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Results of a plume-chase measurement campaign in the Netherlands

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Samenvatting

Het meten en monitoren van een groot aantal voertuigen in het Nederlandse wagenpark is cruciaal om een beter inzicht te krijgen in het aandeel high-emitters in het wagenpark en om effectieve beleidsvorming in Nederland te ondersteunen. Het meten van verontreinigende emissies kan worden uitgevoerd met verschillende technieken, waarvan de plume-chase remote-sensing techniek het beste compromis biedt tussen meetkosten, meetduur en nauwkeurigheid voor metingen aan een groot aantal voertuigen.

In 2024 is een meetcampagne met een plume-chase auto uitgevoerd om inzicht te krijgen in het aandeel high-emitters in het Nederlandse wagenpark, en om een eerste indruk te krijgen of deze meettechniek geschikt is om de absolute NO_x-uitstoot van het Nederlandse wagenpark te onderzoeken. In totaal zijn er 402 valide metingen gedaan op Nederlandse snelwegen. Gemeten voertuigen werden specifiek geselecteerd om in de dataset zoveel mogelijk het aandeel per voertuigtype in het Nederlandse wagenpark te weerspiegelen; hier is gekeken naar benzine personen- en bestelwagens, diesel personen- en bestelwagens en diesel vrachtwagens. In deze meetcampagne zijn alleen in Nederland geregistreerde voertuigen meegenomen.

De resultaten van de plume-chase metingen zijn nader geanalyseerd om zo de NO_x-uitstoot van elk gemeten voertuig te bepalen in mg/km. High-emitters onder personen- en bestelwagens werden in dit werk gedefinieerd als voertuigen met emissies die minimaal twee keer zo hoog zijn als de gemiddelde gemeten emissies van voertuigen in dezelfde emissieklasse. Onder vrachtwagens werden high-emitters geïdentificeerd m.b.v. een selectiedrempel van 1700 mg/km voor Euro VI voertuigen die voorkomt uit beschikbare literatuur. Deze selectiedrempel werd ook vergeleken met de selectiemethode voor personen- en bestelwagens.

Parallel aan de meetcampagne werd een kleinschalige validatiestudie uitgevoerd naar de toepasbaarheid van plume-chase metingen voor het bepalen van de emissies van benzinevoertuigen. Uit deze validatiestudie bleek dat de gemiddelde onzekerheid voor voertuigen met lage tot normale emissies +40 mg/km op het meetresultaat bedroeg. De meetonzekerheden voor voertuigen met hogere emissies zijn nog niet vastgesteld. De validatieresultaten tonen aan dat de plume-chase techniek in zijn huidige vorm kan worden gebruikt om benzinevoertuigen met hoge emissies te identificeren op de weg. Er is echter meer ontwikkelings- en validatiewerk nodig om de resultaten van deze metingen te gebruiken om de absolute emissieniveaus van benzinevoertuigen op de weg te bepalen.

Uit plume-chase metingen aan 200 benzine personen- en bestelwagens en 77 diesel personen- en bestelwagens werd een gemiddeld aandeel van high-emitters van respectievelijk 8% en 7% gevonden. Benzinevoertuigen met de emissieklassen Euro 4, Euro 5 en Euro 6 vertonen onderling vergelijkbare NO_x-emissieniveaus, wat in lijn der verwachtingen is vanwege de grotendeels vergelijkbare uitlaatgas nabehandelingssystemen die in deze voertuigen worden gebruikt. Er werden echter meer high-emitters gevonden onder voertuigen met hogere kilometerstanden, wat samenvalt met een hoger aandeel Euro 4- en Euro 5-voertuigen in deze groep. De emissies van dieselvoertuigen zijn daarentegen veel afhankelijker van de emissieklasse van het voertuig.

Bij dieselvoertuigen met een kilometerstand binnen de durability eis van 160.000 km voor Euro 5 en Euro 6 voertuigen, werd een aanzienlijk aandeel high-emitters waargenomen in Euro 5 (en Euro 4) voertuigen. Metingen aan Euro 6 dieselvoertuigen laten een duidelijk effect van de emissieklasse op de emissies zien, samenvallend met de invoering van de RDE-wetgeving voor voertuigen met een emissieklasse van Euro 6d-Temp en hoger. De spreiding in gemeten emissies en absolute emissieniveaus is voor deze voertuigen aanzienlijk kleiner dan voor Euro 6 voertuigen vóór de invoering van RDE. Er werd tevens een lager aandeel high-emitters gevonden van 5% ten opzichte van 7%. Op basis van de resultaten in dit rapport wordt aanbevolen om aanvullend onderzoek te doen naar het mogelijk gelijktrekken van de Euro 6d VERSIT+ emissiefactor met de emissiefactor voor Euro 6d-Temp voertuigen.

Uit plume-chase metingen op 125 diesel vrachtwagens werd een gemiddeld aandeel high-emitters van 6% voor Euro VI voertuigen gevonden. Het aantal gemeten Euro V voertuigen is te klein om relevante statistische conclusies te trekken. De meeste Euro VI voertuigen vertonen slechts een beperkte toename van de emissies bij hogere kilometerstanden. Net als bij diesel personen-en bestelwagens werden echter significante high-emitters gevonden bij voertuigen met kilometerstanden binnen de durability eisen van de verschillende vrachtwagen categorieën.

In 2025 wordt het plume-chase emissiemeetprogramma voortgezet. De in dit rapport besproken dataset zal worden uitgebreid met datapunten gericht op diesel bestelwagens met emissieklasse Euro 6d en nieuwer,, en diesel vrachtwagens met emissieklasse Euro VI (en nieuwer). Voor vrachtwagens zullen dan ook buitenlandse voertuigen die op Nederlandse snelwegen rijden worden meegenomen.

Dit onderzoek is uitgevoerd in het kader van de programmatische samenwerking tussen het Ministerie van Infrastructuur en Waterstaat (IenW) en TNO.

Summary

Measuring and monitoring of a large set of vehicles in the Dutch fleet is crucial to generate better insight in the share of high-emitters in the fleet and to support effective policy making in the Netherlands. Pollutant emission measurements can be performed with multiple techniques, of which the plume-chasing remote-sensing technique offers the best compromise between measurement cost, duration and accuracy for measurements on a large set of vehicles.

A plume chase measurement campaign was conducted in 2024 to get an impression of the share of NO_x high-emitters in the Dutch fleet, and to obtain a first impression whether this measurement technique is suitable for investigating the absolute Dutch fleet NO_x-emissions. In total 402 valid measurement records were gathered from measurements on Dutch motorways. Sampling of vehicles was done to match the share of vehicle types in the Dutch fleet to include light-duty (LDV) petrol, light-duty diesel and heavy-duty (HDV) diesel vehicles. Only vehicles registered in the Netherlands were considered in this measurement campaign.

Plume chase measurement results are analysed to determine the NO_x-emissions in units of mg/km of each measured vehicle. LDV High-emitters are defined – in this work – as the vehicles with emissions above two times the average measured emissions of vehicles in the same emission class. For heavy-duty vehicles, high emitters are determined based on selection thresholds available in literature of 1700 mg/km for Euro VI vehicles. This selection method is also compared to the selection method for light-duty vehicles.

A small-scale validation study to the applicability of plume chase measurements for the determination of petrol vehicle emissions was performed in parallel with the measurement campaign. From this validation study an average uncertainty for vehicles with low to normal emissions of +40 mg/km on the measured result is found. Measurement uncertainties for vehicles with high emissions are not determined yet. The validation results show that plume-chasing in its current form can be used to identify petrol high emitters under real world conditions. However, more development and validation work is needed to use petrol plume chase results to determine absolute emission levels of petrol vehicles on the road.

From plume chase measurements on 200 light-duty petrol vehicles and 77 light-duty diesel vehicles, an average high-emitter share of 8% and 7% was found respectively. Petrol vehicles of Euro 4, Euro 5 and Euro 6 emission classes show similar NO_x-emission levels, which is expected due to the largely similar exhaust gas aftertreatment systems used across these vehicles. There is however a higher occurrence of high-emitters at higher mileages, coinciding with a higher share of Euro 4 and Euro 5 vehicles. Emissions of diesel vehicles are much more dependent on the emission class of the vehicle. For diesel vehicles with mileages below the durability requirement threshold of 160,000 km for Euro 5 and 6 vehicles, significant high-emitters are observed in Euro 5 (and 4) vehicles. Measurements on Euro 6 diesel vehicles show a clear effect on emissions, coinciding with the introduction of RDE legislation for Euro 6d-Temp and above vehicles. The spread in measured emissions and absolute emission levels is significantly reduced for these vehicles compared to Euro 6 vehicles before the introduction of RDE, and a lower high-emitter occurrence of 5% is found.

From the results presented in this study, additional research and possible alignment of the Euro 6d VERSIT+ emission factor with the factor for Euro 6d-Temp vehicles is advised. From plume chase measurements on 125 heavy-duty diesel vehicles an average high-emitter share of 6% for Euro VI vehicles was found. The number of measured Euro V vehicles is too low to provide relevant statistical observations. The majority of Euro VI vehicles show only a limited increase in emissions at higher mileages. However, similar to the observations for light-duty diesel vehicles, significant high-emitters are found with mileages below the durability requirement thresholds of the different HDV categories.

In 2025, a continuation of this plume-chase emission-measurement programme is being conducted. Continued measurements will add datapoints focused on Euro 6d and newer light-duty commercial diesel vehicles and Euro VI (and newer) heavy-duty diesel vehicles to the dataset discussed in this report. For heavy-duty vehicles also foreign vehicles traveling on Dutch motorways will be considered.

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

Contents

1 Introduction

Throughout the years, road vehicle emission regulations have become more stringent, and pollutant emissions from on-road vehicles have gradually reduced due to better exhaust gas aftertreatment systems and the ingrowth of electric vehicles in the fleet. Emissions from the remaining internal combustion engine (ICE) vehicle fleet will however remain relevant even after the foreseen stop on new ICE vehicles in 2035 due to aging effects of the existing fleet. A large share of automotive emissions is currently already caused by a small fraction of high-emitters due to poor maintenance or tampering, rather than due to the lack of capable exhaust gas aftertreatment systems. This has been shown in previous work [1] [2] where 6% of petrol vehicles on Dutch roads were found to be responsible for 36% of the total NO_x -emissions in the petrol vehicle fleet. The sample size is however still small, measuring and monitoring of a larger set of vehicles is crucial to generate better (statistically significant) insight in the real-world emissions on Dutch roads and to support effective policy making.

The fleet emissions statistics have traditionally been established using extensive emission testing of individual vehicles with on-road measurements using a portable emission measurement system (PEMS). This method provides detailed insight into the emission behaviour of a specific vehicle, but often requires multiple days of work, including vehicle instrumentation and testing. The plume-chasing remote-sensing method provides a less detailed but much faster method for measuring on-road NO_x-emissions of multiple vehicles without the need for extensive installation of individual vehicles. A typical measurement of a single vehicle takes between 2 to 5 minutes, with 10 to 15 vehicles being measured per hour in practice.

The effectiveness of this method for identifying high and low emitting diesel vehicles has already been shown in the European CARES project [3]. In addition, in 2023, TNO performed a first plume-chasing campaign on Dutch roads with 120 measured passenger vehicles to provide the first insights into the NO_x-emissions of light-duty petrol and diesel vehicles in the Dutch fleet as reported in [4].

This report details the plume-chasing measurement results of the 2024 measurement campaign, along with the plume chase methodology employed for these measurements. The results of this campaign are used to estimate the share of high-emitters in the Dutch fleet. Plume chase measurements were performed on Dutch vehicles on several motorways in the Netherlands and are representative for the cross section of vehicle types in the Dutch fleet. Due to a low number of measurements on heavy-duty vehicles (HDV's) in the 2024 data, the presented dataset is enriched with HDV measurement data from the first half of the 2025 campaign.

In Chapter 2 of this report, the research methodology of this study is described.
The measurement results are then presented and discussed in Chapter 3, and conclusions on the results are presented in Chapter 4.

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

2 Methodology

Pollutant emission measurements can be performed with multiple techniques. In general, two main categories of techniques can be distinguished: direct tailpipe measurements and remote (indirect) sensing measurements. Direct tailpipe measurements offer highly accurate results for individual vehicles, but are prohibitively expensive for measurements of the entire fleet. Remote-sensing measurements give less accurate results for individual vehicle measurements, but do not require extensive instrumentation of the individual vehicles to be measured. Therefore, for remote-sensing techniques, the cost and measurement time per vehicle are much lower compared to direct tailpipe measurements. In addition, as cooperation of vehicle owners of tampered vehicles will be limited to instrumented measurement campaigns, sampling of vehicles with remote-sensing is more representative of the fleet. As a result, remote-sensing techniques are very relevant to determine the fleet-wide emissions and share of high emitters on a statistically relevant set of vehicles.

Within remote-sensing, techniques can either be classified as stationary measurements such as offered by OPUS [5] and HEAT [6], or dynamic measurements, often referred to as plume chase measurements. These dynamic measurements offer longer measurement durations on individual vehicles and are less sensitive to the measurement location to determine vehicle emissions [7]. In contrast to static measurements, they can therefore also provide relevant information on an individual vehicle with only a single measurement [8].

Dutch fleet nitrogen oxides (NO_x) emissions in this report are measured using the plume-chasing technique. The remainder of this chapter details the measurement setup, measurement programme and data post-processing methodology used to obtain the emission results further detailed in Chapter 3.

2.1 TNO plume chase vehicle

Plume-chasing is a remote-sensing technique in which a measurement vehicle equipped with various measurement instruments is employed to measure vehicle emissions without the need for instrumentation of the measured vehicle. Measurements are performed by ‘chasing’ a vehicle of interest for up to 5 minutes while measuring emission plume samples of the chased vehicle, taken at the front of the plume chase vehicle.

The TNO plume chase vehicle shown in Figure 2.1 incorporates these techniques for the measurement of NO_x-emissions. To that extent, ambient NO_x 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[1]. When relevant, driver behaviour of the vehicle of interest can be monitored using a bumper mounted radar.

[1] 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 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. Note that while a particle number (PN) measurement instrument is available in the plume chase vehicle, PN results will not be discussed in this report due to the experimental nature of these measurements. The remainder of the used plume chase hardware is listed in Table A.2 of 0.

2.2 Plume chase measurements

In 2024, a plume chase measurement campaign was performed on the road to measure the NO_x-emissions of vehicles in the Dutch fleet under real-world conditions. 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.

Measured vehicles are selected at random to obtain a representative sample of vehicle shares in the Dutch fleet. The targeted vehicle shares in the measurement results, in line with the Dutch fleet share, are shown in Figure 2.2. Only vehicles registered in the Netherlands are measured in this measurement programme. L-cat vehicles and vehicles with an emission class preceding Euro 4 are not considered in this study.

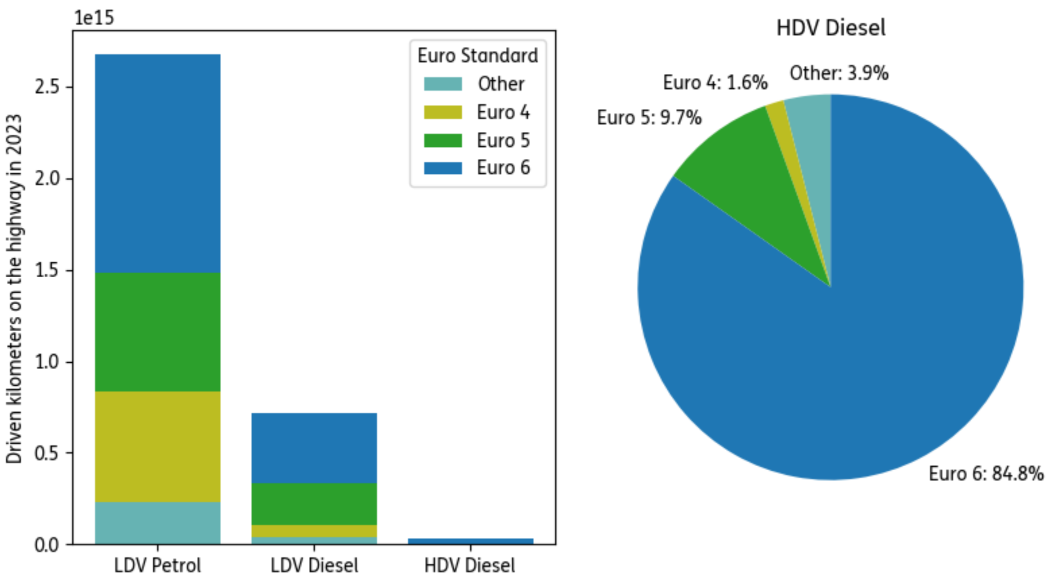

Figure 2.2: Distance driven share by vehicle type and emission class for the Dutch 2023 vehicle fleet.

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. The minimum target measurement duration for different emission levels is based on:

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[3] class. On average, approximately 12 vehicles per hour are measured using this method.

When large temporal variations in the CO_2 normalised[2] emissions are observed, the duration of the measurement is increased to increase confidence in the post-processed results.

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,
- 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 a myriad of causes which are unknown to the plume chase operator at the time of measuring.

[2] CO_2 normalised emissions: pollutant emissions expressed in gram pollutant per kilogram carbon dioxide.

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[3] class, Taxonomy[4] code and CO_2 emission factor of each vehicle in the Dutch fleet. Licence plate information of heavy-duty vehicles (HDVs) is added manually by the plume chase vehicle operator.

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 [3] 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 [3] giving confidence in these measurements. Validation studies on the use of plume-chasing techniques for light-duty petrol vehicles have not been reported yet. For a preliminary insight in the applicability of plume-chasing for these types of measurements, a short validation programme carried out with a single LDV petrol vehicle equipped with PEMS is discussed in Paragraph 3.2.1 of this report.

2.3 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 [9], [10] and [11].

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 licence plate from the M1 model [12] for LDVs and the bottom-up methodology [13] from the Dutch Emission Inventory for HDVs.

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 [8] to ensure only measurement values are taken into account from samples taken in the emission plume of the chased vehicle.

[3] VERSIT+: Road traffic emission model developed by TNO to predict emission factors of vehicle fleets [25]. Emission factors of each VERSIT class are determined based on emission measurements and estimated ageing effects of the vehicles in this class.
[4] Taxonomy code: A controlled vocabulary and vehicle classification system for all passenger cars on the road [26]

3 Results & discussion

During the plume chase campaign in 2024, a total of 404 vehicles with Dutch licence plates were measured on motorways in the Netherlands. From all measured vehicles, a total of 301 valid measurement records are available. The dataset includes a total of 200 petrol vehicle records and 101 diesel vehicle records. Due to the fleet-composition based sampling, only very few (24) heavy-duty vehicle datapoints are available in the 2024 data. For heavy-duty vehicles, 101 additional measurements performed in 2025 are added to the dataset in this report to increase statistical relevance of the conclusions. This chapter discusses the first emission measurement results and observations per fuel type.

Note that in 2025 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 2025 measurement campaign will be reported later.

3.1 Diesel vehicles

In 2024 a total of 101 diesel vehicles were measured of which 77 light-duty vehicles and 24 heavy-duty vehicles across different emission classes. 101 additional heavy-duty measurements are available from the first half of 2025. Results are discussed separately for light-duty and heavy-duty vehicles below.

3.1.1 Light-duty vehicles

In total, 77 light-duty diesel vehicles were measured in the 2024 plume chase campaign of which 28 passenger cars and 49 delivery vans across Euro 4 to 6. Figure 3.1 shows the distribution of NO_x-measurement results for the diesel light duty vehicles. Note that the final bin aggregates measured emissions up to 3123 mg/km (not shown). The NO_x-emission measurement results on these vehicles show a left-skewed distribution with average measured emissions of 415 mg/km. The tail of this distribution can be accredited to both the spread of emissions over different emission classes and potential high-emitters in the fleet. The distribution of measured vehicles into the different emission classes is shown in Table 3.1.

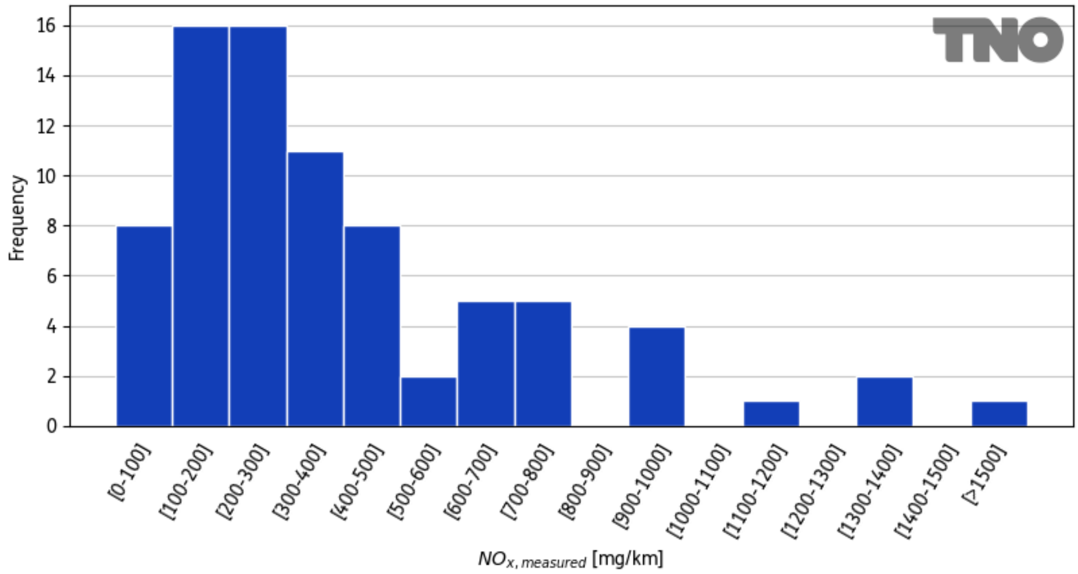

Figure 3.1: Plume-chasing NO_x-emissions results for light-duty diesel vehicles, the horizontal axis represents the measured NO_x-emissions in mg/km. The overflow bin (>1500) contains measured emissions up to 3123 mg/km.

Table 3.1: Emission class distribution of measured light duty diesel vehicles.

Emission class	Measured vehicles	Share of measurements
4	9	12%
5	22	28%
6a	9	12%
6b	16	21%
6c	2	3%
6d-Temp	11	14%
6d	8	10%

The share of measured vehicles per emission class is similar to the distribution of driven kilometres per emission class in the Dutch fleet shown in Figure 3.2. The Euro 6 vehicles are slightly oversampled (60%) in the measurements compared to the share in the total driven kilometres-normalised fleet. The higher number of Euro 6 vehicles in the random sampling may be attributed in part to the additional ingrowth of Euro 6 vehicles between 2023 and 2024, and to older vehicles (Euro 4 & 5) being used more often on urban roads than on the motorway as found in [14].

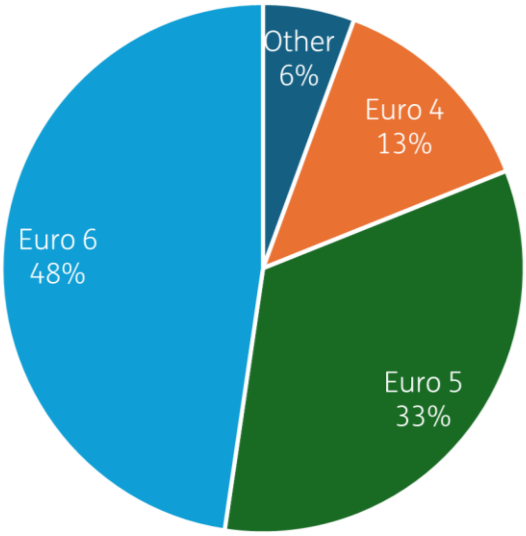

Figure 3.2: Distribution of driven kilometres per Euro class of light-duty diesel vehicles in the Dutch fleet of 2023 [15].

Individual vehicle measurements for light-duty diesel vehicles are shown in Figure 3.3. In general, the spread of measured NO_x-emissions is found to be lower for more modern vehicles. There is a significant difference in spread and average values of the measured emissions before and after the implementation of Euro 6d(-Temp). While a narrow emission distribution for Euro 6d-Temp and Euro 6d vehicles can be in part be related to a relatively small sample set and low mileages, the low average emissions and limited spread closely match the expectations for vehicles complying with Real Driving Emissions (RDE) legislation.

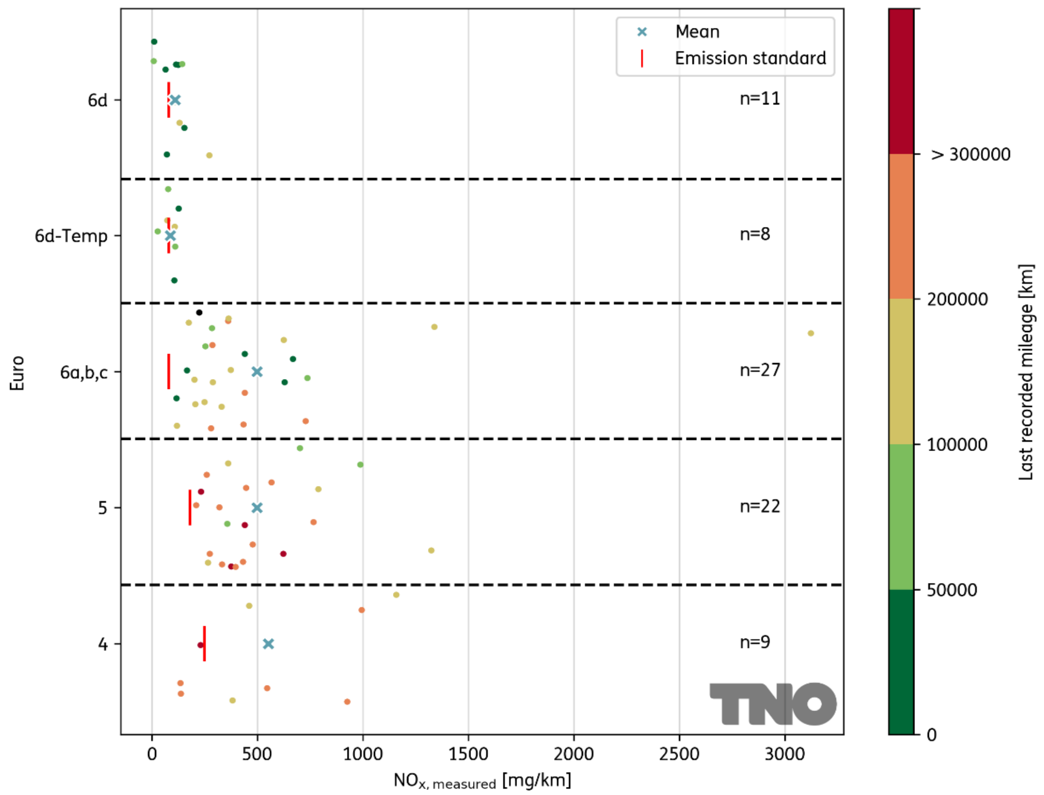

Figure 3.3: NO_x-emission measurement results for light-duty diesel vehicles per emission class. The colour of each data point indicates the last recorded mileage of the vehicle. The average measured NO_x-emission (Mean) and regulatory limit value per emission class (Emission Standard) are indicated for reference. The total number of vehicles measured for each emission class is denoted by n.

While the majority of vehicle measurements show emission levels above the regulatory limit value, not all elevated measurements indicate a high-emitter. It is important to note that regulatory limit values are based on a standardised driving cycle under controlled conditions. For non-continuous on-road emission measurements, deviations from the regulatory limit value are expected. High-emitters should be considered as those vehicles showing emissions outside of the emissions range observed for the majority of vehicle measurements. In this work, this corresponds well to a high-emitter threshold of twice the average measured emissions in the sample. Based on this definition, a high-emitter share (as weighed for the number of vehicles observed in the respective vehicle emission classes) of 7% across all emission classes is determined from these measurements. Note that the occurrence of high-emitters in vehicles with emission class Euro 6d-Temp or newer is lower with a 5% share.

Furthermore, an observation can be made that low mileage vehicles are not always clean vehicles. At least for Euro 6 a, b & c, several vehicles with low mileages (0 – 50,000 km) show elevated emissions. On the other side of the spectrum, a few Euro 4 vehicles with high mileages (> 200,000 km) performed very well during the measurement.

To compare the emission measurements with the emission factors in the Dutch Emission Inventory, each emission measurement result is plotted against the emission factor of the measured vehicle based on its VERSIT class in Figure 3.4.

On average, the VERSIT+ emission factors for Euro 6d-Temp match the average emissions measured during the campaign. For Euro 4 and Euro 5, average measured emissions are lower than the VERSIT+ emission factor, emission factors therefore account for a higher share of high-emitters compared to those found during the measurement campaign. For Euro 6 a, b & c the average measured emissions are slightly above the VERSIT+ emission factors, and for Euro 6d vehicles, the emission factors are much lower than the measured emissions. Note that due to the low emissions of Euro 6d vehicles, the ratio between measured emissions and the emission factor is much more sensitive to absolute deviations compared to vehicles with higher emissions. In previous work [16] Euro 6d vehicles were found to outperform Euro 6d-Temp vehicles, resulting in a lower emission factor in the Dutch Emission Inventory. During this campaign, the real-world performance of Euro 6d and Euro 6d-Temp vehicles is found to be largely similar. The main performance difference between Euro 6d-Temp and Euro 6d vehicles is however expected at low engine load conditions, which were not measured in this campaign.

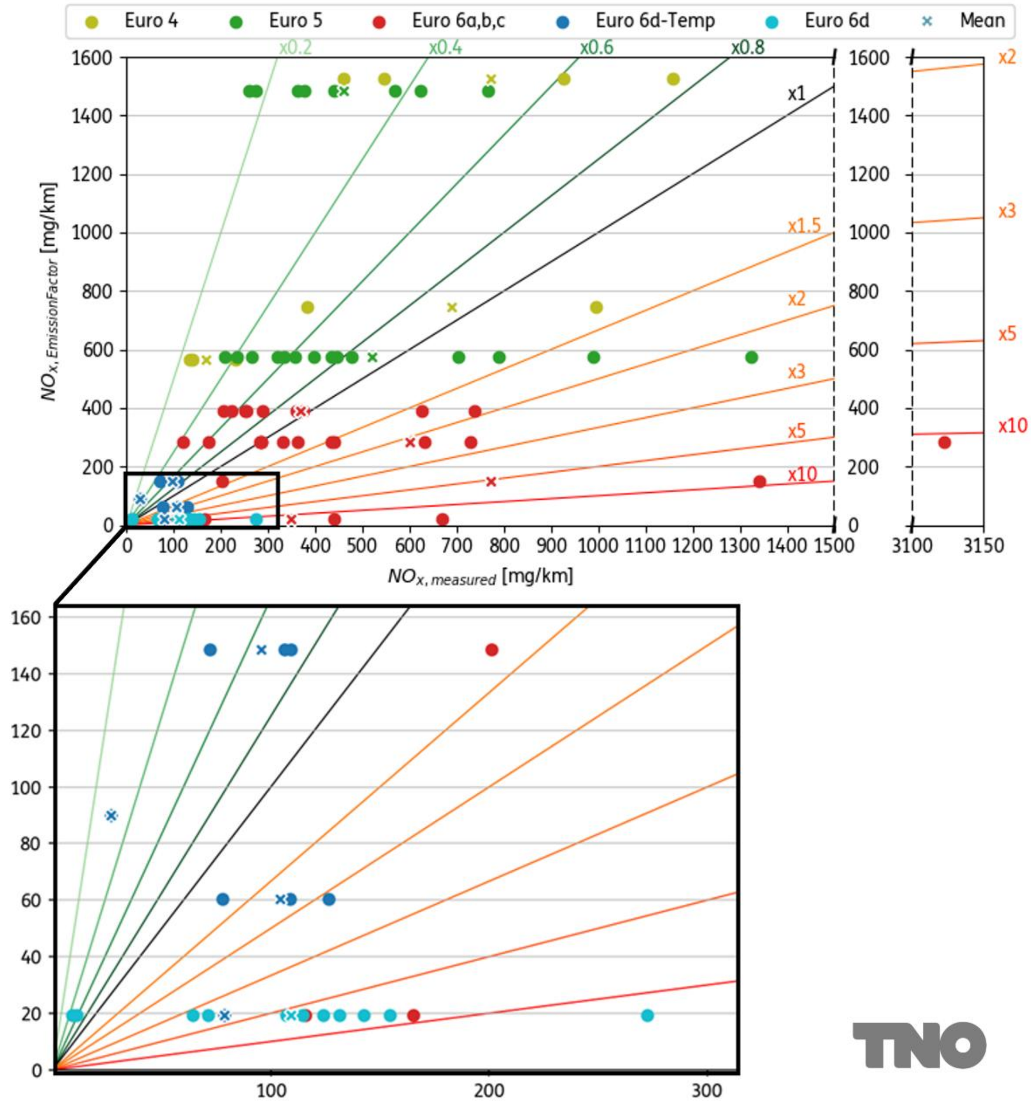

Figure 3.4: NO_x-emission measurement results for light-duty diesel vehicles set out against their NO_x-emission factor for motorway driving in the Dutch emission registration. Coloured lines represent the division of measured emissions by the VERSIT+ Emission Factor. Average measured emissions per VERSIT class are added as crosses for reference with the applicable emission factor.

Emissions of diesel vehicles are expected to increase over time due to ageing effects. In Figure 3.5 the light-duty diesel vehicle measurement results are plotted against the last recorded mileage of the vehicle. Note that very high mileages above 300,000 km are only found in Euro 4 and Euro 5 vehicles and only limited measurement points are available. Therefore, based on these results, no statistically supported conclusion can be drawn on the emissions of very high mileage vehicles in the fleet.

Vehicles with European type approvals need to comply with their respective emission standards for up to 160,000[5] km or 8 years, whichever comes first. As of the introduction of Euro 5, vehicles need to be tested on their in-service conformity up to a mileage of 100,000 km. With the introduction of Euro 6d-Temp, these tests include real driving emissions (RDE) with PEMS testing on the road. While no clear trend can be observed in the amount of high-emitters over the vehicle mileages, it is good to note the occurrence of significantly elevated emissions of Euro 5 and Euro 6 vehicles before the durability requirement.
For Euro 6d(-Temp) vehicles the majority of vehicles shows comparable emissions, with only one vehicle showing increased emissions after the in-service conformity mileage threshold. Note that after this threshold Euro 6d-Temp and above vehicles can no longer be tested for compliance with the acting emission limits with an RDE PEMS measurement.

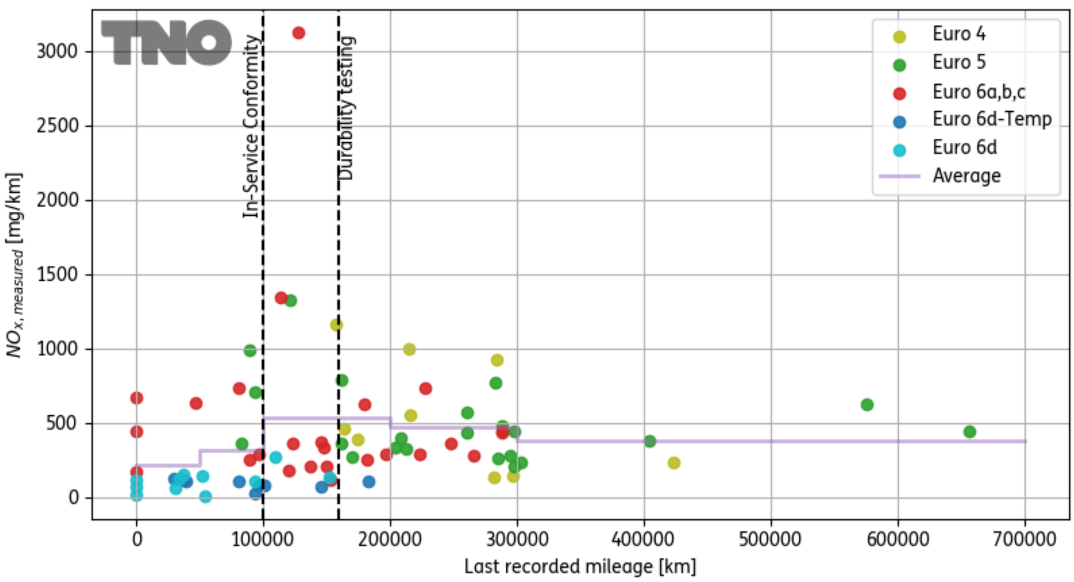

Figure 3.5: Measured NO_x-emissions and last recorded mileage of the measured light-duty diesel vehicles in 2024. Average emissions are shown as a step function between 50k, 100k, 200k, 300k+ km. The in-service conformity and durability testing mileage limits for Euro 5 and 6 vehicles are added for reference.

Comparing the measurements performed in 2024 with the data collected in 2023 shows a similar range of measured NO_x-emissions for both years, as shown in Figure 3.6.
The measurement campaign in 2023 resulted in significantly less vehicle measurements, as such distributions between both campaigns cannot be compared directly. The similar range of measured emissions is however one indicator that plume chase emission measurements can produce repeatable results.

[5] 100,000 km for Euro 4 vehicles.

For the use of plume chase data to update the Dutch Emission Inventory more data is needed to increase the statistical confidence of the average measured emissions, and additional validation studies should be performed to indicate the absolute uncertainty on the measurement results.

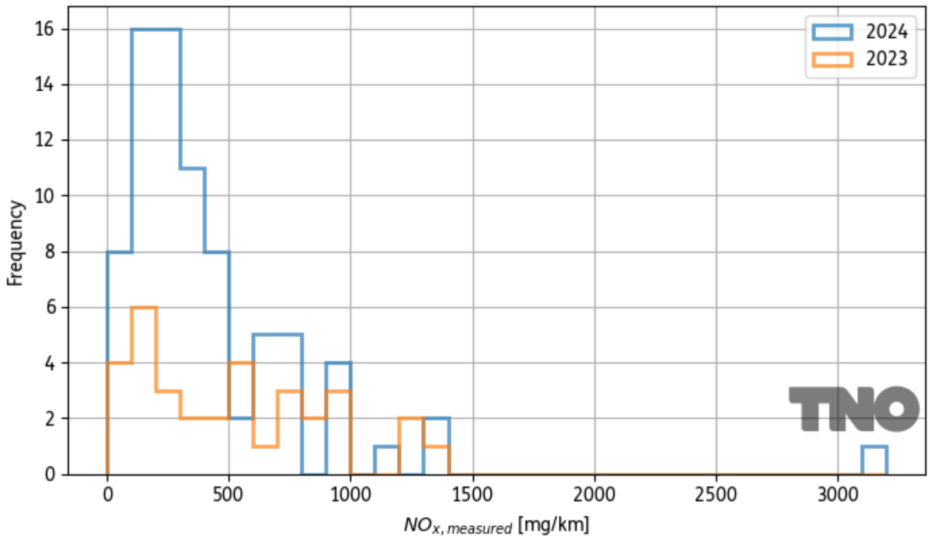

Figure 3.6: Plume-chasing NO_x emissions results for light-duty diesel vehicles measured in 2023 and 2024.

3.1.2 Heavy-duty vehicles

In total, 24 heavy-duty diesel vehicles registered in the Netherlands were measured in the 2024 plume chase campaign. 101 heavy-duty diesel vehicles registered in the Netherlands measured in the first half of 2025 are added to the analysis in this report to increase the statistical relevance of the reported measurement results. Of the 125 vehicles in total, 35 lorries, 4 busses and 86 road tractors across Euro V and VI were found. On average, the NO_x-emissions of measured vehicles were 880 mg/km.

The distribution of measured vehicles into the different emission classes is shown in Table 3.2. The share of Euro VI vehicles in the measurement sample is significantly higher than the share of Euro V vehicles. The share of Euro VI vehicles in the Dutch fleet is slightly lower with an 85% share[6]. Especially for Euro V, the small number of measured vehicles prohibits statistically relevant conclusions to be drawn from this dataset. Note that in practice, a large share of the heavy-duty vehicles on Dutch roads are vehicles registered in countries other than The Netherlands. These vehicles are not taken into account in the presented measurement results.

Table 3.2: Distribution of measured HDV to emission classes.

Euro class	Measured vehicles	Share of measurements
V	10	8%
VI	115	92%

[6] Share of vehicles in the Dutch fleet in 2023.

Individual vehicle measurements and average emissions per emission class are shown in Figure 3.7. Note that no emission limit is shown due to the difference in units between the measured emissions (mg/km) and the regulatory emission limit value (mg/kWh). A converted transient limit value based on an average fuel consumption of a tractor trailer of 32.6 L/100 km [17] and 40% engine efficiency would correspond to approximately 640 mg/km for Euro VI vehicles. Euro VI vehicles are split on build year before and after 1st of January 2019 to approximate the vehicles before and after introduction of RDE as of step D.

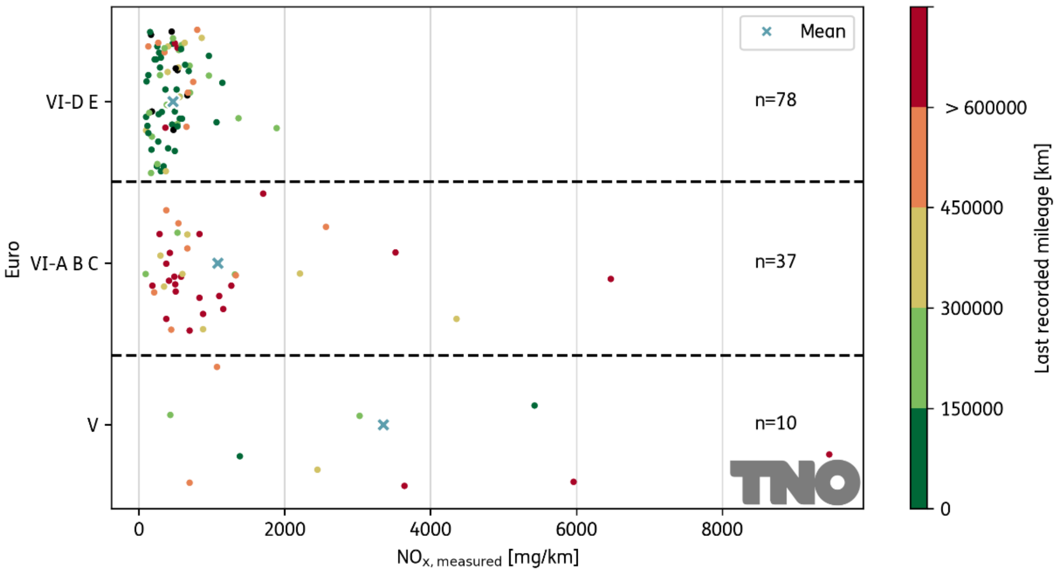

Figure 3.7: NO_x-emission measurement results for heavy-duty diesel vehicles per emission class. The colour of each data point indicates the last recorded mileage of the vehicle. The average NO_x-emission per emission class is indicated for reference with a cross. The total number of vehicles measured for each emission class is denoted by n.

The spread in measured emissions for Euro VI-D E vehicles is smaller and more skewed towards lower emissions compared to the spread in measured Euro VI-A B C vehicles. Note that this might also be caused by the much higher share of older vehicles in this latter category.

Identification of HDV high-emitters is already described in literature with HDV suspicious (high) emitter thresholds of approximately 1700 mg/km[7] and 3500 mg/km[8] proposed for Euro VI and Euro V respectively [18]. This would result in 6% high-emitters for Euro VI vehicles, where the majority of high-emitters is found in Euro VI-A B C vehicles. For Euro V no percentage is presented due to the small sample size. When applying the same selection strategy as introduced for light-duty vehicles with a selection threshold of twice the average measured emissions per group, a slightly higher high-emitter share is found. The high-emitter share (as weighed for the number of vehicles observed in the respective VI-D E and VI-A B C categories) then comes to 9,5%. This higher number is mostly due to the low average and spread in emissions for Euro VI-D E vehicles, resulting in a relatively high number of vehicles labelled as a high-emitter.

[7] Converted value based on 1200 mg/kWh using 32,6 l/100km and 40% engine efficiency.
[8] Converted value based on 2500 mg/kWh using 32,6 l/100km and 40% engine efficiency

As shown in Figure 3.7, for both Euro VI and Euro V vehicles, low to medium mileage vehicles (< 300,000 km) with high emissions and high mileage vehicles (> 450,000 km) with low emissions can be observed from the dataset. This suggests that mileage is not necessarily a good indicator for the probability of a high-emitter.

To compare the emission measurements with the VERSIT+ emission factors in the Dutch Emission Inventory, each emission measurement result is plotted against the emission factor for motorway driving of the measured vehicle based on its VERSIT class in Figure 3.8. With the limited dataset on Euro V vehicles, the average measured NO_x-emissions correspond well with the VERSIT+ emission factors due to some high-emitters. For Euro VI vehicles, the average measured emissions are lower than the relevant VERSIT+ emission factors with only limited vehicles showing emissions above their VERSIT+ emission factor. Note however that these results are only based on vehicles registered in the Netherlands. The bias towards lower emissions may in part be due to the lack of vehicles with higher emissions registered outside the Netherlands in this dataset, in line with findings in [19] and [20].

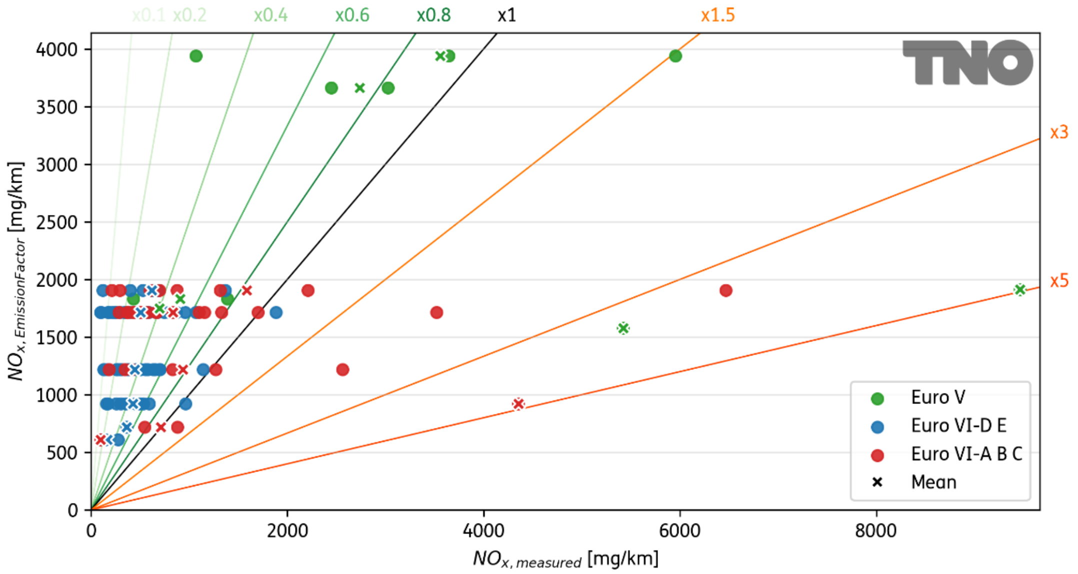

Figure 3.8: NO_x-emission measurement results for heavy-duty diesel vehicles set out against their NO_x-emission factor for motorway driving in the Dutch emission registration. Coloured lines represent the division of measured emissions by the VERSIT+ emission factor.

Emissions of diesel vehicles are expected to increase over time due to ageing effects. In Figure 3.9 the diesel HDV measurement results are plotted against the last recorded mileage of the vehicle. Note that emissions for the majority of Euro VI vehicles only show a very limited increase with higher mileages. The increase in average emissions at higher mileages is largely determined by distinct high-emitters in the dataset. Note that the majority of high emissions for Euro VI vehicles only occur with mileages above the durability requirements for N2 vehicles at 300,000 km. The emissions of Euro VI-D E vehicles in general remain low, with the exception of a high-emitter before the durability requirement threshold of 700,000 km, applicable for its vehicle class.

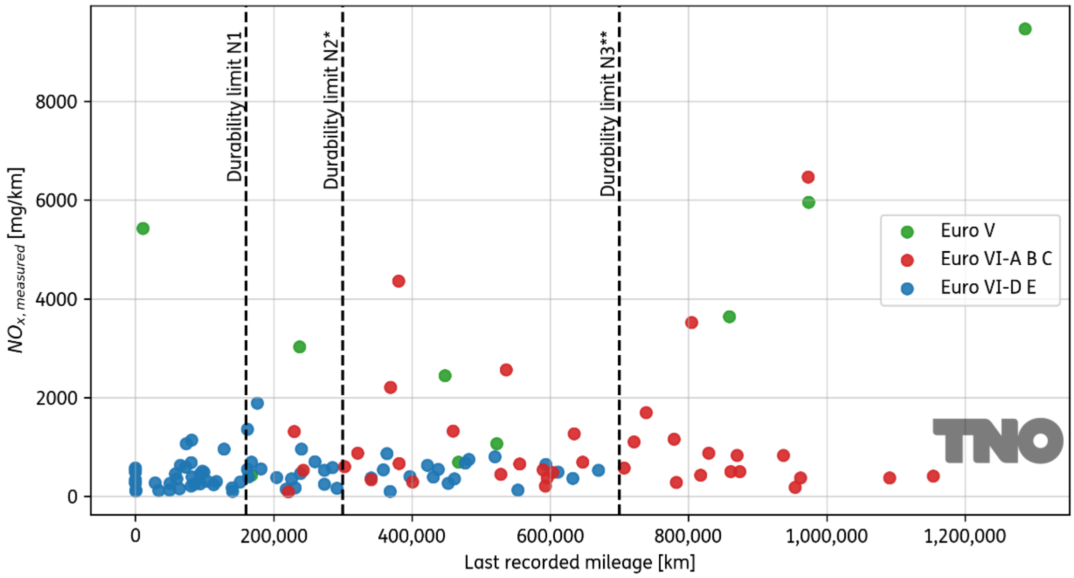

Figure 3.9: Measured NO_x-emissions and last recorded mileage of the measured heavy-duty diesel vehicles in 2024 and 2025. *Including N3 vehicles with a weight less than or equal to 16 ton. **N3 vehicles with a weight above 16 ton.

3.2 Petrol vehicles

In 2024 a total of 200 light-duty petrol vehicles were measured across different emission classes using the plume chase method. Unlike measurements on diesel vehicles, plume chase measurements on light-duty petrol vehicles are not widely discussed or validated in literature.

Apart from the measurement results presented in Paragraph 3.2.2, a stand-alone petrol validation study is briefly introduced in Paragraph 3.2.1 based on reference measurements with a PEMS equipped vehicle. The outcomes of this validation study are used in the presented results of Paragraph 3.2.2 to indicate the uncertainty ranges of the measurements for low NO_x-emission values. As plume chase measurements of light-duty petrol vehicles are still largely unproven, the presented results should be interpreted carefully and not be directly compared to acting limit values or emission factors.

3.2.1 Validation measurements

As mentioned above, in contrast to heavy-duty vehicle plume chase measurements, validation of light-duty vehicle (LDV) measurements using plume chase techniques are not widely discussed in literature. For LDV diesel vehicles, limited validations have been performed in for example [21] and [22]. However, for LDV petrol vehicle measurements, no published validation studies were found.

In order to ensure proper interpretation of the plume chase results presented in this report on light-duty petrol vehicles, a small-scale validation at TNO with a PEMS equipped petrol vehicle was organised. The outcome of this validation is briefly discussed in this paragraph as a reference for the discussion in Paragraph 3.2.2. Note that the outcome of this validation study is preliminary and only based on measurements on a single petrol vehicle with relatively low emissions.

Measurement uncertainties for plume chase measurements are expected to become larger for lower emitting vehicles due to the relatively larger influence of assumptions on background concentrations and external influences such as passing vehicles with higher emissions. Uncertainties on low emitting vehicle measurements are therefore expected to represent the worst-case values. Further research and analysis are required to determine the measurement uncertainty over a wide range of emission levels and to potentially improve measurement uncertainties for future results.

The validation was performed on a Euro 4 light-duty petrol vehicle with a mileage of 171,000 km. The validation vehicle was equipped with a portable emission measurement system (PEMS) to provide a reference on the NO_x-and CO_2-concentration emissions of the vehicle. A measurement programme was conducted on the public road to verify the correspondence of plume chase measurements with the PEMS measured emissions under various real-world conditions on both motorway and urban roads. Plume chase measurements were evaluated based on the method described in Paragraph 2.3.

Average measured emissions from plume-chasing (PC) and PEMS are shown in Figure 3.10 for individual tests. Especially for lower emissions, significant deviations in measured emissions are observed in some cases. On average, the plume chase measurements overestimate the vehicle emissions with 40 mg/km, with a maximum deviation of 75 mg/km. While the observed differences are significant, the uncertainty on emission measurement results for low-emitting vehicles is well below the difference of a clean and high-emitting vehicle. In its current state, the plume-chasing set-up for LDV petrol vehicles is therefore suitable for the identification of high-emitters on the road, but not yet suitable for the characterisation of absolute emission levels under real world conditions.

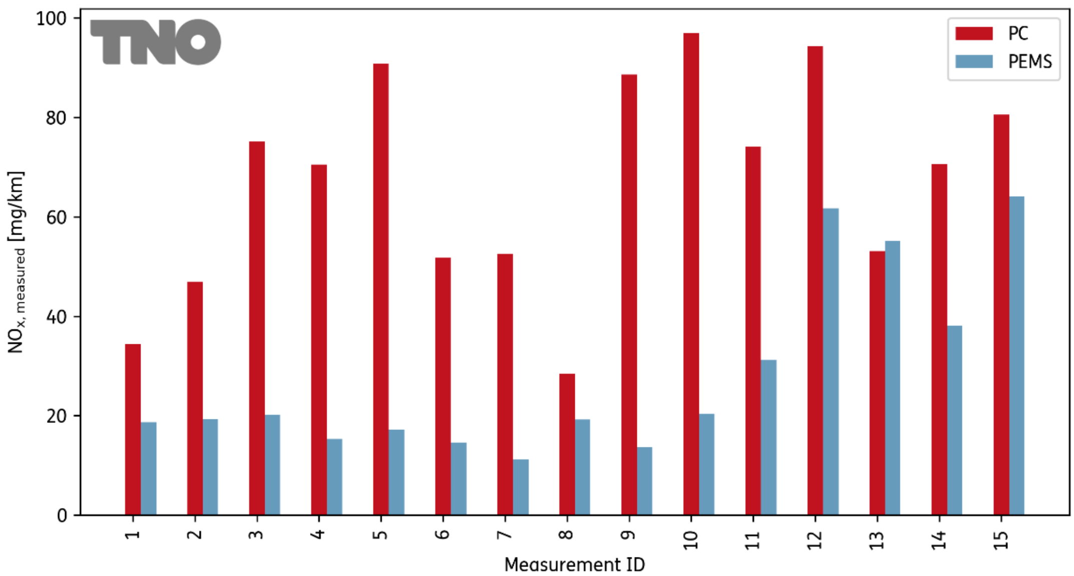

Figure 3.10: Plume Chase (PC) and PEMS NO_x-emission measurement results on different validation measurement tests performed on a Euro 4 light-duty petrol vehicle.

Potential reasons for deviations in measurement results between both techniques can be an unequal dilution of the NO_x and CO_2 gases in the exhaust plume, contamination of the measurements by other vehicles passing by, or an inaccurate NO_x and/or CO_2 background estimate, among other factors.

Especially the latter provides significant opportunities for improving the measurement uncertainty with follow-up research. Measurement uncertainties are expected to reduce significantly for higher emission levels as sensitivity to the most likely causes for deviations reduces with higher emission concentrations.

The average deviation in the validation measurements is used in the presentation of light-duty petrol results in Paragraph 3.2.2 to indicate the range in which the measured vehicle emissions most likely fall. An additional error bar is added to indicate the maximum observed absolute deviation from the validation measurements. Note that uncertainty indications are only applied to vehicles with low average emissions as no validation was performed on vehicles with higher emissions and measurement uncertainties for these measurements is expected to be lower.

Future validation studies should further investigate the assumptions on background and plume dilution to minimize the measurement uncertainties for vehicles with low emissions. In addition, the measurement uncertainty for both low and high emission levels should be determined on a larger set of measurements to increase the statistical basis for reported values.

3.2.2 Emission measurements

In total, 200 light-duty petrol passenger cars were measured in the 2024 plume chase campaign of which 16 hybrid vehicles and 184 petrol vehicles across Euro 4 to 6.
The distribution of measured vehicles over the different emission classes is shown in Table 3.3.

Table 3.3: Distribution of measured light-duty petrol vehicles to emission classes.

Euro class	Measured vehicles	Share of measurements
4	33	17%
5	45	22%
6 before RDE	52	26%
6 after RDE	70	35%

The share of measured vehicles per emission class is similar to the distribution of driven kilometres per emission class in the Dutch fleet shown in **Fout! Bladwijzer niet gedefinieerd.**. The Euro 6 vehicles are slightly oversampled (61%) in the measurements compared to the share in the total-driven-kilometres-normalised fleet. The higher number of Euro 6 vehicles in the random sampling may be attributed in part to; the additional ingrowth of Euro 6 vehicles between 2023 and 2024, to older vehicles (Euro 4 & 5) being used more often on urban roads than on the motorway as found in [14], and a high share of measurements performed close to the Randstad.

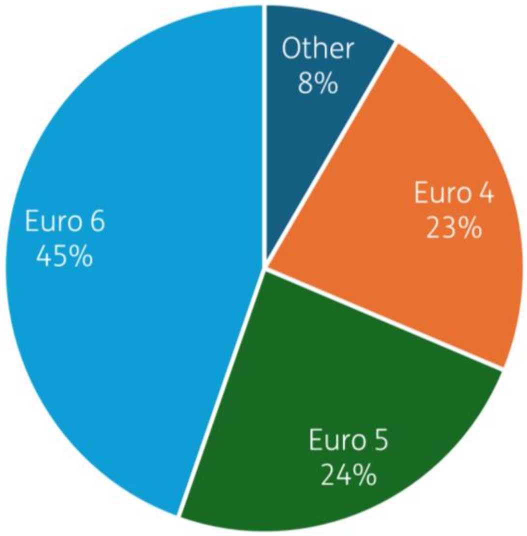

Figure 3.11: Distribution of driven kilometres per euro class of light-duty petrol vehicles in the Dutch fleet of 2023.

Individual vehicle measurements for light-duty petrol vehicles are shown in Figure 3.12. Emission measurements are shown as a coloured line based on the last registered mileage of the vehicle. The line indicates the possible emission range based on the plume chase measurement result and the average measurement uncertainty found during the validation study for low emitting petrol vehicles as described in Paragraph 3.2.1. Black error bars are added to indicate the maximum discrepancy between plume chase measurements and PEMS measurements in this validation study. Note that measurement uncertainty corrections are not applied to vehicles with higher measured emissions as the measurement uncertainty on higher emission values is expected to be significantly lower.

For all emission classes, a clear grouping of measurement results is observed around the regulatory limit value with some vehicles showing large deviations from the group emissions. Emissions of the majority of vehicles in all measured emission classes are largely similar, as is expected due to the similar regulatory limit values and use of the same exhaust gas aftertreatment technology in these vehicles. Unlike light-duty diesel vehicles, no significant differences in emissions between Euro 6 before RDE and Euro 6 after RDE vehicles is observed. While spread in emissions of Euro 4 and Euro 5 is slightly higher compared to Euro 6 measurement results, their higher average emissions can largely be explained by the occurrence of vehicles with much higher emissions.

While significant share of vehicles has measured emissions above the regulatory limit value, not all elevated measurements are indicative for a high-emitter. It is important to note that regulatory limit values are based on a standardised driving cycle under controlled conditions. For non-continuous on-road emission measurements, deviations from the regulatory limit value are expected. High-emitters should be considered as those vehicles with emissions outside of the emissions range observed for the majority of vehicle measurements. This corresponds well to a high-emitter threshold of twice the average measured emissions in the sample. Based on this definition, a high-emitter share (as weighted for the number of vehicles observed in the different vehicle emission classes) of 8% across all emission classes is determined from these measurements (not taking into account corrections for the measurement uncertainty).

It is worth noting that Euro 4 vehicles have a notably higher share of high-emitters compared to other emission class vehicles with 4 high-emitters in 33 measured vehicles (12,1%).

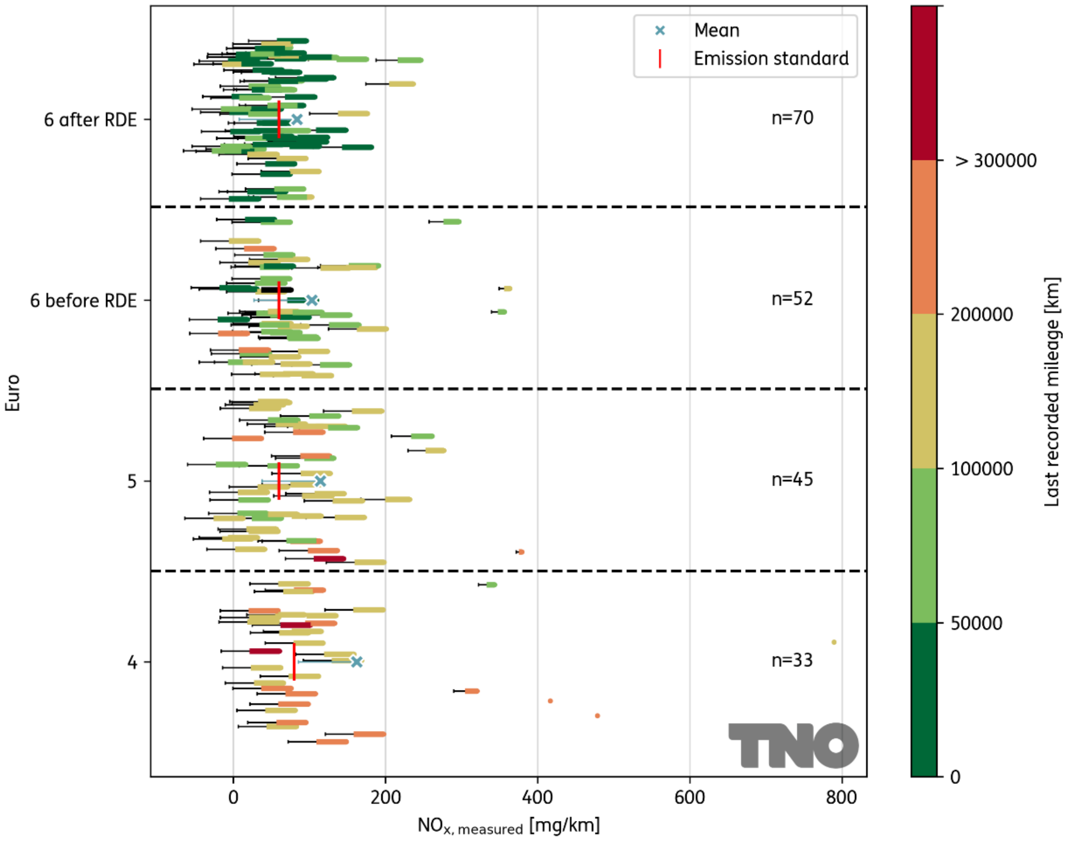

Figure 3.12: NO_x-emissions results for light-duty petrol vehicles per emission class. Each coloured line represents the estimated NO_x-emission range for a single vehicle, based on the actual measurement result and calculated uncertainty from the validation measurements. The error bar indicates the maximum discrepancy between plume-chasing and PEMS measurements from the validation data. The colour of each data line indicates the last recorded mileage of the vehicle. The average NO_x -emission and regulatory limit value per emission class are indicated for reference. The total number of vehicles measured for each emission class is denoted by n.

Ageing effects on petrol vehicles are expected to be limited compared to diesel vehicles due to a more robust emission aftertreatment technology (3-way catalyst compared to a selective catalytic reduction (SCR) system). Both in Figure 3.12 and Figure 3.13, mileage related data is shown of all individual vehicle measurements in two different formats.
In Figure 3.13, average emissions are seen to increase with higher mileages mostly related to a large share of older vehicles in this range. The increase in average emissions is largely caused by the occurrence of a higher fraction of high-emitters at higher mileages. Some high mileage Euro 4 and 5 vehicles are measured at similar levels compared to the average low mileage 'Euro 6 after RDE' vehicle, showing the used emission aftertreatment technology is capable of keeping the vehicle emissions low over time. The observation should however be made that high (~ >200 mg/km) to very high emissions (~ >400 mg/km) do occur in all emission classes even before the durability requirement threshold of 160,000 km.

These high emissions are potentially caused by poor maintenance or even removal of the exhaust gas aftertreatment system. Note that also for Euro 6 after RDE vehicles, elevated emissions are observed before the in-service conformity threshold of 100,000 km.

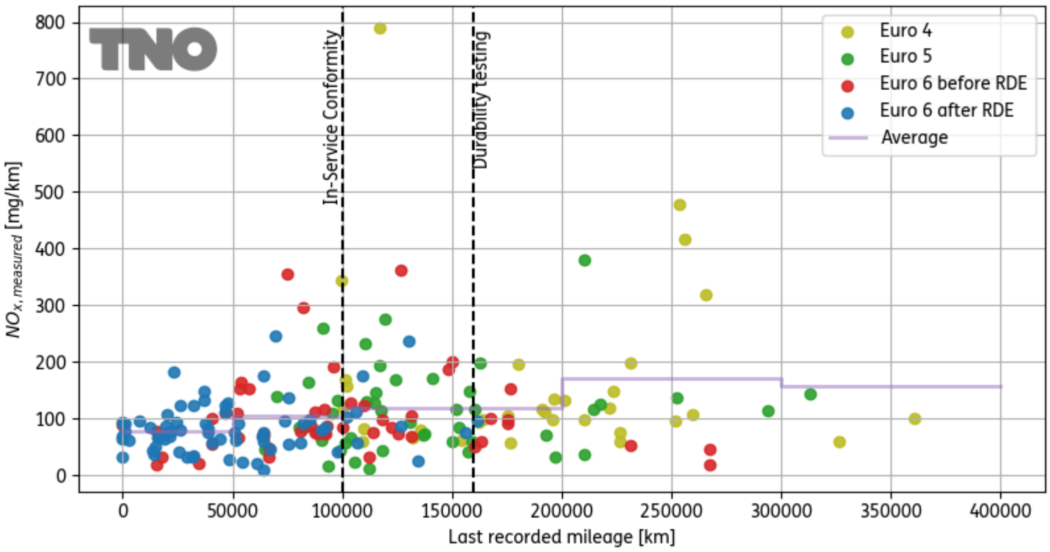

Figure 3.13: Measured NO_x-emissions and last recorded mileage of the measured light-duty petrol vehicles in 2024. Average emissions are shown as a step function between 50k, 100k, 200k, 300k+ km. The in-service conformity and durability testing mileage limit are added for reference.

Comparing the measurements performed in 2024 with the data collected in 2023 [4] shows a similar range of measured NO_x-emissions for both years, as shown in Figure 3.14. The measured NO_x-emission distributions of both years correspond reasonably well, with the average emissions measured in 2024 slightly lower than the results from 2023. More data and validation is however needed to improve the accuracy of the measurement technique and increase the statistical confidence of the average measured emissions.

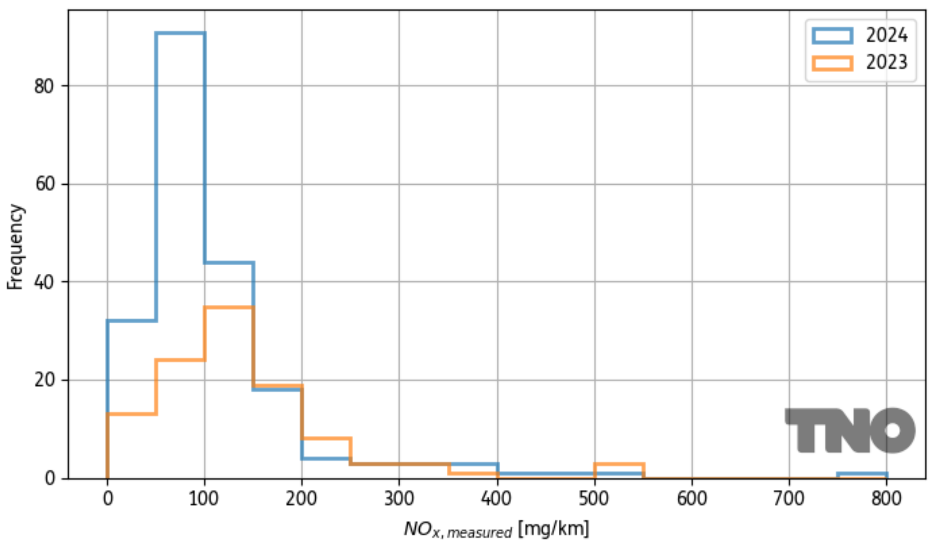

Figure 3.14: Plume-chasing NO_x-emissions results for heavy-duty petrol vehicles measured in 2023 [4] and 2024.

4 Conclusion

A plume chase measurement campaign was conducted in 2024[9] to determine the share of NO_x high-emitters in the Dutch fleet, and to obtain a first impression whether this measurement technique is suitable for investigating the absolute Dutch fleet NO_x-emissions. Only vehicles registered in the Netherlands are considered in this measurement campaign. In total 402 valid measurement records were obtained, matched to the share of vehicle types in the Dutch fleet.

From plume chase measurements on 200 light-duty petrol vehicles, an average high-emitter occurrence of 8% was found based on a selection threshold equal to twice the average measured emissions in the emission class. Vehicles of Euro 4, Euro 5 and Euro 6 emission classes show similar emission levels, but there is a higher occurrence of high-emitters at higher mileages, coinciding with a higher share of Euro 4 and Euro 5 vehicles with on average higher mileages. From a small-scale validation study of the plume chase measurement uncertainties on low emitting petrol vehicles, an average uncertainty of +40 mg/km on the measured result is found. This uncertainty is well below the difference in emissions of a high and low emitting vehicle, making the measurement method suitable for the detection of high-emitters. More research towards the improvement and validation of this measurement technique for use on petrol vehicles is however needed to verify if measurement results can be used as input for emission factors in the Dutch Emission Inventory in the future.

From plume chase measurements on 77 light-duty diesel vehicles, an average high-emitter occurrence of 7% was found based on a selection threshold equal to twice the average measured emissions in the emission class. This high-emitter share is very similar to the high-emitter share found for light-duty petrol vehicles.
No clear trend in mileage dependant emissions can be observed from the data, significant high-emitters are however observed in Euro 4 and Euro 5 vehicles before the durability requirement threshold at 160,000 km. Although only limited datapoints were measured for mileages above 300,000 km, the emissions of the majority of vehicles are seen to remain stable for mileages above 150,000 km.

Measurements on Euro 6 diesel vehicles show a clear effect on emissions with the introduction of RDE legislation for Euro 6d-Temp and newer vehicles. The spread in measured emissions and absolute emission levels is significantly reduced for these vehicles compared to Euro 6 vehicles before the introduction of RDE. While both Euro 6d-Temp and Euro 6d vehicles perform well in practice, a mismatch is observed between the measured NO_x-emissions of Euro 6d vehicles and the VERSIT+ emission factor of these vehicles in the Dutch Emission Inventory. In earlier work [16], the VERSIT+ emission factor of Euro 6d vehicles was lowered based on measurements showing very low emissions. From the results presented in this study, alignment of the Euro 6d VERSIT+ emission factor with the factor for Euro 6d-Temp vehicles may be advised. Note however that the main performance difference between Euro 6d and Euro 6d-Temp is expected at lower engine load. This does not occur under motorway driving conditions and is therefore not taken into account in the presented results.

[9] With an extension into 2025 for additional HDV measurements.

The number of plume chase measurements on heavy-duty vehicles was limited in the 2024 campaign. In total 24 vehicles were measured of which 19 Euro VI and 5 Euro V vehicles. This dataset was augmented with 96 Euro VI and 5 Euro V HDV measurements performed in the first half of 2025. The number of Euro V vehicles remains too low to provide relevant statistical observations. For Euro VI truck, a 6% high-emitter share was found based on emissions thresholds for suspicious emitters from literature [18] of 1700 mg/km. Applying the light-duty selection strategy of vehicles with more than twice the average measured emissions yields a higher high-emitter share of 9.5%. This higher share is mostly due to the low average emissions and spread in emissions for Euro VI-D E vehicles found in the measurements.

The majority of Euro VI vehicles show only a limited increase in emissions at higher mileages. However, similar to the observations for light-duty diesel vehicles, significant high-emitters are measured with mileages below the durability requirement thresholds of the different HDV categories. Emission measurements on Euro VI heavy-duty vehicles show on average lower emissions than the VERSIT+ emission factors for these vehicles. This may in part be due to the omission of foreign HDV's driving in the Netherlands with potential higher emissions in this dataset.

In 2025, this plume chase emission measurement programme has been continued. Continued measurements will add datapoints focused on Euro 6d and newer light-duty commercial diesel vehicles and Euro VI (and newer) heavy-duty diesel vehicles to the dataset discussed in this report. For heavy-duty vehicles also foreign vehicles traveling on Dutch motorways will be considered. Further developments could also be made to include a wider range of pollutant emission measurements to the measurement programme. Currently, research is being conducted towards the identification high particle number (PN) emissions due to faulty diesel particulate filters in light- and heavy-duty vehicles. After validation this technique may also be useful in the detection of petrol vehicle PN-high-emitters.

Additional data points are needed to increase the statistical basis for conclusions and recommendations towards the identification of Euro 6d and newer LDV and Euro VI and newer HDV diesel NO_x-high-emitters. Additional validations on diesel light- and heavy-duty vehicles, both on high and low emitting vehicles, are also desirable to determine measurement uncertainties on measured diesel NO_x-emissions. These uncertainties are especially relevant before updates can be made to the emission factors in the Dutch Emission Inventory with plume chase results.

Petrol plume chase results are shown to be useful in determining high-emitter shares in the fleet under real world conditions. However, plume chase measurements on light-duty petrol vehicles should be further developed and validated to verify the suitability of this measurement method for the characterization of petrol vehicle emissions under real world conditions.

References

[1] G. Kadijk, M. Elstgeest, G. Q. Vroom, M. Paalvast, N. E. Ligterink and P. J. v. d. Mark, "On road emissions of 38 petrol vehicles with high mileages.," TNO, The Hague, 2020.

[2] G. Kadijk, M. Elstgeest, N. Ligterink and P. v. d. Mark, "Emissions of twelve petrol vehicles with high mileages.," TNO, The Hague, 2018.

[3] J. Borken-Kleefeld, Y. Bernard, N. Farren, A. Hallquist, N. Ligterink, D. Pöhler, C. Rushton and M. Knoll, "D4.8 - Final Report on High-emitter & clean vehicle identification," CARES, Laxenburg, 2023.

[4] G. Q. Vroom, N. E. Ligterink, S. Spijker, M. R. Kranendonk, V. E. Verhagen and J. M. d. Ruiter, "NO_x high emitters in the Dutch fleet. Characterizing the problem and researching methods for recognizing petrol high emitters," TNO, The Hague, 2024.

[5] T. Sano, M. Suzuki, M. Watanabe, S. Yoshida, Y. Yui-Yamashita, S. Okumura, K. Shibasaki, A. Kuze, T. Kawashima and T. Ogawa, "Instrument design of Ozone and Pollution measuring Ultraviolet Spectrometer (OPUS)," in *IEEE International Symposium on Geoscience and Remote Sensing*, Toronto, 2002.

[6] k. Ropkins, T. H. DeFries, F. Pope, D. C. Green, J. Kemper, S. Kishan, G. W. Fuller, H. Li, J. Sidebottom, L. R. Grilley, L. Kramer, W. J. Bloss and J. S. Hager, "Evaluation of EDAR vehicle emissions remote sensing technology," *Science of The Total Environment,* vol. 609, pp. 1464-1474, 2017.

[7] y. Chen, Y. Zhang and J. Borken-Kleefeld, "When is Enough? Minimum Sample Sizes for On-road Measurements of Car Emissions.," *Environmental Science & Technology,* vol. 53, no. 22, pp. 13284-13292, 2019.

[8] C. Schmidt, D. Pöhler, S. Schmitt, U. Platt, Q. Vroom, N. E. Ligterink, N. J. Farren, D. C. Carslaw and Å. Sjödin, "Towards better air quality using the plume chasing method: validation studies of real driving NO_x-emission measurements of vehicles," *Transportation Research Procedia,* vol. 72, pp. 1848-1854, 2023.

[9] G. A. Bischop and D. H. Stedman, "Measuring the Emissions of Passing Cars," *Accounts of Chemical Research,* vol. 29, no. 10, pp. 489-495, 1996.

[10] D. Pöhler, T. Engel, U. Roth, J. Reber, M. Horbanski, J. Lampel and U. Platt, "NOx RDE measurements with Plume Chasing - Validation, detection of high emitters and manipulated SCR systems.," in *23th Transport and Air Pollution Conference*, Thessaloniki, 2019.

[11] Z. Tong, Y. Li, Q. Lin, H. Wang, S. Zhang, Y. Wu and K. M. Zhang, "Uncertainty investigation of plume-chasing method for measuring on-road NOx emission factors of heavy-duty diesel vehicles," *Journal of Hazardous Materials,* p. 127372, 2022.

[12] J. d. Ruiter, R. v. Gijlswijk and N. Ligterink, "Model M1: estimation of the real-world CO2 emissions of passenger cars based on vehicle properties," TNO, The Hague, 2021.

[13] G. Geilenkirchen, M. Bolech, J. Hulskotte, S. Dellaert, N. Ligterink, E. v. Eijk, K. Geertjes, M. Kosterman and M. '. Hoen, "Methods for calculating the emissions of transport in the Netherlands," RIVM, Bilthoven, 2024.

[14] N. E. Ligterink, "The fleet composition on the Dutch roads relevant for vehicle emissions," TNO 2017 R10517, The Hague, 2017.

[15] H. Witt, G. Geilenkirchen, M. Bolech, S. Dellaert, E. van Eijk, K. Geertjes and M. Kosterman, "Methodology for the calculation of emissions from the transport sector," RIVM, Bilthoven, 2025.

[16] P. van Mensch, M. Elstgeest, N. E. Ligterink, J. de Ruiter, A. Indrajuana and P. J. van der Mark, "Dutch In-service Emissions Measurement Programme for Light-Duty Vehicles 2021 and status of in-vehicle NO_x monitoring.," TNO, The Hague, 2022.

[17] M. Rexeis, M. Röck and S. Hausberger, "Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe," International council on clean transportation, Washington, 2018.

[18] D. Pöhler, C. Schmidt, M. Horbanski, S. Schmitt and J. Lampel, "Identification of Manipulated & Defective Truck NO_x Emission Reduction Systems with Plume Chasing for Authority Inspections," *Transportation Research Procedia,* vol. 72, pp. 1661-1668, 2023.

[19] D. Pöhler, "HDV (Heavy Duty Vehicles) emission measurement with "Plume Chasing" and subsequent inspection of high emitters," Flanders Environmental Agency, Aalst, 2022.

[20] J. Janssen and N. Hagberg, "Plume Chasing - A way to detect high NOx emitting vehicles," Danisch Road Traffic Authodity, 2019.

[21] C. Schmidt, D. C. Carslaw, J. N. Farren, R. N. Giijlswijk, M. Knoll, E. N. Ligterink, J. P. Lollinga, M. Pechout, S. Schmitt, M. Vojtisek, Q. Vroom and D. Pöhler, "Optimisation and validation of Plume Chasing for robust and automated NOx and particle vehicle emission measurements.," *Atmospheric Environment: X,* vol. 25, p. 100317, 2025.

[22] P. Simonen, J. Kalliokoski, P. Karjalainen, T. Rönkkö, H. Timonen, S. Saarikoski, M. Aurela, M. Bloss , G. Triantafyllopoulos, A. Kontses, S. Amanatidis, A. Dimaratos, Z. Samaras, J. Keskinen, M. Dal Maso and L. Ntziachristos, "Characterization of laboratory and real driving emissions of indicvidual Euro 6 light-duty vehicles - Fresh particles and secondary aerosol formation," *Environmental Pollution,* vol. 255, p. 113175, 2019.

[23] Rijksdienst voor wegverkeer, "APK handboek - Geluid en milieu," RDW, [Online]. Available: https://apk-handboek.rdw.nl/personenautos/motor/geluid-en-milieu. [Accessed 04 2025].

[24] T. Dallmann, Y. Bernard, U. Tietge and R. Muncrief, "Remote sensing of motor," The real urban emissions initiative, 2019.

[25] R. Smit, R. Smokers and E. Rabé, "A new modeling approach for road traffic emissions: VERSIT+," *Journal of Transporation Research Part D,* vol. 12, pp. 414-422, 2007.

[26] J. de Ruiter, A. Indrajuana, M. Elstgeest, R. van Gijlswijk, N. Ligterink and P. Tilanus, "D1.2 Augmented emission maps are an essential new tool to share and investigate detailed emission data.," uCARe, The Hague, 2021.

Signature

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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	

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