.7% of the measurements correspond to Euro V vehicles.

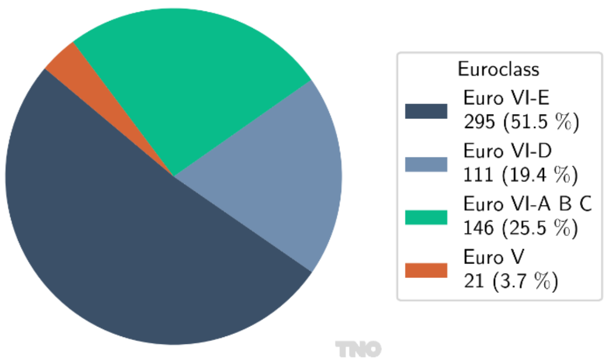

Figure 4.3: Number of HDV diesel vehicles by Euro class measured by plume chasing.

4.1.1.1 NO_x-emissions

A wide range of real-world NO_x-emissions is observed from plume-chase measurements on Dutch Euro V or newer diesel HDVs. The distribution of the calculated work-normalised NO_x-emissions of these vehicles is shown in Figure 4.4. The distribution shows that the majority of measurements are concentrated at lower NO_x-emission levels, with the highest number of observations falling in the bin between 200 to 400 mg/kWh. At higher emission levels, the occurrence of observed emissions decreases rapidly, although a limited number of vehicles reach substantially higher NO_x-emissions up to several thousand mg/kWh.
The last bin has been grouped for NO_x-emissions larger than 4000 mg/kWh.
For completeness, this figure, as well as all subsequent figures in the heavy-duty section, are also provided with distance-normalised emissions in Appendix B.

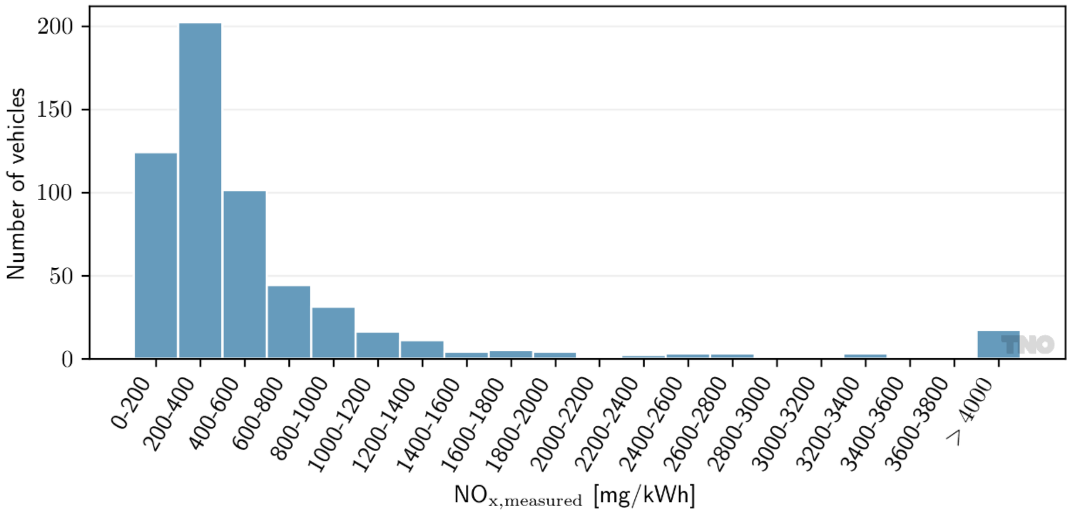

Figure 4.4: NO_x-emissions distribution of plume-chase measurements for Dutch HDV diesel vehicles. $NO_{x,\ measured}$ indicates the work-normalised NO_x-emissions measured by plume chasing.

In general, the NO_x-emissions of newer vehicles with a higher Euro class are lower than those for older vehicles. However, substantial variability in the emission within each Euro class remains as can be observed from the work-normalised NO_x-emissions for Dutch diesel HDVs in Figure 4.5. Each data point in Figure 4.5 corresponds to an individual plume-chase measurement of a vehicle and the colour of the data point indicates its last recorded mileage. For Euro V vehicles, NO_x-emissions are generally high and widely spread, with several measurements reaching well above 5 000 mg/kWh, some measurements even up to 17 000 mg/kWh and an average NO_x emission of 5445 mg/kWh. The Euro VI step A, B and C vehicles show a significant reduction in average NO_x-emissions compared to Euro V, but still display a broad range, including a number of measurements with high emissions up to ~10 000 mg/kWh and an average NO_x-emission of 840 mg/kWh. For the most recent Euro VI step E and VI step D vehicles, the majority of measurements are clustered at relatively low NO_x-levels, with considerably less spread than observed for earlier Euro classes and an average NO_x emission of 396 mg/kWh and 457 mg/kWh, respectively. Nevertheless, even within these newer groups, individual plume-chase measurements with higher NO_x-emissions up to around 2500 mg/kWh are observed.

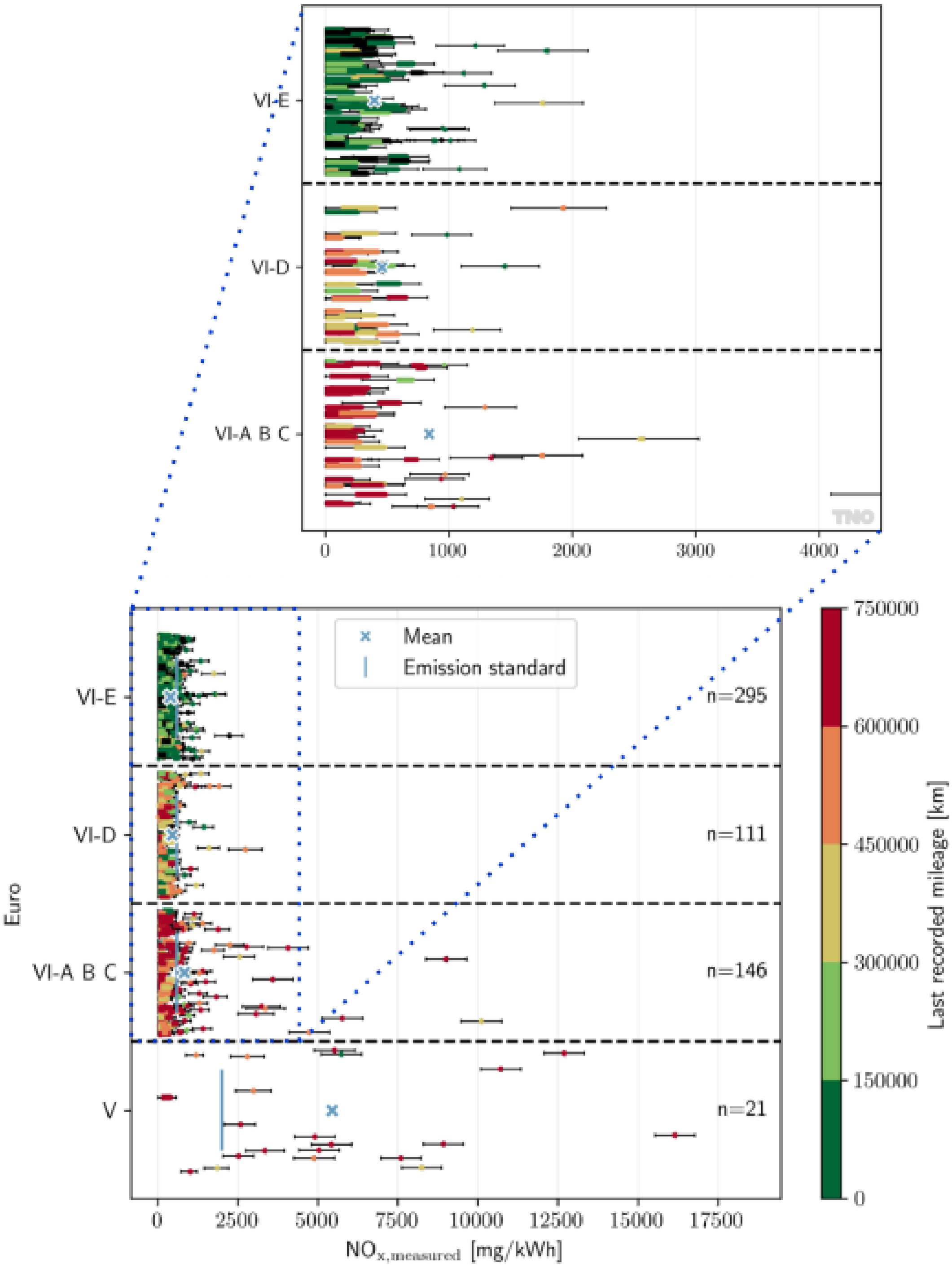

Figure 4.5: Bottom: Work-normalised NO_x-emissions for Dutch HDV diesel vehicles by Euro (sub-)class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The blue lines represent the emission standard for each Euro class. The sample size is indicated by n. Top: Zoomed in version of the bottom panel for Euro VI-E, VI-D and VI-A B C. For display purposes only every third data point is shown.

Apart from the correlation between observed emission levels and the Euro class of the measured vehicles, also the mileage of these vehicles is expected to have an influence on the real world emissions due to ageing of the engine and emissions aftertreatment system.

The sensitivity to Euro class versus mileage cannot be fully decoupled in the analysis, however general mileage related trends can obtain within each Euro class as is shown in Figure 4.6. Here the solid lines show the average work-normalised NO_x-emissions per Euro class per binned mileage range. Averages are only calculated for bins containing at least five measurements. For Euro VI-E, VI-D and VI-A B C vehicles, average NO_x-emissions remain relatively low at mileages below 250 000 km. The emissions for Euro VI-E and Euro VI-A B C increase by 56% and 78% within the second mileage bin, while almost no change is observed for Euro VI-D. The NO_x-emissions for Euro VI-D and VI-A B C vehicles for mileages above 700 000 km remains relatively constant with only small changes of +10% and +20%, respectively. Euro V vehicles show a pronounced increase of 55% in average NO_x-emissions for mileages above 700 000 km, although the averages remain strongly influenced by a limited number of measurements for Euro V. Overall, the binned averages suggest an increase in NO_x-emissions with increasing mileage for all Euro classes.

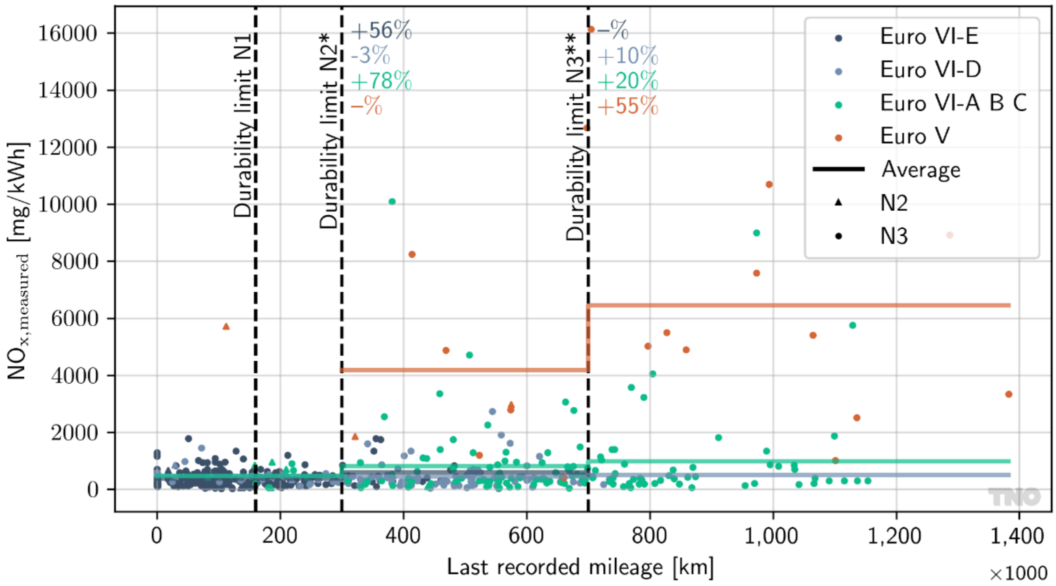

Figure 4.6: Work-normalised NO_x-emissions versus the last recorded mileage for HDV diesel vehicles. The colour coding of the data points represent their respective Euro class. Triangle markers indicate N2 vehicles and N3 vehicles are shown as circle markers. The solid line shows the average emissions per Euro class using binned mileage values and is only calculated for bins with a sample size of at least five. The coloured percentage values indicate the average emission increase per Euro class compared to the previous bin. *Including N3 vehicles with a weight less than or equal to 16 ton. **N3 vehicles with a weight above 16 ton.

By adding a threshold definition for high emitting vehicles, the share of high-emitters in the measured sample can be determined. One possible definition as discussed in (Frateur, Kunz, & Aschersleben, 2025) is to select vehicles with more than two times the distance-normalised emissions compared to the average observed emission levels in its category. Alternatively, the identification of HDV high-emitters can be performed with HDV high-emitter thresholds of 1200 mg/kWh and 2500 mg/kWh for 'suspicious' vehicles, and 2200 mg/kWh and 3500 mg/kWh for high-emitters, proposed in literature for Euro VI and Euro V, respectively (Pöhler, Schmidt, Horbanski, Schmitt, & Lampel, 2023). While the first definition identifies high-emitters based on fleet characteristics, the second definition is fleet independent. With the first definition, a general high-emitter share for Dutch HDVs of 10% is found; 10% for Euro V, 11% for Euro VI step E, 7% for Euro VI step D, and 11% for Euro VI step A B C vehicles.

The second definition results in a general suspicious emitter share for Dutch HDVs of 10%; 81% for Euro V, 3% for Euro VI step E, 5% for Euro VI step D, and 16% for Euro VI step A B C vehicles. Adopting the high-emitter definition from the literature results in a general high-emitter share for Dutch HDVs of 5%; 57% for Euro V, 0% for Euro VI step E, 1% for Euro VI step D, and 8% for Euro VI step A B C vehicles. Note that the number of measurements for Euro V are quite limited, which could at least partly explain the large high-emitter share for Euro V. These results are summarised in Table 4.1.

Table 4.1: High-emitter share per euro class for two different high-emitter threshold methods.

Euro class	High-emitter share (two times average NO_x threshold)	Suspicious- | High-emitter share (absolute NO_x threshold)
V	10 %	81 % | 57 %[8]
VI-A B C	11 %	16 % | 8 %
VI-D	7 %	5 % | 1 %
VI-E	11 %	3 % | 0 %
Fleet average	10 %	10 % | 5 %

Based on the first definition, high-emitters are responsible for 35% of the activity weighted emissions[9] on the road of Dutch heavy-duty diesel vehicles. This illustrates that a relatively small fraction of vehicles contributes to a disproportionately large share of the overall NO_x-emissions. Different threshold factors would lead to different high-emitter fractions and weighted emission shares as is shown in Figure 4.7. Each data point represents a different threshold factor, expressed as a multiple of the Euro-subclass-specific average calculated NO_x-emissions. With increasing threshold factors, the number fraction of high-emitters decreases, while the emission fraction remains substantial, indicating that the highest-emitting vehicles have a strong influence on total fleet emissions. The high-emitter shares and their corresponding activity-weighted emission shares using multiples of the emission standards as threshold factors is shown in Appendix B.

[8] Note that the number of measurements for Euro V are quite limited, which might at least partially explain the large high-emitter share for Euro V.
[9] Activity weighted emissions based on the share of driven kilometres on Dutch roads shown in **Figure 4.2**.

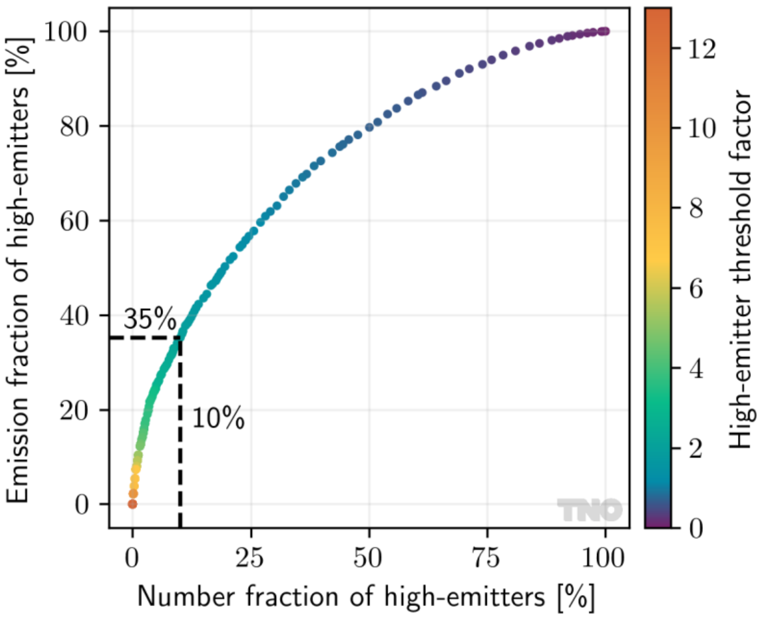

Figure 4.7: Emission fraction of high-emitters versus number fraction of high-emitters for Dutch HDV diesel vehicles. The colour of the data points indicates the applied high-emitter threshold factor, defined as a multiple of the average NO_x-emissions per Euro class, which is used to classify high-emitters. The dashed lines indicate a high-emitter threshold factor of exactly 2. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

The average distance-normalised emissions of the measured vehicles per VERSIT class should serve as a good representation of the average emissions in the Dutch fleet under free flowing motorway conditions. While the VERSIT+ NO_x-emission factors in the Dutch emission inventory represent average fleet emissions for a wider scope than what is captured with plume chasing, careful comparison between both numbers can offer some useful insight. For Euro VI vehicles in general, the average measured NO_x-emissions are found to be slightly lower than the corresponding VERSIT+ emission factors as is shown in Figure 4.8. On the other hand, average measured NO_x-emissions for Euro V vehicles are higher than the corresponding VERSIT+ emission factors. Note that the solid black line in Figure 4.8 indicates a 1:1 relationship where plume-chase measured emissions are equal to the corresponding VERSIT+ emission factor. The dashed lines show the mean ratio for each Euro class. For Euro VI-E and VI-D vehicles, the distribution is centred below the 1:1 line and a mean ratio of around 0.3, indicating that measured real-world NO_x-emissions are on average only 30% of the corresponding road-type-specific emission factors. Euro VI-A B C vehicles show a broader distribution, with the mean ratio at around 0.6 and a substantial fraction of measurements both below and above the 1:1 line. In contrast, Euro V vehicles exhibit a distribution shifted towards higher ratios, with the mean ratio at around 2.3.

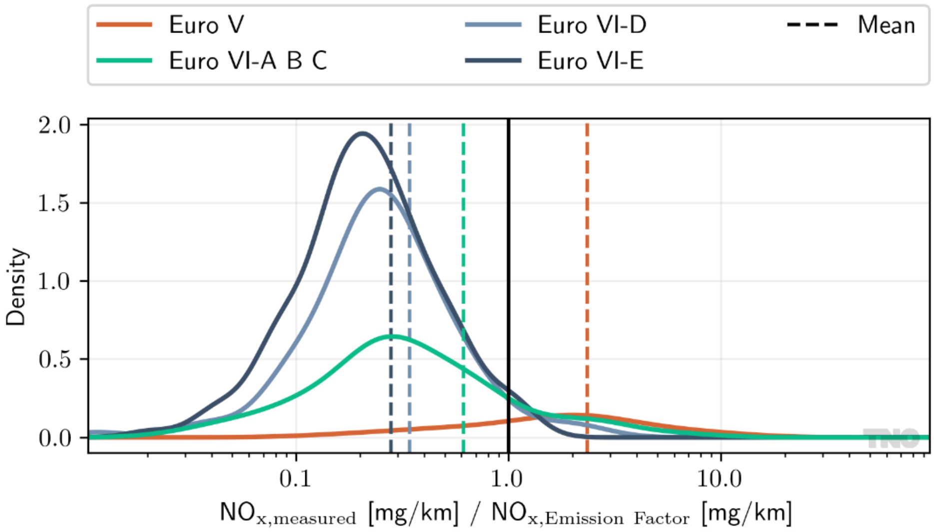

Figure 4.8: Distribution of the ratio between measured NO_x-emissions and the corresponding NO_x-emission factors for Dutch HDV diesel vehicles. Curves show kernel density estimates per Euro class. Dashed vertical lines indicate the mean ratio per Euro class, and the solid black line represents a 1:1 relationship between measured emissions and emission factors.

4.1.1.2 PN-emissions

Unlike the NO_x-emission measurements, the current measurement setup for PN-emissions of the plume-chase vehicle only serves as a preliminary indication of vehicles with potential malfunctioning or tampered DPF systems.

The majority of measured vehicles (approximately 75%) have very low particle number emissions meaning they fall under the detection limit of the measurement setup (which is high-emitter detection focused). With the current measurement setup, any significant particle number measurements above the measurement device's detection limit of 5 k#/cm3 can be assumed to indicate suspicion for issues with the vehicles DPF system.

Figure 4.9 shows the distribution of average PN concentrations measured by plume chasing for Dutch Euro VI diesel HDVs with detectable particle number emissions, expressed in k#/cm^3. Only Euro VI vehicles are included in this analysis, as these vehicles should all be equipped with DPF systems. A total of 26 vehicles, or 4.1 % of the measured HDV diesel vehicles, show average measured PN concentrations above 5 k#/cm^3 and are therefore suspected to have an issue with their DPF system. It should be emphasised once again that these findings are preliminary, and further validation is needed to couple these findings to the resulting emission levels from these vehicles.

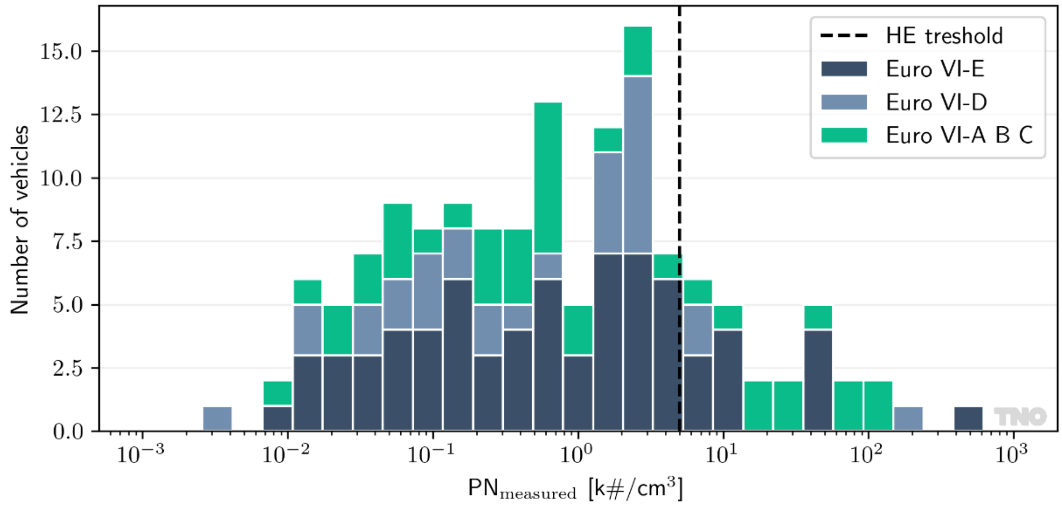

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Figure 4.9: PN concentration distribution of plume-chase measurements for Euro VI Dutch diesel HDVs. $PN_{measured}$ indicates the average measured PN concentrations in k#/cm^3 per vehicle. The colour coding displays the Euro sub classes. The dashed line indicates the threshold for suspicious vehicles. For display purposes, only average $PN_{measured}$ measurements larger than zero are shown.

4.1.2 Vehicles registered outside the Netherlands

Apart from the heavy-duty vehicles with Dutch license plates, also international road tractors from a variety of countries of origin have been measured during the 2025 measurement campaign. The origins of the measured vehicles in this category are shown in Figure 4.10. The majority of encountered vehicles are registered in either Poland (PL, 73 vehicles), Germany (DE, 46 vehicles) or Lithuania (LT, 35 vehicles). Note that, due to the limited amount of vehicle information available on these international vehicles, the analysis on the measurement results is less extensive compared to Dutch registered vehicles.

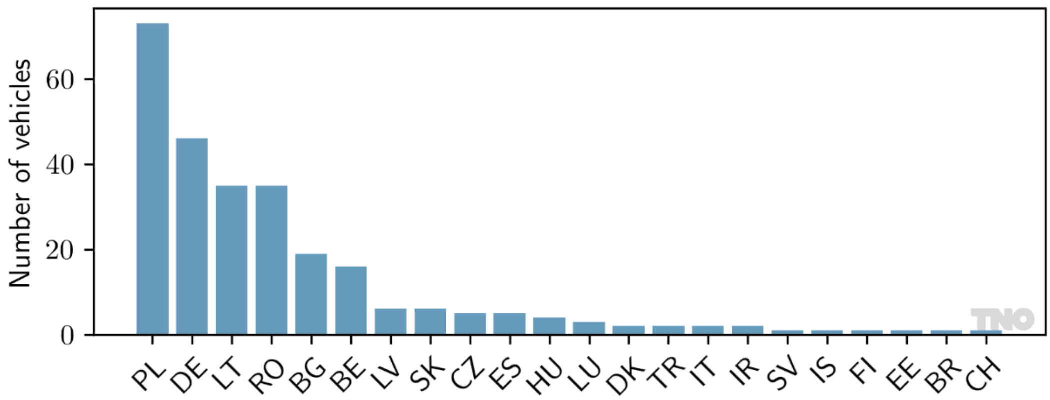

Figure 4.10: Distribution of vehicle registration countries of the international road tractor vehicles measured by plume chasing.

The analysis for the international road tractor diesel vehicles is only performed for Euro VI, as our sample size for Euro V and older is too small to draw robust conclusions from the dataset. The work-normalised NO_x-emissions of the international road tractors show a wide spread in NO_x-emissions as shown in Figure 4.11.

Individual plume-chase measurements of the dataset range up to almost 8 000 mg/kWh. The majority of measurements are clustered at relatively low NO_x-emission levels, while a limited number of vehicles exhibits substantially higher emissions, contributing to a pronounced right-hand tail in the emission distribution. The average NO_x-emissions of international Euro VI diesel road tractors vehicles within our dataset is 702 mg/kWh.

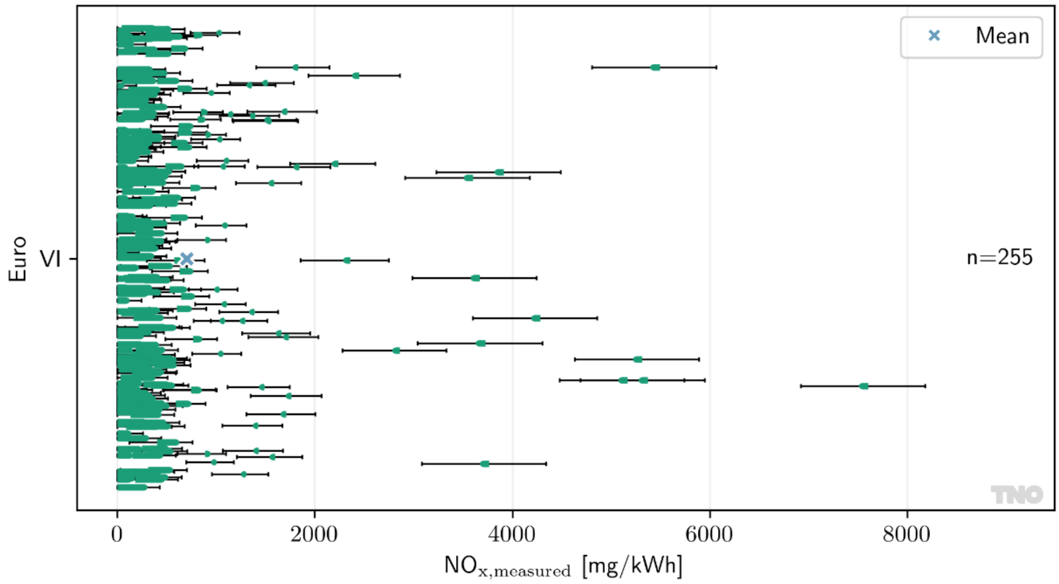

Figure 4.11: Work-normalised NO_x-emissions for international Euro VI diesel road tractor vehicles. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. The blue cross shows the averages for all measured vehicles. The sample size is indicated by n.

The statistical test described in Section 2.2.1.4 is applied to evaluate whether the fraction of high-emitting vehicles between Dutch and international road tractors differs significantly. Based on a high-emitter definition of vehicles with emissions above twice the average emissions of all vehicles in the same Euro sub class, 37 Dutch Euro VI road tractors are classified as high-emitters, corresponding to 9.0% of the Dutch fleet sample. For international Euro VI road tractors, 45 vehicles are identified as high-emitters, corresponding to a fraction of 17.6%. The difference between the Dutch and international fleets is statistically significant at the 95% confidence level (p =0.00097[10]), indicating a higher share of high-emitting vehicles among international road tractors. When restricting the analysis to international road tractors registered in Eastern European countries, 35 vehicles are classified as high-emitters, corresponding to a fraction of 20%. This fraction is also significantly higher than that of the Dutch fleet at the 95 % confidence level (p =0.00021). Performing the analysis on ‘other international’ vehicles, i.e. non-Dutch and non-East European vehicles, results in 10 high emitting vehicles and a high-emitter share of 12.5%. The difference between the Dutch and ‘other international’ fleet is not statistically significant at a 95% confidence level (p=0.33064). These results are visualized in Figure 4.12 and indicate that the East-European fleet shows a statistically higher share of high NO_x emitters compared to Dutch road tractors. The influence on alternative high-emitter thresholds on these results is investigated and discussed in detail in Appendix B.

[10] Lower p-values indicate a stronger statistical evidence for the observed difference in the high-emitter share between the Dutch and international fleet, while higher p-values indicate a weaker evidence for a real difference.

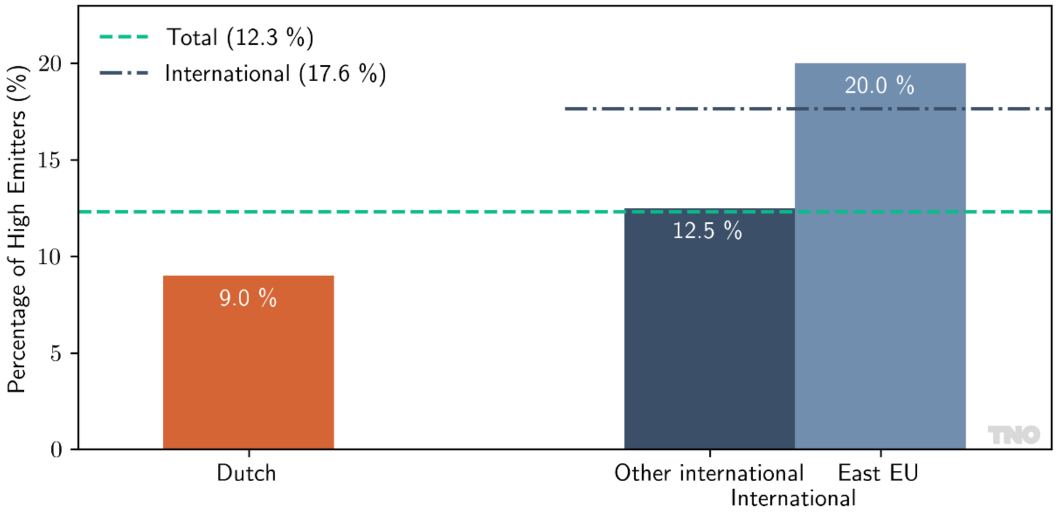

Figure 4.12: Percentage of high-emitters[11] within the Dutch, East EU and other international road tractor diesel vehicle fleet indicated by the bars. The high-emitter percentage of all international vehicles is shown by the dark blue, dash-dotted line. The high-emitter percentage of all road tractors combined (Dutch & international; total) is shown by the cyan, dashed line.

4.2 Light-duty vehicles

In the following sections, we differentiate light-duty vehicles between delivery vans and passenger cars. In contrast to the heavy-duty section, the NO_x-emissions calculated in this section are expressed in distance-normalised units to match both the units of the regulatory limits and those of the applicable VERSIT+ emission factors in the Dutch emission inventory.

4.2.1 Diesel delivery vans

Delivery vans make up a large fraction of the light-duty diesel vehicles in the Dutch fleet. In total, 162 diesel delivery vans were measured on Dutch motorways in this study of which 81% were Euro 6 vehicles, and 19% were Euro 5 vehicles. Further classification of the different sub-euro classes within the Euro 6 group are shown in Figure 4.13. Note that at this moment, no Euro 6e vehicles have been found on the road during the plume-chase measurements.

[11] Based on vehicles with emissions above twice the average emissions of vehicles in the same Euro sub class.

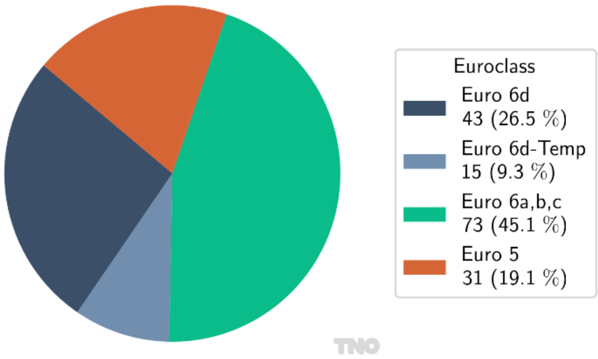

Figure 4.13: Number of LDV diesel delivery van vehicles by Euro class measured by plume chasing.

4.2.1.1 NO_x-emissions

The distance-normalised NO_x-emissions of LDV diesel delivery vans show a broad range of emission levels on the road, with the highest number of measured values in the range between 0 and 100 mg/km. Figure 4.14 shows the distribution of distance-normalised NO_x-emissions derived from plume-chase measurements. The distribution shows a much lower occurrence of higher measured values compared to emission values in the lower bins. However, a long tail towards higher emission levels is observed with individual vehicles exceeding 1 000 mg/km, showing there is a wide spread in vehicles with higher emissions. Note that the highest bin aggregates all measurements above 2 000 mg/km up to 5 000 mg/km for visualisation purposes.

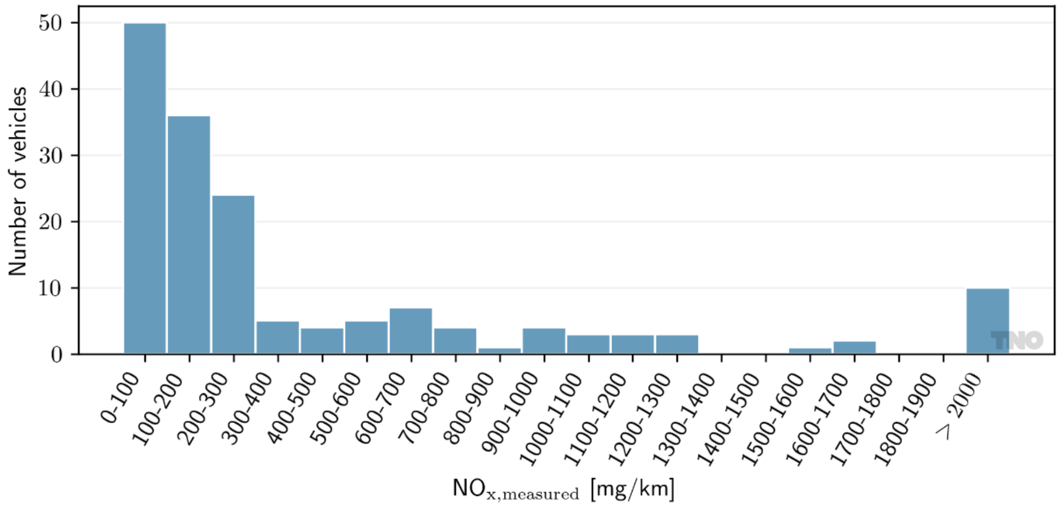

Figure 4.14: NO_x-emissions distribution of plume-chase measurements for Dutch LDV diesel vans. $NO_{x,\ measured}$ indicates the distance-normalised NO_x-emissions measured by plume chasing.

In general, vehicles with higher emission classes show lower emissions, although substantial variability remains within each group. The distance-normalised NO_x-emissions for all measured Dutch diesel vans of Euro class 5 and 6 are shown in Figure 4.15. Measured Euro 5 vehicles show high and widely spread NO_x-emissions, with average emissions of 1 392 mg/km and individual values reaching up to around 4 000 - 5 000 mg/km. For Euro 6a,b,c vehicles, average NO_x-emissions are substantially lower with 358 mg/km.

However, a wide spread in the measured emissions remains, including several measurements with elevated emissions exceeding 2 000 mg/km. Euro 6d-Temp and Euro 6d vehicles show a further reduction in their average NO_x-emissions of respectively 134 mg/km and 178 mg/km, and in their variability. Nevertheless, individual plume-chase measurements with higher NO_x-emissions in these groups are still present. Note that the difference in average measured emissions between Euro 6d-Temp and Euro 6d vehicles are most likely heavily influenced by the small sample size of euro 6d-Temp vehicles.

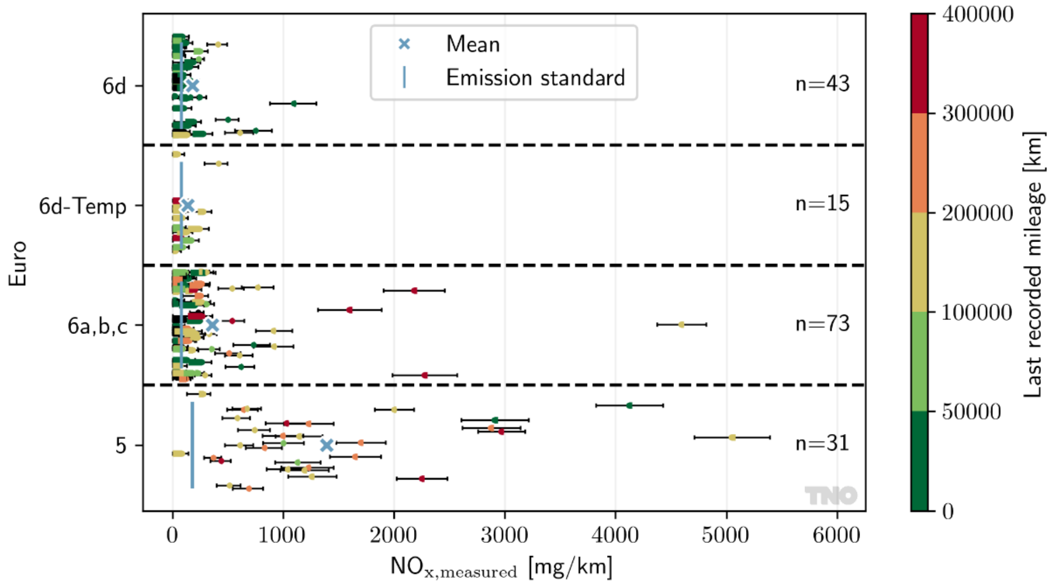

Figure 4.15: Distance-normalised NO_x-emissions for Dutch LDV diesel vans by Euro class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The blue lines represent the emission standard for each Euro class. The sample size is indicated by n.

Differences in Euro class related emissions can also be influenced by the average mileages of each vehicle group. In general, a wide spread in NO_x-emissions is observed over the full mileage range for each Euro (sub) class, indicating substantial vehicle-to-vehicle variability at all stages of vehicle use. Figure 4.16 shows the distance-normalised NO_x-emissions versus the last recorded mileage for LDV diesel vans. The solid lines show the average emissions per Euro class for binned mileage values, and is only calculated for bins containing at least five samples.

At lower mileages, average observed NO_x-emissions are relatively low, and emissions of all measured Euro 6 vehicles behave similarly. However, a significant increase of average emissions (+182%) is observed for Euro 6a,b,c vehicles for vehicles with mileages above the in-service conformity limit of 100 000 km. Unfortunately, only very limited data is available in the dataset on Euro 6d-Temp and 6d vehicles at high mileages. Therefore, no conclusions on the milage dependency of the NO_x-emissions can be drawn from the data of those Euro classes.

From comparison of Euro 5 vehicles with all Euro 6 vehicles at similar mileages, Euro 5 vehicles clearly show significantly higher emissions.

This means the observed differences between average emissions of Euro 5 and Euro 6 vehicles is mostly determined by applied technologies and not by the age of the vehicle. I.e. even at higher mileages and therefore ageing of the exhaust gas aftertreatment system, the applied technologies seem to have an effect on the average vehicle emissions.

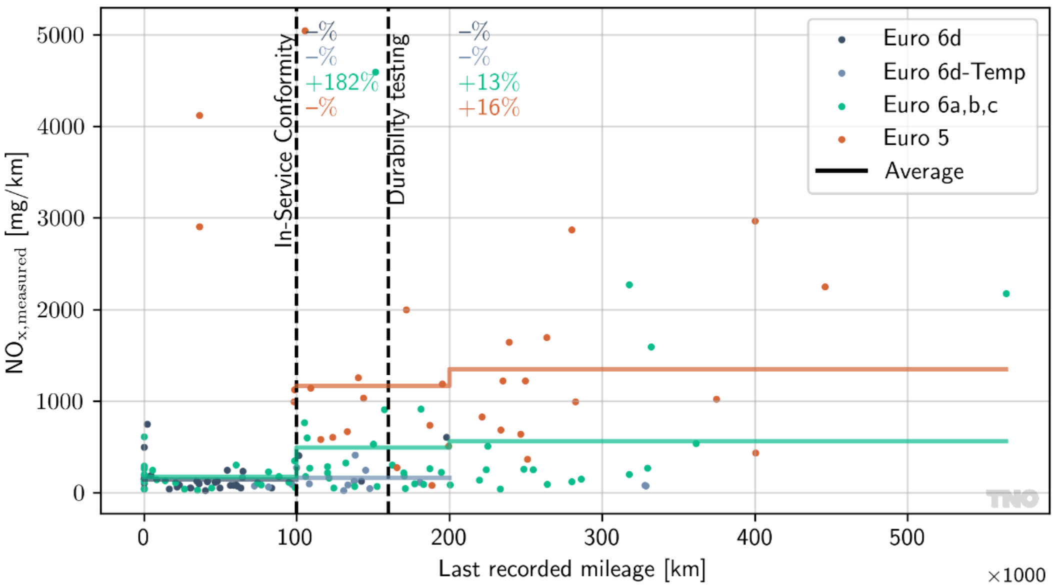

Figure 4.16: Distance-normalised NO_x-emissions versus the last recorded mileage for LDV diesel van vehicles. The colour coding of the data points represent their respective Euro class. The solid line shows the average emissions per Euro class for binned mileage values and is only calculated for bins with at least 5 samples. The dashed lines show the applicable "In-Service Conformity" threshold at 100,000 km and the "Durability testing" threshold at 160,000 km.

Similarly to the analysis of HDV vehicles, we define high-emitters primarily as vehicles with emissions more than two times above the average distance-normalised emissions of vehicles in the same Euro sub class. Based on this definition, a general high-emitter share of 12% is found for Dutch LDV diesel delivery vans; 16% for Euro 5, 11% for Euro 6a,b,c, 13% for Euro 6d-Temp, and 12% for Euro 6d vehicles. These vehicles represent the subset within each Euro sub class with the highest emissions, and are together responsible for 43% of the activity weighted emissions on the road of diesel delivery vans. Alternatively, the threshold can be determined with respect to the average emissions of all vehicles corresponding to the same main Euro class as is shown in Table 4.2. From this approach, the relative performance of different generations within a given Euro class becomes apparent. Here Euro 6d and 6d-Temp are observed to have significantly lower high-emitter rates than Euro 6a,bc vehicles. It is interesting to note that no high-emitters are present in the Euro 6d-Temp group in this definition, meaning these vehicles are in general less prone to tampering or defects compared to Euro 6d vehicles. However, the limited sample size for this Euro sub class likely also contributes to the low high-emitter share.

Other threshold factors than 2 are possible depending on what insight should be obtained. Each factor represents a fraction of high-emitters and their corresponding contribution to emissions on the road as is shown in Figure 4.17. The dashed lines highlight the applied threshold factor of two in relation to the average emissions for each Euro sub class.

The slope of the number-fraction to emission-fraction ratio for the applied high emitter threshold is found to be very similar to the one observed for heavy-duty diesel vehicles in the previous section, and indicates once again that a small fraction of high-emitter delivery vans is responsible for a disproportionate amount of NO_x-emissions. The high emitter shares and their corresponding activity-weighted emission shares using multiples of the Euro class specific emission standard as high-emitter thresholds are shown in Appendix C.2.

Table 4.2: High-emitter shares for LDV diesel delivery vans based on vehicles having more than twice the average emissions of its Euro sub class and main Euro class.

Euro class	High-emitter share (two times Euro sub class average)	High-emitter share (two times main Euro class average)
5	16%	16%
6a,b,c	11%	14%
6d-Temp	13%	0%
6d	12%	7%
Fleet average	12 %	11 %

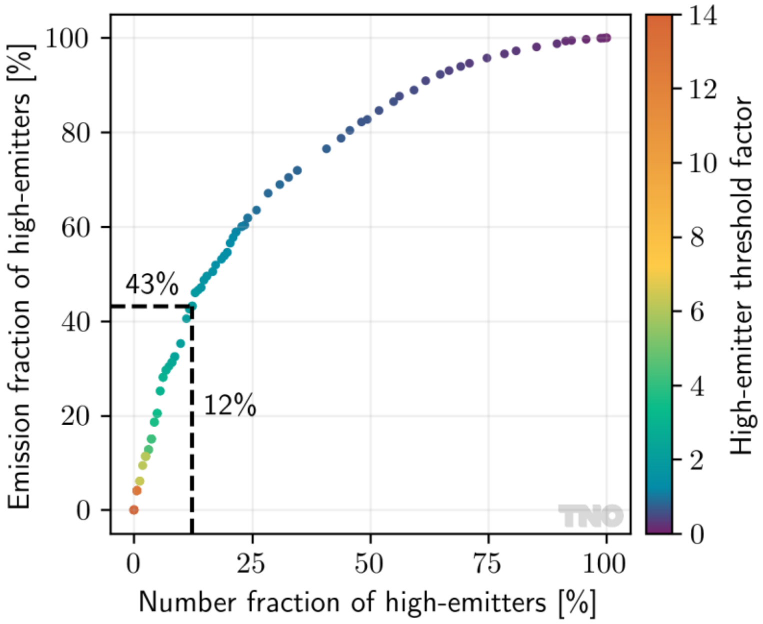

Figure 4.17: Emission fraction of high-emitters versus number fraction of high-emitters for Dutch LDV diesel delivery van vehicles. The colour of the data points indicates the applied high-emitter threshold, defined as a multiple of the average NO_x-emissions per Euro class, which is used to classify high emitters. The dashed lines indicate a high-emitter threshold factor of exactly 2. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

The average distance-normalised emissions of the measured vehicles per VERSIT class should serve as a good representation of the average emissions in the Dutch fleet under free flowing motorway conditions. In addition to the sensitivities mentioned in Section 2.2.1.1, the influence of measurement bias for low emitting vehicles discussed in Section 3 should be considered before making comparisons to the corresponding VERSIT+ emission factors.

For light-duty Euro 6 vehicles, the influence of this bias may be significant due to the many vehicles with low to very low emissions. As such, a careful comparison of the average plume-chase results to emission factors is only included in Appendix C.1.

4.2.1.2 PN-emissions

Unlike the NO_x emission measurements, the current measurement setup for PN-emissions of the plume-chase vehicle only serves as a preliminary indication of vehicles with potential malfunctioning or tampered DPF systems.
The majority of measured diesel delivery van vehicles (approximately 70%) have very low particle number emissions, meaning they fall under the detection limit of the measurement setup (which is high-emitter detection focused). With the current measurement setup, any significant particle number measurements above the measurement device's detection limit of 5 k#/cm³ can be assumed to indicate suspicion for issues with the vehicles DPF system.

Figure 4.18 shows the distribution of average PN concentrations measured by plume chasing for 30% of the measured diesel Euro 6 delivery vans with detectable particle number concentrations in units of k#/cm³. A total of 7 vehicles, or 5.3% of all measured diesel delivery vans, show average measured PN concentrations above 5 k#/cm³ and are therefore suspected to have an issue with their DPF system. This is similar to the fraction found for heavy-duty diesel vehicles.

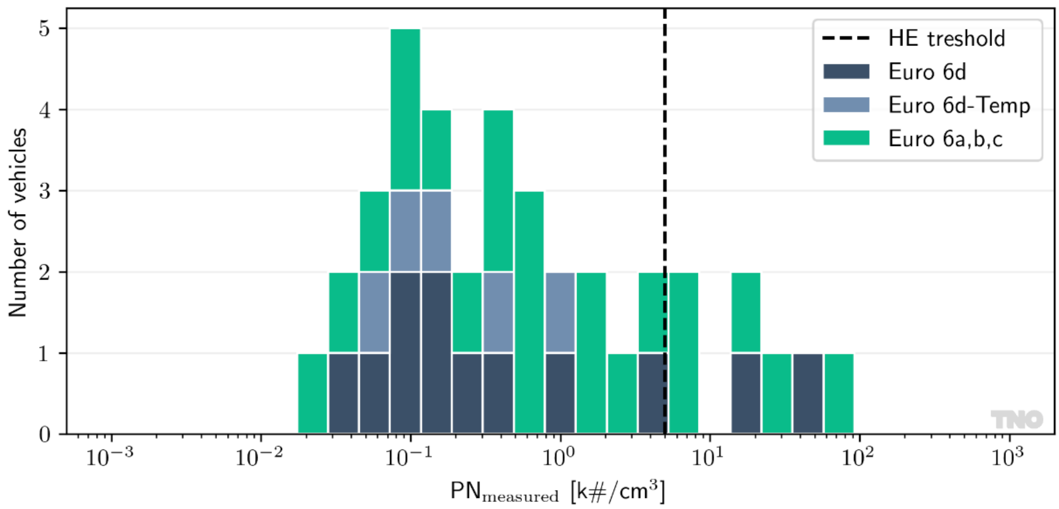

Figure 4.18: PN concentration distribution of plume-chase measurements for Euro 6 Dutch LDV diesel delivery van vehicles. $PN_{measured}$ indicates the average vehicle PN concentrations in k#/cm³ measured by plume chasing. The colour coding displays the Euro sub classes. The dashed line indicates the threshold for suspicious vehicles. For display purposes, only average $PN_{measured}$ concentrations larger than zero are shown.

4.2.2 Diesel passenger cars

Only 23 diesel passenger cars were measured during the 2025 measurement campaign, as the focus of the measurements was mainly on HDVs and delivery vans. Due to the limited number of measurements, the analysis for diesel passenger cars was not performed to the same extent as for the other vehicle categories. Therefore, no high-emitter statistics, comparison to emission factors, mileage correlations and PN measurements are reported for these vehicles.

The distribution of Euro classes in the dataset on these vehicles is shown in Figure 4.19. Around 70% of vehicles are Euro 6 vehicles, with 26.1% Euro 6d and 6d-Temp vehicles, and 43.5% Euro 6a,b,c vehicles. The remaining 30.4% of vehicles belong to Euro 5.

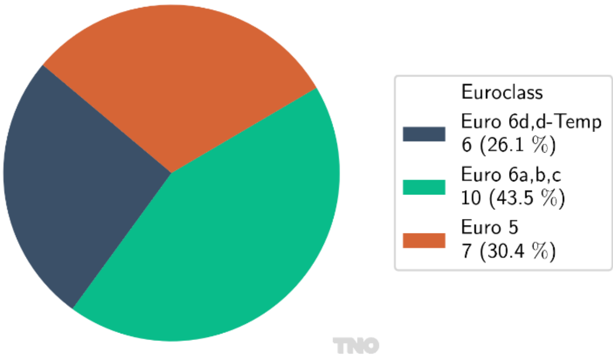

Figure 4.19: Number of LDV diesel passenger vehicles by Euro class measured by plume chasing.

Despite the low number of data points, a reduction in average distance-normalised NO_x-emissions can be observed for newer Euro classes compared to older Euro class vehicles, as is shown in Figure 4.20. Euro 5 vehicles show the highest NO_x-emissions, with an average value of 697 mg/km and individual measurements extending up to approximately 1 600 mg/km. For Euro 6a,b,c vehicles, the average NO_x-emission is reduced to 372 mg/km. However, a wide spread remains, with maximum observed values of around 1 600 mg/km. The more recent Euro 6d and 6d-Temp vehicles show substantially lower NO_x-emissions, with an average of 55 mg/km.

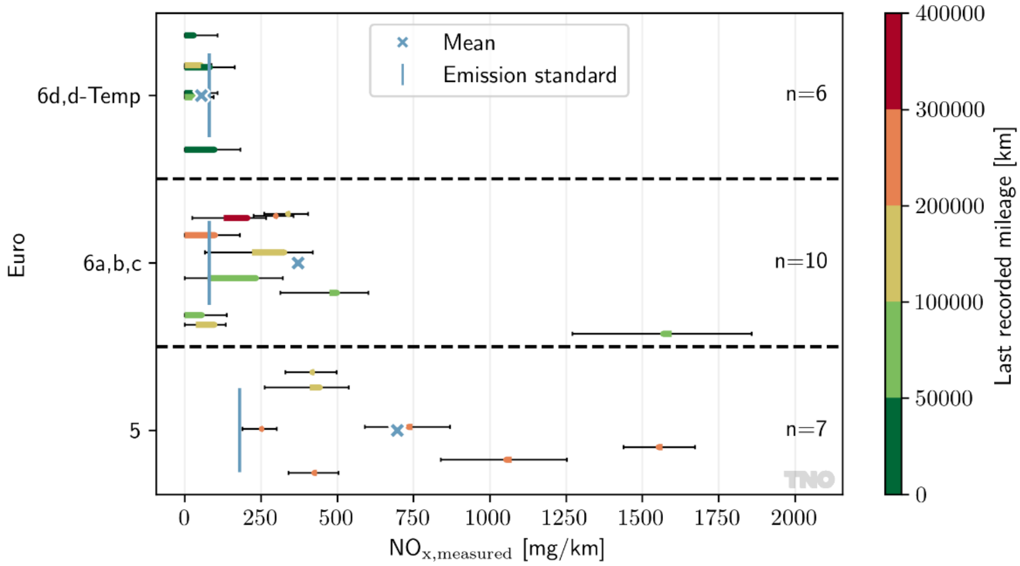

Figure 4.20: Distance-normalised NO_x-emissions for Dutch LDV diesel passenger vehicles by Euro class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The blue lines represent the emission standard for each Euro class. The sample size is indicated by n.

4.2.3 Petrol passenger cars

A total of 128 plume-chase measurements on LDV petrol passenger cars is available in the dataset of this study. The majority of measured petrol vehicles are Euro 6 vehicles, with about half of them being registered before the introduction of RDE and the other half being registered after the introduction of RDE, as can be seen in Figure 4.21. The remaining 22% and 21% of the measured vehicles belong to Euro 5 and Euro 4, respectively.

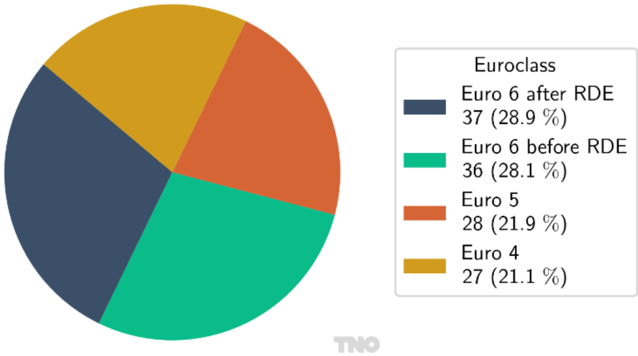

Figure 4.21: Number of LDV petrol passenger vehicles per Euro class measured by plume chasing.

The distance-normalised NO_x-emissions of LDV petrol passenger cars show a left skewed distribution, meaning only a smaller fraction of vehicles shows significantly elevated emissions compared to the average measured values. The highest number of emission measurements is situated in the range of 50 to 100 mg/km, as can be seen in Figure 4.22. At higher emission levels, the observation frequency decreases rapidly, although a noticeable tail towards elevated NO_x-emissions is present. Only a very limited number of vehicles show NO_x-emissions exceeding 500 mg/km, with individual measurements extending up to a maximum value of 1 862 mg/km. For visualisation purposes, the highest bin groups all measurements above 1 000 mg/km.

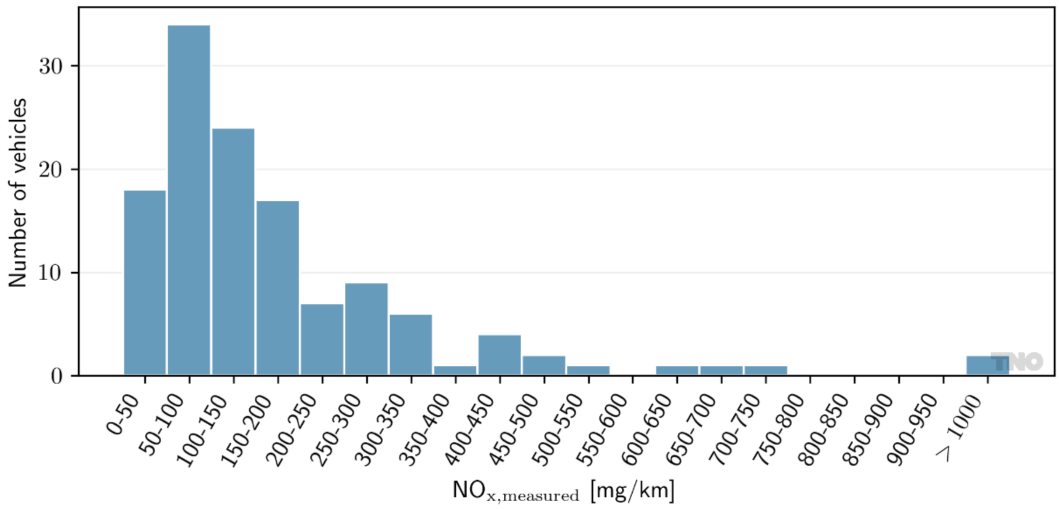

Figure 4.22: NO_x-emissions distribution of plume-chase measurements for Dutch LDV petrol passenger vehicles. $NO_{x,\ measured}$ indicates the distance-normalised NO_x-emissions measured by plume chasing.

Also for petrol vehicles, a clear decrease in average NO_x-emissions in successive Euro classes can be observed, although the absolute differences are less pronounced compared to those of diesel LDV's. Euro 4 petrol passenger cars show the highest NO_x-emissions, with a broad spread of values and individual measurements extending well above 1 000 mg/km as can be seen in Figure 4.23. The average NO_x-emission for Euro 4 vehicles in this dataset is 294 mg/km. For Euro 5 vehicles, both the average NO_x-emission and the overall spread are reduced compared to Euro 4, with an average emission of 200 mg/km. Euro 6 vehicles registered before the introduction of RDE show a further reduction in average NO_x-emissions to 139 mg/km, while Euro 6 vehicles registered after the introduction of RDE display the lowest average NO_x-emissions at 129 mg/km and a more compact distribution. Nevertheless, even for the most recent Euro 6 petrol vehicles, individual plume-chase measurements with higher NO_x-emissions up to around 500 mg/km are observed.

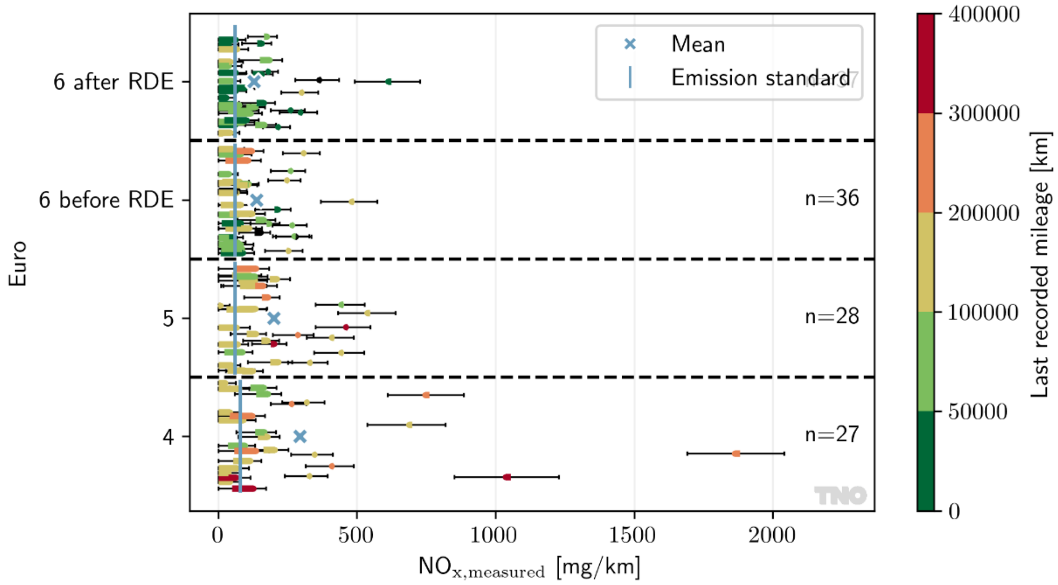

Figure 4.23: Distance-normalised NO_x-emissions for Dutch LDV petrol passenger vehicles by Euro class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The blue lines represent the emission standard for each Euro class. The sample size is indicated by n.

At lower mileages, average NO_x-emissions are relatively low for all Euro classes as can be seen from Figure 4.24. After the In-service conformity threshold of 100 000 km, average NO_x-emissions decrease by 24 % for Euro 6 vehicles registered after the introduction of RDE, whereas an increase of 21 % is observed for Euro 6 vehicles registered before RDE. Note that the observed decrease in emissions of Euro 6 after RDE vehicles is most likely due to the relatively small sample size available in the second mileage bin.

Only very limited data is available on Euro 4 and 5 vehicles with mileages below 100 000 km. However, for higher mileages between the second and third mileage bin, Euro 4 vehicles still show a pronounced increase in average NO_x-emissions of 190 %, while for Euro 5 vehicles an increase of 29 % is observed here. In general, the emissions set out against the mileage of the measured vehicles show that also for petrol vehicles, the NO_x-emissions are influenced by the age of the vehicle. However, the effect is much less pronounced compared to the effect seen for diesel vehicles, especially up to 200 000 km.

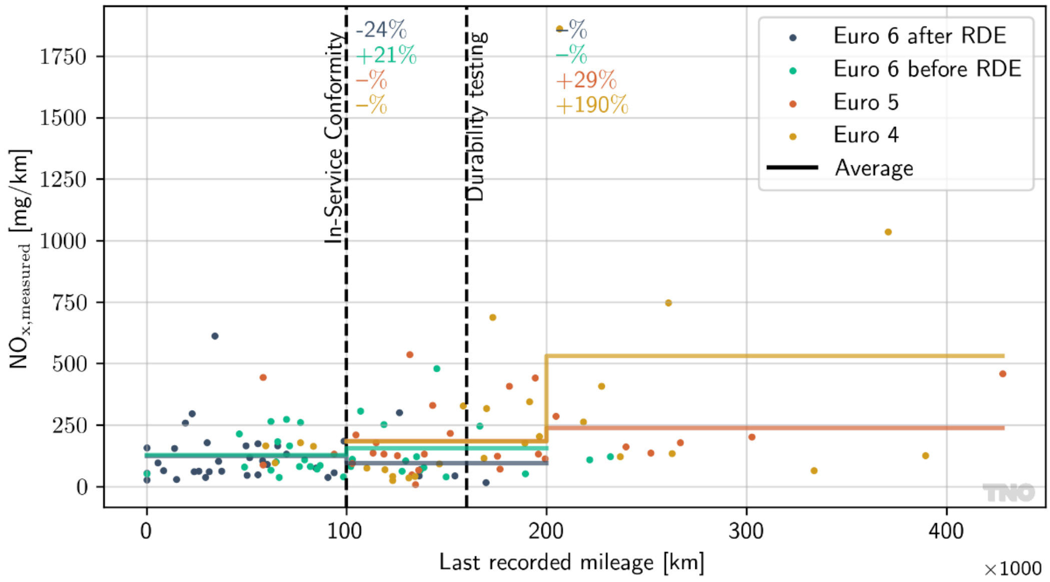

Figure 4.24: Distance-normalised NO_x-emissions versus the last recorded mileage for LDV petrol passenger vehicles. The solid line shows the average emissions per Euro class using binned mileage values and is only calculated for bins with a sample size of at least five. The dashed lines show the “In-Service Conformity” threshold at 100,000 km and the “Durability testing” threshold at 160,000 km.

Applying the high-emitter threshold of two times the distance-normalised emissions compared to the average observed emission of vehicles of the same Euro sub class, a general high-emitter share of 13% is found; 15% for Euro 4, 18% for Euro 5, 8% for Euro 6 before RDE, and 14% for Euro 6 after RDE vehicles. These vehicles represent the subset within each Euro sub class with the highest emissions, and are together responsible for 33% of the activity weighted emissions on the road of petrol passenger vehicles. Alternatively, the threshold can be determined with respect to the average emissions of all vehicles corresponding to the same main Euro class, or all light-duty petrol vehicles in general, as is shown in Table 4.3. By selecting based on a factor on the average Euro class results, the relative performance of different generations within a given Euro class become apparent. Here Euro 6 vehicles before and after RDE are observed to have the same high-emitter rates, suggesting absolute performance of both groups is the same. It should however be noted that due to a limited sample size of both vehicle groups, a single high emitter has significant influence on the high-emitter fraction. In addition, selection based on a factor on the overall average petrol vehicle results indicates relative performance within the fleet. Here a general high-emitter share of 10% is found; 19% for Euro 4, 18% for Euro 5; 3% for Euro 6 before RDE and 5% for Euro 6 after RDE vehicles. This is an interesting result as legislative and technological differences between Euro 4, Euro 5 and Euro 6 petrol vehicles are relatively low. The significant decrease in high-emitters for Euro 6 vehicles compared to Euro 4 and Euro 5 vehicles therefore is most likely attributed to ageing effects rather than technological differences.

Other threshold factors than 2 are possible depending on what insight should be obtained. Each factor represents a fraction of high-emitters and their corresponding contribution to emissions on the road as is shown in Figure 4.25. The dashed lines in this figure highlights the applied threshold factor of two in relation to the average emissions for each Euro sub class.

Compared to the emission fraction shares found in the previous sections on diesel vehicles, similar high-emitter shares of petrol passenger vehicles are found to contribute slightly less to the total NO_x-emissions on the road of the total petrol fleet. Nonetheless, also for petrol passenger vehicles, the high-emitters are responsible for a disproportionate amount of NO_x-emissions.

Table 4.3: High-emitter shares for LDV petrol passenger cars based on vehicles having more than twice the average emissions of its Euro sub class and main Euro class.

Euro class	High-emitter share (two times Euro sub class average)	High-emitter share (two times main Euro class average)	High-emitter share (two times all vehicle average)
4	15 %	15 %	19 %
5	18 %	18 %	18 %
6 before RDE	8 %	11 %	3 %
6 after RDE	14 %	11 %	5 %
Fleet average	13 %	13 %	10 %

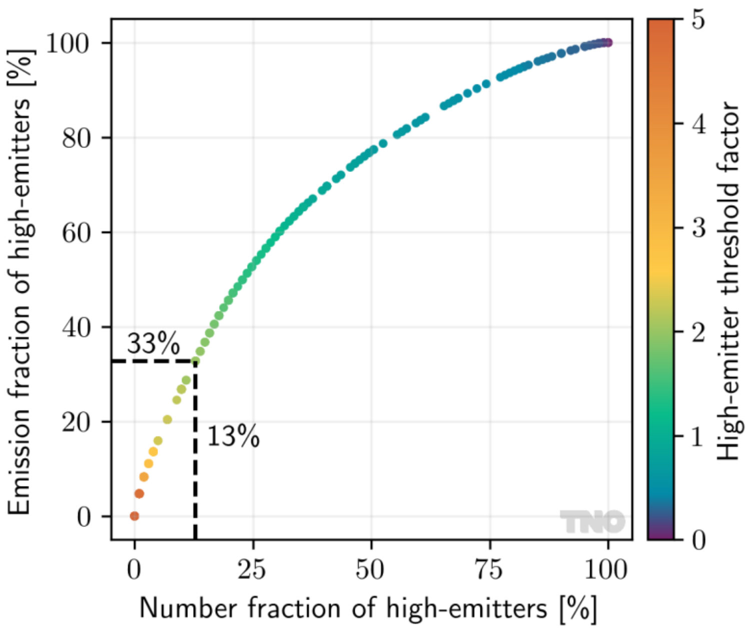

Figure 4.25: Emission fraction of high-emitters versus number fraction of high-emitters for Dutch LDV petrol passenger vehicles. The colour of the data points indicates the applied high-emitter threshold, defined as a multiple of the average NO_x-emissions per Euro class, which is used to classify high emitters. The dashed lines indicate a high-emitter threshold factor of 2. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

The average distance-normalised emissions of the measured vehicles per VERSIT class should serve as a good representation of the average emissions in the Dutch fleet under free flowing motorway conditions. In addition to the sensitivities mentioned in Section 2.2.1.1, the influence of measurement bias for low emitting vehicles discussed in Section 3 should be considered before making comparisons to the corresponding VERSIT+ emission factors.

For light-duty Euro 6 vehicles, the influence of this bias may be significant due to the many vehicles with low to very low emissions. As such, a careful comparison of the average plume-chase results to emission factors is only included in Appendix C.1.

5 Conclusion

During the 2025 plume-chase measurement campaign, TNO substantially expanded the real-world emissions dataset for vehicles on Dutch motorways, with a particular focus on commercial vehicles. Compared to previous campaigns, the focus shifted towards heavy-duty vehicles (HDVs), light-duty diesel delivery vans, and international road tractors, while the plume-chase methodology was extended to include initial measurements of particle number (PN) emissions. In total, 971 valid vehicle measurements were obtained in 2025 and an additional 182 heavy-duty vehicle records from measurements in January and February of 2026 were included. Measurements of diesel passenger cars were limited in number, as this vehicle category was not a primary focus of the 2025 campaign. As a result, no major conclusions are drawn for diesel passenger cars beyond indicative trends in NO_x-emissions.

The validation measurements performed during the 2025 campaign confirm that the plume-chase methodology provides robust and reliable estimates of real-world NO_x-emissions, particularly for medium- and high-emitting vehicles. Comparisons with reference measurements from instrumented vehicles show good agreement in NO_x-to-CO_2 ratios across a wide range of driving conditions and emission levels. A consistent positive bias is observed at very low NO_x-emission levels, where background concentrations and contributions from surrounding traffic have a relatively larger influence on the derived emission values. While this bias leads to some overestimation of absolute NO_x-emissions for low-emitting vehicles, the validation results demonstrate that plume chasing remains highly suitable especially for identifying high-emitting vehicles on the road. These findings support the use of plume chasing as an efficient screening tool for large-scale, real-world emission monitoring, while also highlighting the importance of cautious interpretation of the results at the lowest emission levels.

The NO_x-emission results show clear and consistent differences between vehicle categories and Euro classes. For Dutch HDV diesel vehicles, average NO_x-emissions decrease substantially with successive Euro standards, with Euro VI-D and VI-E vehicles showing significantly lower emissions than earlier Euro VI and Euro V vehicles. Nevertheless, considerable variability remains within each Euro class, and individual HDVs with very high NO_x-emissions are observed across the fleet. Diesel delivery vans show a similar trend, with Euro 6 vehicles emitting substantially less NO_x on average than Euro 5 vehicles, but with a wide spread of emissions and a pronounced tail towards high values. For petrol passenger cars, average NO_x-emissions are generally much lower than for diesel vehicles and decrease steadily from Euro 4 to Euro 6, with the lowest average emissions observed for Euro 6 vehicles registered after the introduction of RDE. Despite these improvements, all vehicle categories exhibit significant vehicle-to-vehicle variability, underscoring the importance of inventory-based real-world measurements.

Across all analysed vehicle categories, the results consistently show that a relatively small fraction of vehicles is responsible for a disproportionately large share of total NO_x-emissions on the road. For Dutch HDV diesel vehicles, 10% of vehicles are classified as a high emitter based on selection of vehicles with more than twice the average emissions of all vehicles corresponding to the same Euro sub class. However, this small group accounts for 35% of total NO_x-emissions within their category. A comparable pattern is observed for LDV diesel delivery vans, where a high-emitter share of 12% contributes to 43% of total NO_x-emissions.

For LDV petrol passenger cars, a high-emitter share of 13% contributes 33% of total NO_x-emissions. While the relative impact of petrol high-emitters seems to be smaller, overall, these findings confirm that high-emitting vehicles remain a key driver of real-world NO_x-emissions across vehicle categories. This underlines the importance of targeted identification and mitigation of this relatively small but highly influential subset of the fleet.

The comparison between Dutch-registered and international road tractor emissions reveals systematic differences in real-world NO_x performance. International road tractors show higher average NO_x-emissions and a significantly larger fraction of high-emitting vehicles compared to Dutch road tractors. While Dutch Euro 6 road tractors show a high-emitter share of only 9.0%[12], international Euro 6 road tractors were found to have a high-emitter share of 17.6%. When focusing specifically on road tractors registered in Eastern European countries, the fraction of high-emitters is found to be even higher at 20%. In contrast, the high-emitter share of other international road tractors, which are not registered in an Easter European country, is substantially lower at 12.5% and not statistically different from that of the Dutch fleet. These results suggest that factors beyond Euro classification, such as maintenance practices or tampering play an important role in real-world emissions. From a policy perspective, the findings highlight the relevance of international vehicles on Dutch roads, and in particular those registered in Eastern European countries, for the Dutch air quality.

The comparison between plume-chase NO_x-measurements on HDVs and the corresponding NO_x emission factors used in the Dutch emission inventory shows differences that vary per Euro class. The plume-chase NO_x-emissions for Euro VI tend to be lower than their corresponding emission factors, while the opposite is observed for Euro V vehicles. It should however be noted that the comparison of plume-chase NO_x measurements to the VERSIT+ NO_x emission factors in the Dutch emission inventory needs to be interpreted with caution. In contrast to the plume chase measurements, emission inventory numbers represent yearly average fleet emissions taking into account driving behaviour as well. These effects are not fully captured with plume chase measurements focused on smooth driving motorway conditions during discrete moments in time.

Analysis of NO_x-emissions as a function of vehicle mileage indicates, as is to be expected, a general tendency towards increasing emissions with higher mileages. Although the strength and consistency of this effect differ between vehicle categories and Euro classes. For HDV diesel vehicles, average NO_x-emissions increase with mileage for all Euro classes, although the effect is much more pronounced for Euro V vehicles than for Euro VI vehicles at mileages above 300 000 km. For LDV diesel delivery vans, a similar trend is observed, with increasing average NO_x-emissions at higher mileages, particularly for Euro 6a, b and c vehicles after the in-service conformity mileage threshold of 100 000 km. For LDV petrol passenger cars, the increase in NO_x-emissions with increasing mileages is much less pronounced compared to the trends observed for diesel vehicles, especially up to mileages of 200 000 km. This suggests ageing effects are less significant for petrol vehicles in the fleet compared to those for diesel vehicles. Overall, the results indicate that vehicle ageing, next to the emission aftertreatment technology levels, is a significant contributor to real-world NO_x-emissions, especially for diesel vehicles.

During the 2025 plume-chase campaign, PN plume chasing was deployed for the first time in an operational state.

[12] Based on selection of vehicles with more than twice the average emissions of all vehicles in the same Euro sub class.

The initial PN measurements conducted during the campaign provide first insights into real-world particle emissions across different diesel vehicle categories with DPF technology inside. For Euro VI HDV diesel vehicles, Euro 6 LDV diesel delivery vans and Euro 6 petrol passenger cars, the majority of vehicles show no detectable PN signal. Approximately 75% of HDVs and around 70% of delivery vans show PN-emissions of zero. A small fraction of vehicles shows elevated PN-emissions, and based on a first conservative threshold definition, approximately 4-5 % of diesel HDVs and diesel delivery vans are suspected to have issues with their DPF system as a result of poor maintenance or tampering. It should be emphasised that the PN results presented in this report are preliminary, as a dedicated on-road plume-chase validation campaign for PN measurements has not yet been performed. Further validation and expanded datasets are therefore required before quantitative PN- emission factors or more definitive conclusions can be drawn.

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Signature

TNO ⟩ Mobility & Built Environment ⟩ The Hague, 24 April 2026

Fieke Beemster	Thomas Frateur
Research manager	Author

Appendix A
Plume-chase equipment

Table A.1: TNO plume-chase vehicle: emission measurement instruments

Instrument name	Measurement parameters	Units	Comments
EcoPhysics nCLD	NO_x	ppb	
LiCor-6262	CO_2	ppm	
TEN AEM	PN	k#/cm^3	PTI particle device used for real world PN measurements.

Table A.2: TNO plume-chase vehicle: used hardware components

Instrument name	Measurement parameters	Comments
GPS	Position, velocity	
ANPR camera	Licence plates	Used to couple vehicle properties to measurement data.
Continental radar	Relative position and velocity of the chased vehicle	
Smart Emission Monitoring System (SEMS)	Data logger	

Appendix B
Heavy-duty vehicles

Heavy-duty

In Section 4.1, the NO_x-emissions of HDVs were mainly expressed as work-normalised emissions. The majority of the figures that follow in this section focus on the distance-normalised NO_x-emissions of HDVs. If not stated otherwise, the methods and assumptions used to create the following figures are identical to the ones described in Section 4.1.
As expected, the distance-normalised emissions of Dutch HDV diesel vehicles show a similar distribution to their work-normalised equivalents. Figure B.1 shows the distribution of distance-normalised NO_x-emissions of Dutch HDV diesel vehicles. The largest number of vehicles show emissions in the range of 200-400 mg/km. At emission levels above 400 mg/km, the number of observed vehicles decreases progressively with increasing emission levels with some vehicles reaching emissions of >4000 mg/km.

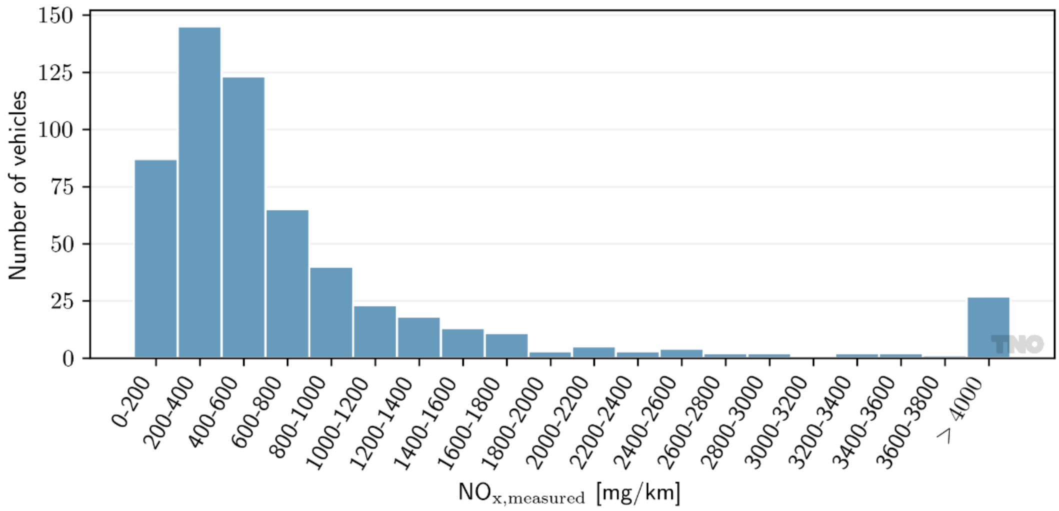

Figure B.1: Distance-normalised NO_x-emissions distribution of plume-chase measurements for Dutch HDV diesel vehicles. $NO_{x,\ measured}$ indicates the NO_x-emissions measured by plume chasing.

The average distance-normalised NO_x-emissions of the Dutch HDV diesel vehicles strongly depend on their respective Euro (sub)class. While Euro V vehicles average NO_x-emissions of 6706 mg/km, Euro VI results in significantly lower emission levels: 1123 mg/km for Euro VI- A B C, 624 mg/km for VI-D and 505 mg/km for Euro VI-E. The distance-normalised NO_x-emissions for Dutch HDV diesel vehicles by Euro class is shown in Figure B.2.
HDVs can be further classified into road tractors. In Section 4.1, the work-normalised NO_x-emissions between Dutch and international road tractors were compared. For completeness, the work-normalised NO_x-emissions for Dutch diesel road tractor vehicles by Euro class are shown in Figure B.3. On average, Dutch road tractors show NO_x-emissions of 4730 mg/kWh for Euro V, 732 mg/kWh for Euro VI-A B C, 427 mg/kWh for Euro VI-D and 410 mg/kWh for Euro VI-E.

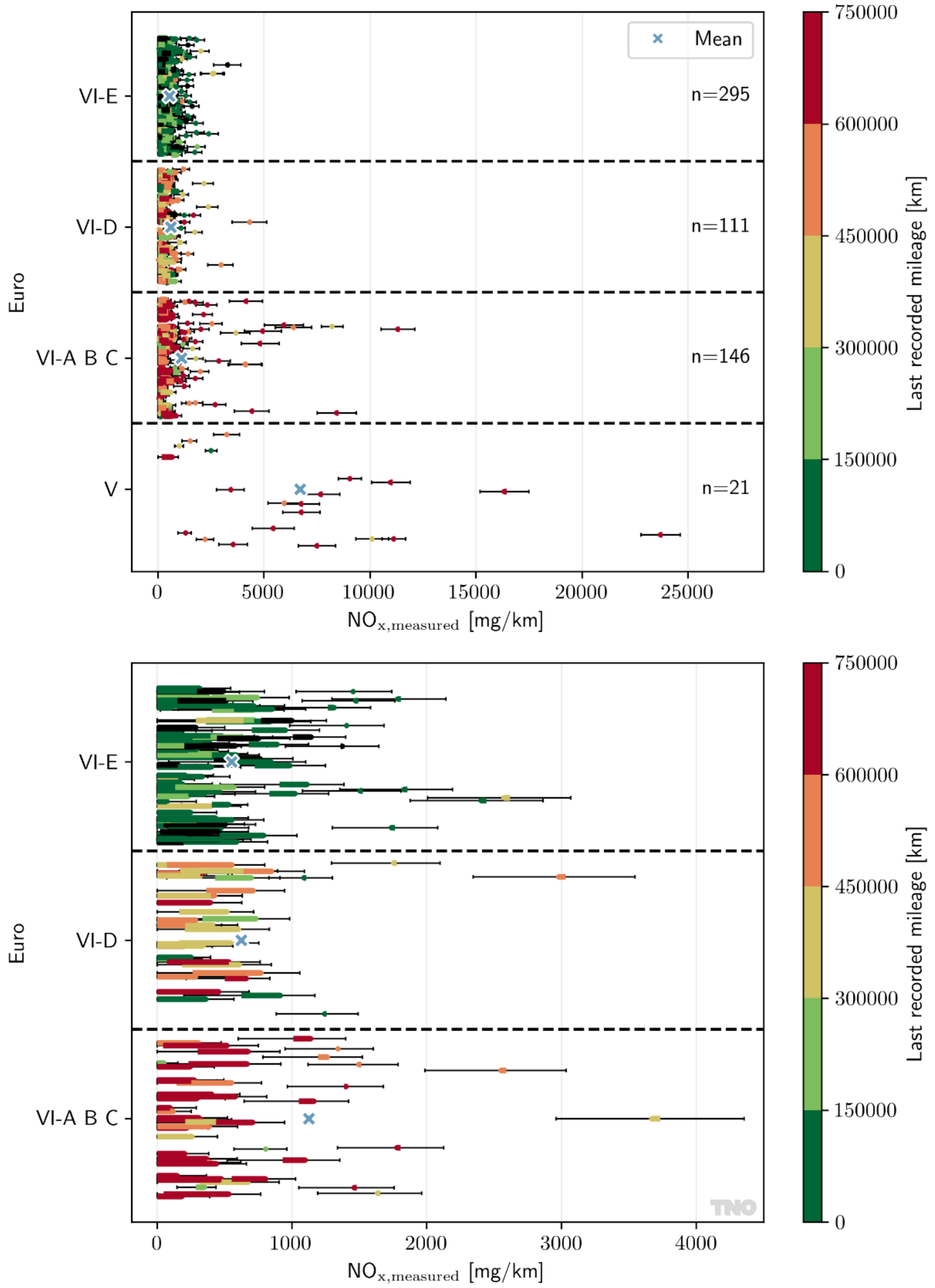

Figure B.2: Top: Distance-normalised NO_x-emissions for Dutch HDV diesel vehicles by Euro class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The sample size is indicated by n. Bottom: Zoomed in version of the top panel for Euro VI-E, VI-D and VI-A B C. For display purposes only every third data point is shown.

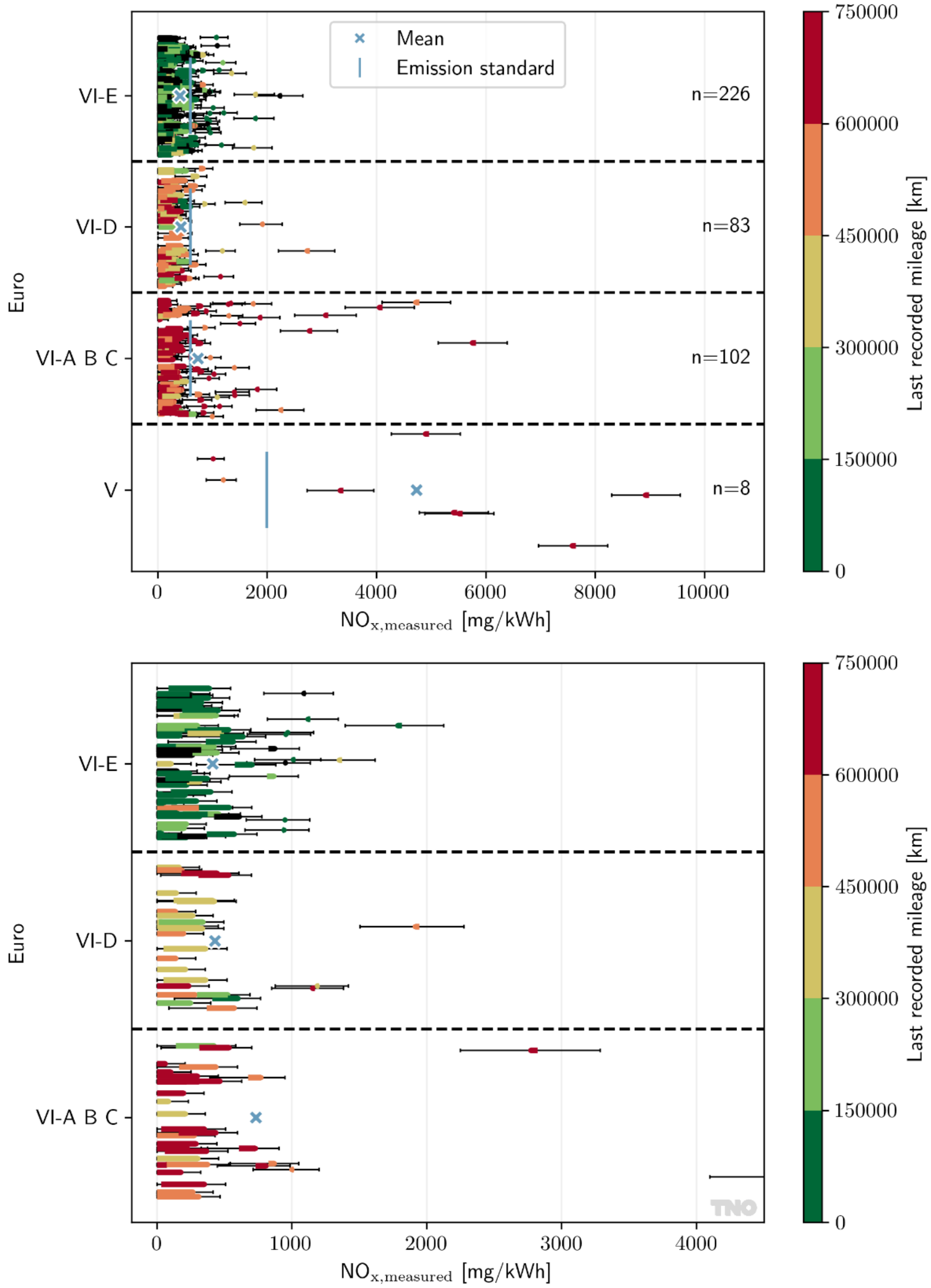

Figure B.3: Top: Work-normalised NO_x-emissions for Dutch diesel road tractor vehicles by Euro class. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. Colour indicates last recorded mileage and black points denote unavailable data. The blue crosses show averages per Euro class. The blue lines represent the emission standard for each Euro class. The sample size is indicated by n. Bottom: Zoomed in version of the top panel for Euro VI-E, Euro VI-D and VI-A B C. For display purposes only every third data point is shown.

As discussed in Section 4.1, a variety of NO_x emission thresholds can be applied to define high-emitting vehicles. While multiples of the average NO_x-emissions of the measured fleet were used as high-emitter thresholds in the main text, the following paragraph investigates multiples of the Euro class specific emission standard as high-emitter thresholds. While the former approach depends on the NO_x-emissions of the fleet, the latter is fleet independent. The work-normalised emission standards adapted for this analysis are 2000 mg/kWh for Euro V (steady-state testing) (EC, 2005) and 600 mg/kWh for Euro VI ('Off-Cycle Emissions'/'In-Service Conformity' (OCE/ISC) requirements) (EC, 2019). Note that, in contrast to the average NO_x fleet emission approach, no distinction is made for Euro subclasses here. Similarly to the approach discussed in Section 4.1, multiples of the emission standards are used as thresholds to calculate the number fraction of high-emitters and the emission fraction of high-emitters. At a high-emitter threshold of 2.5 times the Euro class specific emission standard, 10% of vehicles are classified as high-emitters, which are responsible for 35% for the total activity weighted emissions of HDV diesel vehicles on the Dutch roads. Figure B.4 shows the activity weighted emission fraction of high-emitters versus the number fraction of high-emitters for a wide range of multiples of the emission standard as high-emitter thresholds. The curve of Figure B.4 shows a similar pattern to the results shown in Figure 4.7, indicating that both approaches lead to consistent conclusions regarding the relationship between the fraction of high-emitting vehicles and their disproportionate contribution to total emissions.

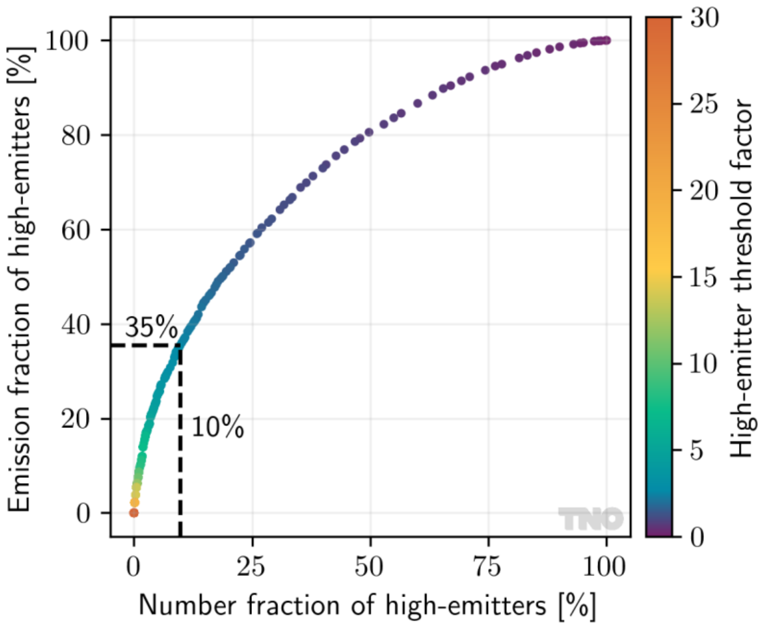

Figure B.4: Emission fraction of high-emitters versus number fraction of high-emitters for Dutch HDV diesel vehicles. The colour of the data points indicates the applied high-emitter threshold factor, defined as a multiple of the emission standard per Euro class, which is used to classify high-emitters. The dashed lines indicate a high-emitter threshold factor of exactly 2.5. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

Figure B.5 shows an alternative way to compare the NO_x emission factors for motorway driving as reported in the Dutch emission inventory with the NO_x-emissions measured by plume chasing for HDV diesel vehicles. The figure shows that a significant fraction of Euro V vehicles have measured NO_x-emissions that are substantially higher than the corresponding VERSIT+ emission factors.

In particular, many measurements lie above the 1:1 line, frequently exceeding the x1.5 bands, and in some cases approaching or exceeding the x5 and x10 ratios. This behaviour is less pronounced for the Euro VI vehicles, for which the majority of measurements lie below the 1:1 line.

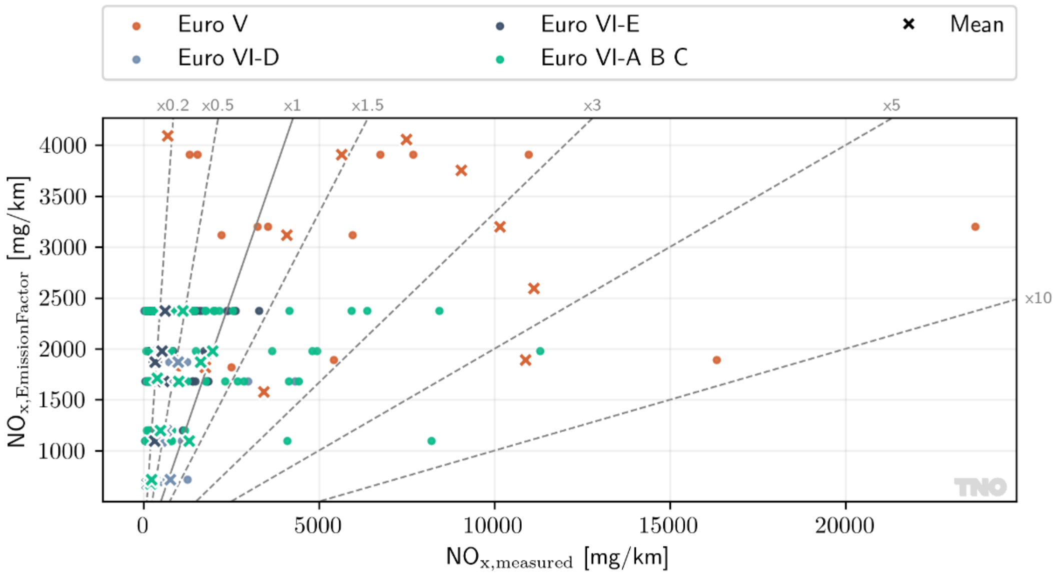

Figure B.5: Distance-normalised NO_x emission factor for motorway driving in the Dutch emission inventory versus the NO_x-emissions measured with plume chasing for HDV diesel vehicles. The colour coding of the data points represent their respective Euro class. The grey dashed lines indicate different bands, showing where the measured NO_x-emissions lie relative to the emission factor. The black line represents a 1:1 relationship (x1).

The dependency of the NO_x-emissions of HDV diesel vehicles can further be investigated based on their distance-normalised emissions. Similarly, to the behaviour observed for the work-normalised emissions, a larger mileage seems to have negative impact on distance-normalised emissions across all Euro classes. Figure B.6 shows the distance-normalised NO_x-emissions versus the last recorded mileage for HDV diesel vehicles. In comparison to the work-normalised emissions in Figure 4.6, the increase in NO_x-emissions for higher mileages seems to be even more pronounced for distance-normalised emissions. This is indicated by the percentual increase of NO_x-emissions within each mileage bin, which are higher for almost each mileage bin and Euro class for the distance-based NO_x-emissions.

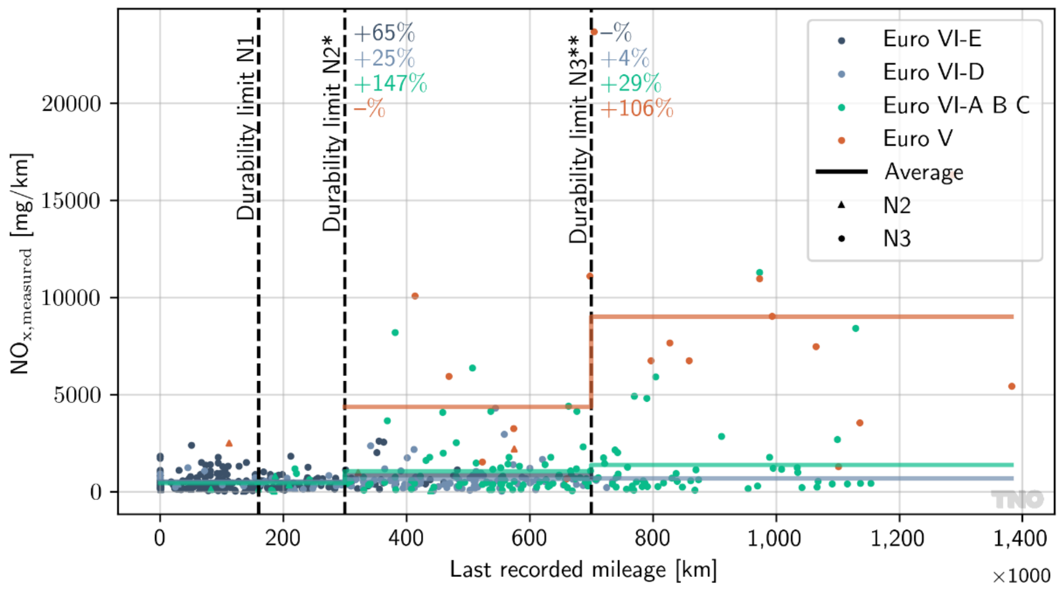

Figure B.6: Distance-normalised NO_x-emissions versus the last recorded mileage for HDV diesel vehicles. The colour coding of the data points represent their respective Euro class. Triangle markers indicate N2 vehicles and N3 vehicles are shown as circle markers. The solid line shows the average emissions per Euro class using binned mileage values and is only calculated for bins with a sample size of at least five. The coloured percentage values indicate the average emission increase compared to the previous bin. *Including N3 vehicles with a weight less than or equal to 16 ton. **N3 vehicles with a weight above 16 ton.

For completeness, the distance-normalised NO_x-emissions of international road tractors are briefly discussed in this paragraph. As only very few number of Euro V vehicles were measured for international road tractors, only the results for Euro VI international road tractors are shown. On average, international diesel road tractors result in 1023 mg/km for Euro VI. The distance-normalised NO_x-emissions for international road tractor diesel vehicles for Euro VI are shown in Figure B.7. As expected, the distance-normalised NO_x-emissions of international road tractors show similar patterns to the work-normalised emissions. A large bulk of vehicles show emissions up to 1000 mg/km, with few vehicles reaching emissions of up to approximately 10 000 mg/km.

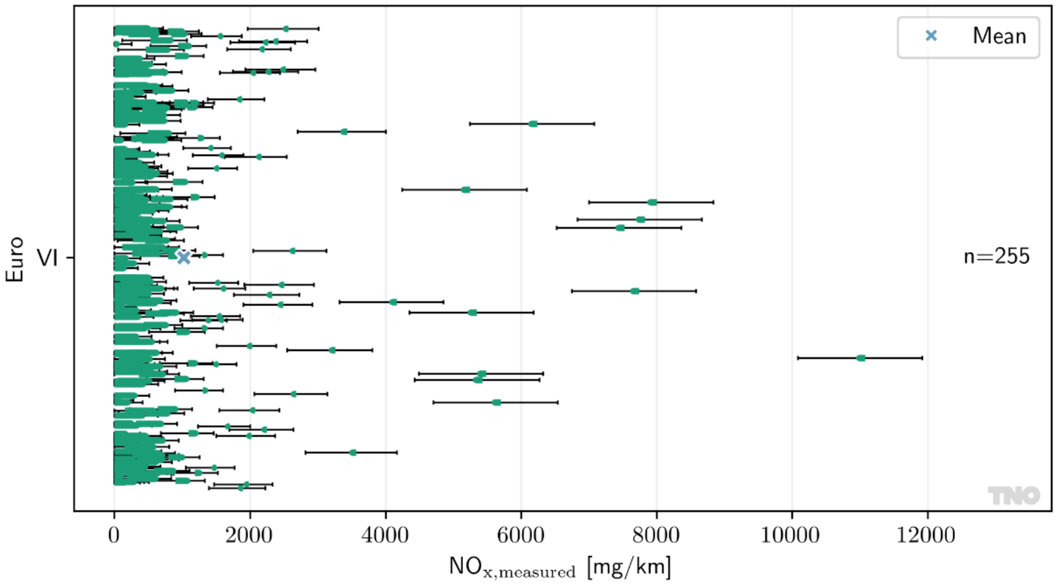

Figure B.7: Distance-normalised NO_x-emissions for international road tractor diesel vehicles for Euro VI. The width of each data point reflects the bias-adjusted emissions and error bars show the one-sigma uncertainty. The blue cross shows the averages for Euro VI. The sample size is indicated by n.

Section 4.1 covered the comparison of high-emitter shares within the Dutch and East-EU road tractor fleet. We defined a high-emitters as vehicles, whose work-normalised NO_x-emissions exceed twice the average NO_x-emissions of the Dutch Euro VI road tractor fleet. In this paragraph, we briefly investigate the influence of the choice of the high-emitter threshold on these results. Figure B.8 shows the number fraction of high-emitters for East-EU road tractor diesel vehicles versus number fraction of high-emitters for Dutch road tractor diesel vehicles, depending on the high-emitter threshold. The black solid line indicates the condition under which the number fraction of East-EU high-emitters equals the number fraction of Dutch high-emitters. Data points above the black line show high-emitter thresholds, at which the high-emitter share of the East-EU road tractors is larger than the high-emitter share of Dutch road tractors. Data points below the black line show high-emitter thresholds, at which the high-emitter share of the East-EU road tractors is lower than the high-emitter share of Dutch road tractors. As shown in Figure B.8, almost all data points lie above the black line. This indicates, that almost independent of the high-emitter threshold, East-EU road tractors show a larger high-emitter share than Dutch road tractors. The only exception are very large (> 12 times the average NO_x-emissions of the Dutch Euro VI road tractor fleet) and very low (< 0.5 times the average NO_x-emissions of the Dutch Euro VI road tractor fleet) high-emitter thresholds, at which the number share of high-emitters of Dutch and East-EU road tractors are roughly equal. We therefore conclude, that (almost) independent of the high-emitter threshold, the high-emitter share of East-EU road tractors is larger than the high-emitter share of the Dutch road tractor fleet.

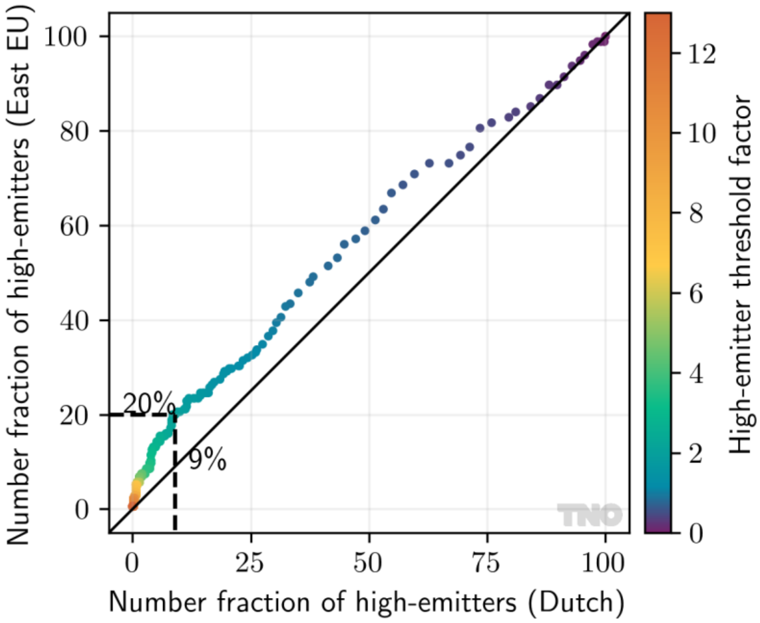

Figure B.8: Number fraction of high-emitters for East-EU road tractor diesel vehicles versus number fraction of high-emitters for Dutch road tractor diesel vehicles. The colour of the data points indicates the applied high-emitter threshold factor, defined as a multiple of the average NO_x-emissions of the Dutch Euro VI road tractor fleet, which is used to classify high-emitters. The dashed lines indicate a high-emitter threshold factor of exactly 2. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

Appendix C
Light-duty vehicles

C.1 Comparison with emission factors

The average distance-normalised emissions of the measured vehicles per VERSIT class should serve as a good representation of the average emissions in the Dutch fleet under free flowing motorway conditions. Note, however, that the VERSIT+ NO_x emission factors in the Dutch emission inventory represent average fleet emissions for a wider scope than what is captured with plume chasing. Therefore, the comparison between both numbers can offer some useful insight but needs to be interpreted with caution. In addition to the sensitivities mentioned in Section 2.2.1.1, the influence of measurement bias for low emitting vehicles discussed in Section 3 should be considered before making comparisons to the corresponding VERSIT+ emission factors. For light-duty Euro 6 vehicles, the influence of this bias may be significant due to the many vehicles with low to very low emissions. Therefore, comparison to of plume chase measurement results of these vehicle types are only shown for information purposes with this disclaimer. No final conclusions can be drawn on this analysis yet without further examining the cause and effects of the identified uncertainties.

C.1.1 Diesel delivery vans

Measured NO_x-emissions for diesel delivery vans show some differences relative to the corresponding VERSIT+ emission factors. While similar values are observed for certain Euro classes, other Euro classes show higher measured emissions than the inventory-based emission factors. Figure C.1 shows the distribution of the ratio between measured NO_x-emissions and the corresponding VERSIT+ NO_x-emission factors for Dutch LDV diesel delivery vans. For Euro 6d-Temp vehicles, the distribution has a mean ratio approximately equal to 1, indicating that average measured real-world NO_x-emissions are very similar to the corresponding emission factors of these vehicles. Euro 5 vehicles show a distribution with a mean ratio of 1.2, suggesting that the plume-chase measurements show slightly higher emissions than the emission factors. In contrast, Euro 6a,b,c vehicles, and Euro 6d vehicles show a broader distribution that is clearly shifted towards higher ratios, with a mean value of around 4.2 and 9.2 respectively. This indicates that measured NO_x-emissions frequently exceed the corresponding emission factors. The same data is also displayed in Figure C.2, here also the absolute emission levels are portrayed for additional insight.

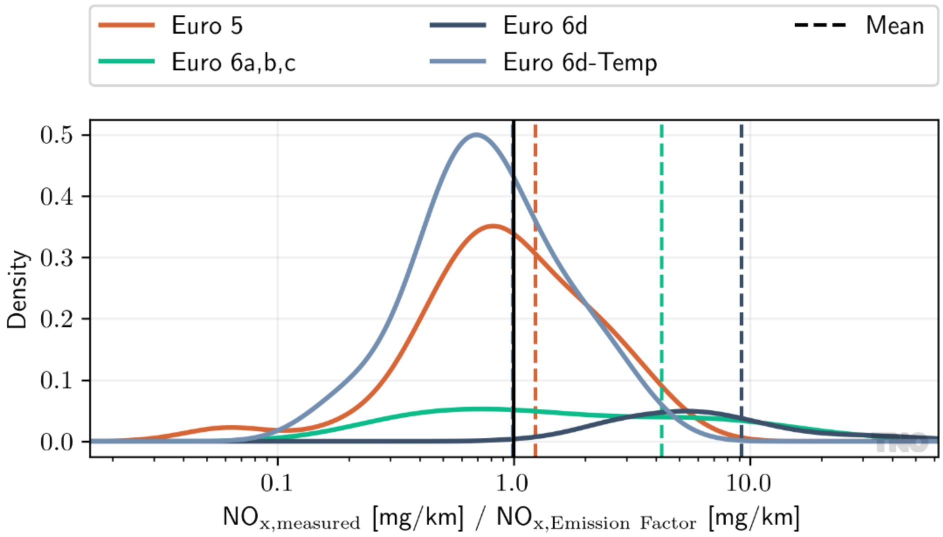

Figure C.1: Distribution of the ratio between measured NOx-emissions and the corresponding NOx-emission factors for Dutch LDV diesel delivery vans. Curves show kernel density estimates per Euro class. Dashed vertical lines indicate the mean ratio per Euro class, and the solid black line represents a 1:1 relationship between measured emissions and emission factors. It should be noted that for Euro 6a,b,c and Euro 6d vehicles, the low absolute NOx-emission factors may partially explain the relatively high observed ratios.

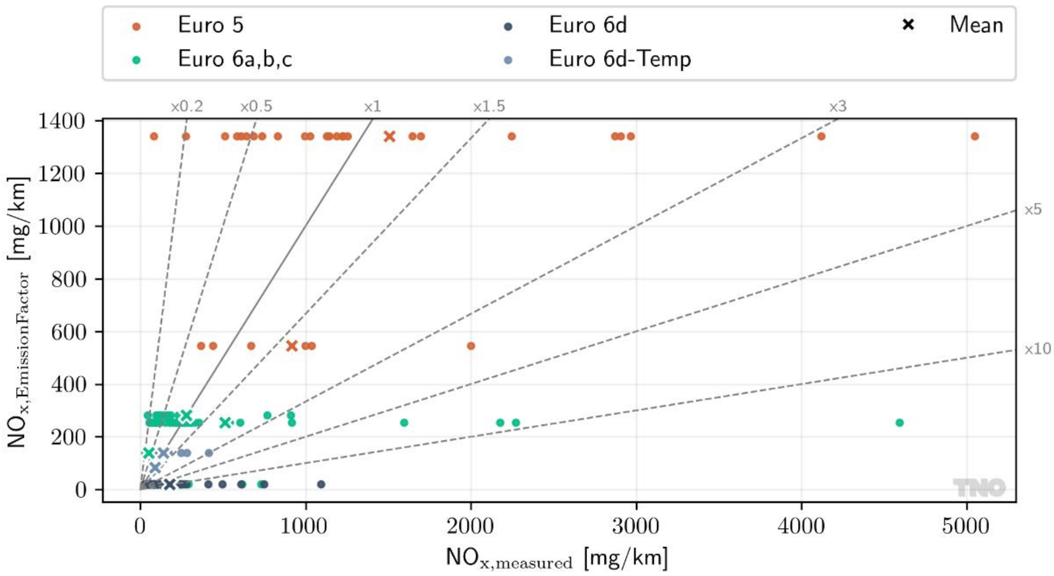

Figure C.2: Distance-normalised NO_x-emission factor for motorway driving in the Dutch emission inventory versus the NO_x-emissions measured by plume chasing for LDV diesel van vehicles. The colour coding of the data points represent their respective Euro class. The grey lines indicate different bands, showing where the measured NO_x-emissions lie relative to the emission factor. The black line represents a 1:1 relationship (x1).

C.1.2 Petrol passenger cars

Similarly to the previous section, measured NO_x-emissions for Dutch LDV petrol passenger vehicles show some differences relative to their corresponding VERSIT+ emission factors. Note, however, that the overestimation of NO_x-emissions of plume chasing at low emission levels as described in Section 3.1 is expected to play a particularly large role for petrol passenger vehicles, as the emissions of these vehicles are typically lower compared to the HDVs and diesel delivery vans. The distribution of the ratio between measured NO_x-emissions and the corresponding NO_x-emission factors for Dutch LDV petrol passenger vehicles is shown in Figure C.3. For Euro 4 and Euro 5 vehicles mean ratios of 1.9 and 1.8 are found respectively, indicating that measured NO_x-emissions are on average about a factor of 2 higher than their corresponding emission factors in the Dutch emission inventory. Euro 6 vehicles registered before the introduction of RDE show on average higher ratios, with a mean ratio around 3.8. Similarly, Euro 6 vehicles registered after RDE also show a distribution shifted towards higher ratios, with a mean ratio of 3.5. Furthermore, it is interesting to note that the distributions of Euro 6 before RDE, Euro 6 after RDE and Euro 5 show a mild secondary peak in their distribution. While this feature is relatively weak for Euro 5 vehicles, it is more clearly pronounced for both Euro 6 before RDE and Euro 6 after RDE vehicles. This suggests that the plume-chase measurements of vehicles of some VERSIT classes within those Euro classes are more similar to their corresponding emission factors than other vehicles within the same Euro class. The same data is also displayed in Figure C.4, here also the absolute emission levels are portrayed for additional insight.

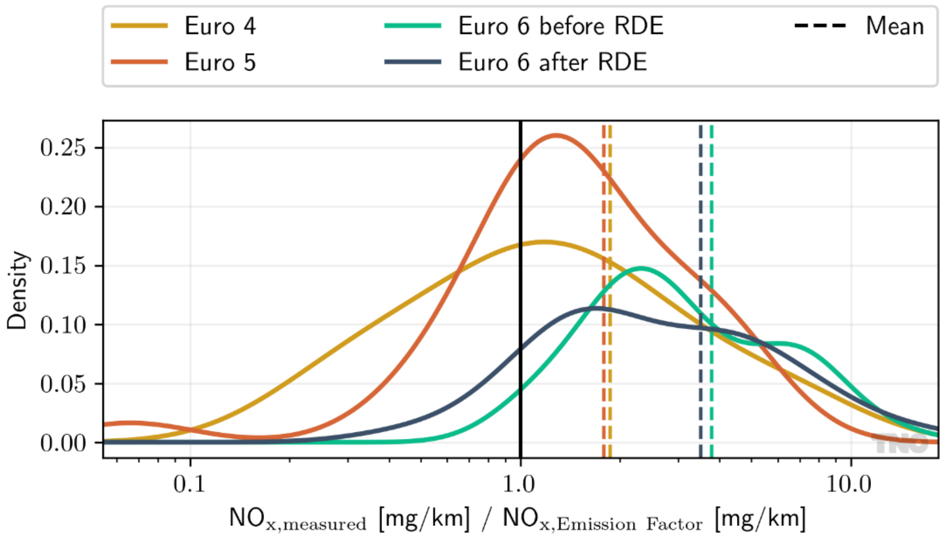

Figure C.3: Distribution of the ratio between measured NO_x-emissions and the corresponding NO_x-emission factors for Dutch LDV petrol passenger vehicles. Curves show kernel density estimates per Euro class. Dashed vertical lines indicate the mean ratio per Euro class, and the solid black line represents a 1:1 relationship between measured emissions and emission factors.

Figure C.4 compares the NO_x-emission factors for motorway driving as reported in the Dutch emission registration with the NO_x-emissions measured by plume chasing for petrol passenger vehicles. The figure shows that the large majority of vehicles have measured NO_x-emissions that are substantially higher than the corresponding emission factors reported in the registration.

Many measurements lie above the 1:1 line, frequently exceeding the x1.5 and x3 bands, and in some cases approaching or exceeding the x5 and x10 ratios. This behaviour is observed across all Euro classes. Note once again, however, that the plume-chase validation campaigns indicated that the current plume-chase measurement tend to significantly overestimate NO_x-emissions at low emission levels. Therefore, the measured NO_x-emissions for petrol passenger vehicles might be overestimated, likely contributing to the observed discrepancy with the VERSIT+ emission factor.

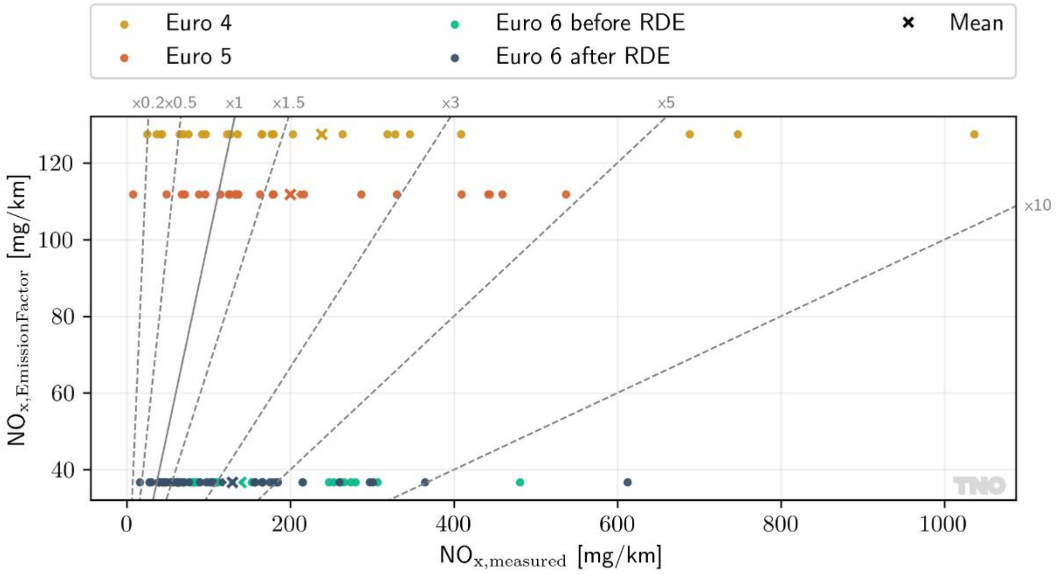

Figure C.4: Distance-normalised NO_x-emission factor for motorway driving in the Dutch emission registration versus the NO_x-emissions measured by plume chasing for LDV petrol passenger vehicles. The colour coding of the data points represent their respective Euro class. The grey lines indicate different bands, showing where the measured NO_x-emissions lie relative to the emission factor. The black line represents a 1:1 relationship (x1).

C.2 Diesel delivery vans – extended analysis

Similarly to the analysis shown in the previous section, the following paragraph investigates multiples of the Euro class specific emission standard as high-emitter thresholds for LDV diesel delivery vans. The distance-normalised emission standards adapted for this analysis are 80 mg/km for Euro 6 and 180 mg/km for Euro 5. Note once again that, in contrast to the average NO_x fleet emission approach, no distinction is made for Euro subclasses here. Similarly to the approach discussed in Section 4.2.1, multiples of the emission standards are used as thresholds to calculate the number fraction of high-emitters and the emission fraction of high-emitters. At a high-emitter threshold of 2.5 times the Euro class specific emission standard, 45% of vehicles are classified as high-emitters, which are responsible for 73% for the total activity weighted emissions of LDV diesel delivery van vehicles on the Dutch roads. Figure C.5 shows the activity weighted emission fraction of high-emitters versus the number fraction of high-emitters for a wide range of multiples of the emission standard as high-emitter thresholds. The curve of Figure C.5 shows a similar shape compared to the results shown in Figure 4.17, indicating that both approaches lead to consistent conclusions regarding the relationship between the fraction of high-emitting vehicles and their disproportionate contribution to total emissions.

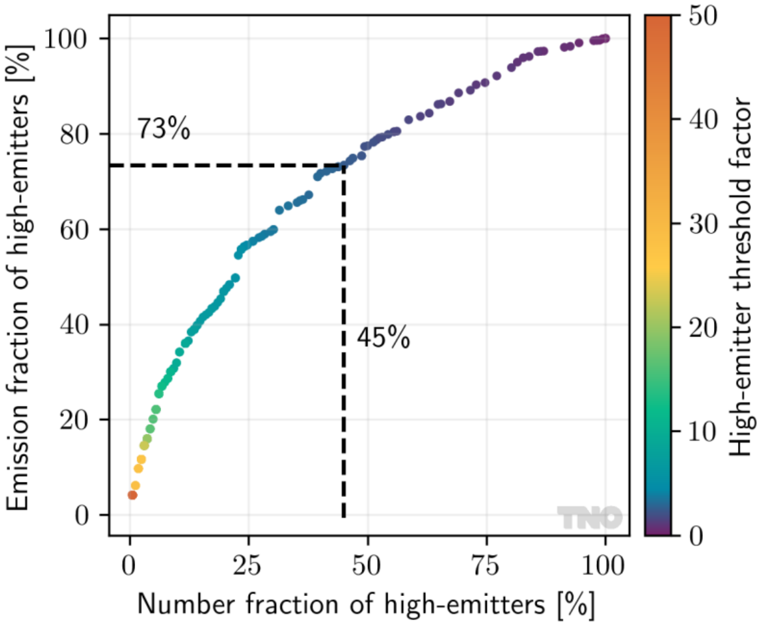

Figure C.5: Emission fraction of high-emitters versus number fraction of high-emitters for Dutch LDV diesel delivery vans.The colour of the data points indicates the applied high-emitter threshold factor, defined as a multiple of the emission standard per Euro class, which is used to classify high emitters. The dashed lines indicate a high-emitter threshold factor of exactly 2.5. The percentage values denote the corresponding emission fraction and number fraction of high-emitters at this threshold.

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Anna van Buerenplein 1
2595 DA Den Haag
www.tno.nl

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